

Structured Probabilistic Modelling for Dialogue Management

Doctoral Dissertation by

Pierre Lison



Department of Informatics
Faculty of Mathematics and Natural Sciences
University of Oslo

Submitted for the degree of Philosophiae Doctor

30th October 2013

“Probability theory is nothing but common
sense reduced to calculation.”

Pierre Simon de Laplace.
Théorie Analytique des Probabilités (1812).

Abstract

This thesis presents a new modelling framework for dialogue management based on the concept of *probabilistic rules*. Probabilistic rules are defined as *if...then...else* constructions associating logical conditions on input variables to probabilistic effects over output variables. These rules function as high-level templates for the generation of a directed graphical model. Their expressive power allows them to represent the probabilistic models employed in dialogue management in a compact and efficient manner. As a consequence, they can drastically reduce the amount of interaction data required for parameter estimation as well as enhance the system’s ability to generalise over unseen situations. Furthermore, probabilistic rules can also be exploited to encode domain-specific constraints and assumptions into statistical models of dialogue, thereby enabling system designers to incorporate their expert knowledge of the problem structure in a concise and human-readable form. Due to their integration of logical and probabilistic reasoning, we argue that probabilistic rules are particularly well suited to devise hybrid models of dialogue management that can account for both the complexity and uncertainty that characterise many dialogue domains.

The thesis also demonstrates how the parameters of probabilistic rules can be efficiently estimated using both supervised and reinforcement learning techniques. In the case of supervised learning, the rule parameters are learned by imitation on the basis of small amounts of Wizard-of-Oz data. Alternatively, rule parameters can also be optimised via trial and error from repeated interactions with a (real or simulated) user. Both learning strategies rely on Bayesian inference to iteratively estimate the parameter values and provide the best fit for the observed interaction data. Three consecutive experiments conducted in a human–robot interaction domain attest to the practical viability of the proposed framework and its advantages over traditional approaches. In particular, the empirical results of a user evaluation with 37 participants show that a dialogue manager structured with probabilistic rules outperforms both purely hand-crafted and purely statistical methods on an extensive range of subjective and objective metrics of dialogue quality.

The modelling framework presented in this thesis is implemented in a new software toolkit called OpenDial, which is made freely available to the research community and can be used to develop various types of dialogue systems based on probabilistic rules.¹

¹The toolkit is released under an open source license and can be downloaded at: <http://opendial.googlecode.com>.

Acknowledgements

The present thesis is the product of five years of work. Many of the ideas behind this dissertation were first sketched during my employment at the DFKI Language Technology Lab in Saarbrücken (from 2008 to 2010), and then further developed upon starting a PhD at the Department of Informatics of the University of Oslo (from 2011 until now). Needless to say, this project could not have been completed without the help and support of the many people that have accompanied me on this long research journey.

My first thanks go to my thesis supervisors: Stephan Oepen, Erik Velldal and Geert-Jan M. Kruijff. Their guidance and encouragements on my research work have been invaluable. They also contributed with numerous advices on several revisions of this dissertation and played a key role in helping me improve the form and content of the final draft. I am particularly grateful to Stephan and Erik for welcoming me to the Language Technology Group (LTG) and for accepting to supervise a thesis topic which ventured outside the group’s traditional areas of expertise. I am equally indebted to Geert-Jan, who was my research supervisor while working at DFKI and kindly accepted to serve as co-supervisor of this thesis when I relocated to Oslo and enrolled in the PhD program there. Geert-Jan also taught me a lot about how to conduct research, write papers, give talks, and participate in large collaborative projects.

I naturally want to thank my colleagues for the great working environment and friendly atmosphere during all these years. I especially wish to express my gratitude to all my LTG workmates for making me feel welcome and part of this fantastic group from day one. Their competence in multiple areas of natural language processing also helped me broaden my research interests and pique my curiosity for other fields of investigation. Likewise, I want to thank my previous colleagues at DFKI for their friendliness and for many inspiring discussions on dialogue systems and human–robot interaction that contributed to shaping the direction of this thesis. My former project partners from the EU-funded projects CogX and ALIZ-E also deserve a special mention for enlightening me on many aspects of software engineering and cognitive robotics.

The thesis greatly benefited from exchanges with other international researchers, and in particular with the regular participants to the “Young Researchers’ Roundtable on Spoken Dialogue Systems” (YRRSDS) organised every year to foster discussions and collaborations between young researchers working in this exciting field. I enjoyed many stimulating discussions with Timo Baumann, Nina Dethlefs, Jana Götze, Matt Henderson, Srinivas Janarthanam, Casey Kennington, Alejandra Lorenzo, Raveesh Meena, Lina Rojas, Ethan Selfridge and William Yang Wang on various topics related to dialogue processing. I would especially like to thank Timo, Casey, Matt, Raveesh and Nina for accepting to read through parts of my thesis draft. I am similarly indebted to Amanda Stent and Heriberto Cuayáhuatl for their insightful feedback on several of my conference papers.

As any researcher in robotics will tell you, working with real robots can be at times a frustrating

experience and brings a host of low-level technical challenges, from broken motors and defective sensors to countless software integration issues. I was fortunate to conduct my experiments with the Nao robot from Aldebaran Robotics. I am grateful to the Department of Informatics for allowing us to acquire this robot and to Aldebaran Robotics for making available this excellent robotic platform and for always going the extra mile when it comes to technical support. I also wish to acknowledge the support of the NOTUR high-performance computing facilities employed for our simulation studies. Finally, I want to thank all the participants in the Wizard-of-Oz trials and the user evaluation, as none of the experiments presented in this thesis would have been remotely possible without their active contribution.

Last but certainly not least, I am without words to thank my wife and life partner, Caroline, for all her love and support through the years, and for being the reason I moved to Norway in the first place. Thank you for everything.

Pierre Lison
Oslo, 30th October 2013.

Typesetting of this thesis

The thesis is written with \LaTeX 2_ε based on a document layout prepared by the University of Oslo. The bibliographical references are generated with $\text{\BIB}\text{\TeX}$. The keyword index at the end of this dissertation is produced with the help of `makeindex`. The diagrams and data plots are drawn using Apple's *Pages* and *Numbers* productivity tools, while the mathematical figures are rendered with the *MATLAB* numerical computing environment.

Contents

1	Introduction	1
1.1	Motivation	1
1.2	Contributions	3
1.3	Outline of the thesis	6
2	Background	9
2.1	What is spoken dialogue?	9
2.1.1	Turn-taking	10
2.1.2	Dialogue acts	11
2.1.3	Interpretation of dialogue acts	12
2.1.4	Grounding	14
2.2	Spoken dialogue systems	16
2.2.1	Architectures	16
2.2.2	Components	19
2.2.3	Applications	22
2.3	Dialogue management	23
2.3.1	Hand-crafted approaches	23
2.3.2	Statistical approaches	25
2.4	Summary	29
3	Probabilistic models of dialogue	33
3.1	Graphical models	33
3.1.1	Representations	34
3.1.2	Inference	38
3.1.3	Learning	39
3.2	Reinforcement learning	43
3.2.1	Markov Decision Processes	44
3.2.2	Partially Observable Markov Decision Processes	46
3.2.3	Factored representations	49
3.3	Application to dialogue management	50
3.3.1	Supervised approaches	50
3.3.2	MDP dialogue policies	50
3.3.3	POMDP dialogue policies	53
3.4	Summary	56

4	Probabilistic rules	59
4.1	Structural leverage	59
4.2	Formalisation	62
4.2.1	Probability rules	63
4.2.2	Utility rules	65
4.2.3	Quantification	67
4.3	Rule instantiation	68
4.3.1	Probability rules	69
4.3.2	Utility rules	71
4.3.3	Quantification	74
4.4	Processing workflow	77
4.4.1	Domain representation	77
4.4.2	Update algorithm	77
4.4.3	Detailed example	82
4.5	Advanced modelling	85
4.5.1	Operations on lists	85
4.5.2	Operations on strings	86
4.6	Relation to previous work	86
4.7	Conclusion	88
5	Learning from Wizard-of-Oz data	91
5.1	Parameters of probabilistic rules	91
5.1.1	General methodology	91
5.1.2	Parameter priors	93
5.1.3	Instantiation	96
5.2	Supervised learning of rule parameters	98
5.2.1	Wizard-of-Oz training data	98
5.2.2	Learning cycle	99
5.3	Experiments	102
5.3.1	Dialogue domain	103
5.3.2	Wizard-of-Oz data collection	104
5.3.3	Experimental setup	109
5.3.4	Empirical results and analysis	111
5.4	Conclusion	113
6	Learning from interactions	115
6.1	Bayesian reinforcement learning	115
6.2	Optimisation of rule parameters	118
6.2.1	Model-based approach	118
6.2.2	Model-free approach	123
6.3	Experiments	126
6.3.1	Dialogue domain	126
6.3.2	Simulator	127
6.3.3	First experiment	135

6.3.4	Second experiment	138
6.4	Conclusion	139
7	Implementation	143
7.1	Toolkit design	143
7.1.1	Generalities	143
7.1.2	Specification of dialogue domains	145
7.1.3	Core algorithms	147
7.1.4	Comparison with other architectures	150
7.2	System integration	153
7.2.1	Architecture	153
7.2.2	Individual modules	154
7.2.3	Graphical interface	157
7.3	Conclusion	158
8	User evaluation	161
8.1	Interaction scenario	161
8.1.1	Dialogue domain	162
8.1.2	System architecture	163
8.1.3	Wizard-of-Oz data collection	166
8.2	Dialogue management models	168
8.2.1	Approach 1: hand-crafted model	168
8.2.2	Approach 2: factored statistical model	171
8.2.3	Approach 3: rule-structured model	174
8.2.4	Learning curves	175
8.3	User trials	176
8.3.1	Experimental setup	176
8.3.2	Results	178
8.3.3	Discussion	183
8.4	Conclusion	185
9	Concluding remarks	187
9.1	Summary of contributions	187
9.2	Future work	190
A	Relevant probability distributions	193
B	Domain specifications	199
B.1	Experiments in Section 5.3	199
B.2	Experiments in Section 6.3	200
B.3	Experiments in Chapter 8	204
	Bibliography	213
	Index	233

Mathematical notations

Probability distributions:

X	Random variable
$Val(X)$	Range of values for the random variable X
$P(X)$	Probability distribution for the random variable X
$P(X_1, \dots, X_n)$	Joint probability distribution for X_1, \dots, X_n
$P(X_1, \dots, X_n \mid Y_1, \dots, Y_m)$	Conditional distribution for X_1, \dots, X_n given Y_1, \dots, Y_m
$E(X)$	Expectation of the random variable X
$P(\mathbf{X} \mid \mathbf{e})$	Posterior distribution of variables \mathbf{X} given evidence \mathbf{e}
$U(\mathbf{X} \mid \mathbf{e})$	Expected utility of variables \mathbf{X} given evidence \mathbf{e}
θ_X	Parameters associated with the random variable X
$P(X; \theta_X)$	Probability of X given the parameters θ_X

Graphical models:

\mathcal{B}	Bayesian network
$P_{\mathcal{B}}(X)$	Probability distribution for X in the Bayesian network \mathcal{B}
$(\mathbf{X} \perp \mathbf{Y} \mid \mathbf{Z})$	Conditional independence of variables \mathbf{X} and \mathbf{Y} given \mathbf{Z}
$Y \rightarrow X$	Directed edge from variable Y to variable X
$parents(X)$	Parents of X such that $Y \rightarrow X$ for all $Y \in parents(X)$

Reinforcement learning:

s	Current state
\mathcal{S}	Set of possible states
a	System action
\mathcal{A}	Set of possible actions
$R(s, a)$	Immediate reward of action a in state s
γ	Discount factor
h	Planning horizon
$V(s)$	Value function for state s
$Q(s, a)$	Action–value function for action a in state s
o	Observation
b	Belief state $b(s) = P(s)$
$V(b)$	Value function for belief state b
$Q(b, a)$	Action–value function for action a in belief state b
π	(PO)MDP dialogue policy

Dialogue-specific variables:

u_u	Last user utterance
\tilde{u}_u	Speech recognition hypotheses for user utterance
a_u	Last user dialogue act
\tilde{a}_u	Speech understanding hypotheses for user dialogue act
i_u	Current user intention
a_m	System dialogue act
u_m	System utterance

Probabilistic rules:

\mathcal{B}	Dialogue state expressed as a Bayesian network
r	Probabilistic rule
c_i	i -th condition of a rule
$e_{(i,j)}$	j -th effect for condition c_i
$p_{(i,j)}$	Probability of effect $e_{(i,j)}$
I_1, \dots, I_k	Set of input variables of a rule
O'_1, \dots, O'_l	Set of output variables of a probability rule
D'_1, \dots, D'_l	Set of decision variables of a utility rule
\mathbf{e}	Conjunction of effects $e_1 \wedge \dots \wedge e_n$
$\mathbf{e}(X)$	(Possibly empty) set of values for variable X in \mathbf{e}
\mathbf{y}	Universally quantified variables of a rule
\mathbf{g}	Possible grounding for the quantified variables \mathbf{y}
X^p	Prior on future variable X

Miscellaneous:

$\mathbf{1}(\phi)$	Indicator function: $\mathbf{1}(\phi) = 1$ if ϕ is true and 0 otherwise
$\phi[a/b]$	Formula ϕ where occurrences of a are replaced by b

Chapter 1

Introduction

Spoken language is one of the most powerful systems of communication at our disposal. A large part of our waking hours is spent in social interactions mediated through natural language. The central role of spoken language in our daily lives is largely due to its remarkable ability to convey (sometimes highly elaborate) ideas in a robust and efficient manner.

Is it possible to exploit this basic fact to develop more user-friendly technologies? Most of our everyday activities are now relying on “smart” electronic devices of various kinds, from mobile phones to personal computers and navigation systems. As these technologies gain in autonomy and sophistication, the design of appropriate user interfaces becomes increasingly important. Human–computer interfaces should provide the user with rich and flexible communication channels while remaining easy to understand and control. One natural way to achieve this goal is to endow computers with a capacity to understand, even if in a limited manner, the medium of information exchange that is most intuitive to human beings, namely spoken language.

The ongoing research on *spoken dialogue systems* (SDS) is precisely trying to realise this objective. A spoken dialogue system is a computational agent that can converse with humans through everyday spoken language. Such systems are expected to play an ever-increasing role in our interactions with technology. They have a wide spectrum of applications, ranging from voice-enabled mobile applications to in-car navigation assistants, smart home environments, tutoring systems, and (in a not-too-distant future) service robots assisting us in our daily chores.

Figure 1.1 depicts an example of interaction between a human user and a spoken dialogue system. When the user starts talking, the system extracts the corresponding speech signal through a microphone. The speech signal is then processed to analyse its content. Once this analysis is completed, the system must determine how to react. In this case, the system decides to greet back the user and selects the words to express it (“*good morning, sir*”). The final step is to synthesise these words through an artificial voice, which closes the loop.¹

1.1 Motivation

Although spoken dialogue systems can greatly enhance the user interaction experience in many of today’s technologies, their practical development can be a demanding enterprise. Speech is indeed much more complex than other types of (e.g. graphical or touch-based) user interfaces.

¹ Needless to say, the schema hides a great deal of internal complexity. The next chapter describes in more detail the software architectures used to design practical spoken dialogue systems.

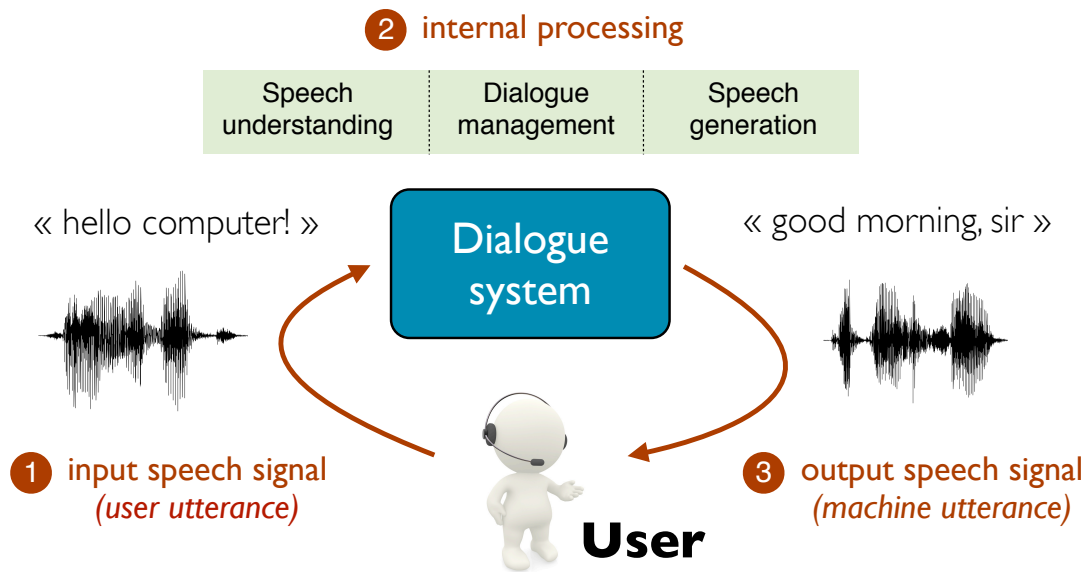


Figure 1.1: Schematic view of a spoken dialogue system.

The present thesis concentrates on the problem of *dialogue management*. Dialogue management is a central component in dialogue systems and lies at the crossroads between language understanding and generation. It serves a double role. Its first function is to maintain a representation of the current dialogue state. This representation reflects the system knowledge of the current conversational situation, and often includes multiple variables related to the dialogue history, the external context, and the tasks to perform. This dialogue state is regularly updated with new information in the form of new user utterances or changes in the external context.

The second function of dialogue management is to make decisions. Based on the current dialogue state, dialogue management must decide which actions to undertake. Dialogue management is thus in charge of controlling the flow of the interaction by (1) interpreting the user intentions in their context and (2) selecting which actions to perform given this context. In the example from Figure 1.1, this step corresponds to the decision of responding to the user utterance “*hello computer!*” with another greeting action, “*good morning, sir*”. The actions selected by the dialogue manager can be both verbal (e.g. uttering a sentence) or non-verbal (e.g. making a gesture).

Along with speech recognition, dialogue management is arguably one of the most difficult processing tasks in spoken dialogue systems. This difficulty stems from two defining characteristics of verbal interactions:

1. Verbal interactions are *complex*. Taking part in a dialogue requires tracking a multitude of factors, such as the interaction history, the hypothesised goals and preferences of the dialogue participants, and the external context. These factors depend on one another through multiple relations straddling the linguistic and extra-linguistic boundaries. Selecting the action that is most appropriate in a particular situation is thus a difficult decision problem.
2. Verbal interactions are also riddled with *uncertainties*. In order to make sense of a given dialogue, a conversational agent must handle numerous sources of uncertainty, including error-prone speech recognition, lexical, syntactic and referential ambiguities, partially observable environments, and unpredictable interaction dynamics.

The combination of these two properties leads to a particularly challenging task. In order to make sense of the interaction and act appropriately, the dialogue system must resort to sophisticated reasoning in order to interpret the user intentions in their context and plan the best course of action. And it must do so under high levels of noise and uncertainty, where many pieces of information can be erroneous, missing, ambiguous, or fragmentary. This task is an instance of *sequential decision-making under uncertainty*, which is known to be one of the most perplexing problems in artificial intelligence. Decision-making and action execution must also occur in real-time, since dialogue is by nature a real-time process.

Research on dialogue management can be divided into two main lines of investigation that reflect their focus on either of the two challenges we just mentioned.

On the one hand, structural complexity is often dealt with using conceptual tools borrowed from formal logic and classical planning. These approaches provide principled methods for the interpretation and generation of dialogue moves through logical reasoning on the basis of a formal representation of the mental states of the dialogue participants (including their shared knowledge). Based on such representations, dialogue is then framed as a collaborative activity in which the dialogue participants work together to coordinate their actions, maintain a shared conversational context, resolve open issues and satisfy social obligations (Allen et al., 2000; Larsson, 2002; Jokinen, 2009). These approaches can yield detailed analyses of various conversational behaviours, but they generally assume complete observability of the dialogue state and provide only a limited account of errors and uncertainties. In addition, the knowledge base on which the inference is grounded must be completely specified in advance by domain experts. Their deployment in practical applications is therefore non-trivial.

On the other hand, the problem of uncertainty is usually addressed by probabilistic modelling techniques (Roy et al., 2000; Frampton and Lemon, 2009; Young et al., 2010). The state of the dialogue is here represented as a probability distribution over possible worlds. This distribution represents the system’s current knowledge of the interaction and is regularly updated as new observations are collected. These probabilistic models provide an explicit account for the various uncertainties that can arise during the interaction. They also enable the dialogue behaviour to be automatically optimised in a data-driven manner instead of relying on hand-crafted mechanisms. Dialogue strategies can therefore be adapted to new environments or users without having to be re-programmed. However, probabilistic models typically depend on large amounts of training data to estimate their parameters – a requirement that is hard to satisfy for many dialogue domains. Probabilistic models of dialogue are also usually limited to a handful of state variables and are difficult to scale to domains featuring more elaborate conversational contexts.

The work described in this thesis aims at reconciling these two strands of research through a new, hybrid framework to dialogue modelling and control.

1.2 Contributions

The present thesis develops an original approach to dialogue management based on *structured probabilistic modelling*. The overarching motivation for this work is to design probabilistic models of dialogue that are scalable to rich interaction domains, yet only necessitate modest amounts of training data for their statistical optimisation.

An extensive body of work in the machine learning and decision-theoretic planning literature

shows how to confront this issue by relying on more expressive representations, able to capture relevant aspects of the problem *structure* in a compact manner. By taking advantage of hierarchical or relational abstractions, system designers can leverage their domain knowledge to yield probabilistic models which are both easier to learn (due to a reduced number of parameters) and more efficient to use (since the structure can be exploited by inference algorithms).

This thesis demonstrates how to transfer these insights into dialogue modelling. The three central research questions of this thesis are:

1. How can we integrate prior domain knowledge into probabilistic models of dialogue?
2. How can the parameters of these structured probabilistic models be estimated from data, using methods from supervised and reinforcement learning?
3. What is the empirical effect of such modelling techniques on the quality and efficiency of verbal interactions?

Probabilistic graphical models (Koller and Friedman, 2009) constitute the theoretical foundations for a large part of our work. Graphical models provide a generic, principled framework for representing and reasoning over complex probabilistic problems. They also come with well-defined data structures and general-purpose algorithms for model estimation and inference. As shown in previous work (see for instance Thomson and Young, 2010), one can elegantly represent the dialogue state as a Bayesian network (a well-known type of directed graphical model) factored in a set of state variables describing various aspects of the conversational situation. The dialogue state is graphically depicted as a directed acyclic graph where the nodes correspond to particular variables while the edges denote conditional dependencies between variables. To exploit such a representation for decision-making tasks, the dialogue state can be extended with action and utility nodes that describe the utility for the agent of performing particular actions in a given situation.

Statistically speaking, the estimation of such complex probabilistic structures is, however, a difficult endeavour, owing to the large number of variables and dependencies involved. The main novelty of our approach is the idea of representing the model distributions in a structured manner through the use of *probabilistic rules*. Probabilistic rules encode conditional distributions between variables in terms of structured mappings that associate conditions expressed on a set of input variables to probabilistic effects on a set of output variables. The conditions and effects of probabilistic rules are defined as logical formulae, thereby allowing complex relationships between variables to be expressed in a concise and human-readable form. Utility distributions can also be specified in a similar formalism. As new information becomes available to the dialogue manager, the Bayesian network representing the current dialogue state is updated by instantiating the rules in the form of new nodes mediating between the input and output variables. Probabilistic rules are therefore employed as *high-level templates* for the generation of a classical probabilistic model.

The resulting modelling framework offers two major benefits. Most importantly, the reliance on more expressive representations can drastically reduce the number of parameters associated with the models. Instead of being encoded through traditional probability tables, the conditional distributions between state variables are expressed through high-level rules that capture conditional dependencies with a compact set of parameters (one for each possible effect). As a consequence, these models are much easier to learn and generalise to unseen data. In addition, the framework enables expert knowledge to be directly integrated in the probabilistic dialogue models. System

developers can therefore exploit powerful abstractions to encode their prior knowledge of the dialogue domain in the form of pragmatic rules or domain-specific assumptions. While the usefulness of such constraints has long been recognised, their use has most often been reduced to a mere external filter for classical statistical models (Heeman, 2007; Williams, 2008b). By contrast, our approach incorporates these knowledge sources in the very structure of the statistical model.

We conducted several experiments to assess the viability of our approach in three distinct learning scenarios:

1. The first experiment focused on the problem of estimating action utilities given a small data set collected from Wizard-of-Oz interactions.² Based on dialogue models encoded with probabilistic rules, the utilities of the different actions were learned through imitation learning. The experiment showed that the rule structure enabled the learning algorithm to converge faster and with better generalisation performance than unstructured models. This work was originally presented in Lison (2012d).
2. The second experiment extended the above approach to reinforcement learning. The goal of this study was to estimate the transition model of the domain from interactions with a user simulator. We compared the relative learning performance of two modelling approaches: one relying on unstructured distributions, and one based on probabilistic rules. The empirical results demonstrated the benefits of capturing the domain structure with probabilistic rules. The results were initially published in Lison (2013).
3. The third and final experiment was designed to evaluate the empirical effect of our modelling framework through a user evaluation in a human–robot interaction domain. The experiment compared three alternative dialogue management methods: a purely hand-crafted approach (based on a finite-state automaton), a purely statistical approach (based on factored models) and a hybrid approach based on probabilistic rules. The rule-structured approach was shown to outperform the two baseline strategies on a broad range of quality metrics, including both objective metrics extracted from the interaction logs and subjective metrics derived from responses to a user survey.

An additional contribution of this thesis is the development of a software toolkit that implements all the data structures and algorithms presented in this work. The toolkit is called *OpenDial* and is made freely available to the research community under an open source licence.³ The purpose of the toolkit is to enable system developers to design and evaluate dialogue systems based on probabilistic rules. All domain-specific knowledge is declaratively specified in the probabilistic rules for the domain. The system architecture is therefore reduced to a core set of generic algorithms for accessing, updating and reasoning over the dialogue state (Lison, 2012a). The *OpenDial* toolkit comes with a user interface allowing system developers to interactively test their dialogue models and visualise how the dialogue state is evolving over time.

²A Wizard-of-Oz interaction is an experimental procedure borrowed from the field of human–computer interaction (Dahlbäck et al., 1993). In a Wizard-of-Oz study, the human subjects are asked to interact with a computer system that has all the appearances of reality, but is actually remotely controlled by an (unseen) human agent. Wizard-of-Oz studies are often conducted to provide the system designers with interaction data from real users before the system is fully implemented. The term is a cultural reference from the 1939 film “The Wizard of Oz” where an illusionist impersonates a powerful wizard by controlling an intimidating display from behind a curtain.

³The toolkit can be downloaded at <http://opendial.googlecode.com>.

The experiments described in this thesis were all conducted in a specific application domain, namely *human–robot interaction* (HRI). The choice of this application domain as a test bed for our framework was motivated by two complementary factors. The first factor is the presence of a rich external context that must be accounted for by the dialogue manager. By their very definition, human–robot interactions indeed take place in a physical, situated environment. This environment is often inherently complex and in constant evolution – for instance, the physical location of objects and persons may change in the course of the dialogue. Furthermore, human–robot interactions must typically deal with multiple sources of noise and errors caused by e.g. imperfect sensory devices, unreliable motors, and failure-prone speech recognition. The robot’s understanding of the current situation is therefore bound to remain partial and imperfect. This combination of a rich conversational context and high levels of uncertainty is precisely the focus of the present work and justifies the selection of human–robot interaction as a test bed to evaluate the performance of our modelling approach in real settings.

The particular robotic platform employed in our experimental studies was the Nao robot V4 (NextGen) developed by Aldebaran Robotics.⁴ Figure 1.2 shows a concrete example of an interaction with the robot. The experiments involved the Nao robot conversing with a human user in a shared visual environment featuring a few basic objects that can be both perceived and grasped by the robot. The interactions generally revolved around the completion of simple tasks such as moving small objects from one location to another under the supervision of a human user. Chapters 5–8 provide a detailed description of the interaction scenarios, data collection, system architectures and evaluation setups followed for each experiment.

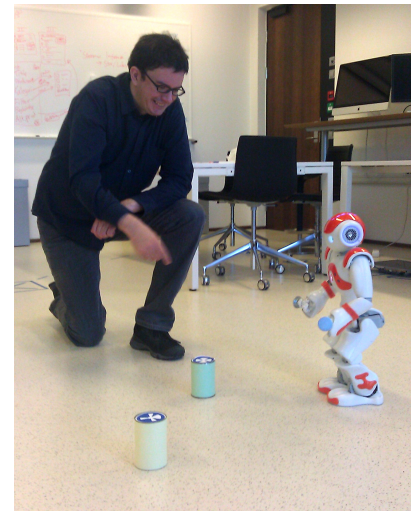


Figure 1.2: Human user interacting with the Nao robot.

1.3 Outline of the thesis

A brief overview of the thesis structure, chapter by chapter, is provided below.

Chapter 2: Background

This chapter introduces the fundamental concepts and methods used throughout this thesis. We start with an overview of some of the core linguistic properties of dialogue and describe key notions such as turn-taking, dialogue acts and grounding. We then describe a range of software architectures employed to design spoken dialogue systems and the role of each component within them. We also mention a range of important applications for spoken dialogue systems. Finally, we survey the various approaches that have been put forward in the research literature to address the dialogue management problem, including both hand-crafted and statistical methods.

⁴cf. <http://www.aldebaran-robotics.com>.

Chapter 3: Probabilistic modelling of dialogue

The chapter starts by reviewing the core elements of directed graphical models, which constitute the formal basis for our framework. We explain how Bayesian networks are constructed and show how they can be augmented to capture temporal sequences and decision-theoretic problems. We also briefly describe the most important algorithms for learning and inference developed for such models. We then move to the field of reinforcement learning and spell out its most central notions, such as Markov Decision Processes, value functions and policies. We also examine how reinforcement learning methods can be extended to partially observable settings. Finally, the last section translates these concepts and methods to the field of dialogue management, and discusses both supervised and reinforcement learning approaches to the optimisation of dialogue policies.

Chapter 4: Probabilistic rules

This chapter lays down the central concepts and algorithms of our own modelling approach to dialogue management. We define what probabilistic rules are and how they are internally structured through conditions and effects. We describe two main types of rules, used to respectively encode probability and utility distributions. We then explain how the rules are practically instantiated in the Bayesian network representing the dialogue state, as well as the algorithms employed to update the dialogue state and perform action selection. The chapter also addresses some advanced modelling questions related to the use of universal quantifiers and the manipulation of special data structures such as lists and strings. The chapter concludes by comparing our framework to previous work.

Chapter 5: Learning from Wizard-of-Oz data

This chapter shows how the parameters of probabilistic rules can be automatically learned from training data through the use of supervised learning techniques. The algorithm employed for estimating the rule parameters is grounded in Bayesian learning. To validate our approach, we detail an experiment on a statistical estimation task based on Wizard-of-Oz data collected in a human–robot interaction domain. The experiment illustrates the benefits of probabilistic rules compared to unstructured distributions.

Chapter 6: Learning from interactions

Chapter 6 extends parameter estimation to a reinforcement learning context. We show how the parameters of rule-structured models can be efficiently learned from observations collected during the interaction itself, without having access to any gold standard annotations. The procedure follows a Bayesian reinforcement learning approach and can be applied to optimise the rule parameters using both model-based and model-free variants. Finally, we report the results of two experiments carried out with a user simulator. The experiments concentrated on the estimation of the transition model for a human–robot interaction domain and evaluated the relative performance of a rule-structured model compared to a factored model as well as the learning efficiency of model-based vs. model-free methods.

Chapter 7: Implementation

Chapter 7 uncovers how the various algorithms and data structures presented in this thesis are technically integrated in the system architecture. We explain how the OpenDial toolkit is structured, describe how dialogue domains are practically specified in a generic XML format and discuss the implementation and performance tuning of the algorithms used for probabilistic inference and online planning. We also compare the OpenDial architecture to related software frameworks. Finally, the chapter presents the integrated dialogue system employed to carry out the experiments in this thesis and the graphical user interface developed to visualise the evolution of the dialogue state over the course of the interaction.

Chapter 8: User evaluation

This chapter presents an extensive user evaluation of our approach in a human–robot interaction domain with 37 participants. Based on a small training set of Wizard-of-Oz interactions, the evaluation contrasted the empirical performance of three dialogue management strategies: a hand-crafted approach expressed as a finite-state automaton, a statistical approach based on factored models, and a hybrid approach encoded with probabilistic rules. The empirical results showed that the use of rule-structured models yields significant improvements in both objective and subjective metrics of interaction quality compared to the two baselines.

Chapter 9: Concluding remarks

The final chapter concludes this dissertation with a summary of the presented research contributions, followed by an outline of possible future work.

Chapter 2

Background

This chapter introduces the most important concepts and methods employed in the field of spoken dialogue systems, with special emphasis on dialogue management. We start by reviewing some key linguistic concepts that are particularly relevant for our work: turn-taking, dialogue acts and grounding. A proper understanding of these aspects is indeed a prerequisite for the design of conversationally competent dialogue systems. After this linguistic overview, we move to a more technical discussion of the software architectures used to implement practical dialogue systems. These architectures typically comprise multiple processing components, from speech recognition to understanding, dialogue management, output generation and speech synthesis. We briefly describe the role of each component and their positions in the global processing pipeline.

Last but not least, the final section of this background chapter delves into the diverse set of approaches that have been put forward to tackle the dialogue management problem. We first present hand-crafted approaches, starting with finite-state policies and moving on to more sophisticated methods grounded in logic- or plan-based reasoning. Finally, we survey the more recently developed statistical approaches to dialogue management that seek to automatically extract dialogue strategies from data, based on supervised and reinforcement learning methods.

2.1 What is spoken dialogue?

We communicate in order to fulfil a wide array of social functions, such as exchanging ideas, re-collecting experiences, sustaining relationships, or collaborating with others to accomplish shared goals. These communication skills are developed in early childhood, and our cognitive abilities are in many ways shaped and amplified by this disposition for verbal interaction.

One of the most important properties of dialogue is that it is fundamentally a *collaborative activity*, with emphasis on both words. It is, first of all, an *activity* motivated by the desire to fulfil specific (practical or social) goals. This activity is subject to particular costs to minimise (the communicative effort) and is composed of a temporal sequence of events (the dialogue turns). Furthermore, if we abstract from so-called “internal dialogues” with oneself, dialogue involves per definition at least two participants that must act together to keep the dialogue on track. As shown by a wealth of studies in psychology and linguistics (Clark and Schaefer, 1989; Allwood et al., 1992; Clark, 1996; Garrod and Pickering, 2004; Tomasello et al., 2005), human conversations are characterised by a high degree of *collaboration* between interlocutors. Individuals participating in a dialogue routinely collaborate in order to coordinate their contributions and ensure mutual

understanding, thereby making the interaction more efficient. This collaboration is done mostly unconsciously and is part and parcel of the conversational skills we develop as speakers of a given language.

We describe in the next sections four major aspects of this collaborative activity:

1. The dialogue participants take *turns* in a conversation.
2. These turns are structured into basic communicative units called *dialogue acts*.
3. The interpretation of dialogue acts is subordinated to the *conversational context* in which they are uttered.
4. The participants continuously provide *grounding signals* to each other in order to indicate how they understand (or fail to understand) each other's contributions.

2.1.1 Turn-taking

Turn-taking is one of the most basic (yet often neglected) aspects of spoken dialogue. The physical constraints of the communication channel require that participants take turns in order to speak. Turn-taking is essentially a resource allocation problem. In this case, the resource to allocate is called the *conversational floor*, and social conventions dictate how the dialogue participants are to take and release their turns.

The field of *conversation analysis* investigates what these conventions are and how they interact to shape conversational behaviours. The control of the conversational floor in human conversations is indeed remarkably efficient. Empirical cross-linguistic studies have shown that the average transition time between turns revolves around 250 ms., although this time varies across cultural groups (Stivers et al., 2009). An overview of recent experimental findings on pauses, gaps and overlaps in natural interactions is presented in Heldner and Edlund (2010).

A wide variety of cues are used to detect turn boundaries, such as silence, hesitation markers, syntax (completeness of the grammatical unit), intonation (rising or falling pitch), intensity, and body language, as described by Duncan (1972). These cues can occur jointly or in isolation. Upon reaching a turn boundary, a set of social conventions governs who is allowed to take the turn. The current speaker can explicitly select the next person to take the turn, for instance when greeting someone or asking a directed question (Sacks et al., 1974). This selection can also occur via other mechanisms such as gaze. When no such selection is indicated, other participants are allowed to take the turn. Alternatively, the current speaker can continue to hold the floor until the next boundary.

Turn-taking is closely related to the notion of *initiative* in human–computer interaction. The vast majority of dialogue systems currently deployed are either system-initiated or user-initiated. In a system-initiated dialogue, the dialogue system has full control over how the interaction is unfolding – i.e. the system is asking all the questions and waiting for the user responses. A user-initiated dialogue is the exact opposite: in such settings, the user is assumed to lead the interaction and request information from the system. The most complex – but also most natural – interaction style is the mixed-initiative, where both the user and the dialogue system are allowed to take the initiative at any time and decide to either provide or solicit information whenever they see fit (Horvitz, 1999).

The turn-taking behaviour of most current-day dialogue systems remains quite rudimentary. The most common method to detect the end of a user turn is to wait for a silence longer than a manually fixed threshold, typically ranging between ½ and 1.0 second. Many current systems follow what is sometimes called a “ping-pong” type of interaction with a strict sequence of turns between the user and the system, one speaker at a time. Such constraints unfortunately ignore important and pervasive conversational phenomena such as interruptions, speech overlap, back-channels and co-completion of utterances (Ström and Seneff, 2000; Baumann, 2013). Turn-taking has recently become a focus of research in its own right in the dialogue system literature (Raux and Eskenazi, 2009; Gravano and Hirschberg, 2011), in an effort to break away from the rigid interaction styles that still characterise most current dialogue interfaces.

2.1.2 Dialogue acts

Each turn is constituted of one or more utterances. As argued by Austin (1962) and Searle (1969), utterances are nearly always purposeful: they have specific goals and are intended to evoke a specific psychological effect on the listener(s). They are therefore best described as actions rather than abstract statements about the world. The notion of dialogue act embodies precisely this idea.¹ (Bunt, 1996, p. 5) defines a dialogue act as a “functional unit [*of a dialogue*] used by the speaker to change the context”.

In his seminal work in the philosophy of language, Searle (1975) established a taxonomy of speech acts divided in five central categories:

Assertives: Committing the speaker to the truth of a proposition.

Examples: “*I swear I saw him on the crime scene.*”, “*I bought more coffee.*”

Directives: Attempts by the speaker to get the addressee to do something.

Examples: “*Clean your room!*”, “*Could you post this for me?*”

Commissives: Committing the speaker to some future course of action.

Examples: “*I will deliver this review before Monday.*”, “*I promise to work on this.*”

Expressives: Expressing the psychological state of the speaker about a state of affairs.

Examples: “*I am so happy for you!*”, “*Apologies for being late.*”

Declaratives: Bringing about a different state of the world by the utterance.

Examples: “*You’re fired.*”, “*We decided to let you pass this exam.*”

Modern taxonomies of dialogue acts are significantly more detailed than the one introduced by Searle. They also provide detailed accounts of various dialogue-level phenomena such as grounding (cf. next section) that were absent from Searle’s analysis. The most well-known annotation scheme is DAMSL (Dialogue Act Markup in Several Layers) and was initially formalised by Core and Allen (1997). DAMSL defines a rich, multi-layered annotation scheme for dialogue acts that

¹Dialogue acts have gone through multiple names over time, owing to the broad range of research fields that study them, from philosophy to descriptive and computational linguistics. As listed in McTear (2004), other denominations include speech acts (Searle, 1969), communicative acts (Allwood, 1976), conversation acts (Traum and Hinkelman, 1992), conversational moves (Sinclair and Coulthard, 1975) and dialogue moves (Larsson and Traum, 2000).

is both domain- and task-independent. A modified version of this scheme was applied to annotate the Switchboard corpus² based on a set of 42 distinct dialogue acts, including greeting and closing actions, acknowledgements, clarification requests, self-talk, responses, and many more (Jurafsky et al., 1997). An interesting aspect of DAMSL is the use of two complementary dimensions in the markup: the *forward-looking functions*, which are the traditional speech acts in Searle’s sense (assertions, directives, information requests, etc.) and the *backward-looking functions* that respond back to a previous dialogue act and can signal agreement, understanding, or provide answers. Both backward- and forward-looking functions can be present in the same utterance. Bunt (2011) describes further standardisation efforts to bring about a unified, multi-dimensional annotation scheme for dialogue acts that not only specifies the exact semantic content and communicative function(s) of each dialogue act but also encodes a variety of relations between dialogue acts (such as feedback or rhetorical relations). The reliance on a multi-dimensional annotation format allows dialogue acts to be explicitly associated with multiple communicative functions – for instance, a question such as “*could you tell me where to find the library?*” contains both an information request and a selection of the next person to take the turn.

Determining the dialogue act corresponding to a given utterance is a non-trivial operation. The syntactic type of the utterance only gives a partial indication of the underlying dialogue act – a question can for instance express a directive (“*Could you post this for me?*”). In order to accurately classify a dialogue act, a variety of linguistic factors must be taken into account, such as prosody, lexical, syntactic and semantic features, and the preceding dialogue history (Jurafsky et al., 1998; Shriberg et al., 1998; Stolcke et al., 2000; Keizer and op den Akker, 2007).

2.1.3 Interpretation of dialogue acts

Dialogue acts are strongly contextual in nature: their precise meaning can often only be comprehended within the particular conversational context in which they appear. The successful interpretation of dialogue acts must therefore venture beyond the boundaries of isolated utterances. We briefly review here three striking aspects of this dependence on context.

Non-sentential utterances

Non-sentential (also called elliptical) utterances are linguistic constructions that lack an overt predicate. They include expressions such as “*where?*”, “*around 8 PM*”, or “*brilliant!*”. Their interpretation generally requires access to the recent dialogue history to recover their intended meaning. This can lead to ambiguities in the resolution, as illustrated in these three examples modified from Fernández et al. (2007):

- A: When do they open the new station?
- B: Tomorrow (*short answer*)

- A: They open the station today.
- B: Tomorrow (*correction*)

²The Switchboard corpus is a corpus of spontaneous telephone conversations collected in the early 1990’s. It includes about 2430 conversations averaging 6 minutes in length; totalling over 240 hours of recorded speech with native speakers of American English (Godfrey et al., 1992).

- A: They open the station tomorrow.
B: Tomorrow (*acknowledgement*)

Various accounts of non-sentential utterances have been proposed, based on e.g. discourse coherence (Schlangen and Lascarides, 2003) or interaction-oriented semantics (Fernández, 2006; Ginzburg, 2012). Machine learning approaches to the classification of non-sentential utterances have also been developed (Schlangen, 2005; Fernández et al., 2007).

Conversational implicatures

As shown by Grice (1989), an important part of the semantics of dialogue acts is not explicitly stated but rather implied from the context. Consider the following constructed example:

- A: Is William working today?
B: He has a cold.

In order to retrieve the “suggested” meaning behind B’s utterance (namely, that William is probably not working), one needs to assume that B is cooperative and that the response is therefore relevant to A’s question. If an utterance initially seems to deliberately violate this principle, the listener must search for additional hypotheses required to make sense of the dialogue act. Grice (1989) formalised these ideas in terms of a cooperative principle composed of four conversational maxims that are assumed to hold in a natural conversation: the maxim of quality (“be truthful”), the maxim of quantity (“be exactly as informative as required”), the maxim of relation (“be relevant”), and the maxim of manner (“be clear”). A computational account of these implicatures – and their application to dialogue systems – is provided by Benotti (2010).

Referring expressions

Finally, dialogue acts are replete with linguistic expressions that refer to some aspect of the conversational context. These references can be either deictic or anaphoric.

A deictic marker is a reference to an entity that is determined by the context of enunciation. Examples of such markers are “*here*” (spatial reference), “*yesterday*” (temporal reference), “*this mug*” (demonstrative), “*you*” (reference to a person), or even pointing gestures. By their very definition, deictic markers refer to different realities depending on the situation in which they are used: “*here*” uttered in a classroom differs from “*here*” uttered in the countryside.

In addition, dialogue can also include anaphoric expressions – that is, expressions that refer to an element that has been previously mentioned through the history of the dialogue. A simple example of such an anaphoric expression can be seen in the question-answer pair “*Is William working today?*” → “*He has a cold.*”, where the pronoun “*he*” must be resolved to “*William*”.

The appropriate processing of deictic and anaphoric expressions is an important question in dialogue systems, and pertains both to the interpretation and production process. Multiple approaches have been pursued, relying on symbolic (Eckert and Strube, 2000) or statistical techniques (Strube and Müller, 2003; Stent and Bangalore, 2010). Researchers have also investigated the integration of salience measures (Kelleher and Van Genabith, 2004), multimodal cues (Frampton et al., 2009; Chen et al., 2011), the processing of spatial referring expressions (Zender et al., 2009) and the incrementality of the resolution process (Schlangen et al., 2009; Poesio and Rieser, 2011).

2.1.4 Grounding

Dialogue acts are executed as part of a larger collaborative activity that requires the active coordination of all conversational partners, i.e. speaker(s) as well as listener(s). This coordination takes place at various levels. The first and most visible level is the content of the conversational activity. The partners must ensure mutual understanding of each others' contribution, to control that they remain "on the same page". In addition, they also coordinate the process by which the conversational activity moves forward, through signalling that they are attending to the person who currently holds the conversational floor and acknowledging their contributions to the dialogue.

As an illustration, consider this short excerpt from a conversation transcribed in the British National Corpus (Burnard, 2007):

KATHLEEN : How come they can take time off yet you can't?
STEVE : He's been there longer than me.
KATHLEEN : Oh.
STEVE : I can, I might have two holidays now, two days' holiday. ...
KATHLEEN : Well ... I don't get that, me.
STEVE : What?
KATHLEEN : All these two days' holiday and this, you've had Christmas.
STEVE : You get two point summat³ days per month worked
KATHLEEN : Oh so you should've got them for January? ...
STEVE : right?
KATHLEEN : Yeah.
STEVE : And I worked three month before Christmas so I got six point summat days
KATHLEEN : For Christmas.
STEVE : so then I had all Christmas off.
KATHLEEN : Oh!
Yeah I get it now.
... I thought you got Christmas off like we got Christmas off.
STEVE : No.
You gotta earn them. ...

(<http://www.phon.ox.ac.uk/SpokenBNCdata/KCX.html>)

We can observe in this short dialogue that the interlocutors constantly rely on the *common ground* of the interaction to move the dialogue forward. They regularly check what pieces of information are mutually known and understood (e.g. "right?"). They also make use of a variety of signals to indicate when things are properly grounded ("oh", "yeah", "I get it") and when they are not ("I don't get that", "what?"). The common ground progressively expands as the dialogue unfolds – for instance, the system of holiday entitlement is not initially part of the shared knowledge for both speakers at the onset of the conversation, but becomes so towards the end.

The common ground is defined as the collection of shared knowledge, beliefs and assumptions that is established during an interaction. For a given piece of information to be shared by the conversational partners, the information must be known to all participants and each participant must

³"Summat" is slang for "something" in the Yorkshire region.

be aware that the information is shared by the other conversational partners. Formally speaking, a proposition p is therefore part of the common ground for a particular group of individuals when all the individuals know p , and they also all know that they all know p , and they all know that they all know that they all know p , and so on *ad infinitum*.

Each dialogue act is built upon the current common ground and participates in its gradual expansion and refinement. This process is called *grounding*. A variety of feedback mechanisms can be used to this effect. As described by Clark and Schaefer (1989), positive evidence of understanding can be expressed via cues such as:

Continued attention: The listener shows that she or he continues to attend to the speaker.

Relevant next contribution: The listener produces a relevant follow-up, as in the answer “He’s been there longer than me” following the question that precedes it.

Acknowledgement: The listener nods or utters a backchannel such as “mm”, “uh-uh”, “yeah”, or an assessment such as “I see”, “great”, “I get it now”.

Demonstration: The listener demonstrates evidence of understanding by reformulating or completing the speaker utterance.

Display: The listener reuses part of the previous utterance.

Communication problems can also occur, owing to e.g. misheard or misunderstood utterances. The listeners are in this case expected to provide negative feedback to signal trouble in understanding. A large panel of clarification and repair strategies are available to recover from these communicative failures. These strategies include backchannels (“mm?”), confirmations (“Do you mean that...?”), requests for disambiguations, invitations to repeat, and tentative corrections.

All in all, these positive and negative signals enable the dialogue participants to dynamically synchronise what the speaker intends to express and what the listeners actually understand. This grounding process operates mostly automatically, without deliberate effort. It is closely related to the concept of interactive alignment that has recently been put forward by Garrod and Pickering (2004, 2009). Humans show a clear tendency to (unconsciously) imitate their conversational partners. In particular, they automatically align their choice of words, a phenomenon called lexical entrainment (Brennan and Clark, 1996). But alignment also occurs on several other levels such as grammatical constructions (Branigan et al., 2000), pronunciation (Pardo, 2006), accents and speech rate (Giles et al., 1991), and even gestures and facial expressions (Bavelas et al., 1986).

Various computational models of grounding have been proposed in the literature, among which the PTT model developed in Poesio and Traum (1997) and Matheson et al. (2000) and the formal theory of conversation articulated by Ginzburg (2012). These models rely on rich logical representations of the “information state” associated with each participant to the dialogue. The purpose of this information state is to summarise all the (domain-relevant) information known to a given participant at any particular point of the interaction. The information state notably encodes the grounding status of every piece of content introduced through the dialogue. On the basis of these formal representations, each dialogue act is viewed as performing an update on the information states of the conversational partners, notably allowing for the gradual extension of the common ground through various forms of explicit and implicit feedback.

A proper treatment of grounding actions is critical for the development of conversational interfaces. As already mentioned in the introductory chapter, comprehension errors are indeed ubiquitous in spoken dialogue systems. The potential sources of misunderstandings are abundant, from error-prone speech recognition to out-of-domain utterances, unresolved ambiguities, and unexpected user responses. Appropriate grounding strategies are crucial to address these pitfalls. Grounding for dialogue systems is an active area of research and important advances have been made regarding the generation of clarification requests (Purver, 2004; Rieser and Moore, 2005), the elaboration of human-inspired error handling strategies (Skantze, 2007), the integration of non-verbal cues such as gaze, head nods and attentional focus (Nakano et al., 2003) and the development of incremental grounding mechanisms (Visser et al., 2012).

2.2 Spoken dialogue systems

After reviewing some of the core properties of human dialogues, we now discuss how to develop practical computer systems that aim to emulate such types of conversational behaviour. In the introduction chapter, Figure 1.1 represented a dialogue system as a black box taking speech inputs from the user and generating spoken responses. Real-world dialogue systems have, however, a complex internal structure, as we detail in the next pages.

2.2.1 Architectures

Spoken dialogue systems (SDS) often take the form of complex software architectures that encompass a wide range of interconnected components. These components are dedicated to various tasks related to speech processing, understanding, reasoning and decision-making. These tasks can be grouped into five major components:

1. *Speech recognition*, in charge of mapping the raw speech signal to a set of recognition hypotheses for the user utterance(s).
2. *Natural language understanding*, in charge of mapping the recognition hypotheses to high-level semantic representations of the dialogue act performed by the user.
3. *Dialogue management*, in charge of interpreting the purpose of the dialogue act in the larger conversational context and deciding what communicative action to perform (if any).
4. *Natural language generation*, in charge of finding the best linguistic (and extra-linguistic) realization for the selected communicative action.
5. And finally, *speech synthesis*, in charge of synthesizing an audio signal out of the generated utterance.

Figure 2.1 shows the flow of information for a prototypical spoken dialogue system. In practice, dialogue system architectures often employ additional middleware to provide the “software glue” between the components and handle the information exchange and scheduling of modules (Turunen, 2004; Herzog et al., 2004; Bohus and Rudnicky, 2009; Schlangen et al., 2010).

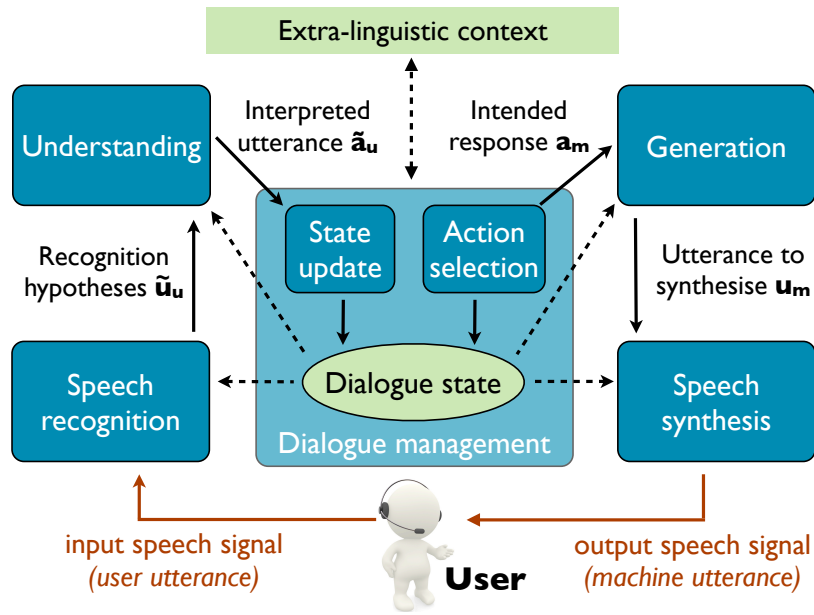


Figure 2.1: Information flow for a typical spoken dialogue system. The solid lines denote the main input and outputs while the dashed lines represent optional contextual information.

Spoken dialogue systems can include other modalities than speech. As shown by e.g. Wahlster (2006), multiple modalities such as touch, gestures, gaze, and other body movements can be exploited to enrich communication in both directions (understanding and generation). In particular, the system can refine its understanding of the actual user intentions by fusing information perceived through multiple information channels such as gestures (Stiefelwagen et al., 2004) or gaze (Koller et al., 2012). Non-verbal modalities can also be employed to enhance how information is presented back to the user and convey additional grounding signals, through e.g. facial expressions and gestures. The use of multiple modalities can notably reduce understanding errors and cognitive load (Oviatt et al., 2004) as well as improve the overall user experience (Jokinen and Hurtig, 2006). For all their advantages, multimodal architectures do, however, pose a number of additional challenges related to timing, synchronisation and increased system complexity.

In addition to these non-verbal modalities, many dialogue domains are also grounded in an external context that must be accounted for. This external context might be a physical environment for human–robot interaction, a virtual world for embodied virtual agents, a spatial location for in-car navigation systems, or simply a database of factual knowledge for information retrieval systems. Contextual factors of relevance for the application must be continuously monitored by the dialogue system and updated whenever necessary, as many components depend on the availability of such context models for their internal processing. Furthermore, the agent can often actively influence this context through external actions – for instance, a grasping action will modify the location of the gripped object. This contextual awareness necessitates the integration of additional functionalities for perception and actuation. In human–robot interaction, these extra-linguistic modules can notably include subsystems for object and scene recognition, spatial navigation, and various motor routines for locomotion and manipulation (see Goodrich and Schultz, 2007, for a survey of the field).

Several types of architectures have been proposed to assemble these components in a unified framework. The simplest approach is to arrange the components sequentially in a pipeline starting from speech recognition and ending with speech synthesis. This approach, although relatively straightforward to develop, suffers from a number of shortcomings, amongst which the rigidity of the information flow and the difficulty of handling feedback loops between components. Pipelines also offer poor turn-taking capabilities, since the system is unable to react before the pipeline has been fully traversed (Raux and Eskenazi, 2009). More advanced architectures – including the one put forward in this thesis – are based on the notion of *information state* (Larsson and Traum, 2000; Bos et al., 2003). These approaches are essentially blackboard architectures revolving around a central dialogue state that is read and written by various modules connected to it.⁴ These modules monitor the state for relevant changes, in which case they trigger their processing routines and update the state with the result. The main advantages of such architectures are (1) a more flexible information flow, since the modules are allowed to process and update information in any order, and (2) the possibility to define modules that take full advantage of the contextual information encoded in the dialogue state. Specific update strategies must, however, be devised to determine which modules are to be triggered (and in which order of priority). Figure 2.2 provides a graphical illustration of the difference between pipeline and information state-based architectures.

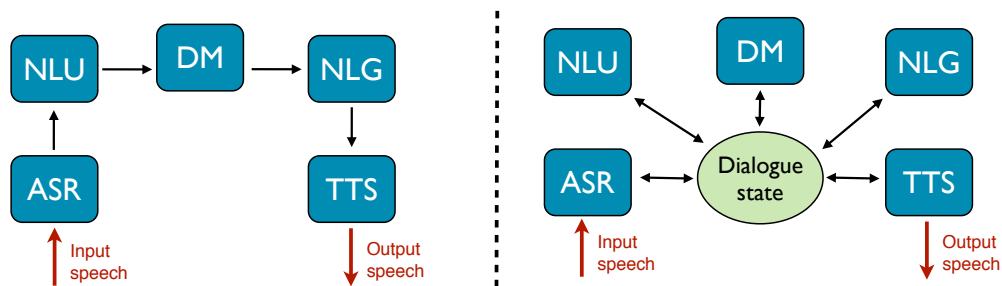


Figure 2.2: Comparison between pipeline (left) and information state (right) system architectures. ASR = *Automatic Speech Recognition*, NLU = *Natural Language Understanding*, DM = *Dialogue Management*, NLG = *Natural Language Generation*, and TTS = *Text-to-Speech Synthesis*.

Finally, a last aspect of dialogue system architectures that has been subject to recent research pertains to *incremental processing*. Many dialogue architectures wait until an utterance is fully pronounced in order to start its interpretation and decide on subsequent actions. This workflow usually leads to poor reactivity and unnatural conversational behaviours. A more interactive approach is to process and generate utterances in an incremental manner, as soon as partial inputs become available. New architectures have been proposed to integrate incremental processing at various stages of interpretation and decision-making (Brick and Scheutz, 2007; Schlangen and Skantze, 2011; Baumann, 2013).

⁴A blackboard architecture is a task-independent software architecture in which a central knowledge base (called the blackboard) is iteratively updated by a group of specialist components that cooperate in order to solve a given task. The name of this paradigm is a reference to a classroom teaching context where the teacher and the students share their knowledge through the blackboard and collaborate on this blackboard in order to solve a given problem.

2.2.2 Components

As explained in the previous section, the components of a dialogue system can typically be grouped in five major steps. We briefly describe here the role of these components and define their respective types of inputs and outputs.

Speech recognition

Upon detection of a new speech signal emanating from the user, the first task is to recognise the corresponding utterance. Speech recognition is responsible for converting the raw speech signal from the microphone(s) into a set of hypotheses \tilde{u}_u representing the words uttered by the user. To this end, the speech signal is first converted into a digital format and split into short frames of about 10 ms. A collection of acoustic features is then extracted for each frame using signal processing techniques. Once these acoustic features are extracted, two statistical models are combined to estimate the most likely recognition hypotheses: the *acoustic model* and the *language model*.

The acoustic model defines the observation likelihood of particular acoustic features for a given phone⁵, while the language model defines the probability of a given sequence of words. This statistical modelling rests on the formalisation of the speech recognition task as a *hidden Markov model* (HMM), in which the states are represented by the phones while the observations correspond to the acoustic features (Juang and Rabiner, 1991).

For the practical development of spoken dialogue systems, the most important element of a speech recogniser is the language model. The language model effectively represents the set of utterances that can be accepted as inputs to the system (and their relative probabilities). The model can be encoded either in the form of a hand-crafted recognition grammar, or via statistical modelling based on a particular corpus of reference. In the latter case, the language model typically takes the form of an N-gram model, often a bi- or tri-gram Markov chain corrected with appropriate smoothing and back-off techniques (Jelinek, 1997; Chen and Goodman, 1999). It is also often beneficial to dynamically modify the language model at runtime to reflect the changing dialogue context. Real-time model adaptation can be realised by priming the words or expressions that are most contextually relevant (Gruenstein et al., 2005; Lison, 2010a).

The output of the speech recogniser is typically an N-best list (or recognition lattice) representing a set of possible hypotheses for the utterance, together with their relative confidence score or probabilities. Thus, the output of the speech recogniser is a list expressed as:

$$\tilde{u}_u = \langle (\tilde{u}_{u(1)}, p_1), (\tilde{u}_{u(2)}, p_2), \dots, (\tilde{u}_{u(n)}, p_n) \rangle$$

where $\tilde{u}_{u(i)}$ represents a specific recognition hypothesis and p_i its corresponding probability. In order to be proper probabilities, the usual axioms of probability theory $0 \leq p_i \leq 1$ for all p_i and $\sum_{i=1}^n p_i = 1$ must be satisfied. It should also be noted that in practice, many speech recognisers only provide raw confidence scores for their hypotheses. The correspondence between these scores and meaningful probabilities has been investigated by e.g. Williams (2008a).

⁵A phone is an individual sound unit of speech. Technically speaking, acoustic models are not defined over entire phones but over sub-segments, typically decomposed into three parts: beginning, middle and end.

Natural language understanding

Once the recognition hypotheses for the utterance have been generated by the speech recogniser, the next task is to extract its semantic content. The goal of natural language understanding (NLU) is to build a representation of the meaning(s) expressed by the form of a given utterance. This task is a notoriously difficult endeavour, due to the combination of various factors. One major difficulty lies in speech recognition errors, with word error rates (WER)⁶ often revolving around 20% for many dialogue applications. The syntactic and semantic analysis of utterances is likewise complicated by the occurrence of sentential fragments, disfluencies of various sorts (e.g. filled pauses, repetitions, corrections) and ambiguities that must be resolved at multiple linguistic levels.

Natural language understanding can be decomposed in a number of steps. Parsing corresponds to the task of extracting the syntactic structure of the utterance and mapping it to a semantic representation. Spoken language parsing can be realised through various techniques, from keyword or concept spotting (Komatani et al., 2001; Zhang et al., 2007) to shallow semantic parsing (Coppola et al., 2009), grammar-based parsing (Van Noord et al., 1999) and statistical parsing (He and Young, 2005). It has been shown useful to apply upstream preprocessing techniques to correct speech recognition errors (Ringger and Allen, 1996) and filter out disfluencies (Johnson and Charniak, 2004). Referring expressions must also be appropriately resolved (Funakoshi et al., 2012). Finally, the dialogue act(s) associated with the utterance must be determined (Stolcke et al., 2000; Keizer and op den Akker, 2007). De Mori et al. (2008) offer a good survey of the various models and techniques used in the area of spoken language understanding.

Given speech recognition hypotheses \tilde{u}_u provided as inputs, and possibly a representation of the dialogue history and external context, the task of natural language understanding is to extract a corresponding N-best list of dialogue act hypotheses \tilde{a}_u defined as:

$$\tilde{a}_u = \langle (\tilde{a}_{u(1)}, p_1), (\tilde{a}_{u(2)}, p_2), \dots, (\tilde{a}_{u(n)}, p_n) \rangle$$

where $\tilde{a}_{u(i)}$ represents a dialogue act hypothesis, usually represented in a logical form with various predicates and arguments, and p_i its corresponding probability. The number of dialogue act hypotheses in \tilde{a}_u is generally independent of the number of speech recognition hypotheses.

Dialogue management

Dialogue management occupies a central stage in spoken dialogue systems. As already mentioned in the introductory chapter, dialogue management serves a double role. The first task of the dialogue manager is to maintain a representation of the current dialogue state and update it as new information becomes available. This dialogue state should encode every information that is of general relevance for the system, such as the recent dialogue history (encoded as a temporally ordered sequence of dialogue acts performed by the dialogue participants), the current conversational floor, the status of the task(s) to fulfil, and various features describing the context of the interaction. Furthermore, the dialogue state can also include information that is indirectly inferred from the individual observations. In particular, many dialogue models make use of a variable that explicitly represents the hypothesised user intention. This user intention, although never directly observed,

⁶The word error rate is a measure of speech recognition performance and is derived from the (word-level) edit distance between the actual utterance and a particular recognition hypothesis.

can often be derived from the user inputs through a sequence of reasoning steps. Similarly, the dialogue state can also integrate features that characterise the user profiles and their preferences.

The second task of dialogue management is to take decisions based on this dialogue state. This task is often called *action selection*. The dialogue manager is responsible for selecting the next action to perform by the system, which can be a communicative action (e.g. a piece of information to communicate, a question to ask, a grounding signal to convey), an external action (e.g. a physical movement for a robot or a database manipulation for a booking system), a combination of the two, or no action at all. Action selection can take many forms, ranging from a direct mapping between states and actions to the application of logical rules or the use of planning techniques.

The control of a complete dialogue system is sometimes decomposed in a layered structure where each layer is responsible for handling a particular aspect of the interaction. Allen et al. (2000) divide for instance the dialogue management process into various agents (discourse manager, plan manager, behavioural agent, etc.), each agent being in charge of a specific type of decision. Similarly, the Olympus/Ravenclaw architecture of Bohus and Rudnicky (2009) enforces an explicit distinction between the low-level control of the conversational floor and the high-level dialogue decisions. Establishing the exact boundary between these decision layers is, however, not always trivial. This thesis adopts a broad definition of dialogue management without committing to a particular decomposition.

Dialogue management leads to two distinct outcomes: (1) an updated dialogue state that reflects the observations received as inputs (user dialogue acts, contextual changes, etc.), and (2) a selected system action denoted as a_m (the m subscript standing for “machine” to distinguish it from the user dialogue act a_u). As for the user action a_u , the system action a_m is often represented in a logical form composed of predicates and arguments.

Section 2.3 describes in more detail the various approaches and techniques that have been proposed in the literature to formalise the dialogue management task.

Generation

Assuming the selected system action a_m relates to a verbal action, the following step is to find the best linguistic realisation for the abstract communicative goal expressed in a_m . As for natural language understanding, a variety of generation techniques are available, from shallow generation strategies based on canned sentences or templates to more sophisticated approaches based on sentence planning and surface realisation (Stone et al., 2003; Koller and Stone, 2007). More recently, statistical methods have also been pursued in order to enhance the robustness and user-adaptivity of the generation algorithms (Rieser and Lemon, 2010a; Dethlefs and Cuayáhuitl, 2011).

The main input to the generation module is the system action a_m , possibly complemented by additional state variables extracted from the user model and external context. Given this information, the generation module will produce a corresponding user utterance denoted u_m . In the case of multimodal systems, the module may also deliver realisations for other modalities than the speech channel, such as gestures or facial expressions.

Speech synthesis

The final step of the processing cycle is to synthesise the utterance in a speech waveform – a process called *speech synthesis*. This synthesis is performed in two consecutive stages. The utterance is

first converted into a phonemic representation. This conversion involves multiple processing steps related to text normalisation, phonetic and prosodic analysis. Once the conversion is completed, the resulting phonemic representation is fed to a synthesiser in charge of producing the actual waveform. This synthesis can either be performed by gluing together pre-recorded units of speech from a speech database (concatenative synthesis) or by generating sounds using explicit acoustic models of the vocal tract (formant and articulatory synthesis). Most current dialogue systems rely on either pre-recorded speech (when the number of alternative system utterances remains small) or concatenative synthesis techniques such as unit selection (Hunt and Black, 1996).

2.2.3 Applications

Spoken dialogue systems have a wide variety of applications, ranging from academic research prototypes to mature commercial products. The first applications can be found in telephone-based systems for information access and service delivery, such as automated call-routing (Gorin et al., 1997), travel planning (Walker et al., 2001), weather updates (Zue et al., 2000), bus schedule retrieval (Raux et al., 2005) or tourist information (Lemon et al., 2006). The recent emergence of smartphones also led to the development of new voice interfaces for multimodal local search (Ehlen and Johnston, 2013), cross-lingual communication (Xu et al., 2012) and even pedestrian exploration (Janarthanam et al., 2012). Many of these ideas have found their way into commercial products, as evidenced by the popularity of applications such as Apple’s Siri, Nuance’s Dragon Go! and Google Now.

Spoken dialogue systems can also be applied in domains where the use of touch interfaces and screens should be avoided because it is impractical or dangerous. This is notably the case for in-car navigation systems (Hansen et al., 2005; Castronovo et al., 2010) where voice interfaces are to be preferred for safety reasons. The recent trends towards ubiquitous computing and “ambient” intelligence in smart home environments also offer promising applications of dialogue system technology (Vipperla et al., 2009; López-Cózar and Callejas, 2010).

Spoken dialogue systems are deployed in increasingly complex and open-ended interaction domains, where the artificial agent is no longer a mere executor of user commands, but increasingly plays the role of a collaborator or intelligent assistant. Conversational interfaces have in particular been developed in the healthcare sector to monitor – and hopefully improve – the health condition and fitness of patients through interactive dialogues (Bickmore and Giorgino, 2006; Ståhl et al., 2009; Morbini et al., 2012). Substantial research has also been devoted into the development of interactive tutoring assistants in various learning contexts (Chi et al., 2011; Dzikovska et al., 2011; Jan et al., 2011; Traum et al., 2012).

Finally, dialogue systems form an integral part of many robotic systems. Robots are increasingly deployed in social environments, such as homes, offices, schools and hospitals. There is therefore a growing need for robots endowed with communicative abilities. Human–robot interaction is an active area of research and has focused on aspects such as situated dialogue processing (Cantrell et al., 2010; Kruijff et al., 2010, 2012), adaptivity (Doshi and Roy, 2008), symbol grounding (Roy, 2005; Lemaignan et al., 2012) and multimodal interaction (Stiefelhagen et al., 2004; Salem et al., 2012; Mirnig et al., 2013).

2.3 Dialogue management

Various approaches have been proposed to formalise the dialogue management problem. Common to virtually all approaches to dialogue management is (1) the representation of the system's knowledge of the current situation in a data structure called the *dialogue state* and (2) the use of a decision mechanism to select the action to perform in each dialogue state. A wide range of strategies have been proposed to represent, update and act upon this dialogue state. We first describe hand-crafted approaches and then move on to the more recently developed statistical methods.

2.3.1 Hand-crafted approaches

Finite-state automata

The simplest approach to dialogue management is based on finite-state automata (FSA). A finite state automaton is defined by a collection of states and directed edges between them. Decision-making is made possible by associating each state with a specific action to execute at that state. Each edge in the automaton is labelled with a condition on the user input that, if satisfied, will move the current state from the source of the edge to its target. Figure 2.3 illustrates an example of a finite-state automaton for a simple, system-initiated interaction that takes user directions. If the user response is different from the five expected inputs, the system will ask the user to repeat until an admissible input is provided. The system will continue to request directions until the “stop” command is uttered, in which case a final state is reached.

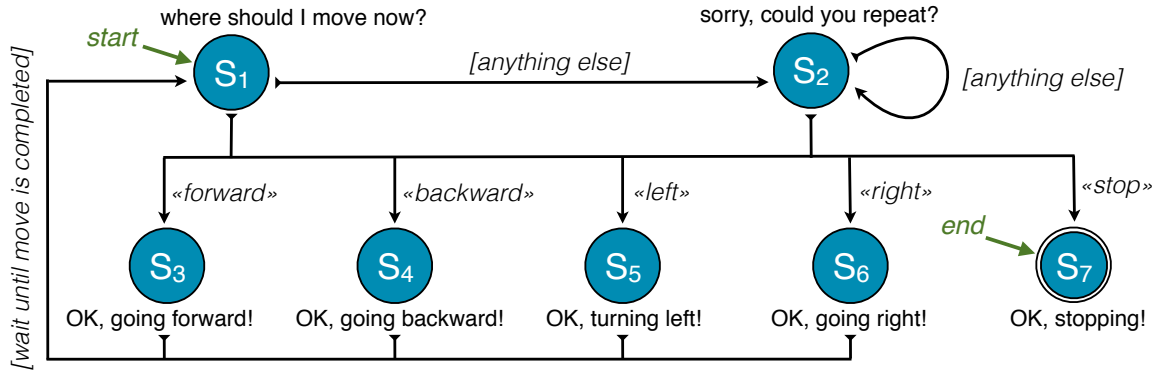


Figure 2.3: Example of finite-state automaton (FSA) for dialogue management, with seven possible states. The starting state for this FSA is s_1 and the (in this case unique) ending state is s_7 . The edges $s_3, \dots, s_6 \rightarrow s_1$ are traversed once the movement is completed, and the two edges $s_1, s_2 \rightarrow s_2$ are traversed for any other user input than the five specified directions.

A finite-state automaton is formally defined as a tuple $\langle \mathcal{S}, \Sigma, \delta, s_0, \mathcal{F} \rangle$, where \mathcal{S} is the set of possible states, Σ the set of inputs that the system can accept (in this case, the possible user inputs), $\delta : \mathcal{S} \times \Sigma \rightarrow \mathcal{S}$ the transition function mapping every $\langle \text{state}, \text{input} \rangle$ pair to its successor state, s_0 the start state, and \mathcal{F} the set of final states.

Finite-state automata provide a simple and versatile framework for the development of a dialogue manager. However, their expressive power is rather limited, as the dialogue state of an FSA is represented as a single, atomic symbol, and the possible user moves by a finite enumeration of possible transitions allowed for each state. Finite-state automata are therefore difficult to scale to

more complex domains where the dialogue state might need to track numerous variables and allow for large numbers of alternative dialogue acts from the user.

Logic- and plan-based approaches

Richer representations of the dialogue state are required to overcome the rigidity of finite-state automata. A popular alternative builds on representations that encode the dialogue state as a *frame* constituted of a set of slot-value pairs (Seneff and Polifroni, 2000). Frame-based systems start with an empty frame that is gradually filled by the user inputs. After each user move, a set of production rules determines which actions to take – typically, a request to elicit a value for a particular slot – based on the current frame. The interaction continues until all slots in the frame are filled, which marks the transition to the next frame or the completion of the dialogue.

Due to their greater expressivity, frame-based systems offer a number of advantages in terms of domain modelling and dialogue control. However, they remain difficult to extend to other domains than classical slot-filling applications such as flight booking. The *information state* approach (Larsson and Traum, 2000) is an attempt at providing a more solid theoretical foundation for dialogue management in rich conversational domains. As already mentioned in Section 2.2.1, information state approaches rely on a blackboard architecture where various modules are attached to a central workspace called the information state. This information state is continuously monitored by the system modules and represents the full contextual knowledge available to the agent. In addition to the usual variables describing the dialogue history and the application task, the information state can also incorporate “mentalist” entities such as the private and shared beliefs of the conversational agents. The information state can exhibit a rich internal structure encoded as attribute-value matrices (AVMs) or typed records (Cooper, 2012).

Upon reception of a relevant input, the dialogue manager modifies this information state using a collection of update rules. In addition to state-internal operations that modify particular variables of the information state, the update rules are also employed to derive the actions to execute by the agent. Given a collection of rules and a generic strategy to apply them, the dialogue manager can both update its state and select the next action to perform by way of logical inference. This action selection can notably be grounded on the set of open questions raised and not yet answered during the interaction (Larsson, 2002; Ginzburg, 2012).

Plan-based approaches such as the ones developed by Freedman (2000), Rich and Sidner (1998) and Allen et al. (2000) go one step further. These approaches also rely on complex representations of the dialogue state that encompass the beliefs, desires and intentions (BDI) of each agent (Cohen and Perrault, 1979; Allen and Perrault, 1980). In such settings, both the user and the system are assumed to act in pursuit of their long-term goals. The interpretation of the user actions is cast as a *plan recognition* problem, where the system seeks to derive the belief, desires and intentions that best explain the observed conversational behaviour of the speaker. Similarly, the selection of system actions is derived from the (task-specific) long term objectives of the system. This search for the best action is an instance of a classical planning task, which can be solved using off-the-shelf planning algorithms. These algorithms require the declaration of a planning domain that specifies the pre-conditions and effects of every action. Agent-based frameworks such as the Constructive Dialogue Modelling approach developed by Jokinen (2009) follow similar lines, with a particular emphasis on conceptualising dialogue as a collaborative activity grounded in communicative principles of

rational and coordinated interaction between agents.

Benefits and limitations of hand-crafted approaches

The primary benefits of hand-crafted approaches to dialogue management lie in their ability to capture rich conversational phenomena and provide the system designer with a fine-grained control over the application behaviour. They have also laid the foundations for substantial advances in the semantic and pragmatic interpretation of dialogue moves (Thomason and Stone, 2006; Ginzburg, 2012), the formalisation of social obligations (Traum and Allen, 1994), the rhetorical structure of dialogue (Asher and Lascarides, 2005), or the use of plan-based reasoning to infer the user intentions (Allen and Perrault, 1980; Litman and Allen, 1987). They nevertheless suffer from two important shortcomings:

1. They generally assume complete observability of the dialogue context and provide only a restricted account of uncertainties. This assumption of full observability is difficult to reconcile with the imperfect and error-prone nature of speech recognition and spoken language understanding. Due to their lack of probabilistic reasoning, most hand-crafted approaches only consider one single top hypothesis in their interpretation of the user inputs (“1-best processing”) and are consequently unable to account for alternative interpretations.
2. They require the dialogue domain to be specified by hand, either through the definition of a finite-state automaton, a collection of update rules or action schemata for planning. This requirement is hard to satisfy for many domains, since the behaviour of real users is often challenging to anticipate (unsurprisingly, human behaviour can be difficult to predict) and can deviate significantly from the expectations of the system developers.

Statistical approaches, to which we now turn, have been specifically developed to address these two issues.

2.3.2 Statistical approaches

Common to all statistical approaches to dialogue management is the idea of automatically optimising a dialogue policy (that is, a function associating each possible dialogue state to a system action) from interaction data. Starting from this shared premise, statistical approaches vary along multiple dimensions such as the type of learning algorithm, the representation of the dialogue state and policy, and the nature of the data on which to estimate the models. This section outlines the core concepts of statistical approaches, which will be articulated in a more formal setting in the next chapter.

Supervised learning

The first possible approach is to learn dialogue strategies on the basis of external examples of interaction. The training data can be extracted from various sources, such as corpora of human–human or human–machine dialogues⁷. Human–machine dialogues are typically preferred to human–human

⁷The most important corpus of human–machine dialogue is the COMMUNICATOR dataset of telephone conversations in the domain of travel planning, with more than 180,000 utterances (90 hours of recording) transcribed and annotated with various understanding and dialogue-level information (Bennett and Rudnický, 2002).

dialogues, as people are known to behave differently when they talk to a machine or a human user (Jönsson and Dahlbäck, 1988). However, the collection of human–machine interactions for a particular domain can lead to a classical “chicken-and-egg” dilemma: In order to collect interaction data, one must first have a full-fledged dialogue system with which the users can interact, but building such a system is difficult without having access to in-domain examples of interaction in the first place (in order to e.g. know what types of user utterances and behaviours are to be expected).

Wizard-of-Oz interactions offer a way to circumvent this dilemma. As already mentioned in the introduction, a Wizard-of-Oz experiment is an interaction in which a human user is asked to interact with a system that is remotely operated by a human agent (typically without the user being aware of this control). One can collect multiple interactions and record the wizard decisions at each point, along with their context. The resulting data set can be fed to a supervised learning algorithm in order to construct a dialogue policy that attempts to imitate the conversational behaviour of the wizard. Learning the dialogue policy is thus seen as a classification problem with states as inputs and actions as outputs. The goal of the learning algorithm is to construct a classifier that optimises the classification accuracy for the Wizard-of-Oz data set, considering the wizard actions as “gold standards”. This classifier can be estimated with standard machine learning methods (decision trees, logistic regression, etc.).

In the supervised setting, action selection is essentially viewed as a sequence of isolated decision problems. As argued by Levin et al. (2000), this formalisation overlooks some important characteristics of conversational behaviour, as dialogue is a dynamic process where the state and action at time t have a direct influence on the resulting state at time $t + 1$. The result of erroneous actions is for instance carried over to subsequent states. This temporal connection between states is typically lost in classical supervised learning approaches. Furthermore, the state space grows exponentially with the number of state variables, and can therefore reach very large sizes. The training data available from a fixed corpus will therefore only cover a fraction of the state space for the domain. As a consequence, many states encountered at runtime will have no appropriate training examples on which to ground the action selection. Generalisation and abstraction techniques can fortunately be used to mitigate this problem of data sparsity, as we will show in Chapter 5.

Reinforcement learning

Reinforcement learning (RL) presents an attractive solution to the problem of dialogue policy optimisation. A reinforcement learning problem typically revolves around an *agent* interacting with its environment, typically to perform some practical task. Through its actions, the agent is able to change the state of its environment. After each action, the agent can observe both the new environment state resulting from its actions, as well as a numerical reward encoding the immediate value (positive or negative) of the executed action in relation to the agent’s goal. The goal of the learning agent is to find the best action to execute in any given state via a process of trial and error – the best action being characterised as the one that maximise the agent’s expected long-term reward.

Reinforcement learning tasks are generally formalised using *Markov Decision Processes* (MDPs), which are defined as tuples $\langle \mathcal{S}, \mathcal{A}, T, R \rangle$ with a state space \mathcal{S} , an action space \mathcal{A} , a transition function T that encodes the probability $P(s' | s, a)$ of reaching state s' after executing action a in state s , and a reward function R that specifies the reward value associated with the execution of action a in state s . Dialogue can be expressed as a Markov Decision Process where the state

space corresponds to the possible dialogue states and the actions to the set of (verbal or extra-verbal) actions available to the dialogue agent. The transition function T captures the “dynamics” of the conversation, and indicates how the dialogue state is expected to change as a result of the system actions. Finally, the reward function R represents the objectives and costs of the application domain. The reward function is typically designed as to associate a high positive reward after the successful completion of the task, a high negative reward for failing to do so, and a small negative reward for every new turn introduced by the system.

Given a particular MDP problem, the goal of the learning agent is to find a policy $\pi : \mathcal{S} \rightarrow \mathcal{A}$ that maps each possible state to the best action to execute at that state. The best action is defined as the action that maximises the expected return for the agent. Simply put, the return is the long-term accumulation of rewards from the current state up to a given horizon.

As the transition model is usually unknown, various learning methods have been devised to automatically extract this optimal policy from interaction experience. Due to the large amounts of cycles that are necessary to converge onto a near-optimal policy, direct interactions with real users are often impossible or highly impractical for many domains. Instead, most recent approaches have relied on the construction of a user simulator able to generate unlimited numbers of interactions on the basis of which the dialogue system can optimise its policy. The user simulator can either be designed by experts or “bootstrapped” from existing datasets or Wizard-of-Oz studies (Pietquin, 2008; Frampton and Lemon, 2009; Rieser and Lemon, 2011). The reliance on a user simulator for policy optimisation has the advantage of allowing the learning agent to explore millions of dialogue trajectories on a scale that would be impossible to achieve with real users. Simulated interactions, however, run the risk of deviating from real user behaviours.

A limitation faced by MDP approaches is the assumption that the dialogue state is fully observable. As frequently noted in the course of this thesis, this assumption simply does not hold for most dialogue domains, owing to the presence of multiple sources of uncertainty, in particular speech recognition errors. An elegant solution to this problem is to extend the MDP framework by viewing the state as a hidden variable that is indirectly inferred from observations. Such an extension gives rise to a *Partially Observable Markov Decision Process* (POMDP). POMDPs are formally defined as tuples $\langle \mathcal{S}, \mathcal{A}, T, R, \mathcal{O}, Z \rangle$. As in a classical MDP, \mathcal{S} represents the state space, \mathcal{A} the action space, T the transition probability $P(s' | s, a)$ between states, and R the reward function $R(s, a)$. However, the actual state is no longer directly observable. Instead, the process is associated with an observation space \mathcal{O} that expresses the set of possible observations that can be perceived by the system (for instance, the N-best lists of user dialogue acts). The function Z finally defines the probability $P(o | s)$ of observing o in the current state s .

In the POMDP setting, the agent knowledge at a given time is represented by the *belief state* b , which is a probability distribution $P(s)$ over possible states. The belief state is continuously updated as additional information becomes available in the form of e.g. new observations. Based on this belief state, a POMDP policy is defined as a function mapping each possible belief state to its optimal action. As for MDP-based reinforcement learning, POMDP approaches usually derive the dialogue policy from interactions with a user simulator (Young et al., 2010; Thomson and Young, 2010; Daubigny et al., 2012b). However, the optimisation process is considerably more complex than for MDPs, as the belief state is a continuous and high-dimensional structure. Approximation techniques are therefore necessary in order to extract dialogue policies of reasonable quality in such a complex space. The next chapter fleshes out the theoretical foundations of these

modelling strategies and their applications to spoken dialogue systems.

Benefits and limitations of statistical approaches

As stated in the previous sections, one key benefit of statistical approaches is the improved robustness towards errors and unexpected events. This robustness stems primarily from the use of probabilistic reasoning techniques that explicitly account for the uncertainty inherent to spoken dialogue. The second benefit is the possibility to optimise dialogue policies in a principled, data-driven manner based on a generic specification of the system objectives expressed in the reward function. This specification allows the system designer to explicitly encode the various goals and costs of the system. This ability to represent trade-offs between multiple, sometimes conflicting objectives is one important advantage of reinforcement learning approaches. Empirical studies have shown that automatically optimised policies can outperform hand-crafted strategies in both simulated environments and real user trials, based on objective and subjective metrics of interaction success (Lemon and Pietquin, 2007; Young et al., 2013), although most experimental results have so far been confined to slot-filling application domains.

Statistical techniques do, however, come with a number of challenges of their own. The most pressing issue is the paucity of appropriate data sets. Statistical models often require large amounts of training data to estimate their parameters. Unfortunately, real interaction data is scarce, expensive to acquire, and difficult to transfer from one domain to another. User simulators can partly alleviate this problem, but must often themselves be bootstrapped from data, and offer no guarantee of producing conversational behaviours that reflect those of real users. The computational complexity of the learning algorithm can also be problematic. Statistical approaches – and especially POMDP-based systems – must often carefully engineer their state and action variables to limit the size of the search space and ensure that the learning process remains tractable. Albeit several dimensionality reduction techniques have been proposed in the literature (Williams and Young, 2005; Young et al., 2010; Cuayáhuít et al., 2010; Crook and Lemon, 2011), most work has so far concentrated on comparatively simple slot-filling applications. Application domains such as tutoring systems, cognitive assistants and human–robot interaction must often deal with state–action spaces that are considerably more elaborate, including multiple tasks to perform, sophisticated user models, and a complex, dynamic environment. In such settings, the dialogue system might need to track a large number of variables in the course of the interaction, which quickly leads to a combinatorial explosion of the state space. How to define suitable statistical models for these types of dialogue remains an open question, to which the present thesis aims to offer preliminary answers.

Finally, many practical dialogue applications need to enforce generic constraints on the dialogue flow. Such constraints may for instance correspond to business rules specific to the application of interest.⁸ The incorporation of such constraints in the policy optimisation process is, however, far from trivial. As noted by Paek and Pieraccini (2008), this lack of direct control on the final policy is one of the main reasons for the slow adoption of reinforcement learning approaches in industrial applications. Although some researchers have worked on the integration of expert knowledge into dialogue policy optimisation (Heeman, 2007; Williams, 2008b), much work remains to be done to bring about a unified approach to dialogue management that combines the robustness of data-

⁸For instance, a flight booking system might be required by law to request the user to explicitly confirm their reservation at least once before printing any ticket.

driven approaches with the control and expressivity of hand-crafted strategies.

Table 2.1 presents a comparison of the most important hand-crafted and statistical methods to dialogue management in terms of state representation, account of state uncertainty (in the sense of capturing multiple hypotheses about the current state, each one assigned with a specific probability), state update procedure and action selection algorithm. The last row also describes how the approach developed in this thesis stands in comparison to these methods.

2.4 Summary

This chapter has presented the most prominent concepts and methods in the area of dialogue processing and management. Starting with a linguistic analysis of various dialogue phenomena, we discussed several key aspects of verbal interactions, such as their articulation in sequences of turns, each turn including one or more dialogue acts. We also stressed the importance of contextual knowledge in the interpretation and production of dialogue acts, and the role of grounding signals to maintain mutual understanding among the conversational partners.

Section 2.2 described how spoken dialogue systems are internally structured. As we have explained, dialogue systems are often instantiated in complex software architectures that comprise components for speech recognition, understanding, dialogue management, natural language generation and speech synthesis. Dialogue systems can also be extended to handle (i.e. both perceive and act upon) extra-linguistic modalities and environmental factors. The range of possible applications of dialogue systems is broad and includes domains as varied as mobile applications for information access and service delivery, in-car navigation systems, smart home environments, cognitive assistants, tutoring systems, and service robots.

The last section presented an overview of the dialogue management task. A key concept shared by virtually all approaches to dialogue management is the *dialogue state*, a data structure used to encode the system knowledge of the current conversational situation. This dialogue state can take multiple forms, from the atomic symbols used in finite-state approaches to the rich nested feature structures employed in logic- and plan-based formalisms. Based on this dialogue state, an action selection mechanism is then responsible for the selection of the next action to execute. In hand-crafted approaches, this mechanism is manually specified by the application developer, either via direct mappings from state to actions, or indirectly through the use of planning techniques. Statistical approaches, on the other hand, seek to automatically optimise dialogue policies from (real or simulated) interaction data. A wide range of learning techniques have been developed for this optimisation, from supervised learning on a Wizard-of-Oz data set to reinforcement learning based on a user simulator and a generic reward function. Reinforcement learning techniques can themselves be divided into MDP-based approaches, where action effects are stochastic but the dialogue state itself is assumed to be known, and POMDP-based approaches, which incorporate both stochastic action effects and state uncertainty.

We concluded our review of dialogue management paradigms by noting that both hand-crafted and statistical methods have significant challenges to overcome. This is especially striking for open-ended application domains such as human–robot interaction, as these domains often have a rich conversational context (including e.g. the dialogue history, the physical situation of the agent and the status of the tasks to perform) but are also associated with high amounts of noise, errors and unexpected events. One of the central claims of this thesis is that these domains are best addressed

Approach	State representation	State uncertainty	State update mechanism	Action selection mechanism
Finite state automata	Atomic state	no	Traversal of matching edge	Action associated with node
Frame-based systems (e.g. Seneff and Polifroni, 2000)	Slot/value pairs	no	Slot-filling given user inputs	Production rules
Information state update (e.g. Larsson and Traum, 2000)	Typed feature structure	no	Update rules	Decision rules
Plan-based systems (e.g. Freedman, 2000; Allen et al., 2000)	BDI model	no	Plan recognition and update of BDI model	Classical planning
Supervised approaches (e.g. Hurrado et al., 2005)	Factored state	no	Extraction of state variables from history and task status	Dialogue policy learned from external examples
MDP-based systems (e.g. Walker, 2000; Levin et al., 2000)	Factored state	no	Extraction of state variables from history and task status	Dialogue policy optimised via reinforcement learning from real or simulated dialogues
POMDP-based systems (e.g. Young et al., 2010)	Factored state	yes	Update of belief state	
Probabilistic rules (this thesis)	Factored state	yes	Update of belief state (with probabilistic rules)	Dialogue policy optimised via (Bayesian) supervised or reinforcement learning

Table 2.1: Comparison of dialogue management approaches.

with a hybrid approach that combines probabilistic modelling with expert knowledge about the domain structure. Chapter 4 develops and formalises such a modelling approach. But before doing so, we first need to lay down the mathematical apparatus required to construct and estimate probabilistic models of dialogue, which is the subject of the next chapter.

Chapter 3

Probabilistic models of dialogue

The previous chapter provided an overview of some of the most influential approaches to dialogue management, and outlined in particular the benefits of statistical techniques to account for the uncertainty and unpredictability inherent to spoken dialogue. The present chapter provides further background on the theoretical and methodological foundations of these statistical approaches as well as their application to the dialogue management task.

The first section of this chapter concentrates on the use of graphical models to design structured representations of probability and utility distributions. Graphical models provide mathematically principled methods for representing, estimating and reasoning over complex probabilistic domains. The section starts with a well-known type of directed graphical model, namely Bayesian networks. We then show how to extend Bayesian networks to capture temporal sequences and express decision-theoretic problems through actions and utilities. We also review the most important inference and learning algorithms developed for these graphical models.

The second section presents the fundamental principles of reinforcement learning, which is the learning framework employed by most recent statistical approaches to dialogue management. The section starts with a formal definition of a Markov Decision Process and explains how policies can be automatically optimised for such a process. The discussion is finally extended to partially observable environments in which the current state is hidden and must be indirectly inferred from observations.

Once the mathematical foundations of graphical models and reinforcement learning are in place, the third and last section of this chapter describes how these concepts and techniques can be practically applied to model dialogue management tasks. The section provides a survey of the multiple approaches that have been developed in the last two decades to automatically optimise dialogue policies based on various flavours of supervised and reinforcement learning.

3.1 Graphical models

We describe in this section the core properties of (directed) graphical models,¹ their formal representation, and their use in learning and inference tasks.

¹A variety of undirected or partially directed graphical models also exist, amongst which we find Markov networks and Conditional Random Fields, but they will not be discussed nor employed in this thesis.

3.1.1 Representations

Bayesian networks

Let $\mathbf{X} = X_1, \dots, X_n$ denote a collection of random variables, where each variable X_i is associated with a range of possible values. This range can be either discrete or continuous. For dialogue models, the range of a variable X_i is typically discrete and can be explicitly enumerated. The enumeration of values for the variable X_i can be written $Val(X_i) = \{x_i^1, \dots, x_i^m\}$.

In the general case, the variables \mathbf{X} can be interrelated by complex probabilistic dependencies. These dependencies can be expressed through the joint probability distribution $P(X_1, \dots, X_n)$. The size of this joint distribution is, however, exponential in the number n of variables, and is therefore difficult to manipulate (let alone estimate and reason over) directly.

We can fortunately exploit conditional independence properties to reduce the complexity of the joint probability distribution. For three disjoint sets of random variables \mathbf{X} , \mathbf{Y} and \mathbf{Z} , we say that \mathbf{X} and \mathbf{Y} are conditionally independent given \mathbf{Z} iff $P(\mathbf{X}, \mathbf{Y} | \mathbf{Z}) = P(\mathbf{X} | \mathbf{Z})P(\mathbf{Y} | \mathbf{Z})$ for all combinations of values for \mathbf{X} , \mathbf{Y} and \mathbf{Z} . This conditional independence is denoted $(\mathbf{X} \perp \mathbf{Y} | \mathbf{Z})$.

Conditional independence allows a joint probability distribution to be decomposed into smaller distributions that are much easier to work with. For a variable X_i in X_1, \dots, X_n , we can define the set $parents(X_i)$ as the minimal set of predecessors² of X_i such that the other predecessors of X_i are conditionally independent of X_i given $parents(X_i)$. The set of parents can be empty if the variable X_i is independent of all other variables. This definition enables us to decompose the joint distribution based on the chain rule:

$$P(X_1, \dots, X_n) = \prod_{i=1}^n P(X_i | X_1, \dots, X_{i-1}) \quad (3.1)$$

$$= \prod_{i=1}^n P(X_i | parents(X_i)) \quad (3.2)$$

This decomposition can be graphically represented in a *Bayesian network*. A Bayesian network is a directed acyclic graph (DAG) where each random variable is represented by a distinct node. These nodes are connected via directed edges that reflect conditional dependencies. In other words, an edge $X_m \rightarrow X_n$ indicates that $X_m \in parents(X_n)$. Each variable X_i in the Bayesian network must be associated with a specific conditional probability distribution $P(X_i | parents(X_i))$. Together with the directed graph, the conditional probability distributions (abbreviated as CPDs) fully determine the joint probability distribution of the Bayesian network.

Given such definitions, the Bayesian network can be directly used for inference by querying the distribution of a subset of variables, often given some additional evidence. Two operations are especially useful when manipulating probability distributions:

- Marginalisation (also called “summing out”), which derives the probability of the variable X given its conditional distribution $P(X | Y)$ and the distribution $P(Y)$:

$$P(X) = \sum_{y \in Val(Y)} P(X, Y=y) = \sum_{y \in Val(Y)} P(X | Y=y)P(Y=y) \quad (3.3)$$

²The predecessors of X_i are simply the variables X_1, \dots, X_{i-1} (under a particular ordering for the variables).

- Bayes' rule, which reverses the order of a conditional distribution between two variables X and Y (possibly with some background evidence e):

$$P(X | Y, e) = \frac{P(Y | X, e)P(X | e)}{P(Y | e)} \quad (3.4)$$

As an illustration, Figure 3.1 provides an example of a Bayesian network that models the probability of occurrence of a fire at a given time. The probability of this event is dependent on the current weather. In addition, two (imperfect) monitoring systems are used to detect possible fires; one on the ground, and one via satellite.

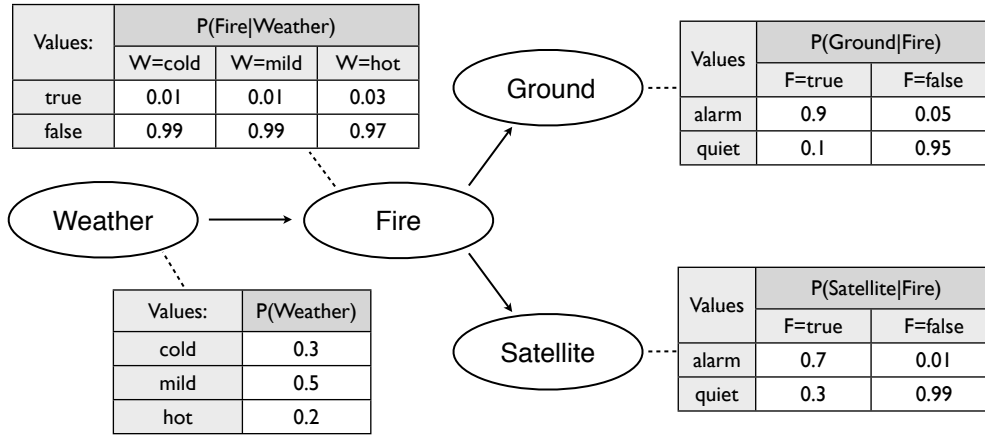


Figure 3.1: Example of a Bayesian network with four random variables.

For each random variable X_i , there is one distinct distribution for every combination of values in $parents(X_i)$. The probabilistic model defined in the figure includes therefore a total of eight distributions (corresponding to the eight columns). The distributions in Figure 3.1 are called *categorical* distributions.³ Categorical distributions can be implemented with look-up tables that map every possible value in $Val(X_i)$ to a particular probability. Many of the probability distributions used throughout this thesis will take the form of categorical distributions. Other representations for discrete CPDs are conceivable, as will be shown later in this thesis.

A Bayesian network can also contain continuous probability distributions. These distributions are usually encoded with *density functions* represented in a parametric form. A well-known parametric distribution is the normal distribution $\mathcal{N}(\mu, \sigma^2)$, which is defined by its two parameters μ (the mean) and σ^2 (the variance). Continuous distributions can alternatively be expressed with non-parametric methods based on e.g. kernel density estimators (see e.g. Bishop, 2006; Koller and Friedman, 2009, for more details on these continuous distributions).

Appendix A enumerates the most important discrete and continuous probability distributions employed in this thesis.

³Categorical distributions are often conflated with *multinomial* distributions, which specify the number of times an event will occur in a repeated independent trial with k exclusive categories, with each category having a fixed probability. A categorical distribution is equivalent to a multinomial distribution for a single observation.

Reasoning over time

In order to apply Bayesian networks to dialogue management, two additional elements are necessary. The first extension is to allow variables to evolve as a function of time. Such temporal dependencies are indeed necessary to account for the dynamic nature of dialogue (the dialogue state is not a static entity). Two assumptions are usually made to capture temporal sequences:⁴

1. The first assumption, called the Markov assumption, stipulates that the variable values at time t only depend on the previous time slice $t-1$. Formally, let \mathbf{X} be an arbitrary collection of variables. We denote by \mathbf{X}_t the random variables that express their values at time t . The Markov assumption states that $(\mathbf{X}_{t+1} \perp \mathbf{X}_{0:(t-1)} \mid \mathbf{X}_t)$.
2. The second assumption is that the process is stationary, which means that the probability $P(\mathbf{X}_t \mid \mathbf{X}_{t-1})$ is identical for all values of t . A *stationary* process must be distinguished from a *static* process: A static process is a stochastic process that remains constant for all time steps. In contrast, a stationary process can change over time, but the transition model that describes the dynamics of this process remains constant.

Given these two assumptions, we can define a stochastic process with a probability distribution $P(\mathbf{X}_t \mid \mathbf{X}_{t-1})$ that specifies the distribution of the variables \mathbf{X} at time t given their values at time $t-1$. Such a model is called a *dynamic Bayesian network* (DBN). The distribution $P(\mathbf{X}_t \mid \mathbf{X}_{t-1})$ can be internally factored and include dependencies both between the time slices $t-1$ and t and within the slice t . Figure 3.2 shows a concrete example of a dynamic Bayesian network.

Given the specification of the distribution $P(\mathbf{X}_t \mid \mathbf{X}_{t-1})$ and an initial distribution $P(\mathbf{X}_0)$, a dynamic Bayesian network can be “unrolled” onto multiple time slices. This unrolled model corresponds to a classical Bayesian network.

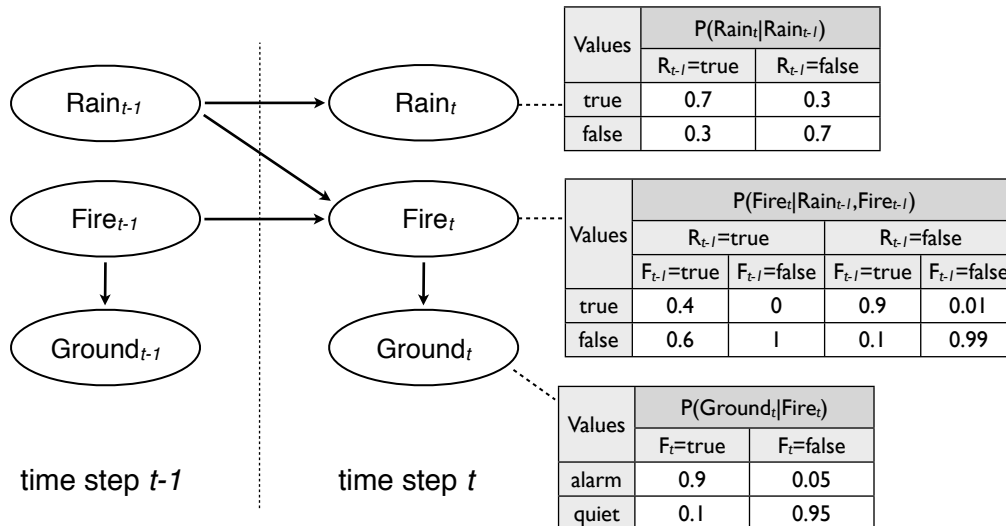


Figure 3.2: Example of a dynamic Bayesian network.

⁴The formalisation presupposes a discrete representation of time, with t representing the current time step.

Decision problems

Dynamic Bayesian networks are well-suited to represent temporal processes. However, in sequential decision tasks such as dialogue management, tracking the current state is only the first step of the reasoning process. The agent must also be able to calculate the relative utilities of the various actions that can be executed at that state. The second extension of Bayesian networks pertains therefore to the inclusion of actions and utilities in addition to state variables.

*Decision networks*⁵ are Bayesian networks augmented with a representation of action variables and their corresponding utilities. Decision networks may include three classes of nodes:

1. *Chance nodes* correspond to the classical random variables described so far. Chance nodes are associated with conditional probability distributions that define the relative probabilities of the node values given the values in the parent nodes.
2. *Decision nodes* (sometimes also called action nodes) correspond to variables that are under the control of the system. The values of these nodes reflect an active choice made by the system to execute particular actions.
3. *Utility nodes* express the utilities (from the system's point of view) associated with particular situations expressed in the node parents. Typically, these parents combine both chance and decision variables. Utility nodes are coupled with utility distributions that associate each combination of values in the node parents with a specific (negative or positive) utility.

Decision networks combined with temporal dependencies are called *dynamic decision networks*. Figure 3.3 illustrates a dynamic decision network with a decision variable containing two alternative actions assigned to distinct utility values depending on the occurrence of fire.

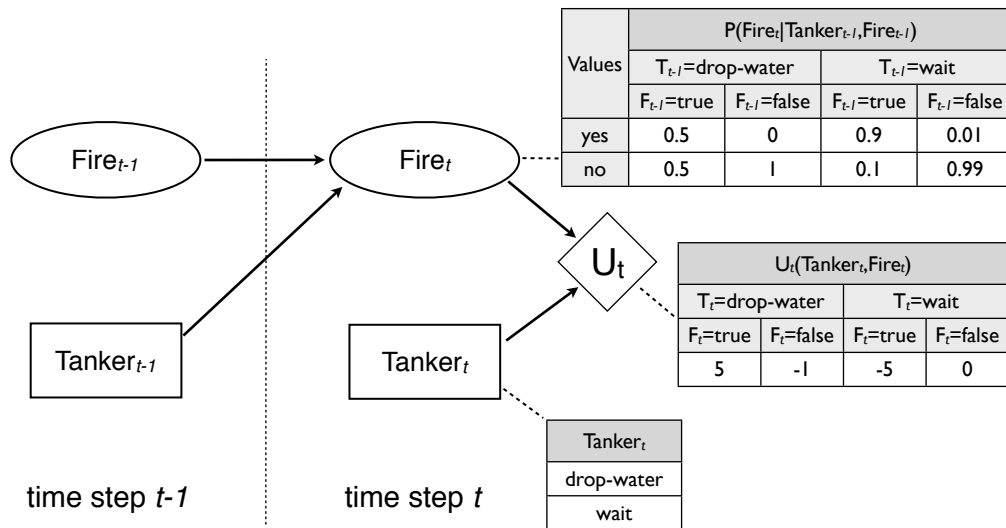


Figure 3.3: Example of a dynamic decision network. By convention, chance nodes are represented with circles, decision nodes with squares, and utility nodes with diamonds.

⁵Decision networks are also called *influence diagrams*.

3.1.2 Inference

Exact and approximate algorithms

The main purpose of probabilistic graphical models is to evaluate *queries* – that is, calculate a posterior distribution over a subset of variables, usually given some evidence. Assuming a graphical model defining the joint probability distribution of a set of variables \mathbf{X} , a probability query is a posterior distribution of the form $P(\mathbf{Q}|\mathbf{e})$, where $\mathbf{Q} \subset \mathbf{X}$ denotes the query variables and \mathbf{e} a specific assignment of values for the evidence variables. If the evidence does not contain any assignment, the query is reduced to the calculation of a marginal distribution. Decision networks can also be used to answer utility queries of the form $U(\mathbf{Q}|\mathbf{e})$. In this case, the query variables often correspond to decision nodes whose utility is to be determined.

A wide range of inference algorithms has been developed to efficiently evaluate these probability and utility queries. These algorithms can be either exact or approximate.

Exact algorithms calculate the precise posterior distribution corresponding to the query through a sequence of manipulations on the probability distributions associated with the graphical model. One popular algorithm for exact inference is variable elimination (Zhang and Poole, 1996). Variable elimination relies on dynamic programming techniques to evaluate a query through a sequence of matrix operations (summation and pointwise product). These operations are defined on so-called “factors” that represent CPDs in a matrix format. Variable elimination can be generalised to handle utility queries using joint factors (Koller and Friedman, 2009). Other algorithms such as message passing on clique trees can also be used (Jensen et al., 1990).

Unfortunately, exact inference remains difficult to scale to large, densely interconnected graphical models, and approximate techniques are often unavoidable in many practical domains. Algorithms for approximate inference in graphical models include approaches such as loopy belief propagation (Murphy et al., 1999), variational methods (Jordan et al., 1999), and a wide array of sampling techniques (MacKay, 1998). Popular sampling techniques include various flavours of importance sampling (Fung and Chang, 1989; Cheng and Druzdzel, 2000) and Markov Chain Monte Carlo (MCMC) approaches such as Gibbs sampling (Pearl, 1987; Gamerman and Lopes, 2006).

The evaluation of probabilistic queries is a difficult computational task in both exact and approximate inference techniques. In fact, inference on unconstrained Bayesian Networks is known to be #P-hard, which is a complexity class that is strictly harder than NP-complete problems. This holds both for exact inference (Cooper, 1990), but also – perhaps more surprisingly – for approximate inference (Dagum and Luby, 1993).

The OpenDial toolkit we have developed for this thesis implements two inference algorithms: generalised variable elimination (Koller and Friedman, 2009, p. 1103) and a specific type of importance sampling method called likelihood weighting (Fung and Chang, 1989), which we outline below. These algorithms are used in the processing workflow of the dialogue manager to (1) update the dialogue state upon the reception of new observations and (2) select system actions on the basis of this updated dialogue state. The details of this workflow will be provided in Chapter 4.

Likelihood weighting

To make our discussion of inference algorithms for graphical models more concrete, we describe below a simple but efficient sampling method called *likelihood weighting* (Fung and Chang, 1989),

which we have used in most of the experiments conducted in this thesis.

The key principle behind all types of sampling algorithms is to estimate the posterior distribution expressed in the query by collecting a large quantity of samples (i.e. assignments of values to the random variables) drawn from the graphical model. Likelihood weighting proceeds by sampling the random variables in the graphical model one by one, in topological order (i.e. from parents to children).⁶ For instance, sampling the network in Figure 3.1 will start with the variable *Weather*, then *Fire* (based on the value drawn for the parent *Weather*), and finally *Ground* and *Satellite* (based on the value drawn for *Fire*). In order to account for the evidence \mathbf{e} , every sample is associated with a specific *weight* that expresses the likelihood of the evidence given the assignment for all the other variables. For graphical models that include utility variables, samples also record the total utility accumulated for the sampled values.

The pseudocode in Algorithm 1 outlines the sampling procedure. The notation $\mathbf{e}(X_i)$ refers to the value specified for the variable X_i in the assignment \mathbf{e} .

Algorithm 1 : GET-SAMPLE (\mathcal{B}, \mathbf{e})

Input: Bayesian/decision network \mathcal{B} and evidence \mathbf{e}

Output: Full sample drawn from \mathcal{B} together with a weight and utility

```

1: Let  $X_1, \dots, X_n$  be a topological ordering for the variables in  $\mathcal{B}$ 
2: Initialise sample  $\mathbf{x} \leftarrow \langle \mathbf{e} \rangle$ 
3: Initialise weight  $w \leftarrow 1$  and utility  $u \leftarrow 0$ 
4: for  $i = 1, \dots, n$  do
5:   if  $X_i$  is a chance variable and is included in the evidence then
6:      $w \leftarrow w \times P(X_i = \mathbf{e}(X_i) \mid \mathbf{x})$ 
7:   else if  $X_i$  is a chance or decision variable then
8:      $x_i \leftarrow$  sample value drawn from  $P(X_i \mid \mathbf{x})$ 
9:      $\mathbf{x} \leftarrow \mathbf{x} \cup \langle x_i \rangle$ 
10:  else if  $X_i$  is a utility variable then
11:     $u \leftarrow u + X_i(\mathbf{x})$ 
12:  end if
13: end for
14: return  $\mathbf{x}, w, u$ 
```

A large number of samples can be accumulated in this manner. Once enough samples are collected (or the inference engine has run out of time), the resulting posterior distribution for the query variables \mathbf{Q} is derived by normalising the weighted counts associated with each value of the query variables, as shown in Algorithm 2. Algorithm 3 extends the procedure to the calculation of utility distributions. In this case, the utility values correspond to a weighted average of the sampled utilities.

3.1.3 Learning

We have so far pushed aside the question of how the distributions in the graphical model are exactly estimated. Early approaches often relied on distributions elicited from human experts based on plausible associations they have observed. Although useful in domains where no data is available,

⁶A partial order on the nodes can always be found since the network is a directed acyclic graph.

Algorithm 2 : LIKELIHOOD-WEIGHTING ($\mathcal{B}, \mathbf{Q}, \mathbf{e}, N$)

Input: Bayesian/decision network \mathcal{B}

Input: Set of query variables \mathbf{Q} and evidence \mathbf{e}

Input: Number N of samples to draw

Output: Approximate posterior distribution $P(\mathbf{Q} | \mathbf{e})$

Let \mathbf{W} be vectors of weighted counts for each possible value of \mathbf{Q} , initialised with zeros

for $i = 1 \rightarrow N$ **do**

$\mathbf{x}, w \leftarrow \text{GET-SAMPLE}(\mathcal{B}, \mathbf{e})$

$\mathbf{W}[\mathbf{x}(\mathbf{Q})] \leftarrow \mathbf{W}[\mathbf{x}(\mathbf{Q})] + w$

end for

Normalise the weighted counts in \mathbf{W}

return \mathbf{W}

Algorithm 3 : LIKELIHOOD-WEIGHTING-UTILITY ($\mathcal{B}, \mathbf{Q}, \mathbf{e}, N$)

Input: (see above)

Output: Approximate utility distribution $U(\mathbf{Q} | \mathbf{e})$

Let \mathbf{W}, \mathbf{U} be vectors of weighted counts for each possible value of \mathbf{Q} , initialised with zeros

for $i = 1 \rightarrow N$ **do**

$\mathbf{x}, w, u \leftarrow \text{GET-SAMPLE}(\mathcal{B}, \mathbf{e})$

$\mathbf{W}[\mathbf{x}(\mathbf{Q})] \leftarrow \mathbf{W}[\mathbf{x}(\mathbf{Q})] + w$

$\mathbf{U}[\mathbf{x}(\mathbf{Q})] \leftarrow \mathbf{U}[\mathbf{x}(\mathbf{Q})] + w \times u$

end for

Average the weighted utility counts $\mathbf{U}(\mathbf{q}) \leftarrow \frac{\mathbf{U}(\mathbf{q})}{\mathbf{W}(\mathbf{q})} \quad \forall \text{ values } \mathbf{q} \text{ of } \mathbf{Q}$

return \mathbf{U}

hand-crafted models are unfortunately difficult to scale (only models with a limited number of parameters can be elicited in such a manner), and are vulnerable to human errors and inaccuracies. It is therefore often preferable to automatically estimate these distributions from real world data – in other words, via statistical estimation based on a collection of examples in a training set.

Two distinct types of learning tasks can be distinguished:

1. The most common task is *parameter estimation*. Parameter estimation assumes the general structure of the graphical model (i.e. the dependencies between variables) is known, but not the parameters of the individual CPDs. Most discrete and continuous distributions are indeed “parametrised” – that is, they depend on the specification of particular parameters that define the exact shape of the distribution. A categorical distribution on k values has for instance k parameters that assign the relative probability of each outcome. Similarly, a normal distribution $\mathcal{N}(\mu, \sigma^2)$ is governed by its two parameters μ and σ^2 .
2. The second possible learning task is *structure learning*. In structure learning, the agent must learn both the structure (i.e. the directed edges) and the parameters of the graphical model, given only the list of variables and the training data. This task is significantly more complex than parameter estimation, as the agent must simultaneously find which variables influence one another and estimate their corresponding conditional dependencies.

We shall concentrate in this thesis on the parameter estimation problem, which is by far the most common type of learning problem in dialogue management. As shall be argued in the next chapters, the dependency relations between state variables can often be derived from prior knowledge of the dialogue domain.

Maximum likelihood estimation

The most straightforward estimation method is called maximum likelihood estimation (MLE). Maximum likelihood estimation searches for the parameter values that provide the best “fit” for the data set. In other words, the parameters are set to the values that maximise the likelihood of the observed data. Given a data set \mathcal{D} , a graphical model and a set of parameters θ to estimate for this model, the objective of MLE is to find the values θ^* that maximise the probability $P(\mathcal{D}; \theta)$, which is the likelihood of the data set \mathcal{D} given the parameter values for θ . This likelihood is often written in logarithmic form to transform the product of probabilities into a summation:

$$\theta^* = \underset{\theta}{\operatorname{argmax}} P(\mathcal{D}; \theta) = \underset{\theta}{\operatorname{argmax}} \log P(\mathcal{D}; \theta) \quad (3.5)$$

If the data samples cover the complete set of variables in the model, this likelihood can be neatly decomposed in a set of local likelihoods, one for each CPD, and the θ^* values can be derived in closed-form. For a categorical distribution, the maximum likelihood estimates will simply correspond to the relative counts of occurrences in the training data.

The learning problem becomes more complex for partially observed domains in which the data samples contain hidden variables. For the Bayesian network in Figure 3.1, an example of a partially observed sample is $[Weather = mild, Ground = alarm, Satellite = quiet]$, where the occurrence of fire is not specified. In such cases, the likelihood function is no longer decomposable, which implies that the maximum likelihood estimate is not amenable to a closed-form solution. The only alternative is to resort to iterative optimisation methods such as gradient ascent (Binder et al., 1997) and Expectation Maximisation (Green, 1990).

The main drawback of maximum likelihood estimation is its vulnerability to overfitting when learning from small data sets. For instance, if we only had collected one single data point $Weather = cold$ for the example above, the maximum likelihood estimate for the probability distribution $P(Weather)$ would be $\langle 1, 0, 0 \rangle$. In other words, maximum likelihood estimation does not take into account any prior knowledge about the relative probability of particular parameter hypotheses, which often leads to unreasonable estimates for low frequency events.

Bayesian learning

An alternative to maximum likelihood estimation is *Bayesian learning*. The key idea of Bayesian approaches to parameter estimation is to view the model parameters as random variables themselves and to derive their posterior distributions after observing the data. Bayesian learning starts with an initial prior over the range of parameter values and gradually refines this distribution through probabilistic inference based on the observation of the samples in the training data. Each distribution $P(X_i | \text{parents}(X_i))$ with unknown parameters is therefore associated with a parent node $\theta_{X_i | \text{parents}(X_i)}$ that define its possible parameters.

Parameter distributions are typically continuous (since probabilities are continuous values), and

often multivariate. Intuitively, we can think of the variable $\theta_{X_i | \text{parents}(X_i)}$ as expressing a “distribution over possible distributions”.

Based on this formalisation, parameter estimation can be elegantly reduced to a problem of probabilistic inference over the parameters. Given a prior $P(\boldsymbol{\theta})$ on the parameter values and a data set \mathcal{D} , the posterior distribution $P(\boldsymbol{\theta} | \mathcal{D})$ is given by Bayes’ rule:

$$P(\boldsymbol{\theta} | \mathcal{D}) = \frac{P(\mathcal{D}; \boldsymbol{\theta}) P(\boldsymbol{\theta})}{P(\mathcal{D})} \quad (3.6)$$

Equation (3.6) allows us to calculate the posterior distribution $P(\boldsymbol{\theta} | \mathcal{D})$ through the use of standard inference algorithms for graphical models.

It is often convenient to encode the distributions of the parameter variables as *conjugate priors* of their associated CPD distribution. In such case, the prior $P(\boldsymbol{\theta})$ and posterior $P(\boldsymbol{\theta} | \mathcal{D})$ after observing the data points \mathcal{D} are ensured to remain within the same distribution family. In particular, if the distribution of interest is a categorical distribution, its parameter distribution can be encoded with a Dirichlet distribution, which is known as the conjugate prior of categorical and multinomial distributions. A Dirichlet distribution is a continuous, multivariate distribution of dimension k (with k being the size of the multinomial) that is itself parametrised with so-called concentration hyperparameters denoted $\boldsymbol{\alpha} = [\alpha_1, \dots, \alpha_k]$. Additional details about the formal properties of Dirichlet distributions can be found in Appendix A.

Figure 3.4 illustrates this Bayesian approach to parameter estimation for the variable *Weather*. As the variable possesses three alternative values, the allowed values for the parameter $\boldsymbol{\theta}_{\text{Weather}}$ are three-dimensional vectors $[\theta_{\text{Weather}(1)}, \theta_{\text{Weather}(2)}, \theta_{\text{Weather}(3)}]$, with the standard constraints on probability values: $\theta_{\text{Weather}(i)} \geq 0$ for $i = \{1, 2, 3\}$ and $\theta_{\text{Weather}(1)} + \theta_{\text{Weather}(2)} + \theta_{\text{Weather}(3)} = 1$. As we can observe in the figure, these constraints effectively limit the range of possible values to a 2-dimensional simplex. The $\boldsymbol{\alpha}$ hyperparameters can be intuitively interpreted as “virtual counts” of the number of observations in each category. In Figure 3.4, we can see that the hyperparameters $\boldsymbol{\alpha} = [5, 10, 5]$ lead to higher probability densities for parameters around the peak $\langle 0.25, 0.5, 0.25 \rangle$. As the number of observations increases, the Dirichlet distribution will gradually concentrate on a particular region of the parameter space until convergence.

In the case of completely observed data, Bayesian learning over several parameters can be decomposed into independent estimation problems (one for each parameter variable):

$$P(\mathcal{D}; \boldsymbol{\theta}) = \prod_{\theta_i \in \boldsymbol{\theta}} P(\mathcal{D}; \theta_i) \quad (3.7)$$

As in the maximum likelihood estimation case, the learning task becomes more complicated when dealing with partially observed data, as the posterior distribution can no longer be represented as a product of independent posteriors over each parameter. In this setting, the full posterior is often too complex to be amenable to an analytic solution. Sampling techniques can be applied to offer reasonable approximations of this posterior. As we shall see in Chapters 5 and 6, the work presented in this thesis is grounded in these approximate Bayesian learning methods. Table 3.1 briefly summarises the parameter estimation methods discussed in this section.

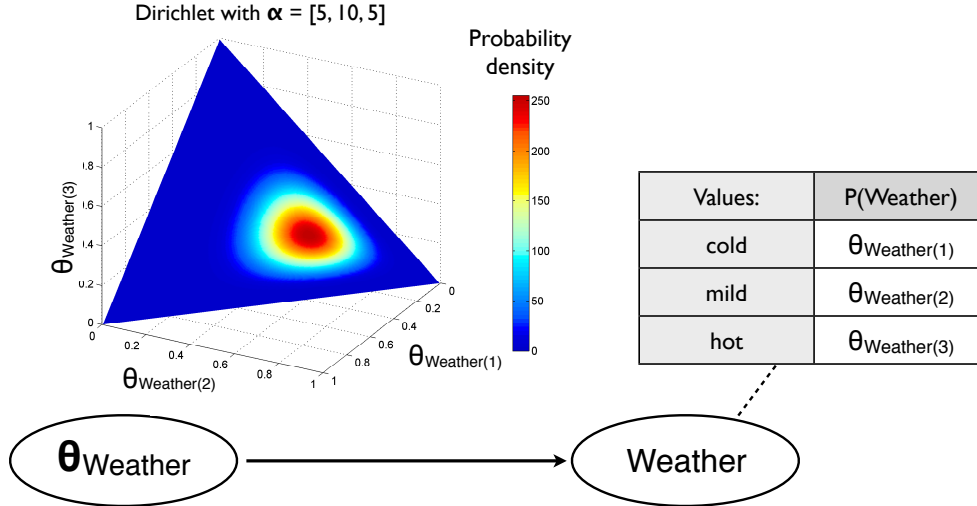


Figure 3.4: Bayesian network with variable *Weather* and associated parameter θ_{Weather} . As *Weather* is a categorical distribution, $P(\theta_{\text{Weather}})$ is expressed as a Dirichlet distribution with three dimensions that reflect the relative probabilities for the three values in $\text{Val}(\text{Weather})$.

Training data	Maximum likelihood estimation	Bayesian learning
<i>Fully observed</i>	Maximisation of local likelihood functions	Query on local posterior distribution over each parameter
<i>Partially observed (hidden variables)</i>	Iterative optimisation of global likelihood function	Query on full posterior over parameters via sampling

Table 3.1: Summary of parameter estimation approaches for directed graphical models.

3.2 Reinforcement learning

Dialogue management is fundamentally a problem of sequential decision-making under uncertainty. The objective of the dialogue manager is to select the “optimal” action – that is, the action that yields the maximum expected long-term utility for the agent. However, in many domains (including dialogue domains), the agent has no knowledge of the internal dynamics of the environment it finds itself in. It must therefore determine the best action to execute in any given state via a process of trial and error. Such a learning process is called *reinforcement learning* (RL). It is worth noting that reinforcement learning effectively strikes a middle ground between supervised and unsupervised learning. Contrary to supervised learning, the framework does not require the provision of “gold standard” examples. However, thanks to the rewards it receives from the environment, the agent is able to get a sense of the quality of its own decisions, an element which is absent in unsupervised learning methods.

We provide here a brief introduction to the central concepts in reinforcement learning, and

refer the interested reader to Sutton and Barto (1998) for more details.

3.2.1 Markov Decision Processes

Reinforcement learning tasks are typically based on the definition of a *Markov Decision Process* (MDP), which is a tuple $\langle \mathcal{S}, \mathcal{A}, T, R \rangle$ where:

- \mathcal{S} is the state space of the domain and represents the set of all (mutually exclusive) states.
- \mathcal{A} is the action space and represents the possible actions that can be executed by the agent.
- $T : \mathcal{S} \times \mathcal{A} \times \mathcal{S} \rightarrow [0, 1]$ is the transition function and encodes the probability $P(s' | s, a)$ of reaching state s' after executing action a in state s .
- $R : \mathcal{S} \times \mathcal{A} \rightarrow \mathbb{R}$ is the reward function associated with the execution of action a in state s .

Markov Decision Processes can be explicitly represented as dynamic decision networks. As we can see from the graphical illustration in Figure 3.5, the state at time $t + 1$ is dependent both on the previous state at time t and the action a_t performed by the system. After each action, the system receives a reward $r_t = R(s_t, a_t)$ that depends both on the state and selected action.

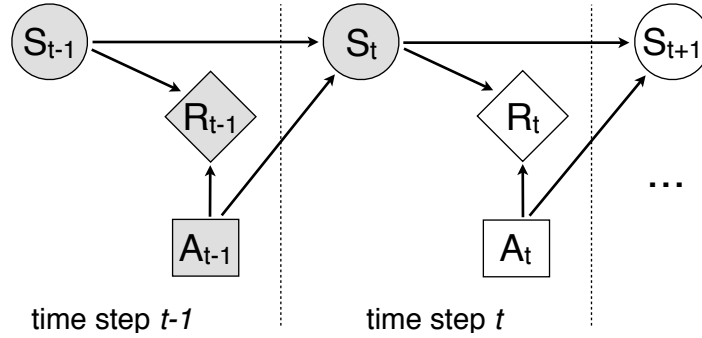


Figure 3.5: Graphical model of a Markov Decision Process (MDP) unfolded on a few time steps. Greyed entities indicate observed variables. In the MDP case, all past states, actions and rewards are observed, as well as the current state.

The objective of the learning agent is to extract an optimal policy $\pi^* : \mathcal{S} \rightarrow \mathcal{A}$ for the given MDP definition. This policy maps each state in \mathcal{S} to the action that maximises the *expected return* of the agent for that state, which is the discounted sum of rewards, starting from the current state up to a potentially infinite horizon. In this sum, a geometric discount factor γ (with $0 \leq \gamma \leq 1$) indicates the relative worth of future rewards in regard to present ones. At one extreme, $\gamma = 0$ corresponds to a short-sighted agent only interested in its immediate reward, while at the other extreme, $\gamma = 1$ corresponds to an agent for which immediate and distant rewards are valued equally. For a given policy π , the expected return for an arbitrary state s in \mathcal{S} is expressed through the *value function* $V^\pi(s)$:

$$V^\pi(s) = E \{ r_0 + \gamma r_1 + \gamma^2 r_2 + \dots \mid s_0 = s, \pi \text{ is followed} \} \quad (3.8)$$

$$= E \left\{ \sum_{i=0}^{\infty} \gamma^i r_i \mid s_0 = s, \pi \text{ is followed} \right\} \quad (3.9)$$

where $r_i = R(s_i, \pi(s_i))$ is the reward received at time i after performing the action specified by the policy π in state s_i . Equation (3.9) can be rewritten in a recursive form, leading to the well-known Bellman equation (Bellman, 1957):

$$V^\pi(s) = R(s, \pi(s)) + \gamma \sum_{s' \in \mathcal{S}} P(s' | s, \pi(s)) V^\pi(s') \quad (3.10)$$

In other words, the expected return in state s equals its immediate reward plus the expected return of its successor state. The recursive definition offered by the Bellman equation is crucial for many reinforcement learning methods, since it allows the value function to be estimated by an iterative process in which the value function is gradually refined until convergence.

Another useful concept is the action–value function $Q^\pi(s, a)$ that expresses the return expected after performing action a in state s and following the policy π afterwards:

$$Q^\pi(s, a) = R(s, a) + \gamma \sum_{s' \in \mathcal{S}} P(s' | s, a) V^\pi(s') \quad (3.11)$$

The value and action–value functions are closely related, as $V^\pi(s) = Q^\pi(s, \pi(s))$.

The objective of the learning process is to find a policy $\pi^* : \mathcal{S} \rightarrow \mathcal{A}$ that selects the action with highest expected return for all possible states: $V^{\pi^*}(s) \geq V^\pi(s)$ for any state s and policy π . For a given MDP, there is at least one policy that satisfies this constraint. The value and action–value functions for this optimal policy are respectively denoted V^* and Q^* .

Two families of reinforcement learning approaches can be used to determine this policy: *model-based* approaches and *model-free* approaches. As we shall see in Chapter 6, these optimisation techniques form the methodological basis for our own reinforcement learning approach to the estimation of dialogue management models.

Model-based approaches

Model-based approaches estimate an explicit model of the MDP and subsequently optimise a policy based on this model. The agent initially collects data by interacting with its environment and recording the reward and successor state following each action. Based on this data, standard parameter estimation methods (as outlined in Section 3.1.3) can be used to learn the MDP parameters, and the resulting model is applied to extract the corresponding optimal policy via dynamic programming (Bertsekas and Tsitsiklis, 1996) or Bayesian learning (Dearden et al., 1999).

The most well-known model-based algorithm is *value iteration*, which operates by estimating the value function via a sequence of updates based on Bellman’s equation. Given a value function estimate V_k available at step k , the estimate at step $k + 1$ is calculated as:

$$V_{k+1}(s) \leftarrow \max_a R(s, a) + \gamma \sum_{s' \in \mathcal{S}} P(s' | s, a) V_k(s') \quad (3.12)$$

Once the iterations have converged, the optimal policy is straightforwardly derived as:

$$\pi^*(s) \leftarrow \operatorname{argmax}_a \left(R(s, a) + \sum_{s' \in \mathcal{S}} P(s' | s, a) V^*(s') \right) \quad (3.13)$$

Model-free approaches

Model-free approaches skip the estimation of the underlying MDP model in order to directly learn Q^* functions from the agent’s interaction experience. The main idea behind model-free methods is to let the agent try out different actions, observe their effects in terms of rewards and successor states, and use this information to refine the estimate of the Q^* function. The estimation process is, however, slightly more intricate than in model-based settings, since the Q -values are not directly accessible to the learning agent. The only feedback perceived by the agent are indeed the immediate rewards resulting from its actions and the subsequent observations.

Temporal-difference algorithms such as Q-learning (Watkins and Dayan, 1992) and SARSA (Rummery, 1995) are amongst the most popular model-free methods. These algorithms rely on Bellman’s equation to incrementally improve the action–value estimates on the basis of the rewards resulting from the agent actions. Temporal-difference algorithms are also called “bootstrapping” methods as they approximate new Q -value estimates based on previous estimates.

The SARSA⁷ algorithm has in particular been applied extensively for dialogue policy optimisation (Rieser and Lemon, 2011). The algorithm follows a simple learning procedure. Let s_t be a state at time t followed by a system action a_t . The execution of the system action a_t results in a reward r_{t+1} and a new state s_{t+1} which is itself followed by a second action a_{t+1} . On the basis of this sequence, the Q -value estimate for the first action a_t can be updated as:

$$Q_{k+1}(s_t, a_t) \leftarrow Q_k(s_t, a_t) + \alpha [r_{t+1} + \gamma Q_k(s_{t+1}, a_{t+1}) - Q_k(s_t, a_t)] \quad (3.14)$$

where α represents the learning rate of the algorithm. The estimate $Q_{k+1}(s_t, a_t)$ is thus modified in direction of the value $[r_{t+1} + \gamma Q_k(s_{t+1}, a_{t+1})]$, with a learning step expressed by α . This operation is repeated for a large number of episodes until convergence.

One key question that must be addressed in both model-based and model-free approaches is how to efficiently explore the space of possible actions. The agent should indeed favour the selection of high-utility actions in most cases (since they are the ones of interest to the agent), but should also occasionally explore actions that are currently thought to be less effective to avoid being stuck in a suboptimal behaviour. This trade-off, called the *exploration–exploitation* dilemma, is one of the central research questions in reinforcement learning.

3.2.2 Partially Observable Markov Decision Processes

A limitation faced by MDP approaches is the assumption that the current state is fully observable. As we already noted in the previous chapter, this assumption does not hold for most dialogue systems, owing to the presence of multiple sources of uncertainty. As briefly alluded to in Chapter 2, an elegant solution to this shortcoming is to extend the MDP framework by allowing the state to be a hidden variable that is indirectly inferred from observations. Such an extension gives rise to a *Partially Observable Markov Decision Process* (POMDP). POMDPs are formally defined as tuples $\langle \mathcal{S}, \mathcal{A}, T, R, \mathcal{O}, Z \rangle$. As in a classical MDP, \mathcal{S} represents the state space, \mathcal{A} the action space, T the transition probability $P(s' | s, a)$ between states, and R the reward function $R(s, a)$. However, the actual state is no longer directly observable. Instead, the process is associated with an observation space \mathcal{O} that expresses the set of possible observations that can be perceived by the system. The

⁷SARSA stands for “State-Action-Reward-State-Action”, as a reference to the algorithm’s processing sequence.

function Z defines the probability $P(o | s)$ of observing o in the current state s . Figure 3.6 provides a graphical illustration of the POMDP framework. As we can see, POMDPs can also be expressed as dynamic decision networks in which the state variable is not directly observed.

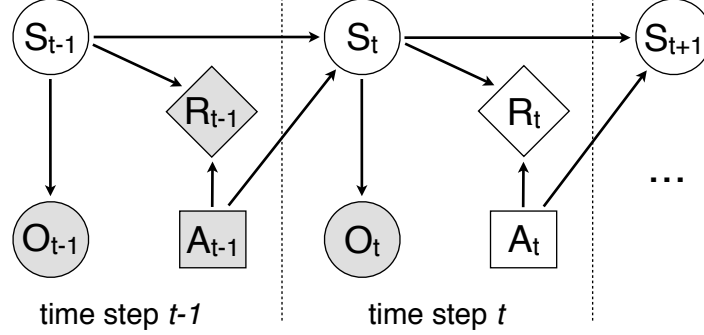


Figure 3.6: Graphical model of a Partially Observable Markov Decision Process (POMDP) unfolded on a few time steps. Compared to Figure 3.5, we notice that the state is no longer directly accessible but must be inferred from the observations and (predicted) state history.

The agent knowledge at a given time is represented by the *belief state* b , which is a probability distribution $P(s)$ over possible states. After each system action a and subsequent observation o , the belief state b is updated to b' in order to incorporate the new information. This belief update is a simple application of Bayes' theorem:

$$b'(s) = P(s' | b, a, o) = \frac{P(o | s') P(s' | b, a)}{P(o | b, a)} \quad (3.15)$$

$$= \eta P(o | s') \sum_s P(s' | s, a) b(s) \quad (3.16)$$

where $\eta = (P(o | b, a))^{-1}$ serves as a normalisation factor and is usually never calculated explicitly.

In the POMDP setting, a policy is a function $\pi = \mathcal{B} \rightarrow \mathcal{A}$ mapping each possible belief state to its optimal action. Mathematically, the belief state space \mathcal{B} is a $(|\mathcal{S}| - 1)$ -dimensional simplex (where $|\mathcal{S}|$ is the size of the state space), which is a continuous and high-dimensional space. The optimisation of the dialogue policy is therefore considerably more complex than for MDPs. The value function V^π for a policy π is the fixed point of Bellman's equation:

$$V^\pi(b) = \sum_{s \in \mathcal{S}} R(s, a) b(s) + \gamma \sum_{o \in \mathcal{O}} P(o | b, \pi(b)) V^\pi(b') \quad (3.17)$$

where b' is the updated belief state following the execution of action $\pi(b)$ and the observation of o , as in Equation (3.16). The optimal value function $V^*(b)$ for finite-horizon problems is known to be piecewise linear and convex in the belief space – and can be approximated arbitrarily well in the case of infinite horizons – as proved by Sondik (1971). The value function can therefore be represented by a finite set of vectors, called α -vectors. Each vector α_i is associated with a specific action $a(i) \in \mathcal{A}$.⁸ The vectors are of size $|\mathcal{S}|$ and $\alpha_i(s)$ is a scalar value representing the value of

⁸The converse is not true: each action can be associated with an arbitrary number of vectors.

action $a(i)$ in state s . Given these vectors, the value function simplifies to:

$$V^*(b) = \max_i \alpha_i \cdot b \quad (3.18)$$

And the policy π^* can be rewritten as:

$$\pi^*(b) = a \left(\operatorname{argmax}_i (\alpha_i \cdot b) \right) \quad (3.19)$$

Extracting the α -vectors associated with a POMDP problem is, however, computationally challenging given the high-dimensional and continuous nature of the belief space, and exact solutions are intractable beyond toy domains. As proved by Papadimitriou and Tsitsiklis (1987), deriving the α -vectors for a given POMDP – also known as “solving” the POMDP – is a PSPACE-complete problem, which means that the best known algorithms will take time $2^{\text{poly}(n,h)}$ to solve a problem with n states and a planning horizon h .

A number of approximate solutions have been developed to address this limitation. One simple strategy is to rewrite the $Q(b, a)$ function in terms of the Q -values for the underlying MDP, as proposed by Littman et al. (1998):

$$Q(b, a) = \sum_{s \in \mathcal{S}} Q_{MDP}(s, a) b(s) \quad (3.20)$$

Although this approximation can work well in some settings, it essentially rests on the assumption that the state uncertainty will disappear after one action. It is therefore a poor model for information-gathering actions – that is, actions that do not change the actual state but might help in reducing state uncertainty. A typical example of such an action in the dialogue domain is a clarification request about the user intention.

Many approximations methods focus on reducing the complexity of the belief state space, notably through the use of grid-based approximations (Zhou and Hansen, 2001). The idea is to estimate the value function only at particular points within the belief simplex. At runtime, the action–value function for the current belief state b is then approximated to the value for the closest point in the grid according to some specific distance measure. Instead of a fixed grid, most recent solution methods rely on sampling techniques to perform local value updates (Pineau et al., 2003; Kurniawati et al., 2008; Shani et al., 2013). Belief compression has also proved to be useful (Roy et al., 2005). Yet another family of approximation methods directly search in the space of possible policies constrained to a particular form such as finite-state controllers (Hansen, 1998).

A final alternative, which we follow in Chapter 6 of this thesis, is to rely on online planning algorithms (Ross et al., 2008; Silver and Veness, 2010). The idea is to let the agent estimate the $Q(b, a)$ values at execution time via look-ahead search on a limited planning horizon. The planning horizon represents the number of future time steps considered by the planner. Compared to offline policies, the major advantage of online approaches is that the agent only needs to consider the current state to plan instead of enumerating all possible ones. It can also more easily adapt to changes in the reward or transition models, as the policy is not compiled in advance but generated at runtime. Moreover, online planning can also be used to simultaneously learn or refine these models during the interaction, as demonstrated by Ross et al. (2011). However, the available

planning time is more limited, since planning is in this case interleaved with system execution and must therefore satisfy real-time constraints.

Despite these recent advances, the optimisation of POMDP policies remains to a large extent an open research question in the fields of reinforcement learning and decision-theoretic planning. One important insight that transpires in much of the POMDP literature is the importance of exploiting the problem structure to reduce the complexity of the learning and planning problems (Pineau, 2004; Poupart, 2005). As detailed in the next chapter, the work presented in this thesis precisely attempts to transfer this insight into dialogue management.

3.2.3 Factored representations

In the previous pages, we modelled the system states and actions as atomic symbols. Such plain representations can unfortunately quickly lead to a combinatorial explosion of the state–action spaces. A more efficient alternative is to apply *factored* representations that decompose the state into distinct variables with possible conditional dependencies between one another. Action variables can also be decomposed in a similar manner. For an MDP, the state will take the form of a set of variables \mathbf{S}_t , and the transition function $P(\mathbf{S}_t | \mathbf{S}_{t-1}, \mathbf{A}_{t-1})$ be represented as a dynamic Bayesian network (Boutilier et al., 1999). The reward function can similarly be decomposed in a collection of utility variables \mathbf{R}_t connected to relevant sets of state and action variables. In that case, the total utility is often defined as the addition of all utilities (Bacchus and Grove, 1995).

POMDPs can be factored in a similar way, with the inclusion of observation variables \mathbf{O}_t connected to the state variables \mathbf{S}_t through conditional dependencies $P(\mathbf{O}_t | \mathbf{S}_t)$. At time t , the observation variables \mathbf{O}_t will be observed while the state variables \mathbf{S}_t remain hidden. Figure 3.7 illustrates this factorisation. As we can observe from the figure, both plain and factored (PO)MDPs form specific cases of dynamic decision networks (cf. Section 3.1.1).

This factorisation of the domain variables through conditional independence assumptions leads to a more compact representation of the domain models and hence a substantial reduction in the number of associated parameters. In addition, the introduced structure can be directly exploited to e.g. improve the efficiency of probabilistic inference (Koller and Friedman, 2009) and the tractability of POMDP solution algorithms (Poupart, 2005).

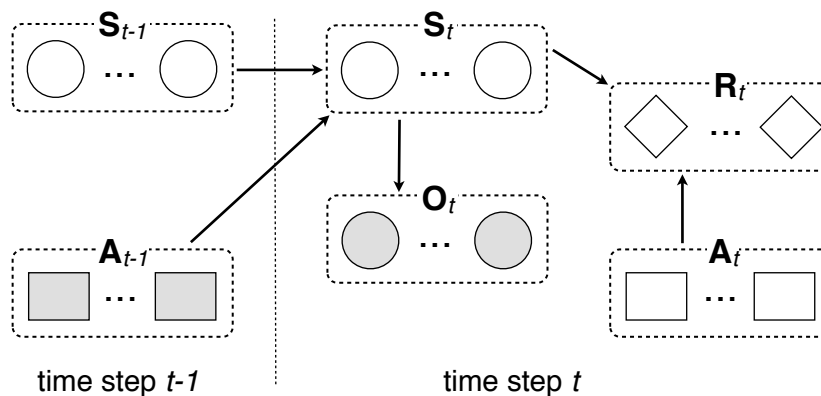


Figure 3.7: Factored representation of a POMDP with state variables \mathbf{S} , action variables \mathbf{A} , observation variables \mathbf{O} , and rewards \mathbf{R} .

3.3 Application to dialogue management

We have now reviewed the key ideas of probabilistic reasoning and reinforcement learning, and are ready to explain how these ideas can be practically transferred to the dialogue management task. After a brief review of supervised learning approaches, we detail how dialogue can be modelled as a Markov Decision Process or Partially Observable Markov Decision Process, and survey the various optimisation techniques that have been developed to automatically optimise dialogue policies for such models based on real or simulated interaction data.

3.3.1 Supervised approaches

The most straightforward use of statistical approaches to dialogue management is to learn dialogue policies in a supervised manner, based on external examples of dialogues. As discussed in the previous chapter, such examples are often collected via Wizard-of-Oz experiments where dialogue management is remotely performed by a human expert. The resulting training data is a sequence $\{\langle s_i, a_i \rangle : 1 \leq i \leq n\}$ of state–action pairs, where s_i is the state at time i and a_i the corresponding wizard action, which is assumed to reflect the best action to perform in this state. Most supervised learning approaches encode the dialogue state as a list of feature-value pairs, and the goal of the learning algorithm is to train a classifier $C : \mathcal{S} \rightarrow \mathcal{A}$ from states to actions that produces the best fit for this training data (modulo regularisation constraints), and will therefore “mimic” the decisions of the expert in similar situations. Various classifiers can be used for this purpose, such as maximum likelihood classification (Hurtado et al., 2005), decision trees (Lane et al., 2004), Naive Bayes (Williams and Young, 2003), and logistic regression (Rieser and Lemon, 2006; Passonneau et al., 2012).

The most important issue faced by supervised learning approaches is data sparsity, as only a fraction of the possible states can realistically be covered by the dialogue examples. Several generalisation techniques can be employed to alleviate this problem. The simplest is to encode the dialogue policy as a linear function of state features. The size of the feature set can be further reduced with feature selection (Passonneau et al., 2012). Yet another approach put forward by Hurtado et al. (2005) is to couple the classifier with a distance measure between states, thereby allowing the reuse of strategies learned from closely related states.

3.3.2 MDP dialogue policies

Instead of learning a dialogue policy by imitating the behaviour of human experts, the dialogue manager can also learn by itself the best action to perform in each possible conversational situation via repeated interactions with a (real or simulated) user. Dialogue management can be cast as a type of Markov Decision Process $\langle \mathcal{S}, \mathcal{A}, T, R \rangle$ in which:

- The state space \mathcal{S} corresponds to the set of possible dialogue states, usually encoded as a list of feature-value pairs that capture relevant aspects of the current conversational context.
- The actions space \mathcal{A} corresponds to the set of (verbal or non-verbal) actions that can be executed by the system.

- The transition function T captures the “dynamics” of the conversation, and indicates how the dialogue state is expected to change as a result of the system actions (and in particular how the user is expected to respond).
- The reward function R expresses the objectives and costs of the application. A common reward function is to assign a high positive value for the successful completion of the task, a high negative value for a failure, and a small negative value for soliciting the user to repeat or clarify their intention.

A common misunderstanding should be clarified at this point. The representation of dialogue as a Markov Decision Process implies that the transition function only considers the previous state and action to predict the next state. It has occasionally been argued that this formalisation makes the decision-making process oblivious to non-local aspects of the dialogue history. This argument, however, is essentially invalid, as the dialogue state is not limited to the mere representation of the last dialogue act but may express any features related to the interaction context, including variables recording dialogue histories of arbitrary length, long-term user intentions, and so forth. It is ultimately up to the system designer to decide which features are deemed relevant to describe the current state of the dialogue.

Dialogue state representation

As for supervised learning methods, MDP-based reinforcement learning approaches to dialogue management encode the dialogue state in terms of feature-value pairs. The dialogue state is thus factored into a number of independent variables (one for each feature). Most early approaches adopted crude state representations with features limited to the status of the slots to fill and the last user utterance (Levin et al., 2000; Singh et al., 2000; Scheffler and Young, 2002). The voice-enabled email client described in Walker (2000) captured additional measures related to the overall task progress, history of previous system attempts, confidence thresholds and timing information. There has also been some work on the automatic identification of relevant state variables, using methods from structure learning in decision networks (Paek and Chickering, 2006) and feature selection (Tetreault and Litman, 2006).

Henderson et al. (2008) were (to our knowledge) the first to explore the extension of reinforcement learning methods to large state spaces based on rich representations of the conversational context. Inspired by information state approaches to dialogue management, their state space captures detailed information such as the complete history of dialogue acts and fine-grained representations of the task status, amounting to a total of 10^{386} possible states. Such rich state representations allow the dialogue manager to exploit much broader contextual knowledge in its decision-making. However, it also creates important challenges regarding action selection, as generalisation techniques are necessary to scale up the learning procedure to such large state spaces.

Policy optimisation (and associated generalisation techniques)

For most dialogue domains, the reward is fixed in advance by the system designer and reflects the task objectives. It can also correspond to a performance metric such as PARADISE (Walker, 2000). In such a case, the performance metric is represented as a linear combination of quantitative measures whose weight is empirically estimated via multivariate linear regression from surveys of

user satisfaction. The quantitative measures of dialogue performance can include measures of *task success* (e.g. ratio of completed vs. failed tasks, κ agreement for slot-filling applications), *dialogue quality* measures (e.g. number of repetitions, interruptions, ASR rejection prompts) and *dialogue efficiency* measures (e.g. number of utterances per dialogue, total elapsed time).

The transition probabilities, however, are typically unknown. Although a few methods have been developed to estimate an explicit transition model for the dialogue domain based on observed interactions (Singh et al., 2002; Tetreault and Litman, 2006), the bulk of the research on dialogue policy optimisation has so far relied on model-free techniques. Due to the significant amounts of data necessary to reach convergence, it is often impossible to directly learn the value function from interactions with real users for most practical domains. A user simulator is instead used to provide unlimited supplies of interactions to the reinforcement learning algorithm. Several options are available to construct this user simulator. The first option is to design the simulator manually based on specific assumptions about the user behaviour (Pietquin and Dutoit, 2006; Schatzmann et al., 2007a). The simulator can also be derived in a data-driven manner from existing corpora (Georgila et al., 2006). In this case, user simulation can be interpreted as a way to expand the initial data set. The third available option is to exploit Wizard-of-Oz studies to tune the simulator parameters (Rieser and Lemon, 2010b). In addition to user modelling, the simulator should also integrate error modelling techniques in order to simulate the errors that may appear along the speech recognition and understanding pipeline (Schatzmann et al., 2007b; Thomson et al., 2012)

The key benefit of user simulation lies in the possibility to explore a large number of possible dialogue trajectories. Such kind of simulation is of great use for prototyping dialogue policies and experimenting with alternative setups (and in particular with various levels of noise and errors). However, simulated interactions are not as valuable as real interactions and offer no guarantee of matching the behaviour and error patterns of actual users. Paek (2006) also argues against the practice of training and evaluating the accuracy of dialogue policies on the same simulator.

A key problem in reinforcement learning methods is the *curse of dimensionality*: The number of parameters grows exponentially with the size of the state and action spaces (Sutton and Barto, 1998). In order to scale the learning procedure to larger domains, factorisation and generalisation techniques are often necessary. An early example of this line of research is the work of Paek and Chickering (2006) on the use of graphical models for dialogue policy optimisation. The domain employed in their experiments was a speech-enabled web browser. Their strategy was to explicitly represent dialogue management as a dynamic decision network and learn both the structure and parameters of this network from user simulations. The state space included features extracted from the interaction logs. Based on the simulated dialogues, the learning algorithm could automatically discover the subset of state variables that were relevant for decision-making as well as the transition probabilities between these variables. They also experimented with various Markov orders (first-versus second-order Markov models) to analyse the impact of longer state histories on the system performance. After learning the decision network, dynamic programming techniques were used to extract a dialogue policy that is optimal with respect to the learned models.

Henderson et al. (2008) demonstrate how to reduce the complexity of model-free learning techniques by way of function approximation. As the large size of their state-action space prevented the use of classical tabular representations for the $Q(s, a)$ function, they instead relied on function

approximation to define the Q -values as a linear function of state features:

$$Q(s, a) = f(s)^T w_a \quad (3.21)$$

where $f(s)$ is a feature vector extracted from the state and w_a a weight vector for action a . The weight vectors were learned with the SARSA algorithm based on a fixed corpus (thereby avoiding the use of user simulators). To further refine the estimation of Q -values, their approach combined estimates from both supervised and reinforcement learning in their final model.

Hierarchical abstraction is another way to reduce the search space of the optimisation process, as shown by Cuayáhuitl (2011). Instead of viewing action selection as a single monolithic policy, the selection is decomposed in their work into multiple levels, each responsible for a specific decision problem. This decomposition is formally expressed via a hierarchical extension of MDPs called Semi-Markov Decision Processes. Contrary to classical Markov Processes, Semi-Markov Decision Processes allow for actions that take a variable amount of time to complete their execution (a characteristic called *temporal abstraction*). Each level in the hierarchy is associated with its own subset of state and action variables. This modular approach allows a complex policy to be split into a sequence of simpler decisions. Such hierarchical formalisation is particularly natural for task-oriented dialogues, which are known to exhibit rich attentional and intentional structures, as notably argued in the seminal work of Grosz and Sidner (1986). It also bears similarities with the approach presented by Litman and Allen (1987) on dialogue understanding based on a plan structure.

Finally, it is worth noting that several researchers have attempted to combine the benefits of supervised and reinforcement learning methods by initialising an RL algorithm with a policy estimated via supervised methods (Williams and Young, 2003; Rieser and Lemon, 2006).

3.3.3 POMDP dialogue policies

To capture the uncertainty associated with some state variables, dialogue can be explicitly modelled as a Partially Observable Markov Decision Process $\langle \mathcal{S}, \mathcal{A}, T, R, \mathcal{O}, Z \rangle$. Modelling a dialogue domain as a POMDP is similar in most respects to the MDP formalisation. The observations typically correspond to the possible N-best lists that can be generated by the speech recogniser and NLU modules, and can also include observations perceived via other modalities.

Dialogue state representation

POMDP approaches express state uncertainty through the definition of a belief state b , which is a probability distribution $P(s)$ over possible states. After a system action a in belief state b followed by observation o , the belief state b is updated according to Equation (3.16), repeated here for convenience:

$$b' = P(s' | b, a, o) = \eta P(o | s') \sum_s P(s' | s, a) b(s) \quad (3.16)$$

Belief update requires the specification of two probabilistic models: the observation model $P(o | s')$ and the transition model $P(s' | s, a)$. Many POMDP approaches to dialogue management factor the state s into (at least) three distinct variables $s = \langle a_u, i_u, c \rangle$, where a_u is the last user

dialogue act, i_u the current user intention(s), and c the interaction context.⁹ Assuming that the observation o only depends on the last user act a_u , and that a_u depends on both the user intention i_u and the last system action a_m , Equation (3.16) is then rewritten as:

$$b' = P(a'_u, i'_u, c' | b, a_m, o) \quad (3.22)$$

$$= \eta P(o | a'_u) P(a'_u | i'_u, a_m) \sum_{i_u, c'} P(i'_u | i_u, a_m, c') P(c') b(i_u) \quad (3.23)$$

The transition model is decomposed in this factorisation into distinct distributions:

1. The distribution $P(a'_u | i'_u, a_m)$ is called the *user action model* and defines the probability of a particular user action given the underlying intention and the last system act. It expresses the likelihood of the user action a'_u following the system action a_m and the compatibility of a'_u with the user intention i'_u (Young et al., 2010).
2. The distribution $P(i'_u | i_u, a_m, c')$ is the *user goal model* and captures how the user intention is likely to change as a result of the context and system actions.

These two distributions are usually derived from collected interaction data. A graphical illustration of this state factorisation is shown in Figure 3.8.

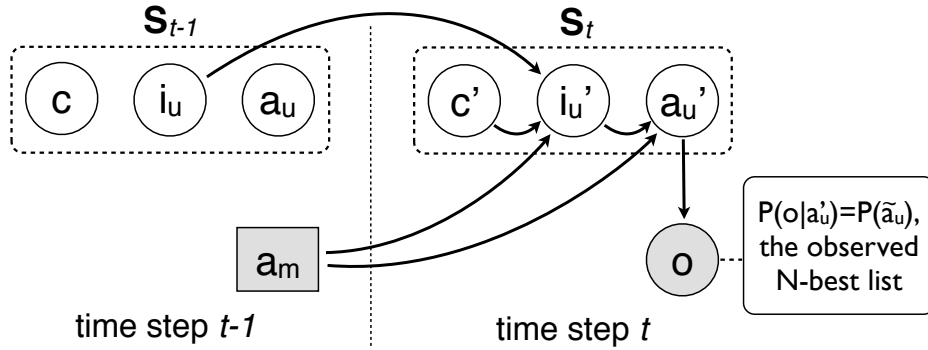


Figure 3.8: Common factorisation of the state space for a POMDP-based dialogue system, where c represents the dialogue context, i_u the user intention, a_u the last user dialogue act, a_m the last system act, and o the observation. The representation omits the conditional dependencies for the variable c' , as this variable is by nature contingent on the dialogue domain.

The observation model $P(o | a'_u)$ is often rewritten as $P(\tilde{a}_u)$, the dialogue act probability in the N-best list provided by the speech recognition and semantic parsing modules (cf. Section 2.2.2), based on the following approximation:

$$P(o | a'_u) = \frac{P(a'_u | o) P(o)}{P(a'_u)} \approx P(a'_u | o) = P(\tilde{a}_u) \quad (3.24)$$

The above approximation rests on the assumption of uniform distributions for the possible observations in the absence of further evidence. Since the probabilities $P(\tilde{a}_u)$ are provided at runtime

⁹Some approaches also define a specific variable for the dialogue history (Young et al., 2010).

by the ASR and NLU modules, the approximation does not require an explicit specification of the observation set \mathcal{O} and model Z at design time. This modelling choice has the advantage of circumventing the statistical estimation of the observation model, a difficult problem since the number of possible N-best lists is theoretically infinite. A few approaches have nevertheless been developed to estimate explicit observation models for small dialogue domains. Williams et al. (2008) investigated in particular how to integrate observations that include continuous-valued ASR confidence scores into a classical POMDP framework and devised ad-hoc density functions for this purpose. Chinaei et al. (2012) showed how an observation model could be empirically estimated from interaction data with a bag-of-words approach.

In the seminal work of Roy et al. (2000) that first introduced the POMDP framework to dialogue management, the state is represented by a single variable expressing the user intention, and hand-crafted models were used for the belief update. Zhang et al. (2001) extended the aforementioned approach by introducing a factored state representation based on Bayesian networks, where the state includes both the user intention and the system state. Williams et al. (2005) and Young et al. (2010) further refined this factorisation by decomposing the dialogue state into three distinct variables that respectively represent the last user dialogue act, the user intention and the dialogue history. The related work of Thomson and Young (2010) used Bayesian networks to encode fine-grained dependencies between the various slots expressed in the user intention. Bui et al. (2009) augmented this representation with a specific variable for the user’s affective state. Substantial work has also been devoted to the inclusion of non-verbal observations and environmental factors into the dialogue state. In the human–robot interaction domain, Prodanov and Drygajlo (2003) and Hong et al. (2007) have applied Bayesian networks for inferring the underlying user intention based on observations arising from both verbal and non-verbal sources.

Policy optimisation

POMDP solution methods can in theory be applied to extract the dialogue policy from any given model specification, as shown by Williams and Young (2007) and Williams et al. (2008). Such a strategy is, however, only suitable for relatively small action-state spaces and requires the specification of an explicit observation model to extract the α -vectors corresponding to the optimal policy. Most recent POMDP approaches have instead focused on the use of reinforcement learning to derive a dialogue policy from interactions with a user simulator (Young et al., 2010; Thomson and Young, 2010; Daubigney et al., 2012b).

The need for effective generalisation techniques is heightened in reinforcement learning for POMDPs, as dialogue policies defined in partially observable environments must be defined in a high-dimensional, continuous belief state space. Approximating the $Q^*(b, a)$ function is thus crucial. One useful approximation method is to reduce the full belief state to a simpler representation such as the “summary state” described by Williams and Young (2005). In addition, the estimation of the action–value function can be further simplified by relying on techniques such as grid-based discretisations (Young et al., 2010) and linear function approximation (Thomson and Young, 2010; Daubigney et al., 2012b). Finally, non-parametric methods based on Gaussian processes have recently been proposed (Gašić et al., 2013).

Reinforcement learning is considerably more difficult for POMDPs than for MDPs due to the partial observability of the state. Png and Pineau (2011) showed how model-based reinforcement

learning can be cast in a Bayesian framework. As described in more detail in Section 6.1, the key idea of Bayesian reinforcement learning is to maintain an explicit probability distribution over the POMDP parameters. This distribution is then gradually refined as more data is observed through Bayesian inference. Our own work on reinforcement learning of rule parameters also follows that line of work, as shall be explained in Chapter 6.

Most POMDP-based approaches to dialogue management assume that the reward model can be encoded in advance by the system designer, with a few notable exceptions. Atrash and Pineau (2009) describe a Bayesian approach to estimate a reward model based on gold-standard actions provided by an oracle. Boularias et al. (2010) and Chinaei and Chaib-draa (2012) present alternative approaches based on inverse reinforcement learning (IRL) for POMDPs. Their main idea was to exploit Wizard-of-Oz data for a voice-enabled intelligent wheelchair to automatically infer a reward model. This task of inferring a reward model from expert demonstrations is a prototypical instance of *inverse reinforcement learning*: The agent observes how an expert performs the task and must find the hidden reward model that best explains this behaviour. Inverse reinforcement learning in partially observable domains is, however, difficult to scale beyond small domains due to the complexity of the optimisation problem (Choi and Kim, 2011).

3.4 Summary

We have presented in this chapter the foundations of probabilistic modelling applied to dialogue, and have surveyed a range of theoretical concepts related to graphical models, reinforcement learning in both fully and partially observable domains, as well as the practical exploitation of these techniques to dialogue management.

The first section of this chapter focused on the use of efficient representations of probability and utility models. We described how directed graphical models could capture various probability and utility distributions. We reviewed the main properties of Bayesian networks, dynamic Bayesian networks, and dynamic decision networks, and described the most important algorithms for inference and parameter estimation that have been tailored for these graphical models. The theoretical appeal of graphical models for the representation of complex stochastic phenomena is elegantly summarised by Jordan (1998, p. 1):

“Graphical models, a marriage between probability theory and graph theory, provide a natural tool for dealing with two problems that occur throughout applied mathematics and engineering – uncertainty and complexity. In particular, they play an increasingly important role in the design and analysis of machine learning algorithms. Fundamental to the idea of a graphical model is the notion of modularity: a complex system is built by combining simpler parts. Probability theory serves as the glue whereby the parts are combined, ensuring that the system as a whole is consistent and providing ways to interface models to data. Graph theory provides both an intuitively appealing interface by which humans can model highly interacting sets of variables and a data structure that lends itself naturally to the design of efficient general-purpose algorithms.”

The second section of this chapter laid down the core concepts and techniques in the field of reinforcement learning. We described the notion of a Markov Decision Process (MDP), composed

of a set of states, a set of actions, a transition function describing temporal relations between states, and a reward function encoding the utilities of particular actions. We explained how MDPs can be extended to capture partial observability (leading to POMDPs), and how policies can be optimised for both MDPs and POMDPs using model-based and model-free techniques.

The final section translated these formal representations and optimisation techniques to the practical problem of dialogue management. Three learning strategies were distinguished: supervised learning, reinforcement learning with MDPs, and reinforcement learning with POMDPs. We surveyed a variety of approaches that differ along dimensions such as the representation of the dialogue state, the learning algorithm employed for the optimisation, the type and structure of the models that are to be estimated, and the source of data samples that is employed for this estimation. We discussed the respective merits and limitations of these dialogue optimisation strategies, and stressed in particular the importance of factorisation and generalisation methods to handle the complexity of real-world dialogue domains. The next chapter will now present in detail our own approach to this prominent problem.

Chapter 4

Probabilistic rules

The previous chapter fleshed out how dialogue could be represented as a stochastic process and argued for the use of probabilistic graphical models to efficiently encode the probability and utility models employed in dialogue management. Plain graphical models, however, must face non-trivial scalability issues when applied to dialogue domains associated with rich conversational contexts. The number of parameters necessary to perform dialogue state update and action selection can indeed increase rapidly with the complexity of the domain models. Alas, only small quantities of genuine training data are available in most dialogue domains, and usually cover only a small fraction of the state–action space of interest.

To address this discrepancy between the size of the parameter space and the amount of data available to estimate them, we introduce in this chapter a new approach to probabilistic dialogue modelling, based on the notion of *probabilistic rules*. Probabilistic rules are structured mappings between conditions and effects, and function as *high-level templates* for the construction of a dynamic decision network. The key advantage of this structured modelling approach is the drastic reduction of the number of parameters compared to traditional representations. We also argue that these expressive representations are particularly well suited to encode the probability and utility models of dialogue domains, where substantial amounts of expert knowledge can often be leveraged to structure the relationships between variables.

The chapter is divided in six sections. Section 4.1 exposes in general terms how structural assumptions can be applied to reduce the size and complexity of probabilistic models. Section 4.2 defines our novel formalism of probabilistic rules and its main theoretical properties. These definitions are then connected in Section 4.3 to the graphical models described in the previous chapter by showing how the rules are instantiated in the Bayesian network representing the dialogue state. Section 4.4 explains how this instantiation procedure is practically employed to update the current dialogue state and perform action selection. Finally, Section 4.5 addresses some advanced modelling questions and Section 4.6 relates our approach to previous work.

4.1 Structural leverage

The starting point of our approach is the observation that the probability and utility models used in dialogue management often exhibit a fair amount of *internal structure*. We have already discussed in the previous chapter one simple instance of this internal structure, namely factored representations based on conditional independences. However, the internal structure of dialogue domains does not

limit itself to these basic independence assumptions, and much can be gained by exploiting other types of structural properties, as shall be argued on the next pages.

Latent variables

The number of parameters required to estimate the distributions of a graphical model can often be reduced by introducing *latent variables* (i.e. unobserved or hidden variables) that act as intermediaries between the source and target variables. Indeed, many application domains are often best explained by the combination of a small number of distinct factors or influences, each encoded by a separate random variable and associated with a subset of input and output variables. This layer of latent variables is usually never observed directly, but can contribute to structuring the model.¹ In the domain of medical diagnosis, the relations between predisposing factors and observed symptoms are for instance best described by postulating an intermediary layer of variables – possible diseases – that mediates between the predisposing factors and the observed symptoms. Figure 4.1 illustrates how latent variables can be exploited to provide an additional layer of abstraction within a graphical model.

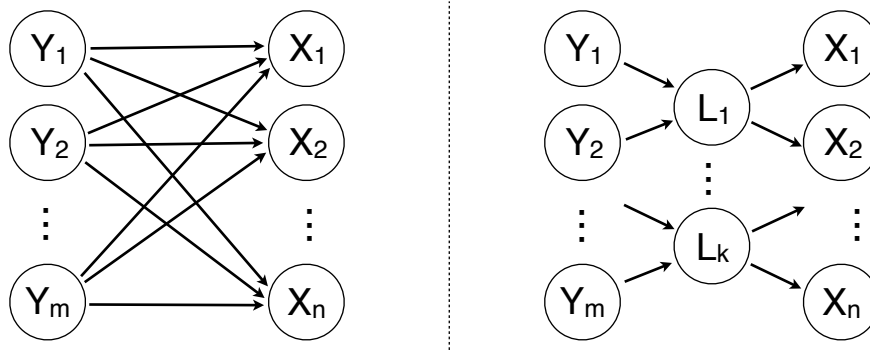


Figure 4.1: Comparison between a model that directly maps variables Y to X (left side) and one relying on latent variables L to serve as intermediaries (right side).

Dialogue models can greatly benefit from the inclusion of such latent variables. Transition functions can for instance be modelled in terms of a limited number of latent variables, each responsible for capturing specific aspects of the interaction dynamics. We shall see in the forthcoming sections that probabilistic rules precisely operate as latent variables when instantiated in the dialogue state.

Partitioning

A random variable X with parent variables Y_1, \dots, Y_m must specify a separate probability distribution for every possible assignment of values for the parent variables. In other words, the number of parameters required to specify the distribution $P(X | Y_1, \dots, Y_m)$ is exponential in the number of parents m . Fortunately, the values of these parent variables can be grouped into *partitions* yielding similar outcomes for X . One can therefore directly define the conditional probability distributions on these groups rather than on the full enumeration of combined values for the parent variables.

¹This notion of latent variables is not exclusive to graphical models but can be encountered in many areas of machine learning. It forms in particular the foundations of deep learning approaches (Bengio, 2009).

Partitioning is an example of an *abstraction mechanism* which can be used to reduce the model complexity and improve its ability to generalise to unseen examples. Partitioning is closely related to the notions of state abstraction and state aggregation in the reinforcement learning and planning literature (Li et al., 2006). State abstraction/aggregation is the process of mapping a large state space into a more compact, abstract state space (corresponding here to the partitions).

Figure 4.2 illustrates such a partitioning operation for the conditional probability distribution $P(\text{Fire} | \text{Weather}, \text{Rain})$. The space of possible values for the parent variables is defined in this example as $\text{Val}(\text{Weather}) \times \text{Val}(\text{Rain})$ and contains 6 possible elements. We can observe that this space can be split in two partitions: $\text{Rain} = \text{true} \vee \text{Weather} \neq \text{hot}$ and $\text{Rain} = \text{false} \wedge \text{Weather} = \text{hot}$. This partitioning allows a significant reduction of the number of parameters required for the conditional probability distribution. However, it should be noted that grouping value assignments into partitions corresponds to a modelling choice and can degrade the model accuracy if the partitions do not reflect actual similarities in the predicted outcomes.

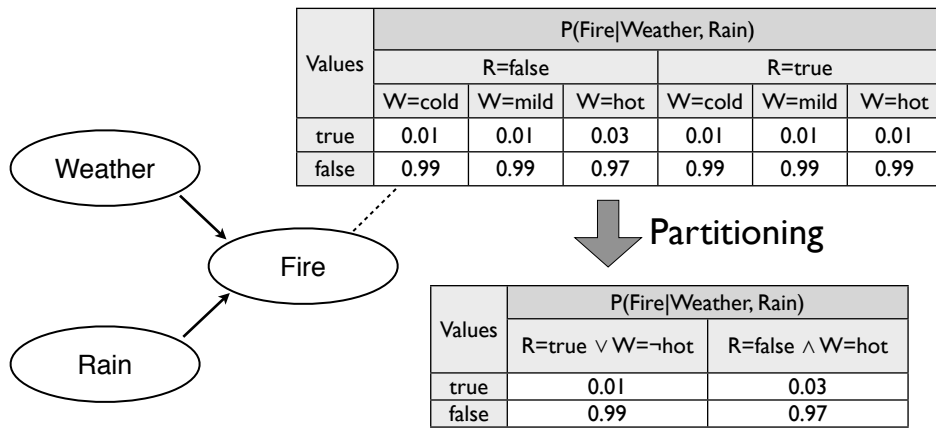


Figure 4.2: Partitioning for the conditional probability distribution $P(\text{Fire} | \text{Weather}, \text{Rain})$.

Partitions must be both exhaustive (each combination of values for the parent variables must belong to one partition) and mutually exclusive (a combination of values can only belong to one partition). As we can observe from the example, partitions can often be concisely expressed via logical conditions on the variable values. A given assignment of values is then grouped in a partition if it satisfies the condition associated with it.

Quantification

Many dialogue domains are composed of objects or entities related to one another. These domains are often difficult to directly represent with a fixed set of random variables, as the number of entities and relations may vary over time. Examples of relational structures include:

- Collections of physical objects in a visual scene, each described by specific features (colour, shape) and relations with other objects (e.g. spatial relations).
- Indoor environments topologically structured in rooms and spaces in which to navigate.
- Collections of tasks to complete by the agent, each task being possibly connected to other tasks via precedence or inclusion relationships.

- Linguistic entities employed in the dialogue acts of a given interaction, linked with one another through multiple syntactic, semantic, referential or pragmatic relations.

First-order logic provides an excellent basis for representing and manipulating such relational structures, as it offers a mathematically principled language for (1) referring to objects connected with one another through functions and relations and (2) describing their properties in a concise manner through the use of universal and existential quantifiers.²

Graphical models encode relational domains by instantiating one random variable for every possible grounding of the functions and predicates defined for the domain for a collection of objects.³ A domain with two objects o_1 and o_2 and a relation $leftOf(x, y)$ will for instance generate the four groundings $leftOf(o_1, o_2)$, $leftOf(o_2, o_1)$, $leftOf(o_1, o_1)$ and $leftOf(o_2, o_2)$. The definition of probability and utility distributions that can capture the relational semantics of such a representation can, however, be problematic. In particular, universal properties and constraints such as $\forall x, \neg leftOf(x, x)$ and $\forall x, y, z, leftOf(x, y) \wedge leftOf(y, z) \Rightarrow leftOf(x, z)$ can be difficult to enforce at a global level, since classical probabilistic models are intrinsically limited to propositional logic and offer no direct support for quantifiers.

The unification of first-order logic and probability theory has spanned a new research area called *statistical relational learning* (Getoor and Taskar, 2007). A common trait of most approaches to statistical relational learning is the definition of a logic-based description language which is employed as a template to generate classical probabilistic models given a set of constants. The introduction of quantifiers provides an abstraction mechanism to reduce the complexity of probabilistic models by describing constraints or relations that hold for all possible groundings of a given formula and can therefore apply to large sets of random variables.

4.2 Formalisation

We now introduce a new, generic modelling framework for expressing the various types of internal structure we have just detailed. This framework revolves around the notion of *probabilistic rules*. The framework was originally presented in Lison (2012d,a). The following sections present the framework and its application to dialogue management. The framework will then be discussed and compared to related approaches in Section 4.6.

The key idea is to represent distributions with the help of *if...then...else* constructions, based on the following skeleton:

```

if (condition 1 holds) then
    Distribution 1 over possible effects
else if (condition 2 holds) then
    Distribution 2 over possible effects
...
else
    Distribution  $n$  over possible effects

```

²We shall not cover in this thesis the mathematical foundations of first-order logic, but the reader is invited to refer to e.g. Gamut (1991) for a formal overview of the logical concepts mentioned throughout this thesis.

³Such an operation is akin to *propositionalisation* in the terminology of first-order logic.

Each *if...then* branch specifies both a *condition* on particular state variables and an associated distribution over possible *effects*. The *if...then...else* construction is read in sequential order, as in programming languages, until a satisfied condition is found, which causes the activation of the corresponding probabilistic effects.

We first present how probabilistic rules can express conditional probability distributions in terms of structured mappings between input and output variables. We then show how to generalise the formalism to utility distributions and extend it with quantification mechanisms.

Terminological note: We shall use the term *probabilistic rules* as an umbrella term that covers all types of rules in this thesis, while *probability rules* will only refer to rules expressing probability distributions over effects, and *utility rules* to rules expressing utility distributions.

4.2.1 Probability rules

Probability rules take the form of *if...then...else* constructions mapping conditions to probabilistic effects. More formally, a rule is expressed as an ordered list $[br_1, \dots, br_n]$ in which br_i denotes the i -th branch of the *if...then...else*. Each branch br_i is a pair $\langle c_i, P(E_i) \rangle$ where c_i is a logical condition and $P(E_i)$ a categorical distribution over a range of possible effects $Val(E_i) = \{e_{(i,1)}, \dots, e_{(i,m_i)}\}$. The value m_i corresponds to the number of alternative effects in the distribution $P(E_i)$. Each effect $e_{(i,j)} \in Val(E_i)$ has a probability denoted $p_{(i,j)}$.

Given these elements, a probability rule reads as such:

$$\begin{aligned}
& \mathbf{if} \ (c_1) \ \mathbf{then} \\
& \quad \left\{ \begin{array}{l} P(E_1 = e_{(1,1)}) = p_{(1,1)} \\ \dots \\ P(E_1 = e_{(1,m_1)}) = p_{(1,m_1)} \end{array} \right. \\
& \mathbf{else if} \ (c_2) \ \mathbf{then} \\
& \quad \left\{ \begin{array}{l} P(E_2 = e_{(2,1)}) = p_{(2,1)} \\ \dots \\ P(E_2 = e_{(2,m_2)}) = p_{(2,m_2)} \end{array} \right. \tag{4.1} \\
& \dots \\
& \mathbf{else} \\
& \quad \left\{ \begin{array}{l} P(E_n = e_{(n,1)}) = p_{(n,1)} \\ \dots \\ P(E_n = e_{(n,m_n)}) = p_{(n,m_n)} \end{array} \right.
\end{aligned}$$

We will often use $P(e_{(i,j)})$ as a notational convenience for $P(E_i = e_{(i,j)})$. We describe below how the conditions c_i , effects $e_{(i,j)}$ and effect probabilities $p_{(i,j)}$ are respectively defined.

Conditions

The conditions c_i are expressed as logical formulae grounded in a subset of random variables in the dialogue state. Conditions can be arbitrarily complex logical formulae connected by conjunction, disjunction and negation. The list of random variables mentioned in the condition corresponds to the *input variables* of the rule, which we shall denote as I_1, \dots, I_k . Table 4.1 details the syntax of a rule condition. The input variables and values are terms of the domain and (as shall be explained in Section 4.2.3) can also include free variables in addition to ground terms.

The two examples $(Rain = true \vee Weather \neq hot)$ and $(Rain = false \wedge Weather = hot)$ in Figure 4.2 are instances of valid conditions on the two input variables *Rain* and *Weather*.

Given that a rule is defined through an *if...then...else* construction, the partitioning is guaranteed by construction to be exhaustive and mutually exclusive (only one branch will be followed, as in programming languages). When provided with an assignment of values on the input variables, the conditions are tested in sequential order until one is satisfied. When no terminating **else** block is explicitly specified at the end of a rule, the framework assumes a final **else** block associated with a void effect to ensure that the partitioning is exhaustive. The last condition c_n is thus guaranteed to always be trivially satisfied irrespective of the input variable values.

It is important to note that the conditions c_1, \dots, c_n themselves need not be mutually exclusive, as the partitioning automatically follows from the *if...then...else* structure. The rule construction offers a compact partitioning of the state space to mitigate the dimensionality curse. Without such a partitioning, a rule ranging over the input variables I_1, \dots, I_k would need to enumerate $Val(I_1) \times \dots \times Val(I_k)$ possible assignments. The reliance on the *if...then...else* structure reduces this number to n partitions, where n corresponds to the number of conditions for the rule and is usually small.

$\langle Condition \rangle$	$::= \langle AtomicCondition \rangle \mid \langle ComplexCondition \rangle \mid \text{'true'}$
$\langle AtomicCondition \rangle$	$::= \langle InputVariable \rangle \langle BinaryOperator \rangle \langle Value \rangle$
$\langle ComplexCondition \rangle$	$::= \text{'('} \langle Condition \rangle \text{'})'$ $\mid \text{'}\neg\text{' } \langle Condition \rangle$ $\mid \langle Condition \rangle \text{'}\wedge\text{' } \langle Condition \rangle$ $\mid \langle Condition \rangle \text{'}\vee\text{' } \langle Condition \rangle$
$\langle BinaryOperator \rangle$	$::= \text{'='} \mid \text{'}\neq\text{' } \mid \text{'<'} \mid \text{'>'}$

Table 4.1: Syntax (in Bachus–Naur form) of a rule condition.

Effects

Associated to each condition c_i stands a collection of possible effects $e_{(i,1)}, \dots, e_{(i,m_i)}$. Each effect $e_{(i,j)}$ represents a specific assignment of values for a set of variables called the *output variables* of the rule. An effect is formally defined as an assignment of values $O'_1 = o_1 \wedge \dots \wedge O'_l = o_l$ where O'_1, \dots, O'_l denote the output variables and o_1, \dots, o_l the corresponding values assigned to these variables. Effects can be void – that is, represent an empty assignment. We shall adopt throughout

this thesis the convention of denoting output variables with a prime to distinguish them from other types of variables.

Table 4.2 details the syntax of a rule effect. In the example from Figure 4.2, the output variable is a singleton and corresponds to $Fire'$. We shall, however, encounter examples of rules with more than one output variable. As for the rule conditions, the output variables and values correspond to arbitrary terms of the domain, and can also include free variables.

$\langle Effect \rangle$	$::= \langle NonVoidEffect \rangle \mid \emptyset$
$\langle NonVoidEffect \rangle$	$::= \langle AtomicEffect \rangle \mid \langle NonVoidEffect \rangle \text{ '}' \wedge \text{ '}' \langle NonVoidEffect \rangle$
$\langle AtomicEffect \rangle$	$::= \langle OutputVariable \rangle \text{ '=' } \langle Value \rangle$

Table 4.2: Syntax (in Bachus–Naur form) of a rule effect.

Probabilities

Each effect $e_{(i,j)}$ in the categorical probability distribution $P(E_i)$ is assigned with a probability $p_{(i,j)} = P(E_i = e_{(i,j)})$ that must satisfy the usual probability axioms. The probabilities can be either fixed by hand or estimated empirically (as will be demonstrated in Chapters 5 and 6).

Example

Rule r_1 illustrates a simple example of a probability rule:

$$\begin{aligned}
 r_1 : \quad & \mathbf{if} (Rain = false \wedge Weather = hot) \mathbf{then} \\
 & \quad \begin{cases} P(Fire' = true) = 0.03 \\ P(Fire' = false) = 0.97 \end{cases} \\
 & \mathbf{else} \\
 & \quad \begin{cases} P(Fire' = true) = 0.01 \\ P(Fire' = false) = 0.99 \end{cases}
 \end{aligned}$$

Rule r_1 has two input variables: $Rain$ and $Weather$ as well as one output variable $Fire'$. The rule specifies that the probability of a fire is 0.03 in case of no rain and a hot weather and 0.01 in all other cases. The rule structure enables the conditional probability distribution for $Fire'$ to be specified with only 4 probabilities in comparison to 12 for the probability distribution shown in Figure 4.2.

4.2.2 Utility rules

The rule-based formalism we have outlined can also be used to express utility distributions with only minor notational changes. Utility rules essentially retain the same form as probability rules, with one important exception, namely that the probabilistic effects are replaced by utility distributions over particular assignments of decision variables.

Formally, a utility rule is an ordered list $[br_1, \dots, br_n]$, where each branch br_i is a pair $\langle c_i, U_i \rangle$, c_i is a condition and U_i an associated utility table over possible assignments of decision variables. The utility distribution U_i specifies a set of possible decisions $d_{(i,1)}, \dots, d_{(i,m_i)}$. Each decision $d_{(i,j)}$ has a utility value denoted $u_{(i,j)}$. Utility rules can be expressed in the following manner:

$$\begin{aligned}
& \mathbf{if} \ (c_1) \ \mathbf{then} \\
& \quad \left\{ \begin{array}{l} U_1(d_{(1,1)}) = u_{(1,1)} \\ \dots \\ U_1(d_{(1,m_1)}) = u_{(1,m_1)} \end{array} \right. \\
& \mathbf{else \ if} \ (c_2) \ \mathbf{then} \\
& \quad \left\{ \begin{array}{l} U_2(d_{(2,1)}) = u_{(2,1)} \\ \dots \\ U_2(d_{(2,m_2)}) = u_{(2,m_2)} \end{array} \right. \tag{4.2} \\
& \dots \\
& \mathbf{else} \\
& \quad \left\{ \begin{array}{l} U_n(d_{(n,1)}) = u_{(n,1)} \\ \dots \\ U_n(d_{(n,m_n)}) = u_{(n,m_n)} \end{array} \right.
\end{aligned}$$

A utility rule assigns utility values to particular system decisions depending on conditions on the state variables. As for probability rules, the conditions c_i are defined as arbitrary logical formulae on input variables I_1, \dots, I_k . The decisions $d_{(i,j)}$ are assignments $D'_1 = d_1 \wedge \dots \wedge D'_l = d_l$ where the variables D'_1, \dots, D'_l are decision variables and d_1, \dots, d_l possible values for these variables. Similarly to the output variables of probability rules, we shall always denote decision variables with a prime. The utility values $u_{(i,j)}$ are real numbers (which may be positive or negative).

Although most utility rules only include one single decision variable, the possibility to integrate multiple decision variables is helpful in domains where the system can execute multiple actions in parallel (for instance to communicate through both verbal and non-verbal channels).

Example

Rule r_2 provides a simple example of a utility rule:

$$\begin{aligned}
r_2 : \mathbf{if} \ (Fire = true) \ \mathbf{then} \\
& \quad \left\{ \begin{array}{l} U(Tanker' = drop-water) = 5 \\ U(Tanker' = wait) = -5 \end{array} \right. \\
& \mathbf{else} \\
& \quad \left\{ \begin{array}{l} U(Tanker' = drop-water) = -1 \\ U(Tanker' = wait) = 0 \end{array} \right.
\end{aligned}$$

Rule r_2 stipulates the respective utilities for the two possible decisions associated with the variable $Tanker'$ depending on the input variable $Fire$.

4.2.3 Quantification

Quantification is a powerful mechanism to abstract over particular relational aspects of the domain structure. Free variables can be included in the specification of both the conditions and effects of a given rule and are universally quantified on top of the rule.⁴ A rule containing the variables $y_1 \dots, y_p$ in its conditions and/or effects is therefore formalised as:

$$\begin{aligned}
& \forall y_1, y_2, \dots, y_p, \\
& \quad \text{if } (c_1) \text{ then} \\
& \quad \quad \left\{ \begin{array}{l} P(E_1 = e_{(1,1)}) = p_{(1,1)} \\ \dots \\ P(E_1 = e_{(1,m_1)}) = p_{(1,m_1)} \end{array} \right. \\
& \quad \text{else if } (c_2) \text{ then} \\
& \quad \quad \left\{ \begin{array}{l} P(E_2 = e_{(2,1)}) = p_{(2,1)} \\ \dots \\ P(E_2 = e_{(2,m_2)}) = p_{(2,m_2)} \end{array} \right. \tag{4.3} \\
& \quad \dots \\
& \quad \text{else} \\
& \quad \quad \left\{ \begin{array}{l} P(E_n = e_{(n,1)}) = p_{(n,1)} \\ \dots \\ P(E_n = e_{(n,m_n)}) = p_{(n,m_n)} \end{array} \right.
\end{aligned}$$

The formalisation allows specific elements y_1, \dots, y_p inside the conditions and effects of a rule to be *underspecified*. The mapping between conditions and effects specified by the rule is therefore duplicated for every possible assignment of the quantified variables. Section 4.3.3 explains how this finite set of possible assignments (also called the *groundings* of the variables) is practically determined on the basis of the current state.

Based on this quantification mechanism, probabilistic rules can cover large portions of the state space in a highly compact manner. One of the main advantages of this representation is that it allows for powerful forms of *parameter sharing*, since the effect probabilities $p_{(i,j)}$ in the above rule are made independent of the various instantiations of the variables y_1, \dots, y_p . The quantification mechanism adopted in this thesis bears similarities to the one employed in Markov logic networks (Richardson and Domingos, 2006), with the constraint that universal quantifiers are in this framework only allowed at the top of the rule. In line with most approaches to statistical relational learning (Getoor and Taskar, 2007) and logic programming (Poole, 2008), the formalisation relies on a “database semantics” that assumes domain closure (the domain does not contain more

⁴These free variables are variables in the sense of first-order logic, and are not to be confused with the random variables of the probabilistic model.

elements than those explicitly specified).

Quantification also applies to utility rules in the same manner, through the inclusion of free variables in the conditions c_i and decisions $d_{(i,j)}$ of the utility rule.

Example

Rule r_3 provides a simple example of a probability rule including a quantified variable:

$$\begin{aligned}
r_3 : \forall y, \\
& \text{if } (shape(y) = sphere) \text{ then} \\
& \quad \begin{cases} P(graspable(y)' = true) = 0.9 \\ P(graspable(y)' = false) = 0.1 \end{cases} \\
& \text{else if } (shape(y) = cone) \text{ then} \\
& \quad \begin{cases} P(graspable(y)' = true) = 0.2 \\ P(graspable(y)' = false) = 0.8 \end{cases}
\end{aligned}$$

Rule r_3 specifies how the graspability of a given object y depends on its shape (a sphere being easier to grasp than a cone). Similarly, rule r_4 defines the utility of a grasping action depending on the task and object graspability:

$$\begin{aligned}
r_4 : \forall y, \\
& \text{if } (task = grasp(y) \wedge graspable(y) = true) \text{ then} \\
& \quad \{ U(a'_m = grasp(y)) = 2 \} \\
& \text{else} \\
& \quad \{ U(a'_m = grasp(y)) = -2 \}
\end{aligned}$$

Rule r_4 associates a utility of 2 to the action of grasping an object y when the object is graspable and corresponds to the task to perform, and a utility of -2 in any other case.

4.3 Rule instantiation

We represent the dialogue state as a Bayesian network over state variables, in line with other dialogue management approaches such as Thomson and Young (2010) and Bui et al. (2009). Rules are then applied at runtime on this dialogue state. The instantiation is performed by creating a distinct node for every rule to apply. The rule nodes are essentially latent variables serving as intermediaries between the input and output variables. Although the presence of these rules is never directly observed, they contribute to structuring the relations between variables and enable the system designer to decompose complex probability and utility models into smaller parts.

We describe below the instantiation procedure for each type of rule. For the sake of clarity, we shall first limit our discussion to rules without universal quantification, and then demonstrate how quantification can be accounted for in the instantiation process.

4.3.1 Probability rules

Let \mathcal{B} be the Bayesian network representing the current dialogue state, and \mathcal{R} a set of rules to apply to this dialogue state. For each rule $r \in \mathcal{R}$, a distinct chance node is created.⁵ This chance node represents a random variable defined on the possible effects of the rule. The node is conditionally dependent on the input variables of the rule (i.e. the set of all variables that are mentioned in the rule conditions), and is also connected via outgoing edges to its output variables (i.e. the set of all variables that are mentioned in the rule effects).

Figure 4.3 illustrates this instantiation process on an abstract, constructed example composed of the two rules r_5 and r_6 . To simplify the rule representation, we shall usually omit the explicit specification of the probability for the empty effect in the effect distributions. The remaining probability mass in each effect specification is thus by default assigned to the empty effect. The first **if** branch of rule r_5 has for instance an empty effect with probability 0.4.

The two rules r_5 and r_6 are applied on the state variables A, B, C and D . The application of the two rules results in an updated variable A' and the creation of a new variable E' .

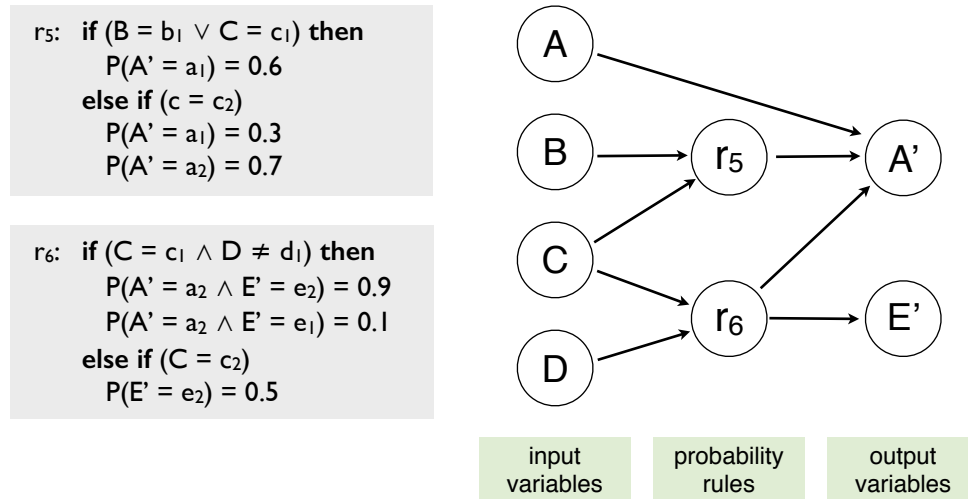


Figure 4.3: Example of instantiation for the two probability rules r_5 and r_6 .

The random variable represented by the node r_5 has three possible values that correspond to the three effects described in the rule: $Val(r_5) = \{\{A' = a_1\}, \{A' = a_2\}, \{\cdot\}\}$, where $\{\cdot\}$ denotes the empty effect. Similarly, the random variable r_6 has four alternative effects: $Val(r_6) = \{\{A' = a_2 \wedge E' = e_2\}, \{A' = a_2 \wedge E' = e_1\}, \{E' = e_2\}, \{\cdot\}\}$.

We shall adopt the following terminology to denote the probability distributions created through the instantiation procedure:

- The conditional probability distributions associated with rule nodes such as r_5 and r_6 given their inputs are *rule distributions*.

⁵The original instantiation algorithm presented in (Lison, 2012d) included two separate nodes: one for the rule condition and one for the effect. The formalism was later simplified to one single node as we realised that only one node was necessary to represent the semantics of the rule.

- The conditional probability distributions associated with output variables such A' and E' given the rule nodes that influence them are *output distributions*.

Rule distributions

The rule distributions directly reflect the rule semantics. Formally, the conditional probability distribution of a rule node r given its input variables I_1, \dots, I_k is defined as:

$$P(r=e \mid I_1=i_1, \dots, I_k=i_k) = P(E_i = e) \quad (4.4)$$

where $i = \min(\{i : c_i \text{ is satisfied with } I_1=i_1 \wedge \dots \wedge I_k=i_k\})$

Formally speaking, a condition c_i is said to be satisfied iff the input assignment logically entails that the condition is true, that is: $(I_1=i_1 \wedge \dots \wedge I_k=i_k) \vdash c_i$. The rule conditions are checked in sequential order until one condition is found to be satisfied. As the last condition c_n corresponds to the final **else** block and is therefore always trivially true, there will always be at least one satisfied condition. Once a satisfied condition c_i is found for the input assignment, the rule distribution is defined as the effect distribution $P(E_i)$ associated with the condition.

As an example, the rule distribution $P(r_5 \mid B=b_1, C=c_1)$ for the node r_5 in Figure 4.3 is straightforwardly defined as:

- $P(r_5 = \{A'=a_1\} \mid B=b_1, C=c_1) = 0.6$
- $P(r_5 = \{\cdot\} \mid B=b_1, C=c_1) = 0.4$

Similarly, the distribution $P(r_6 \mid C=c_1, D=d_1)$ is a distribution with the empty effect $\{\cdot\}$ assigned to a probability 1.

Output distributions

An output node X' is conditionally dependent on all the rule nodes that refer to it in their effects. In addition, output nodes that correspond to the updated version of existing nodes (such as A' in the example of Figure 4.3) also include a conditional dependency on these existing nodes.

The output distribution is a reflection of the combination of effects specified in the parent rules. The conditional probability distribution $P(X' \mid r_1=e_1, \dots, r_n=e_n)$ for an output variable X' with n incoming rule nodes is defined in the following manner:

$$P(X'=x' \mid r_1=e_1, \dots, r_n=e_n) = \begin{cases} \frac{\mathbf{1}(x' \in \mathbf{e}(X'))}{|\mathbf{e}(X')|} & \text{if } \mathbf{e}(X') \neq \emptyset \\ \mathbf{1}(x' = \text{None}) & \text{otherwise} \end{cases} \quad (4.5)$$

where the following notation is used:

- \mathbf{e} is the conjunction of all effects, i.e. $\mathbf{e} = e_1 \wedge \dots \wedge e_n$. This conjunction can include more than one assigned value for a particular variable.
- $\mathbf{e}(X')$ denotes the (possibly empty) list of values specified for the variable X' in \mathbf{e} .
- $\mathbf{1}(b)$ is the indicator function for a boolean b , with $\mathbf{1}(b) = 1$ if b is true and 0 otherwise.

Equation (4.5) stipulates that the distribution for X' will follow the values assigned in the effect(s) provided that at least one effect specifies a value for it. If the effects include conflicting assignments, the distribution is spread uniformly over the alternative values. This uniform division of the probability mass reflects that, in the absence of further knowledge, all rules are assumed to have the same “weight”. If two or more rules generate contradictory effects, there is therefore no way to tell which rule is to take precedence.⁶ If no effects e_1, \dots, e_n specifies a value for X' , its value is set to a default *None* value with probability 1.

If the node X' is an update of an existing node X , the procedure remains essentially the same as for Equation (4.5), except when all the effects specify empty assignments for the variable. In such a case, the distribution for X' will fall back to the value defined for the existing node X instead of being assigned a *None* value:

$$P(X' = x' \mid r_1 = e_1, \dots, r_n = e_n, X = x) = \begin{cases} \frac{\mathbf{1}(x' \in \mathbf{e}(X'))}{|\mathbf{e}(X')|} & \text{if } \mathbf{e}(X') \neq \emptyset \\ \mathbf{1}(x' = x) & \text{otherwise} \end{cases} \quad (4.6)$$

As an example, the output distribution $P(A' \mid r_5 = \{\cdot\}, r_6 = \{A' = a_2 \wedge E' = e_2\}, A = a_3)$ in Figure 4.3 results in a deterministic distribution with a unique value a_2 with probability 1, since $\mathbf{e}(A') = \{a_2\}$ in this situation. If the two rules generate conflicting assignments, the probability mass is divided equally over the alternative values. The output distribution $P(A' \mid r_5 = \{A' = a_1\}, r_6 = \{A' = a_2 \wedge E' = e_2\}, A = a_3)$ provides two alternative values for A' , since $\mathbf{e}(A')$ equates here to $\{a_1, a_2\}$. The output distribution is thus in this case equivalent to a uniform distribution with two values a_1 and a_2 , each with probability 0.5. Finally, if all effects are void, the output distribution is a simple copy of the distribution for the existing variable: $P(A' \mid r_5 = \{\cdot\}, r_6 = \{\cdot\}, A = a_3)$ has a unique value a_3 with probability 1.

As we can observe from Equations (4.5) and (4.6), output distributions are directly derived from the definition of effects in the rule nodes and are thus entirely parameter-free. The ordering of the parent rules in the conditional probability distribution is arbitrary.

Instantiation algorithm

The procedure for instantiating a rule in a given dialogue state is detailed in Algorithm 4.

The first steps of the instantiation process are to extract in the Bayesian network the input variables of the rule (line 1), create a node corresponding to the rule (line 2) and include its dependency edges in the network (line 3). The algorithm then checks whether at least one effect in r is non-empty given its conditional dependencies (lines 4). If all effects are empty, the rule node is irrelevant and can be directly pruned (line 5). Otherwise, the output variables are extracted (line 7), and output nodes that do not already exist in the network are created (line 10-11). The final step is to establish dependency edges between the rule node and these output variables (line 13).

4.3.2 Utility rules

Utility rules are instantiated in the Bayesian network according to a similar procedure, with two notable differences compared to probability rules:

⁶This mechanism could be refined by e.g. associating numerical weights or a dominance hierarchy to the rules.

Algorithm 4 : INSTANTIATEPROBRULE (\mathcal{B}, r)

Input: Bayesian network \mathcal{B} for the current state

Input: Probability rule r to instantiate in network

```
1:  $I_1, \dots, I_k \leftarrow$  input variables for  $r$ 
2: Create chance node  $r$  with the rule distribution in Eq. (4.4)
3: Add node  $r$  and dependency edges  $I_1, \dots, I_k \rightarrow r$  to  $\mathcal{B}$ 
4: if  $Val(r) = \{\cdot\}$  then
5:   Prune  $r$  from  $\mathcal{B}$ 
6: else
7:    $O'_1, \dots, O'_l \leftarrow$  output variables mentioned in the effects of  $r$ 
8:   for all variable  $O' \in O'_1, \dots, O'_l$  do
9:     if  $O'$  not already in  $\mathcal{B}$  then
10:      Create chance node  $O'$  with the output distribution in Eq. (4.5)-(4.6)
11:      Add node  $O'$  and (in case  $O$  exists) dependency edge  $O \rightarrow O'$  to  $\mathcal{B}$ 
12:    end if
13:    Add dependency edge  $r \rightarrow O'$  to  $\mathcal{B}$ 
14:  end for
15: end if
```

- As utility rules define utility distributions, their instantiation corresponds to utility nodes instead of chance nodes.
- Instead of output nodes, utility rules lead to the creation of new decision nodes. The dependency direction is inverted, as the decision node must be input to the utility node.

The result of the instantiation process is a decision network that incorporates chance nodes (corresponding to the state variables), utility nodes (corresponding to the utility rules) and associated decision nodes. Figure 4.4 illustrates the instantiation of two utility rules r_7 and r_8 .

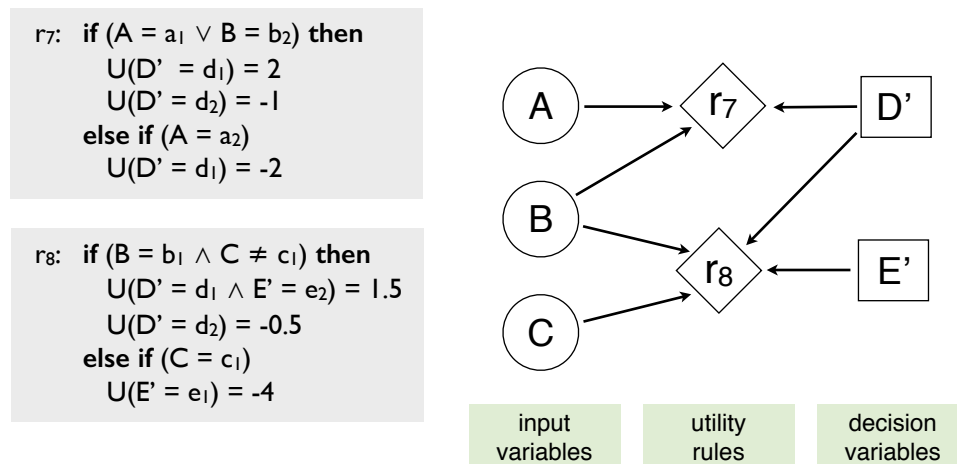


Figure 4.4: Example of instantiation for the two utility rules r_7 and r_8 .

The utility distribution associated with each rule is a direct translation of the *if...then...else* rule structure. Formally, the utility distribution generated by a rule r with input variables I_1, \dots, I_k

and decision variables D'_1, \dots, D'_l is defined as:

$$U_r(D'_1=d_1, \dots, D'_l=d_l \mid I_1=i_1, \dots, I_k=i_k) = U_i(D'_1=d_1 \wedge \dots \wedge D'_l=d_l) \quad (4.7)$$

where $i = \min(\{i : c_i \text{ is satisfied with } I_1=i_1 \wedge \dots \wedge I_k=i_k\})$

If no utility is explicitly specified for $D'_1=d_1 \wedge \dots \wedge D'_l=d_l$ in the utility table, the default value is zero.

As is conventionally assumed in decision networks, the total utility for a given assignment of decision variables is defined as the *sum* of all utilities. On the example of Figure 4.4, we can therefore calculate the total utility for the actions $D'=d_1 \wedge E'=e_1$ in the situation where $A=a_1$, $B=b_1$ and $C=c_1$ to be equal to $2 - 4 = -2$.

Instantiation algorithm

The procedure for instantiating a utility rule is similar to the one already outlined for probability rules. Algorithm 5 details the procedure, starting from the extraction of the input variables, the creation of the rule node, and the inclusion of conditional dependencies (line 1-3). The algorithm then checks if the utility distribution stipulates a non-zero utility for at least one decision (line 4). If the answer is negative, the node is essentially irrelevant and can be pruned (line 5). The decision variables associated with the rule are extracted (line 7), and a corresponding decision node is created if it does not already exist (line 10). Finally, the possible values specified for the decision variable are integrated to the node (line 12), and a dependency edge is established between the decision node and the utility node for the rule (line 13).

Algorithm 5 : INSTANTIATEUTILRULE (\mathcal{B}, r)

Input: Bayesian network \mathcal{B} for the current state

Input: Utility rule r to instantiate in network

- 1: $I_1, \dots, I_k \leftarrow$ input variables for r
 - 2: Create utility node r with the utility distribution in Eq. (4.7)
 - 3: Add node r and dependency edges $I_1, \dots, I_k \rightarrow r$ to \mathcal{B}
 - 4: **if** utility distribution is empty for all inputs **then**
 - 5: Prune r from \mathcal{B}
 - 6: **else**
 - 7: $D'_1, \dots, D'_l \leftarrow$ decision variables mentioned in the effects of r
 - 8: **for all** variable $D' \in D'_1, \dots, D'_l$ **do**
 - 9: **if** D' not already in \mathcal{B} **then**
 - 10: Create decision node D' and add it to \mathcal{B}
 - 11: **end if**
 - 12: Add in $Val(D')$ the action values specified in the effects of r
 - 13: Add dependency edge $D' \rightarrow r$ to \mathcal{B}
 - 14: **end for**
 - 15: **end if**
-

4.3.3 Quantification

We saw in Section 4.2.3 that conditions and effects could include universally quantified variables, but have not yet discussed how such underspecified rules could be practically instantiated in the Bayesian network. The general instantiation principle remains unchanged: To each rule corresponds a distinct rule node responsible for the mapping between input and output variables (or decision variables for utility rules). The instantiation procedure must nevertheless be extended to accommodate the presence of quantified variables. The key idea is to find all relevant *groundings* for the quantified variables, and then calculate the effect distribution for each grounding. This method of handling quantifiers by extracting all possible groundings and reasoning at the propositional level is an instance of *ground inference* (Getoor and Taskar, 2007).

Extraction of input variables

Universally quantified rules may underspecify both the names and values of random variables, as we saw in the examples of Section 4.2.3. Rule r_3 includes for instance a reference to an underspecified random variable $shape(y)$. In order to instantiate the rule, the system must therefore first determine the set of all random variables in the current state that match the underspecified description.

In practice, this extraction of input variables is simply achieved by looping over all current state variables and searching for those that may offer a potential match for at least one underspecified description. If rule r_3 is instantiated in a state containing two objects o_1 and o_2 (each with a specific shape), the resulting input variables will be $shape(o_1)$ and $shape(o_2)$.

Extraction of relevant groundings

Once the input variables are retrieved, the next step is to establish the set of relevant groundings for the universally quantified variables in the rule. The groundings are always determined relative to a particular assignment of values for the (grounded) input variables I_1, \dots, I_k .

Given a particular input assignment $I_1 = i_1 \wedge \dots \wedge I_k = i_k$, the set of groundings is derived by extracting the ground terms (constants and functions of constants) from the input assignment that can function as proper substitutions for the universally quantified variables. At the end of the extraction procedure, the universally quantified variables of the rule will therefore be associated with a set of possible groundings $G = \{g_1, \dots, g_{|G|}\}$. For instance, the rule r_3 and the input assignment $shape(o_1) = sphere \wedge shape(o_2) = cone$ produce the groundings $G = \{[o_1], [o_2]\}$ for the variable y .

Quantified probability rules

As we have seen, probability rules are instantiated as chance nodes associated with a rule distribution. For rules including universal quantifiers, each grounding g in G gives rise to a particular distribution over effects. We can define a grounding-specific rule distribution r_g where the universally quantified variables $\mathbf{y} = y_1, \dots, y_p$ are replaced by the specific grounding g :

$$P(r_g = e[\mathbf{y}/\mathbf{g}] \mid I_1 = i_1, \dots, I_k = i_k) = P(E_i = e) \quad (4.8)$$

where $i = \min(\{i : c_i[\mathbf{y}/\mathbf{g}] \text{ is satisfied with } I_1 = i_1 \wedge \dots \wedge I_k = i_k\})$

The expression $\phi[a/b]$ denotes (as in formal logic) the formula ϕ where all instances of a are substituted by b . The rule distribution in Equation (4.8) is thus identical to Equation (4.4) where all occurrences of the universally quantified variables in the conditions and effects are replaced by their grounded value in \mathbf{g} .

The procedure results in a set of grounding-specific rule distributions $\{P(r_{\mathbf{g}_1}), \dots, P(r_{\mathbf{g}_{|G|}})\}$. Empty and redundant distributions can be discarded from this set. The final probability distribution for the rule node is then defined as the joint distribution over these grounding-specific distributions:

$$P(r = [e_1 \wedge \dots \wedge e_{|G|}] \mid I_1 = i_1, \dots, I_k = i_k) = \prod_{j=1}^{|G|} P(r_{\mathbf{g}_j} = e_j) \quad (4.9)$$

Figure 4.5 shows the instantiation of the rule r_3 in a state with two objects o_1 and o_2 , each associated with a random variable describing its shape. The effects specified for r_3 have two output variables: $graspable(o_1)'$ and $graspable(o_2)'$ which are thus placed as children of the node r_3 .

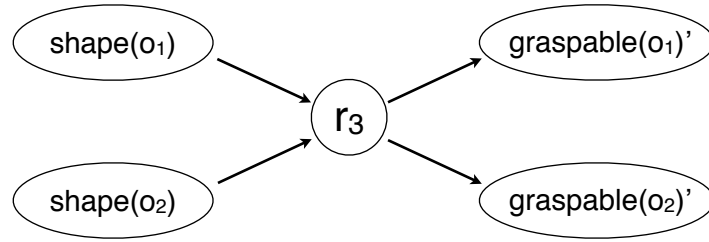


Figure 4.5: Instantiation of the probability rule r_3 on a state with two objects o_1 and o_2 .

To illustrate the application of Equations (4.8) and (4.9), the distribution $P(r_3 \mid shape(o_1) = sphere, shape(o_2) = cone)$ has two relevant groundings $y = o_1$ and $y = o_2$, from which we derive two grounding-specific distributions, and a total of four effects for the joint distribution:

- $\{graspable(o_1)' = true \wedge graspable(o_2)' = true\}$ with probability $0.9 \times 0.2 = 0.18$
- $\{graspable(o_1)' = true \wedge graspable(o_2)' = false\}$ with probability $0.9 \times 0.8 = 0.72$
- $\{graspable(o_1)' = false \wedge graspable(o_2)' = true\}$ with probability $0.1 \times 0.2 = 0.02$
- $\{graspable(o_1)' = false \wedge graspable(o_2)' = false\}$ with probability $0.1 \times 0.8 = 0.08$

Quantified utility rules

Utility rules with universally quantified variables are instantiated in a similar manner. As for probability rules, the instantiation of utility rules proceeds by determining a set of groundings and generating a particular utility distribution for each. The total utility specified by the rule is then defined as the sum of all grounding-specific utilities.

For a utility rule r with input variables I_1, \dots, I_k and decision variables D'_1, \dots, D'_l , the rule

utility for the grounding \mathbf{g} is defined as:

$$\begin{aligned}
U_{\mathbf{g}}(D'_1 = d_1[\mathbf{y}/\mathbf{g}], \dots, D'_l = d_l[\mathbf{y}/\mathbf{g}] \mid I_1 = i_1, \dots, I_k = i_k) \\
= U_i(D'_1 = d_1 \wedge \dots \wedge D'_l = d_l) \\
\text{where } i = \min(\{i : c_i[\mathbf{y}/\mathbf{g}] \text{ is satisfied with } I_1 = i_1 \wedge \dots \wedge I_k = i_k\})
\end{aligned} \tag{4.10}$$

After discarding empty and redundant distributions, the result is a set of utility distributions $\{U_{\mathbf{g}_1}, \dots, U_{\mathbf{g}_{|G|}}\}$. The total utility distribution for the rule r is finally constructed by adding up the grounding-specific utility distributions:

$$U_r(D'_1, \dots, D'_l \mid I_1, \dots, I_k) = \sum_{j=1}^{|G|} U_{\mathbf{g}_j}(D'_1, \dots, D'_l \mid I_1, \dots, I_k) \tag{4.11}$$

The instantiation of rule r_4 given the input variables $task$, $graspable(o_1)$ and $graspable(o_2)$ is shown in Figure 4.6. The utility distribution for the input assignment $task = grasp(o_1) \wedge graspable(o_1) = true \wedge graspable(o_2) = false$ assigns for instance the action $a'_m = grasp(o_1)$ to a utility of 2, while $a'_m = grasp(o_2)$ is assigned to a utility of -2 in this situation.

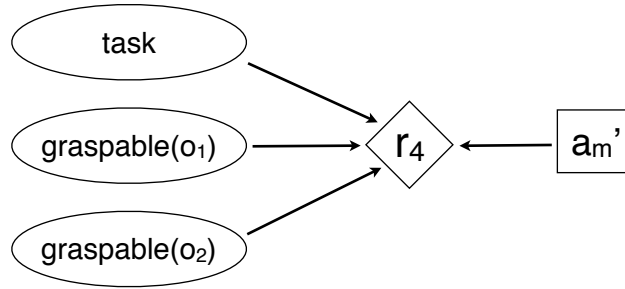


Figure 4.6: Instantiation of the quantified utility rule r_4 on a state with two objects o_1 and o_2 .

Tractability aspects

Although the use of universal quantifiers can greatly improve the expressivity of probabilistic rules, they also tend to increase the in- and out-degrees of rule nodes (that is, the cardinality of their parents and children nodes). Approximate inference techniques are thus necessary to handle this conditional structure in a tractable manner. Sampling methods such as likelihood weighting (cf. Section 3.1.2) have in practice proved to work well in this setting.

The groundings are always extracted *given a specific assignment of values* for the input variables. By restricting the groundings to this limited domain of discourse, we ensure that the number of grounding-specific distributions enumerated in Equations (4.9) and (4.11) remains small. This procedure was found to be more efficient than copying the rule in distinct nodes, as investigated in earlier implementations of the formalism (Lison, 2012c). The procedure also departs from other frameworks such as Markov logic networks, where the functions and predicates are duplicated for every possible grounding of variables in the domain (Richardson and Domingos, 2006).

4.4 Processing workflow

The two previous sections detailed how probability and utility rules are internally defined, and how they can be instantiated as latent nodes of a graphical model. We are now ready to explain how collections of rules are practically applied at runtime to update the dialogue state and perform action selection. The general workflow is strongly inspired by information-state approaches to dialogue management (Larsson and Traum, 2000), as the dialogue state serves as a central blackboard monitored by various groups of rules that are “triggered” upon relevant changes.

The following section first describes how dialogue domains are organised in collections of rules that we call *models*, and then goes on to explain how these models are applied to update state variables and express the utility of particular actions. We also demonstrate the general processing workflow on a detailed example.

4.4.1 Domain representation

The specification of dialogue domains can comprise numerous probability and utility rules. These rules are internally grouped in collections of rules called *models*. A model is simply a collection of rules that are associated with one or more “trigger” variables that specify when the rules should be instantiated. Each model is attached to the dialogue state and monitors it to detect changes affecting its trigger variables. When at least one trigger variable is modified at runtime by another module, they lead to the instantiation of all rules included in the model. Formally, a model m is defined as a pair $\langle \mathcal{T}_m, \mathcal{R}_m \rangle$ where \mathcal{T}_m corresponds to the trigger variables and \mathcal{R}_m to the rules in the model. There is no restriction on the trigger variables \mathcal{T}_m associated with each rule-structured model. In particular, several models can share the same trigger variable(s) and be triggered in parallel upon a relevant change in the dialogue state.

A dialogue domain is represented as a pair $\langle \mathcal{B}_0, \mathcal{M} \rangle$, where \mathcal{B}_0 is the initial dialogue state and \mathcal{M} the set of models attached to it. The organisation of rules into models allows the system designer to structure the application pipeline in a modular manner. Each model can be intuitively viewed as a distinct component responsible for a particular inference or decision step.

Section 7.1.2 explains how dialogue domains (and the models that compose them) are practically encoded in the OpenDial architecture, based on an XML format.

4.4.2 Update algorithm

The dialogue state is represented in our approach as a Bayesian network and is denoted \mathcal{B} . Each node in this Bayesian network represents a distinct state variable and can be connected to other variables through various conditional dependencies. As in information-state approaches to dialogue management, the dialogue state stands at the centre of the architecture and serves as a shared information repository for the whole dialogue system.

The general procedure for updating this dialogue state upon the reception of new observations is shown in Algorithm 6. The observations may for instance correspond to new user inputs processed by the ASR/NLU components or to new elements perceived in the external context. The first step is to insert the observations in the dialogue state (line 2). The algorithm then triggers the instantiation of the relevant domain models (line 3), leading to a chain of updates. If the expanded dialogue state contains decision and utility variables, the algorithm searches for the highest-utility action, selects

it, and activates the models that are triggered as a result (lines 5-7). Finally, the updated state is reduced by pruning away unnecessary nodes and incorporating the evidence (line 9).

Algorithm 6 : UPDATESTATE (\mathcal{B} , \mathbf{O})

Input: Bayesian network \mathcal{B} for the current state

Input: New observations \mathbf{O} to insert in the state

- 1: Initialise evidence $\mathbf{e} \leftarrow \emptyset$
 - 2: $\mathcal{B}, \mathbf{e} \leftarrow \text{ADDToSTATE}(\mathcal{B}, \mathbf{e}, \mathbf{O})$
 - 3: $\mathcal{B}, \mathbf{e} \leftarrow \text{TRIGGERMODELS}(\mathcal{B}, \mathbf{e}, \mathbf{O})$
 - 4: **while** \mathcal{B} contains decision variables **do**
 - 5: $\mathbf{a}^* \leftarrow \text{SELECTACTION}(\mathcal{B}, \mathbf{e})$
 - 6: Assign $\mathbf{A}' = \mathbf{a}^*$
 - 7: $\mathcal{B}, \mathbf{e} \leftarrow \text{TRIGGERMODELS}(\mathcal{B}, \mathbf{e}, \mathbf{A}')$
 - 8: **end while**
 - 9: $\mathcal{B} \leftarrow \text{PRUNESTATE}(\mathcal{B}, \mathbf{e})$
-

We now describe each of these steps in detail.

Adding new observations to the state

The first step in the update procedure is to insert the new observation(s) into the dialogue state. In the case where the observations are known with certainty, this insertion can simply take the form of an assignment of evidence values. However, dialogue systems must frequently integrate observations that are themselves uncertain and represent “soft” or virtual evidence, such as the ASR/NLU hypotheses of the user dialogue act.

Furthermore, dialogue domains often include priors on variables that will be observed in the next time steps. An example of such a prior is the user action model $P(a'_u | i'_u, a_m)$, that predicts the relative likelihoods of the next user dialogue act. To distinguish these predictions from actual observed values, we shall denote such priors with a superscript p . A variable X^p thus represents a prior on the variable X to be observed in the future.

The prior predictions and uncertain observations must be connected in the Bayesian network representing the current dialogue state. Several techniques are available to practically encode such type of “soft” evidence (Pan et al., 2006). The method adopted in this thesis is to create a new boolean-valued chance node, subsequently called the *equivalence node* eq_X , that is conditionally dependent on both the observation X and its prior prediction X^p , as shown in Figure 4.7. The use of a distinct chance node to express the evidence is motivated by the fact that both X and X^p may have arbitrary incoming and outgoing edges with other variables.

The conditional probability distribution for eq_X given X

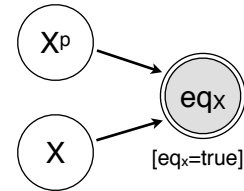


Figure 4.7: Equivalence node eq_X with parents X and X^p (the double circle denotes a deterministic distribution).

and X^p is deterministic:

$$P(eq_X = true \mid X = x, X^p = x^p) = \begin{cases} 1 & \text{if } x = x^p \\ 0 & \text{otherwise} \end{cases} \quad (4.12)$$

The assignment $[eq_X = true]$ is included in the evidence. The posterior distribution given the evidence allows the prediction to act as a prior for the observed distribution:

$$\begin{aligned} & P(X = x \mid eq_X = true) \\ &= \eta P(X = x) \sum_{x^p \in Val(X^p)} P(eq_X = true \mid X = x, X^p = x^p) P(X^p = x^p) \\ &= \eta P(X = x) P(X^p = x) \end{aligned}$$

Algorithm 7 details how the insertion of new observation variables \mathbf{O} into the dialogue state is performed in practice.

Algorithm 7 : ADDTOSTATE (\mathcal{B} , \mathbf{e} , \mathbf{O})

```

1: for all  $X \in \mathbf{O}$  do
2:   if  $X \notin \mathcal{B}$  then
3:     Insert  $X$  in  $\mathcal{B}$ 
4:   end if
5:   if there is a corresponding prediction variable  $X^p \in \mathcal{B}$  then
6:     Create equivalence node  $eq_X$  with distribution in Eq. (4.12)
7:     Insert  $eq_X$  in  $\mathcal{B}$  with parents  $X$  and  $X^p$ 
8:     Add assignment  $[eq_X = true]$  to evidence  $\mathbf{e}$ 
9:   end if
10: end for
11: return  $\mathcal{B}, \mathbf{e}$ 

```

Model instantiation

After adding the new observations in the dialogue state and connecting them to their priors, the next step in the processing workflow is to trigger the relevant rule-structured models.

Algorithm 8 summarises the steps involved in the instantiation of the models. The algorithm takes three arguments: a dialogue state \mathcal{B} represented as a Bayesian network, an assignment of evidence values and a list of random variables that have been recently updated in the dialogue state. The algorithm loops on all domain models and instantiates the ones that are triggered by the updated variables. The rules are instantiated one by one, following the procedure we have outlined in the previous section. Once all models are traversed, the output variables of the instantiated rules become updated variables themselves, and the procedure is repeated until no more models can be applied. To avoid the occurrence of infinite triggering cycles, models are limited to one single instantiation per update. The algorithm returns both the dialogue state expanded with new variables, and the evidence assignments attached to the equivalence nodes.

Algorithm 8 : TRIGGERMODELS ($\mathcal{B}, \mathbf{e}, UpdatedVars$)

```
1: while  $UpdatedVars \neq \emptyset$  do
2:    $NewVars \leftarrow \emptyset$ 
3:   for all models  $m$  do
4:     if  $(UpdatedVars \cap \mathcal{T}_m) \neq \emptyset$  and  $m$  has not yet been applied then
5:       for all rule  $r \in \mathcal{R}_m$  do
6:         if  $r$  is a probability rule then
7:            $\mathcal{B} \leftarrow \text{INSTANTIATEPROBRULE}(\mathcal{B}, r)$ 
8:         else if  $r$  is a utility rule then
9:            $\mathcal{B} \leftarrow \text{INSTANTIATEUTILRULE}(\mathcal{B}, r)$ 
10:        end if
11:        Let  $\mathcal{O}_r$  be the new output variables created by rule  $r$ 
12:         $NewVars \leftarrow NewVars \cup \mathcal{O}_r$ 
13:         $\mathcal{B}, \mathbf{e} \leftarrow \text{ADDTOSTATE}(\mathcal{B}, \mathbf{e}, \mathcal{O}_r)$ 
14:      end for
15:    end if
16:  end for
17:   $UpdatedVars \leftarrow NewVars$ 
18: end while
19: return  $\mathcal{B}, \mathbf{e}$ 
```

Action selection

Whenever the new dialogue state contains utility and decision nodes created as a result of the instantiation of utility rules, the system must decide on the action to perform. Algorithm 9 illustrates how actions can be selected on the basis of the current dialogue state. The algorithm searches for the assignment of action values that maximises the current utility given the current dialogue state and the evidence. This utility maximisation is based on standard inference algorithms for decision networks such as likelihood weighting (cf. Section 3.1.2).

The utility nodes are removed from the state once the decision is made. The action selection procedure described in Algorithm 9 only takes into account the current (immediate) utility and does not rely on forward planning. Chapter 6 demonstrates how this procedure can be extended to perform online planning on a limited horizon.

Algorithm 9 : SELECTACTION (\mathcal{B}, \mathbf{e})

```
1: Let  $\mathbf{A}'$  be the set of all decision variables in  $\mathcal{B}$ 
2: Find highest-utility value  $\mathbf{a}^* = \text{argmax}_{\mathbf{a}} U(\mathbf{A}' = \mathbf{a} | \mathbf{e})$ 
3: Remove utility nodes from the state  $\mathcal{B}$ 
4: return  $\mathbf{a}^*$ 
```

State pruning

The instantiation of the domain models results in the creation of numerous new nodes in the dialogue state. However, many nodes in this expanded Bayesian network only serve as intermediaries and do not directly express meaningful information about the current state of the dialogue. The last step is therefore to reduce the dialogue state to its minimal size, by removing all intermediary

nodes – including rule nodes, outdated versions of state variables, equivalence nodes and predictive nodes that are attached to them – in order to only retain current state variables. The accumulated evidence is also integrated in the posterior distribution of the state variables.

The procedure is outlined in Algorithm 10. The first step is to determine which nodes to keep (lines 1-6). Only the most recent versions of state variables are retained. The nodes are then added one by one in a new dialogue state \mathcal{B}' . The parents of the retained variables are determined, and their conditional probability distributions are calculated given the evidence. The parents of a state variable are the closest ancestors of the variable within the subset of nodes in *NodesToKeep*, and its conditional probability distribution is determined as $P_{\mathcal{B}}(N \mid Parents, \mathbf{e})$. This posterior distribution is calculated by sampling all nodes in \mathcal{B} , then deriving the distributions $P_{\mathcal{B}}(N \mid Parents, \mathbf{e})$ on the basis of the collected samples.

Figure 4.8 illustrates the input and output of the pruning process. Note that the primes attached to the labels of output variables are deleted from the random variable names.

Algorithm 10 : PRUNESTATE (\mathcal{B}, \mathbf{e})

```

1:  $NodesToKeep \leftarrow \emptyset$ 
2: for all node  $N \in \mathcal{B}$  do
3:   if  $N$  is a state variable and  $\nexists N' \in \mathcal{B}$  then
4:      $NodesToKeep \leftarrow NodesToKeep \cup \{N\}$ 
5:   end if
6: end for
7: Create new state  $\mathcal{B}' \leftarrow \emptyset$ 
8: for all node  $N \in NodesToKeep$  do
9:   Add node  $N$  to  $\mathcal{B}'$  (with primes removed from node name)
10:   $Parents \leftarrow \{M \in NodesToKeep : M \text{ is an ancestor of } N \text{ and there is}$ 
       $\text{a path } M \rightarrow^+ N \text{ without node in } NodesToKeep\}$ 
11:  Add dependency edges between  $Parents$  and  $N$  in  $\mathcal{B}'$ 
12:  Assign distributions  $P_{\mathcal{B}'}(N \mid Parents) \leftarrow P_{\mathcal{B}}(N \mid Parents, \mathbf{e})$ 
13: end for
14: return  $\mathcal{B}'$ 

```

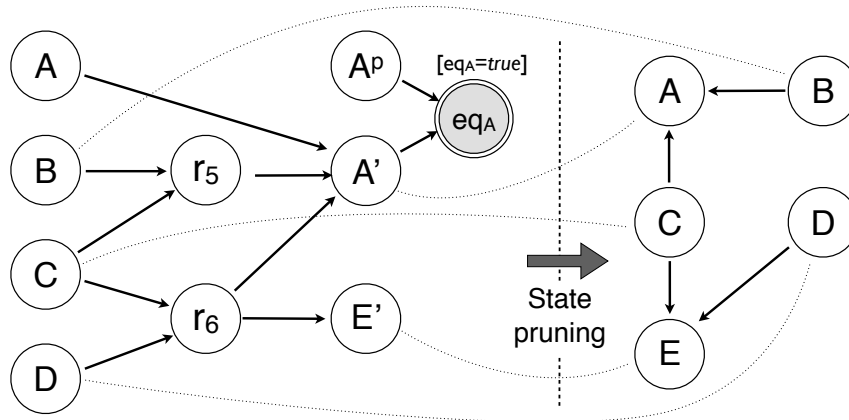


Figure 4.8: Illustration of the state pruning process. Only the nodes A', B, C, D, E' are retained. The dotted lines denote the correspondence between nodes.

4.4.3 Detailed example

To make the update procedure more concrete, we describe below a minimal but complete example of a workflow for a short interaction, detailing step-by-step how the dialogue state is updated in practice and employed to select the system actions.

Description

Assume a domain similar to the one shown in Figure 2.3, where a user can request a robot to move forward, backward, left, right, or stop. The set of dialogue acts a_u that can be recognised by the system in this minimal example is the following:

$$\{Request(Forward), Request(Backward), Request(Left), \\ Request(Right), Request(Stop), Other\}.$$

The corresponding system actions a_m are:

$$\{Move(Forward), Move(Backward), Move(Left), \\ Move(Right), Move(Stop), AskRepeat\}.$$

The objective of the system is to fulfil the user command if it is reasonably confident regarding which action to execute. Otherwise, the system asks the user to repeat.

Domain specification

The domain specification for this constructed example comprises an empty initial state and two rule-structured models m_1 and m_2 :

- Model m_1 is triggered by a_u and includes two utility rules r_9 and r_{10} :

$$\begin{aligned} r_9 : \quad & \forall y, \\ & \mathbf{if} (a_u = Request(y)) \mathbf{then} \\ & \quad \{U(a'_m = Move(y)) = 2 \\ & \quad \mathbf{else} \\ & \quad \quad \{U(a'_m = Move(y)) = -2 \\ r_{10} : \quad & \{U(a'_m = AskRepeat) = 0.5 \end{aligned}$$

Rule r_9 specifies that the utility of executing the action corresponding to the user command is 2, with a penalty of -2 when the wrong action is executed. Rule r_{10} assigns a utility of 0.5 for asking a clarification question.⁷

⁷As the action selection process presented thus far does not perform forward planning, the utilities provided in this example correspond to long-term expected utilities (Q-values in the reinforcement learning terminology).

- Model m_2 is triggered by a_m and has one single predictive rule r_{11} :

$$r_{11} : \forall y, \\ \text{if } (a_m = \text{AskRepeat} \wedge a_u = y) \text{ then} \\ \left\{ P(a_u^{p'} = y) = 0.9 \right.$$

Rule r_{11} specifies that the probability that the user will repeat the last utterance when asked by the system to do so is expected to be 0.9. Note the superscript p in the random variable $a_u^{p'}$, which indicates that the effect expresses a prediction on a future dialogue act a_u .

Processing workflow

We now detail the processing workflow associated with a short (artificial) interaction:

USER : Now move forward

Hypotheses for $\tilde{a}_u = [(Request(Forward), 0.6), (Request(Backward)), 0.4]$

SYSTEM : Could you please repeat?

USER : Please move forward!

Hypotheses for $\tilde{a}_u = [(Request(Forward), 0.7), (Other, 0.3)]$

SYSTEM : OK, moving forward!

The recognition hypotheses \tilde{a}_u produced by the ASR/NLU components are indicated underneath each user utterance:

Figure 4.9 details the steps involved in the state update procedure that follows from the reception of dialogue act hypotheses from the natural language understanding component.

Step 1 inserts the new dialogue act hypotheses in the dialogue state. This insertion triggers the utility model m_1 . The instantiation results in Step 2 in the creation of two utility nodes and one decision node. The optimal action to perform in this case is *AskRepeat*, which is selected by the system in Step 3. The action selection triggers model m_2 in Step 4, which creates a prediction node $a_u^{p'}$ expressing the expected probability distribution for the next user dialogue act. The state is finally pruned of the intermediary rule node in Step 5. System components such as NLG can react on the updated state and generate the proper linguistic realisation of the system action. The system then waits for the user input, which is shown in Step 6. The relation between the predicted and actual user response leads in Step 7 to the creation of an equivalence node, and the inclusion of the assignment $[eq_{a_u} = true]$ to the evidence. We notice that the combination of the prior distribution over predicted values and the actual distribution over dialogue act hypotheses increases the probability of $a'_u = Request(Forward)$. Step 8 triggers the model m_1 based on the new user input. The best action to execute at this stage is *Move(Forward)*, which is selected in Step 9. This selection triggers model m_2 , but rule r_{11} is in this case irrelevant and is thus directly deleted. Finally, the state is pruned of its intermediary nodes in Step 10, retaining only the last user and system actions a_u and a_m .

In comparison to the finite-state solution presented in Figure 2.3, we observe that the rule-structured approach defined by models m_1 and m_2 allows the dialogue manager to accumulate

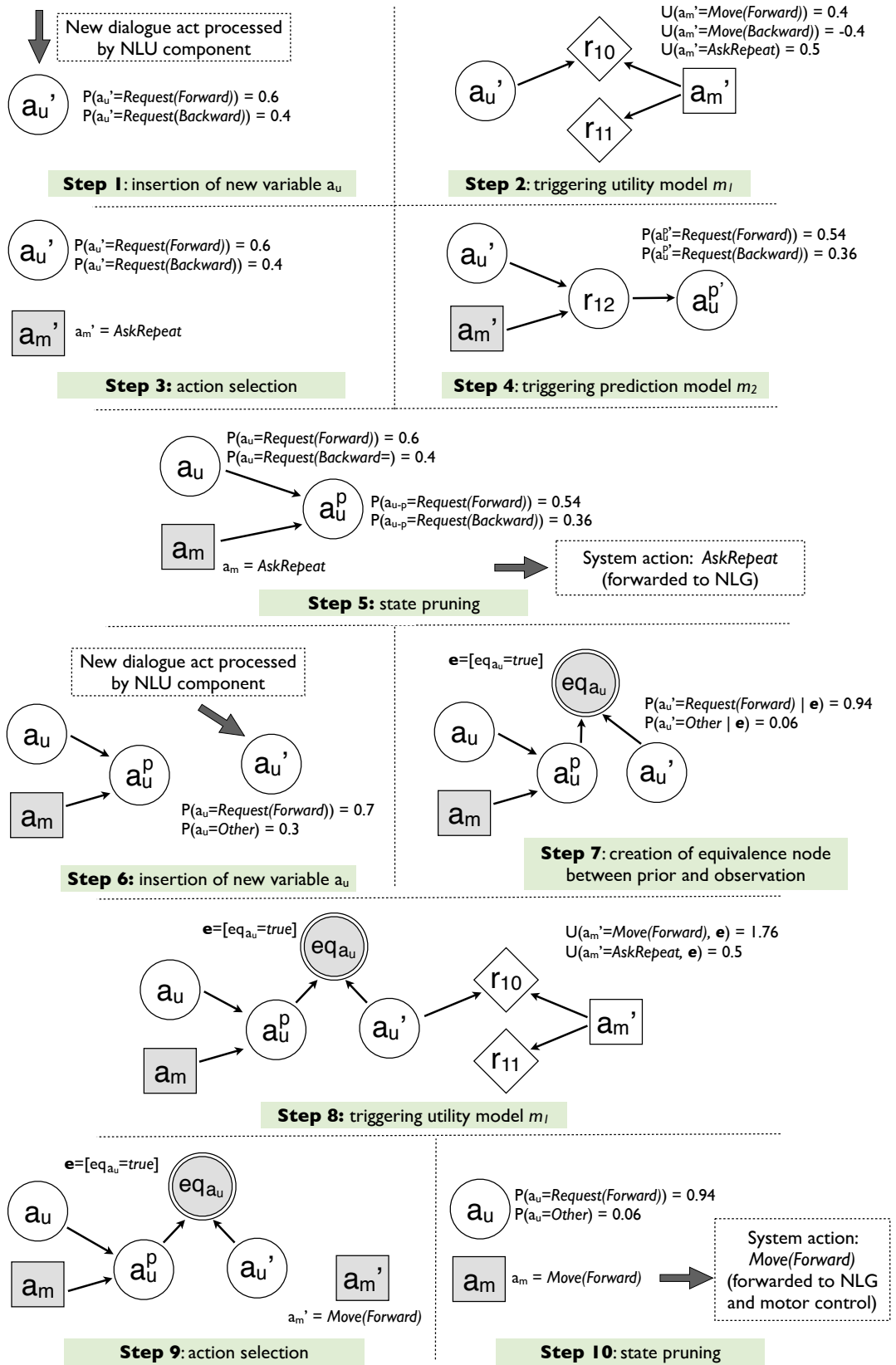


Figure 4.9: Detailed example of processing workflow.

evidence over time and prime the recognition hypotheses of the user dialogue act a_u based on the previous dialogue act. This accumulation of evidence is absent from the FSA, due to its rigid state representation and lack of extended memory.

4.5 Advanced modelling

Dialogue domains often include random variables expressing specific data structures such as lists of elements or strings. The rule-based formalism described in the previous sections can be easily complemented with special-purpose tools to efficiently operate on these data structures. We first explain how conditions and effects can be defined on variables that represent lists, and then discuss how rules can manipulate strings.

4.5.1 Operations on lists

Some state variables are best represented as lists of elements. For instance, the dialogue state may include random variables that enumerate the n most recent dialogue acts in the interaction history, the collection of tasks that must be executed, or the list of visual objects perceived by the system. The range of values for such state variables is the power set of its possible elements.

Special-purpose operators for the manipulation of such lists can be integrated in both the conditions and effects of probabilistic rules:

- The syntax of rule conditions (see Table 4.1) can be extended to include operators to check the presence or absence of particular elements in a list, such as $a \in A$ or $a \notin A$.
- Rule effects can also be augmented to manipulate elements from a list. Three new types of effects are created to this end, in addition to the traditional assignment of output values: *add effects* (adding an element to a list), *delete effects* (deleting an element from a list) and *clear effects* (clearing all elements of a list). This is practically realised by extending the syntax of rule effects (Table 4.2) to include these three types of effects.

Figure 4.10 illustrates two rules that apply these new effects to update a state variable A .

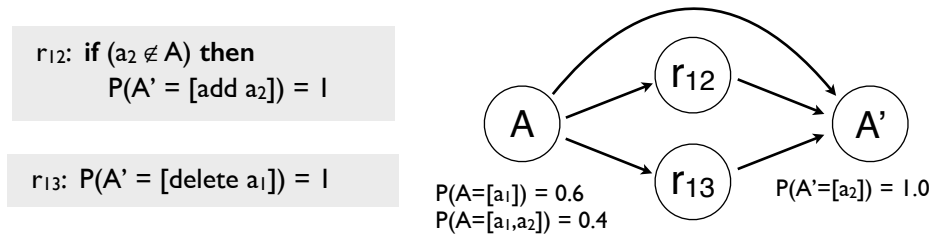


Figure 4.10: Example of rules using add/delete effects to manipulate lists.

These new effects can be incorporated to the framework through a simple modification of the output distribution. Let e denote as before the conjunction of all effects $e_1 \wedge \dots \wedge e_n$. In addition to the previously defined set of values $e(X')$ assigned for the variable X' , we construct two new sets of values $e_{add}(X')$ and $e_{del}(X')$ that represent the values that are respectively added and deleted

for the variable X' through the new effects we just described. The set $e_{del}(X')$ includes all values for X' if the clear effect is applied.

The output distribution in Equation (4.6) is then rewritten as:

$$P(X' = x' \mid r_1 = e_1, \dots, r_n = e_n, X = x) = \begin{cases} \frac{\mathbf{1}(x' \in \mathbf{e}(X'))}{|\mathbf{e}(X')|} & \text{if } \mathbf{e}(X') \neq \emptyset \\ \mathbf{1}(x' = (\mathbf{e}_{add}(X') \cup (x / \mathbf{e}_{del}(X')))) & \text{otherwise} \end{cases} \quad (4.13)$$

The output distribution associated for a new variable (cf. Equation (4.5)) can be rewritten in a similar manner.

4.5.2 Operations on strings

Many of the data structures present in the dialogue state are strings – the most prominent ones being the last user utterance u_u and the last system utterance u_m . The integration of special-purpose functions for manipulating strings within the conditions and effects of probabilistic rules is therefore desirable. In particular, rules can be extended to perform template-based string matching operations. The idea is to include a new type of conditions that checks whether a string matches a given template. Templates can include slots to fill, which are conceptually similar to the quantified variables discussed in Sections 4.2.3. Both full and partial matching can be employed in the condition.

Figure 4.11 illustrates how such templates are applied in practice. $\{OBJ\}$ denotes a slot that is to be filled through matching the template with the value specified in u_u .

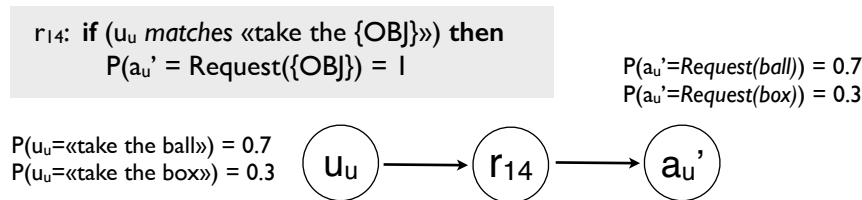


Figure 4.11: Example of rule using string matching operations.

4.6 Relation to previous work

The idea of using structural knowledge in probabilistic models has been explored in many directions, both in the fields of decision-theoretic planning and reinforcement learning (Hauskrecht et al., 1998; Pineau, 2004; Kersting and Raedt, 2004; Lang and Toussaint, 2010; van Otterlo, 2012), and in statistical relational learning (Jaeger, 2001; Richardson and Domingos, 2006; Getoor and Taskar, 2007). The introduced structure may be hierarchical, relational, or both. As in our approach, most of these frameworks rely on the use of expressive representations serving as templates for the generation of classical probabilistic models. The surveys of van Otterlo (2006, 2012)

provide a complete overview of relational and first-order logical approaches for reinforcement learning in Markov decision processes, covering both model-free and model-based methods. While the formalisation presented in this thesis and the aforementioned approaches share many insights, they also reveal several interesting differences:

- Probabilistic rules are primarily tailored for dialogue management tasks and seek to capture dialogue domains by striking a balance between propositional and first-order logic. The formalism deliberately eschews the complexity of full-scale first-order probabilistic inference to ensure that the domains models can be applied under real-time constraints. This design choice sets it apart from other frameworks such as Markov logic networks which can express arbitrary first-order formulae but are often tedious to instantiate due to the size and complexity of the resulting models.⁸
- Probabilistic rules are also designed to operate under partially observable settings, as state uncertainty is a pervasive and unavoidable aspect of verbal interactions. By contrast, most previous work on relational probabilistic models are limited to fully observable environments, with the exception of some limited theoretical studies by Wang and Khardon (2010) and Sanner and Kersting (2010).
- Finally, the presented framework posits that the *if...then...else* skeletons of probabilistic rules are best encoded by the system designers based on their expert knowledge of the domain, while the rule parameters can be estimated empirically. We therefore exclude the problem of structure learning from the scope of this thesis, as opposed to several approaches in which the domain rules and constraints are extracted via machine learning techniques (Pasula et al., 2007; Kok and Domingos, 2009).

Probabilistic rules also bear similarities with planning description languages such as the Planning Domain Definition Language (PDDL, see McDermott et al., 1998) and its probabilistic extension, the Probabilistic Planning Domain Definition Language (PPDDL, see Younes and Littman, 2004). These languages are structured through action schemas that specify how (parametrised) actions can yield particular effects under various conditions. As in probabilistic rules, these languages try to carefully balance between the language expressivity and the complexity of the planning algorithm, based on a limited form of first-order logic. A relational extension of PDDL, named RDDDL, has also been introduced in recent planning competitions (Sanner, 2010). The rule learning techniques developed by Pasula et al. (2007) for the estimation of transition functions based on noisy indeterministic deictic rules are directly related to our approach, as is the recent work of Lang and Toussaint (2010) on probabilistic noisy planning rules. Both frameworks define conditions associated with probabilistic distributions over effects. Their approaches are, however, restricted to fully observable settings.

In the dialogue management literature, most structural approaches rely on a clear-cut task decomposition into goals and sub-goals (Allen et al., 2000; Steedman and Petrick, 2007; Bohus and Rudnicky, 2009), where the completion of each goal is assumed to be fully observable, discarding any remaining uncertainty. Our own work on multi-policy dialogue management in Lison (2011)

⁸Although see Kennington and Schlangen (2012) for an approach that applies Markov logic networks to incremental natural language understanding in dialogue domains.

relaxes the assumption of perfect knowledge of task completion, handling multiple policies as a problem of probabilistic inference over activation variables. Probabilistic rules can be considered an extension of this early work, where the structural knowledge is not confined to task decomposition but is extended to generic rules over state variables.

The processing workflow presented in this chapter is strongly inspired by information state approaches to dialogue management (Larsson and Traum, 2000; Bos et al., 2003), which are also based on a shared state representation that is updated according to a rich repository of rules. Ginzburg (2012) also models conversational phenomena by way of update operations that are encoded with rules mapping conditions to effects. However, contrary to the framework presented here, the rules employed in these approaches are generally deterministic and do not include learnable parameters. The action selection mechanism is also conceptualised slightly differently, as information-state frameworks rely on rules that directly select the most appropriate action given the current state. By contrast, probabilistic rules adopt a decision-theoretic approach that decomposes action selection in two stages: utility rules first determine the utility distributions associated with the space of possible system actions in the current dialogue state, after which the system searches for the action that yields the maximum expected utility on the basis of these distributions.

The literature on dialogue policy optimisation with reinforcement learning also contains several approaches dedicated to dimensionality reduction for large state–action spaces, such as function approximation (Henderson et al., 2008), hierarchical reinforcement learning (Cuayáhuitl et al., 2010) and summary POMDPs (Young et al., 2010). Many of these techniques have already been discussed in Section 3.3 and will therefore not be repeated here. Most current approaches in dialogue policy optimisation focus on large but weakly structured state spaces (generally encoded as large lists of features), which are suited for slot-filling dialogue applications but are difficult to transfer to more open-ended or relational domains. The idea of state space partitioning, implemented here via high-level conditions, has also been explored in recent papers (see e.g. Williams, 2010). Crook and Lemon (2010) explored the introduction of complex user goal states including disjunction and negation operators. Cuayáhuitl (2011) describes a policy optimisation approach based on logic-based representations of the state–action space for relational MDPs. The main difference to our approach lies in his reduction of the belief state to fully observable variables whereas we retain the partial observability associated with each variable. The work of Mehta et al. (2010) and Raux and Ma (2011) demonstrated how tree-structured Bayesian networks called probabilistic ontology trees can improve belief tracking performance. The tree structure is derived in their work from a hierarchical concept structure. Finally, O’Neill et al. (2011) describe a procedure for the selection of dialogue strategies based on probabilistic logic programming.

4.7 Conclusion

This chapter has presented the formalism of probabilistic rules, which forms the core of the modelling approach developed in this thesis. We started by arguing that dialogue models are often highly structured, and that this structure can be leveraged by introducing latent variables, partitioning value assignments, and making use of quantification. We then explained how these structural insights can be transferred into a new computational framework – to which we gave the name of probabilistic rules – that combines concepts borrowed from both first-order logic and probability theory in order to get “the best of both worlds”, i.e. a representation formalism that is both richly

expressive and capable of capturing uncertain knowledge. These rules are practically defined as *if...then...else* constructions that associate high-level conditions on input variables to probabilistic effects on output variables. Multiple extensions of the formalism have been developed to e.g. encode utility distributions, enclose universal quantifiers, and efficiently manipulate data structures such as lists of elements and strings.

At runtime, these rules are instantiated in the Bayesian network representing the current dialogue state. The instantiation procedure creates a latent node for each rule, which is conditionally dependent on the input variables of the rule. For probability rules, this node is a chance node that expresses a probability distribution over the possible effects of the rule. Utility rules are similarly instantiated with a utility node expressing the utility distribution for specific decision variables. Universally quantified variables can be included in the conditions and effects of the rules, allowing particular aspects of the rule to be underspecified. The rules are grouped into models that are attached to the dialogue state and are triggered upon relevant state updates.

Probability and utility rules effectively function as high-level templates for the definition of a dynamic decision network (such as the ones used to represent MDP and POMDP problems). The expressive power of these rules allows them to efficiently encode complex relations between variables, and thereby reduce the number of parameters to estimate. We have, however, not yet detailed how this parameter estimation is practically performed. The next two chapters provide answers to this important question.

Chapter 5

Learning from Wizard-of-Oz data

The previous chapter presented the formalism of probabilistic rules and described their practical instantiation as latent nodes of a graphical model. Probabilistic rules are generally associated to a number of parameters, which may either express probabilities over effects (for probability rules) or utilities associated with particular decisions (for utility rules). But where exactly do these probabilities and utilities come from?

This thesis develops two distinct approaches to this question. The present chapter concentrates on the first approach, which is grounded in supervised learning techniques. We demonstrate how rule parameters can be optimised to best imitate the action choices of a human expert through statistical estimation based on Wizard-of-Oz data. The next chapter will then detail an alternative reinforcement learning approach to the same task.

The chapter is divided in three sections. Section 5.1 describes how uncertainty regarding the value of rule parameters can be explicitly represented through prior distributions. Section 5.2 goes on to explain how these distributions can be gradually refined on the basis of interaction data gathered from Wizard-of-Oz experiments. Bayesian learning is used to progressively narrow down the spread of the parameter distributions to the values providing the best fit for the observed data. Finally, Section 5.3 reports on experimental results in a human–robot interaction domain for which small amounts of Wizard-of-Oz data were recorded. The experiment compared the learning performance of a utility model structured with probabilistic rules against two baselines respectively encoded with plain utility tables and with linear models. The evaluation showed that the rule-structured model was able to imitate the dialogue policy followed by the wizard significantly better than its unstructured counterparts.

5.1 Parameters of probabilistic rules

5.1.1 General methodology

The examples of probabilistic rules seen so far all relied on fixed probability and utility values. These values can, however, be replaced by parameters that reflect unknown values that are to be estimated empirically, on the basis of training data.

The overall structure of such parametrised rules remains essentially identical to the one outlined in the previous chapter. Probability rules are once more defined in terms of conditions c_i associated to probability distributions $P(E_i)$ over effects. The probability of each effect is, however, no longer

fixed but is instead represented by a parameter $\theta_{(i,j)}$, giving rise to the following skeleton:

$$\begin{aligned}
& \mathbf{if} \ (c_1) \ \mathbf{then} \\
& \quad \left\{ \begin{array}{l} P(E_1 = e_{(1,1)}) = \theta_{(1,1)} \\ \dots \\ P(E_1 = e_{(1,m_1)}) = \theta_{(1,m_1)} \end{array} \right. \\
& \quad \dots \\
& \mathbf{else} \\
& \quad \left\{ \begin{array}{l} P(E_n = e_{(n,1)}) = \theta_{(n,1)} \\ \dots \\ P(E_n = e_{(n,m_n)}) = \theta_{(n,m_n)} \end{array} \right.
\end{aligned} \tag{5.1}$$

Analogously, parametrised utility rules replace utility values with unknown parameters:

$$\begin{aligned}
& \mathbf{if} \ (c_1) \ \mathbf{then} \\
& \quad \left\{ \begin{array}{l} U_1(d_{(1,1)}) = \theta_{(1,1)} \\ \dots \\ U_1(d_{(1,m_1)}) = \theta_{(1,m_1)} \end{array} \right. \\
& \quad \dots \\
& \mathbf{else} \\
& \quad \left\{ \begin{array}{l} U_n(d_{(n,1)}) = \theta_{(n,1)} \\ \dots \\ U_n(d_{(n,m_n)}) = \theta_{(n,m_n)} \end{array} \right.
\end{aligned} \tag{5.2}$$

We focus in this work on the problem of parameter estimation given a known and fixed rule structure. The methodological standpoint adopted in this thesis rests on the idea that the structure of probabilistic rules is best determined by the system designer, while the rule parameters are best derived by statistical optimisation techniques. Based on our own practical experience with various dialogue systems, we believe that such a division of labour between the human designer and the learning algorithm is a sensible one, as system designers generally have a good grasp of the domain structure and relations between variables but are often unable to quantify the precise probability of an effect or utility of an action.¹

Although our work concentrates on parameter estimation with a known rule structure, it should be noted that recent developments in statistical relational learning have shown that the structure of stochastic rules can also be extracted from data (Pasula et al., 2007; Kok and Domingos, 2009). These methods are, however, generally confined to domains of limited size and full observability and are therefore difficult to apply to the dialogue domains investigated in this thesis.

¹Humans are indeed notoriously poor at estimating probabilities and are prone to multiple cognitive biases when doing so, as evidenced by numerous studies in behavioural psychology. O'Hagan (2006) provides more details on the human perception of uncertainty and the difficult problem of probability elicitation from experts.

5.1.2 Parameter priors

Throughout this thesis, we follow a *Bayesian* approach to parameter estimation and associate the rule parameters with explicit prior distributions over their range of possible values. These prior parameter distributions have a continuous range of values and can be either univariate or multivariate. The benefits of Bayesian approaches compared to maximum likelihood methods are multiple:

1. Bayesian methods allow domain knowledge to be directly included into the learning cycle through the use of informative priors (cf. discussion below). The system designers are thus able to bias the initial prior distributions according to their domain expertise.
2. Bayesian methods explicitly capture the model uncertainty both at the beginning and at the end of the learning process. The outputs of a Bayesian learning cycle are indeed full posterior distributions over the possible parameter values instead of being reduced to point estimates (as for maximum likelihood estimation). The dialogue agent can therefore explicitly account for parameter uncertainty at runtime and use it to simultaneously learn, reason and act in its environment (Ross et al., 2011). Furthermore, the reliance on full parameter distributions facilitates the combination of multiple learning processes, as the posterior distribution generated by one learner can be passed on as the prior distribution of another.

We describe below possible parameter distributions for probability rules and then discuss the case of utility rules.

Probability parameters

The distributions over the effects of probability rules are categorical probability distributions. As already discussed in Section 3.1.3, the parameter priors of categorical and multinomial distributions are best expressed using *Dirichlet* distributions.

Each distribution over effects $P(E_i)$ is associated with its own Dirichlet distribution of dimension m_i , where m_i is the number of alternative effects (including the empty effect if appropriate). Rule r_1 provides an example of a parametrised probability rule:

$$\begin{aligned}
 r_1 : \quad & \mathbf{if} (Rain = false \wedge Weather = hot) \mathbf{then} \\
 & \quad \begin{cases} P(Fire' = true) = \theta_{r_1(1,1)} \\ P(Fire' = false) = \theta_{r_1(1,2)} \end{cases} \\
 & \mathbf{else} \\
 & \quad \begin{cases} P(Fire' = true) = \theta_{r_1(2,1)} \\ P(Fire' = false) = \theta_{r_1(2,2)} \end{cases}
 \end{aligned}$$

The parameters of rule r_1 can be expressed with two Dirichlets $\theta_{r_1(1)} = \langle \theta_{r_1(1,1)}, \theta_{r_1(1,2)} \rangle$ and $\theta_{r_1(2)} = \langle \theta_{r_1(2,1)}, \theta_{r_1(2,2)} \rangle$ respectively associated with the effect distributions for the first and second condition. The Dirichlet distributions in this example have two dimensions (since two alternative effects are mentioned in the rule), which make them equivalent to *Beta* distributions.

Dirichlet distributions are continuous, multivariate probability distributions defined by the meta-parameters $\alpha = [\alpha_1, \dots, \alpha_k]$, where k corresponds to the dimensionality of the categorical

distribution of interest. Dirichlet distributions over the parameters $\theta_1, \dots, \theta_k$ are formally expressed by the following probability density function:

$$P(\theta_1, \dots, \theta_k; \alpha) = \frac{1}{B(\alpha)} \prod_{i=1}^k \theta_i^{\alpha_i-1} \quad \text{with } B(\alpha) = \frac{\prod_{i=1}^k \Gamma(\alpha_i)}{\Gamma(\sum_{i=1}^k \alpha_i)} \quad (5.3)$$

where $B(\alpha)$ serves as normalisation factor and builds upon the gamma function Γ .² The notation $P(\theta_1, \dots, \theta_k; \alpha)$ refers to the joint density function of the random variables $\theta_1, \dots, \theta_k$ given the specified (hyper-)parameters α .

Figure 5.1 depicts the shape of the probability density functions for several variants of the two-dimensional Dirichlet distribution $P(\theta_1, \theta_2; \alpha)$ (also known as a Beta distribution). The second dimension θ_2 is not explicitly shown in the figure but can be directly derived from the first dimension, since $\theta_1 + \theta_2 = 1$. The figure illustrates how the α hyper-parameters determine the shape of the distribution. As the α counts grow larger, the density function becomes increasingly focused on a particular region of the parameter space. The α counts can therefore be tuned to skew the distribution in a particular direction based on prior domain knowledge. Such prior distributions are called “informative” priors, since their shape is influenced by expert information. In the absence of such information, non-informative distributions such as $\text{Dirichlet}(1, 1)$ can also be employed.

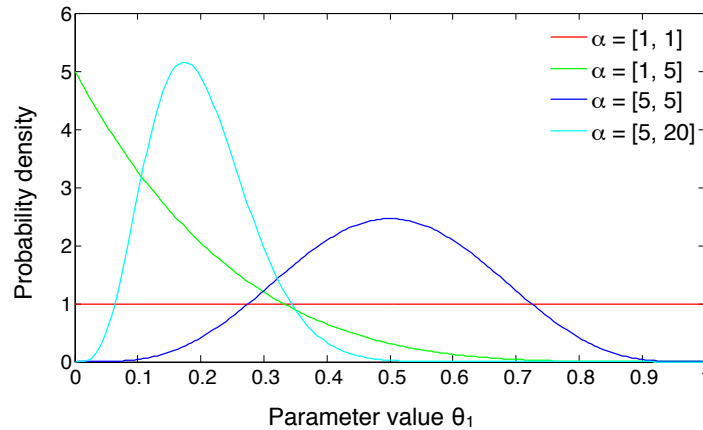


Figure 5.1: Probability density functions for the Dirichlet distribution $P(\theta_1; \alpha)$ according to various values for the α hyper-parameters.

As Dirichlet distributions are conjugate priors of categorical distributions, their posterior distribution after the observation of their corresponding categorical variable remains a Dirichlet distribution with updated counts. As an illustrative example, the posterior distribution of $\theta_{r_1(1)}$ after observing a fire when $Rain = false \wedge Weather = hot$ can be derived from Bayes’ rule:

$$\begin{aligned} &P(\theta_{r_1(1)} \mid Fire' = true, Rain = false, Weather = hot) \\ &= \eta P(Fire' = true \mid Rain = false, Weather = hot; \theta_{r_1(1)}) P(\theta_{r_1(1)}) \\ &= \eta \theta_{r_1(1,1)} \text{Dirichlet}(\alpha_1, \alpha_2) \\ &= \eta' \theta_{r_1(1,1)} [\theta_{r_1(1,1)}^{\alpha_1-1} \times \theta_{r_1(1,2)}^{\alpha_2-1}] = \eta' \text{Dirichlet}(\alpha_1 + 1, \alpha_2) \end{aligned}$$

²The gamma function is a generalisation of the factorial for real numbers, and is defined as $\Gamma(z) = \int_0^\infty t^{z-1} e^{-t} dt$.

where η and η' are normalisation factors. Given a prior probability distribution $P(\boldsymbol{\theta}_{r_1(1)}) \sim \text{Dirichlet}(\alpha_1, \alpha_2)$, the posterior distribution for $\boldsymbol{\theta}_{r_1(1)}$ after the observation $Fire' = true$ is thus another Dirichlet distribution $\sim \text{Dirichlet}(\alpha_1 + 1, \alpha_2)$. This updated Dirichlet distribution results in a slightly higher probability for the occurrence of fire, reflecting the evidence provided by the observation.

Utility parameters

The parameters of utility rules are also defined by probability density functions. However, contrary to probability values, utility values are independent of one another and need not satisfy the probability axioms – in particular, their possible values are not constrained to the range $[0, 1]$ and the distribution does not need to sum up to 1. Each utility value $u_{(i,j)}$ assigned to decision $d_{(i,j)}$ is therefore associated with its own, univariate distribution.

Rule r_2 illustrates a utility rule with four independent parameters:

$$\begin{aligned}
 r_2 : & \text{ if } (Fire = true) \text{ then} \\
 & \quad \begin{cases} U(Tanker' = drop-water) = \theta_{r_2(1,1)} \\ U(Tanker' = wait) = \theta_{r_2(1,2)} \end{cases} \\
 & \text{ else} \\
 & \quad \begin{cases} U(Tanker' = drop-water) = \theta_{r_2(2,1)} \\ U(Tanker' = wait) = \theta_{r_2(2,2)} \end{cases}
 \end{aligned}$$

Several types of density functions can be applied to define the prior distributions over these utility values. This thesis concentrates on two specific families of priors, one non-informative (uniform distributions) and one informative (normal distributions):

1. Continuous uniform distributions are defined on an interval $[a, b]$ which corresponds to the allowed range of utility values, and have the following density:

$$P(\theta; a, b) = \begin{cases} \frac{1}{b-a} & \text{for } \theta \in [a, b] \\ 0 & \text{otherwise} \end{cases} \quad (5.4)$$

2. Normal (also called Gaussian) distributions are defined by a probability density function revolving around a mean μ and variance σ^2 :

$$P(\theta; \mu, \sigma^2) = \frac{1}{\sqrt{2\pi\sigma^2}} \exp \left\{ -\frac{(\theta - \mu)^2}{2\sigma^2} \right\} \quad (5.5)$$

The range of possible values can be further constrained by truncating the density function.

Normal distributions are well suited to represent utility values for which rough initial estimates are available. If a particular utility value is expected to lie in the vicinity of a particular value, its probability distribution can be expressed via a normal distribution with a mean centred on this value and a variance reflecting the confidence in the provided estimate.

Figure 5.2 illustrates three instances of probability density functions for a parameter θ . The first distribution corresponds to a uniform distribution on the interval $[-2, 4]$, while the second and third distributions are truncated normal distributions with mean $\mu = 2$ and variances respectively assigned to $\sigma^2 = 4$ and $\sigma^2 = 1$. The two normal distributions illustrate how prior knowledge about the utility value can be incorporated in the prior – in this case, the distributions rest on the assumption that the true utility value is likely to revolve around the value 2.

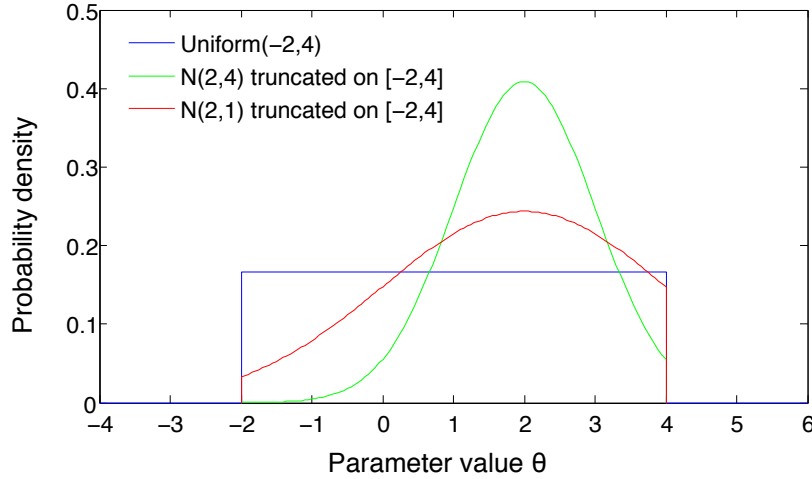


Figure 5.2: Probability density functions $P(\theta)$ over the interval $[-2, 4]$ using a uniform distribution, a truncated normal distribution $\mathcal{N}(2, 4)$ and a truncated normal distribution $\mathcal{N}(2, 1)$.

5.1.3 Instantiation

Parameters are instantiated in the dialogue state as chance nodes. One distinct node is created for each (univariate or multivariate) parameter distribution and included as a parent of its corresponding rule node. The rule distributions defined in Section 4.3 must be slightly adapted to account for these parameters in the parent nodes of the rule. The rest of the instantiation process remains unchanged.

Parameters of probability rules

A parametrised probability rule r structured with n conditions is associated with n multivariate parameter nodes $\theta_{r(1)}, \dots, \theta_{r(n)}$. Each distribution $P(\theta_{r(i)})$ is a Dirichlet distribution of dimension m_i , where m_i is the number of effects associated with the condition c_i (including the empty effect). Figure 5.3 illustrates this instantiation procedure with two probability rules.

The conditional probability distribution of a rule node r given its input variables I_1, \dots, I_k and parameters $\theta_{r(1)}, \dots, \theta_{r(n)}$ is a straightforward adaptation of Equation (4.4):

$$P(r=e \mid I_1=i_1, \dots, I_k=i_k ; \theta_{r(1)}, \dots, \theta_{r(n)}) = P(E_i = e ; \theta_{r(i)}) \quad (5.6)$$

where $i = \min(\{i : c_i \text{ is satisfied with } I_1=i_1 \wedge \dots \wedge I_k=i_k\})$

The rule distribution in the presence of universally quantified variables defined in Equation (4.8) can be similarly adapted to include parameters.

Parameters of utility rules

The parameters of utility rules are also instantiated as distinct chance nodes in the dialogue state, as shown in Figure 5.4. The corresponding utility distribution is adapted from Equation (4.7) as follows:

$$\begin{aligned}
 &U_r(D'_1=d_1, \dots, D'_l=d_l \mid I_1=i_1, \dots, I_k=i_k ; \theta_{r(1)}, \dots, \theta_{r(n)}) \\
 &= U_i(D'_1=d_1, \dots, D'_l=d_l ; \theta_{r(i)}) \\
 &\text{where } i = \min(\{i : c_i \text{ is satisfied with } I_1=i_1 \wedge \dots \wedge I_k=i_k\})
 \end{aligned} \tag{5.7}$$

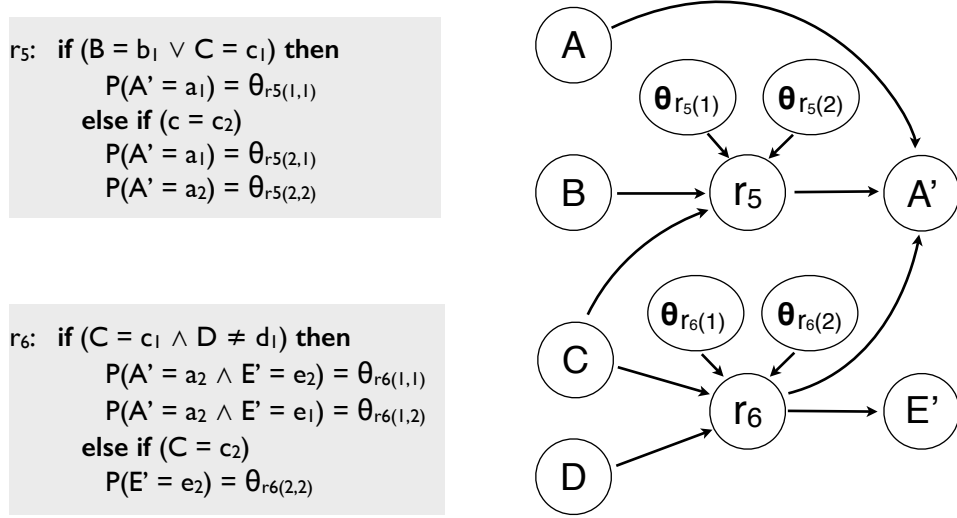


Figure 5.3: Example of instantiation for two parametrised probability rules r_5 and r_6 .

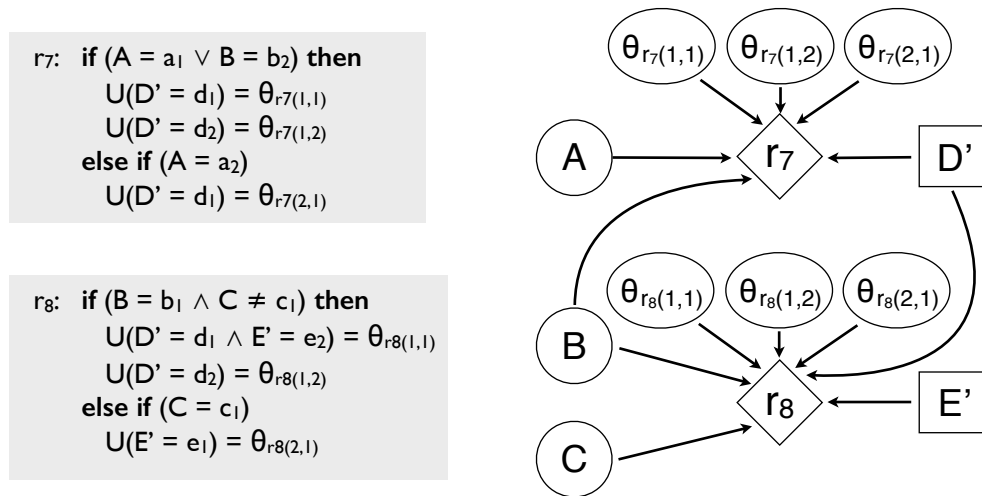


Figure 5.4: Example of instantiation for two parametrised utility rules r_7 and r_8 .

5.2 Supervised learning of rule parameters

Once the rule parameters are instantiated as nodes in the dialogue state, one can calculate their posterior distribution $P(\theta | \mathcal{D})$ after observing a particular data set \mathcal{D} using standard algorithms for probabilistic inference. The estimation of rule parameters corresponds to a learning problem with partial data (cf. Section 3.1.3), since some of the nodes in the dialogue state – such as rule nodes – are not directly observed. The posterior distribution $P(\theta | \mathcal{D})$ is thus no longer guaranteed to remain in the same distribution family as their prior distributions. The solution adopted here is to approximate the parameter distributions via sampling techniques. The estimation of rule parameters from data is practically achieved by cycling through the data sample one after the other and gradually refining the parameter distributions in the light of the observed values. We describe in the next pages the generic representation of the training data as well as the learning algorithm employed for the estimation of rule parameters.

5.2.1 Wizard-of-Oz training data

The focus of this section is on the estimation of rule parameters from a specific type of training data, namely Wizard-of-Oz interactions. Wizard-of-Oz interactions are interactions between human users and a dialogue system which is remotely controlled by a human expert “behind the curtains”. They constitute a simple and efficient method to collect realistic conversational behaviour for a particular domain in the absence of a fully implemented or optimised system.

Representation format

For the specific purpose of estimating the parameters of dialogue management models, we can represent Wizard-of-Oz interactions as a sequence of state–action pairs $\mathcal{D} = \{\langle \mathcal{B}_i, a_i \rangle : 1 \leq i \leq n\}$, where \mathcal{B}_i corresponds to the dialogue state at time i , and a_i is the associated action performed by the wizard. The number n corresponds to the total number of recorded actions. The dialogue state \mathcal{B}_i represents the current conversational situation at time i as it was perceived by the wizard. The dialogue state usually includes the recent dialogue history as well as important contextual features, and is expressed as a Bayesian network. Associated to each dialogue state is the corresponding action a_i selected by the wizard at that state. This action can be void if the wizard decides to take no action at that specific step in the dialogue.

Many conversational situations allow for multiple, equally “correct” system responses. This characteristic of verbal interactions carries over to the state–action pairs of Wizard-of-Oz data sets, as one can occasionally observe similar states mapped to different wizard actions. The wizard actions should therefore be viewed as an indication of good conversational behaviour, but do not constitute absolute gold standards in the traditional sense of being the uniquely appropriate output for a given dialogue state.

Assumptions about the wizard behaviour

The utilities of the system actions are never directly observed – the only data points available to the learning agent are the examples of wizard decisions in various situations. In order to infer the underlying utilities from these examples of decisions, one needs to make a few assumptions about the relation between the action utilities and the decisions made by the wizard.

Parameter estimation on Wizard-of-Oz data rests on the assumption that the wizard is an (approximately) rational agent and will tend to select actions that are deemed most useful in their respective dialogue state. The agent is only assumed to act rationally *given* the perceived (uncertain) dialogue state. The wizard must indeed act on the basis of “noisy” inputs – including e.g. speech recognition errors – and may as a consequence select suboptimal actions if the provided inputs contain erroneous hypotheses. It should therefore be stressed that the assumption of rationality does not equate to an assumption of omniscience on the part of the wizard. Furthermore, in order to account for the occasional errors and inconsistencies in the Wizard-of-Oz data set, the rationality of the wizard decisions is only assumed up to a certain level of confidence (as explained below).

In practice, the posited rationality of the wizard implies that the likelihood $P_{\mathcal{B}_i}(a_i; \theta)$ of a wizard action a_i in a dialogue state \mathcal{B}_i under the parameters θ will depend on the utility of action a_i in \mathcal{B}_i relative to other possible actions. We now formalise this definition of the likelihood.

5.2.2 Learning cycle

The goal of the learning process is to estimate the posterior distribution $P(\theta | \mathcal{D})$ over the rule parameters given the collected Wizard-of-Oz data set \mathcal{D} . The procedure operates in an incremental fashion by traversing the state–action pairs one by one (in a single pass) and updating the posterior parameter distributions after each pair.

Likelihood distribution

One key element of the estimation procedure is the definition of the probability $P_{\mathcal{B}_i}(a_i; \theta)$, which specifies the likelihood of the wizard action a_i in a dialogue state \mathcal{B}_i given the parameters θ . The intuitive purpose of this likelihood is to favour the parameter values that provide a good fit for the wizard action choices. In practice, this is achieved by representing the likelihood of the wizard action a_i in terms of the relative utility of action a_i compared to alternative action choices. The first step is to calculate the utility $U_{\mathcal{B}_i}(a; \theta)$ for all possible actions a , and to subsequently rank the actions in descending order of utility. As the wizard is presupposed to act rationally (modulo a small probability of error), the wizard action is expected to appear at the top of this ranked list of actions. Formally, we express the likelihood of action a_i given the parameters θ as:

$$\begin{aligned}
 P_{\mathcal{B}_i}(a_i; \theta) &= \begin{cases} \eta p & \text{if } a_i \text{ is the action with highest utility given } \theta \\ \eta(1-p)p & \text{if } a_i \text{ is the second-highest action} \\ \eta(1-p)^2 p & \text{if } a_i \text{ is the third-highest action} \\ \dots & \end{cases} \\
 &= \eta(1-p)^{x-1} p \quad \text{where } x \text{ is the position of action } a_i \text{ in the ranked list of actions}
 \end{aligned} \tag{5.8}$$

The η factor in Eq. (5.8) represents as usual the normalisation factor, while the probability p represents the learner confidence in the rationality of the wizard. A value $p = 0.7$ will hence indicate that the wizard is assumed to act rationally – and thus select the highest-utility action – with probability 0.7. The probability p indirectly defines the learning rate of the estimation process: The higher the probability, the faster the learner will converge to a policy that imitates the wizard

actions. However, a high value for p also renders the learner more vulnerable to the occasional errors and inconsistencies on the part of the wizard.

The probability distribution represented by Equation (5.8) is a particular instance of a *geometric* distribution.³ Given a repetition of Bernoulli trials with a probability of success p , the geometric distribution describes the probability $P(n)$ that the first success will be observed at the n -th trial.

The reliance on geometric distributions to formalise the likelihood is motivated by the posited rationality of the wizard decisions. In other words, the formalisation is grounded in the assumption that the wizard will select the highest utility action with probability p , the second-highest action with probability $(1 - p)p$, and so forth. The geometric distribution is monotonically decreasing, which ensures that the probability of a high-utility action will always be higher than its lower-utility alternatives.

Figure 5.5 illustrates a geometric distribution over four action values $[a_1, a_2, a_3, a_4]$ ranked according to their estimated utility – that is, $U_{\mathcal{B}_i}(a_1; \theta) > U_{\mathcal{B}_i}(a_2; \theta) > U_{\mathcal{B}_i}(a_3; \theta) > U_{\mathcal{B}_i}(a_4; \theta)$.

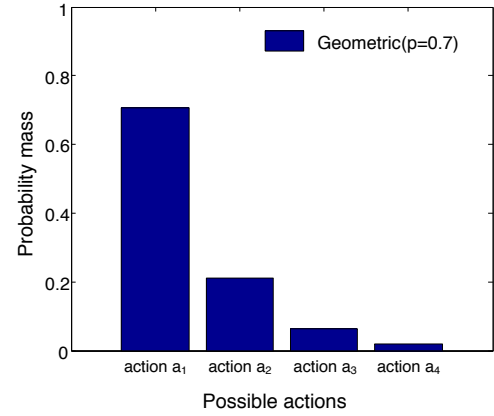


Figure 5.5: Distribution $P_{\mathcal{B}_i}(a_i; \theta)$ for four action values $[a_1, a_2, a_3, a_4]$ ranked by decreasing utility, with $p = 0.7$.

Posterior parameter distribution

Given the aforementioned likelihood distribution, the posterior distribution over the parameters is defined via Bayes' rule:

$$P_{\mathcal{B}_i}(\theta | a_i) = \eta P_{\mathcal{B}_i}(a_i; \theta) P(\theta) \quad (5.9)$$

The factor η is used for normalisation. The calculation of this posterior distribution is a non-trivial inference problem as the probabilistic model contains both continuous and discrete random variables. This inference problem can be solved in two separate manners:

- The first strategy is to discretise the range of parameter values into distinct, mutually exclusive buckets, and thereby transform continuous variables into discrete variables, with a number of values equivalent to the number of buckets employed for the discretisation.
- The second strategy is to retain the continuous nature of the parameters, but approximate the inference process through the use of sampling techniques.

Although both solutions are implemented in the OpenDial toolkit (see Chapter 7), sampling techniques such as likelihood weighting have in practice proved to be more efficient and scalable than discretisation.

³Technically speaking, the definition in Equation (5.8) corresponds to a truncated version of the geometric distribution, as the support of the distribution is finite (the number of possible actions is bounded). The reduction of the distribution to a finite support is achieved via the normalisation factor η .

After sampling, the full joint distribution $P_{\mathcal{B}_i}(\boldsymbol{\theta} | a_i)$ is factored into its individual parameter variables. This factorisation corresponds to a simplifying assumption as parameter independence is theoretically no longer guaranteed when handling partially observed data.

Representation of the posterior

The result of the posterior calculation in Equation (5.9) is a collection of sampled values. In order to derive a full probability density function from these samples, one can either follow a so-called parametric approach and seek to reconstruct the underlying parametric distributions (such as Gaussian or Dirichlet distributions) that best fit the data, or adopt a non-parametric strategy and directly represent the posterior as a function of the collected samples. Parametric approaches, albeit interesting, are difficult to apply in this setting, for two main reasons:

1. The distribution family of the posterior is hard to determine, as the posterior is no longer ensured to remain in the same family as the prior when learning from partial data.
2. Additionally, fitting multivariate distributions such as Dirichlets based on sampled values is a laborious computational problem with no closed-form solutions.⁴

We have consequently adopted a non-parametric representation of the posterior distributions, based on *kernel density estimation* (KDE). The kernel density estimator for a continuous variable X for which a set of samples x_1, \dots, x_n is available is given by:

$$P(x) = \frac{1}{nh} \sum_{i=1}^n K\left(\frac{x - x_i}{h}\right) \quad (5.10)$$

where $K(\cdot)$ is a *kernel function* and h is a smoothing parameter called the *bandwidth*. Multiple kernel functions can be used, but a common choice is to adopt a Gaussian kernel. The kernel density estimator corresponds in this case to a combination of n Gaussians, where each Gaussian is centred on a sample point x_i . This combination of Gaussians is smoothed proportionally to the bandwidth parameter. Figure 5.6 illustrates the use of kernel density estimation for a continuous variable based on a set of 50 samples and a Gaussian kernel. The figure shows the influence of the bandwidth parameter on the shape of the resulting density function. Kernel density estimators do not necessitate any particular assumption about the nature of the underlying distribution, and are therefore well-suited to represent distributions of indeterminate type – as is the case for posterior distributions over the parameters of probabilistic rules.

Multivariate distributions are encoded with a multivariate extension of KDE based on product kernels (Silverman, 1986). All estimators in our experiments employ Gaussian kernels with a bandwidth tuned from the sample variance using Silverman’s rule of thumb (Silverman, 1986).

Learning algorithm

Algorithm 11 presents the general procedure for estimating model parameters from Wizard-of-Oz data. The algorithm loops on each instance pair in the training data. The posterior parameter distribution is estimated via sampling, based on the likelihood of the wizard action (line 4). The

⁴Numerical methods based on fixed-point and Newton-Raphson iterations do exist, however (Minka, 2003).

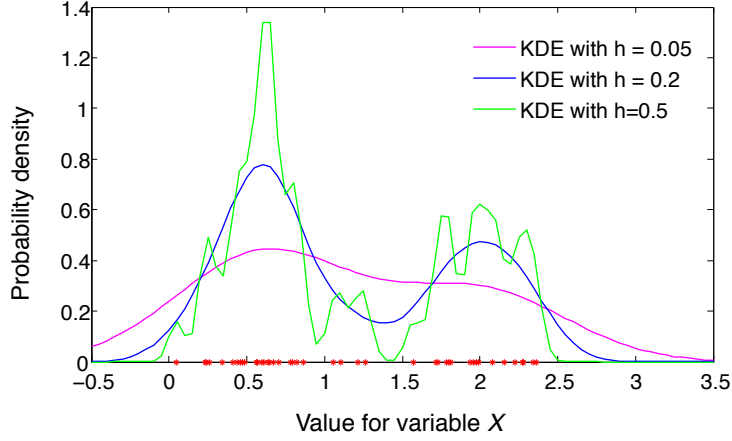


Figure 5.6: Kernel density estimators (KDEs) for a continuous variable X based on 50 samples (shown on the X axis). The density function is shown for three possible bandwidths h .

individual posterior distributions for each parameter are then reconstructed via kernel density estimation on the sampled values (line 5-7), and the process is repeated.

Algorithm 11 : WoZ-LEARNING ($\mathcal{M}, \theta, \mathcal{D}, N$)

Input: Rule-structured models \mathcal{M} for the domain

Input: Model parameters θ with prior distribution $P(\theta)$

Input: Wizard-of-Oz data set $\mathcal{D} = \{\langle \mathcal{B}_i, a_i \rangle : 1 \leq i \leq n\}$

Input: Number N of samples to draw for each learning example

Output: Posterior distribution $P(\theta \mid \mathcal{D})$ for the parameters

- 1: **for all** $\langle \mathcal{B}_i, a_i \rangle \in \mathcal{D}$ **do**
 - 2: Set $\mathcal{B}_i \leftarrow \mathcal{B}_i \cup \theta$
 - 3: Trigger models \mathcal{M} on \mathcal{B}_i (cf. Section 4.4)
 - 4: Draw N samples $\mathbf{x}_1, \dots, \mathbf{x}_N$ from posterior $P_{\mathcal{B}_i}(\theta \mid a_i) = \eta P_{\mathcal{B}_i}(a_i; \theta) P(\theta)$
 - 5: **for all** parameter variable $\theta \in \theta$ **do**
 - 6: Set $P(\theta) \leftarrow \text{KDE}(\mathbf{x}_1(\theta), \dots, \mathbf{x}_N(\theta))$
 - 7: **end for**
 - 8: **end for**
 - 9: **return** $P(\theta)$
-

5.3 Experiments

We evaluated the learning approach outlined in this chapter in the context of a dialogue policy learning task for a human–robot interaction scenario. The goal of the experiment, originally presented in Lison (2012d), was to evaluate whether the parameters of a rule-structured utility model could be efficiently optimised from small amounts of Wizard-of-Oz data. The evaluation metric was defined in this experiment as the proportion of actions corresponding to the wizard selections. The rule-structured model was compared to two baselines encoding the action utilities via traditional representations (plain utility tables and linear functions, respectively).

It should be stressed that the purpose of the experiment is limited to the evaluation of the *learning performance* of the model. The evaluation of the approach in terms of e.g. qualitative and quantitative metrics of interaction success (and user satisfaction) constitutes an important but separate question, which will be addressed in Chapter 8.

We first describe in this section the dialogue domain employed for the experiment, after which we detail the data collection procedure and experimental setup, and finally present and analyse the empirical results.

5.3.1 Dialogue domain

The scenario for the Wizard-of-Oz experiment involved a human user and a Nao robot (nicknamed “Lenny”), which is a programmable humanoid robot developed by Aldebaran Robotics. Figure 5.7 shows a human user interacting with the robot during a data collection experiment.

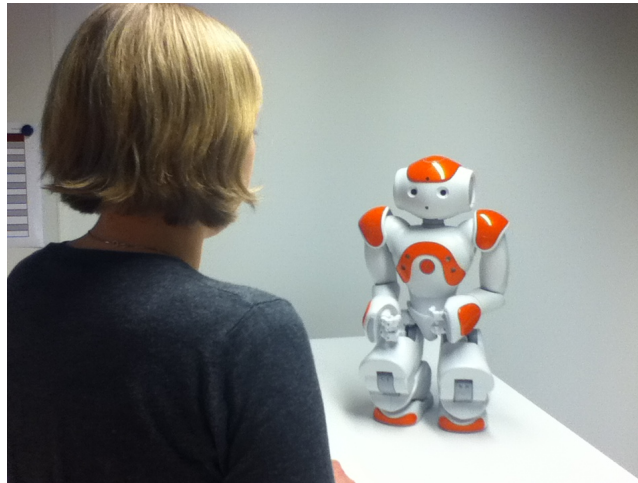


Figure 5.7: Human user interacting with the Nao robot during the Wizard-of-Oz data collection.

The users were instructed to teach the robot a sequence of body movements such as lifting arms, stepping forward, backward, kneeling down, etc. The movements could be performed either in consecutive order or in parallel (provided the movements were not in conflict). The users were free to decide on the movements to perform, and communicated their intention using spoken commands (no gesture recognition was involved). The robot was programmed to memorise the instructed sequence and could “replay” it at any time.

The list of possible dialogue acts for the user is shown in Table 5.1, and includes a total of 15 dialogue act templates (expanding into 40 dialogue acts when counting all possible instantiations of the arguments). The set of user dialogue acts contains both task-specific dialogue moves to convey user commands as well as conversational actions for feedbacks, acknowledgements, corrections and engagement. To respond to these user inputs, the robot/wizard had at its disposal a repository of 11 possible actions (expanding into 40 alternative actions when counting all possible instantiations). The actions included both physical and verbal actions. The verbal actions available to the system comprised various types of clarification requests and grounding acts. The list of system actions is given in Table 5.2.

· MoveArm(x, y) where $x = \{\text{Left, Right, Both}\}$ and $y = \{\text{Up, Down, Lateral, Forward, Folded}\}$	· SitDown
· MoveHead(y) where $y = \{\text{Up, Left, Down, Right}\}$	· DoMovements(y) where $y = \{\text{InParallel, InSequence}\}$
· MoveFoot(x, y) where $x = \{\text{Left, Right}\}$ and $y = \{\text{Forward, Backward}\}$	· RepeatAll
· Turn(y) where $y = \{\text{Left, Right}\}$	· ForgetAll
· Kneel	· Confirm
· StandUp	· Disconfirm
	· Say(x) where $x = \{\text{Hello, Compliment, ThankYou, Goodbye}\}$
	· GoToInitPose
	· Stop

Table 5.1: List of user actions a_u .

· Demonstrate(z) where $z = \{\text{MoveArm}(x, y), \text{MoveHead}(y), \text{Kneel}, \text{StandUp}, \text{SitDown}, \text{MoveFoot}(x, y), \text{Turn}(y)\}$ and x, y take the same values as for the user actions	· AskConfirm
· Say(x) where $x = \{\text{Hello, ThankYou, Goodbye}\}$	· RegisterMove
	· UndoMove
	· AskRepeat
	· Acknowledgement
	· AskIntention
	· DemonstrateAll
	· ForgetAll
	· StopMove

Table 5.2: List of system actions a_m .

5.3.2 Wizard-of-Oz data collection

System architecture

An integrated dialogue system was developed to collect Wizard-of-Oz interactions for the human–robot interaction domain described above. The dialogue system used to collect the Wizard-of-Oz data is equipped with all standard processing modules for speech understanding, generation and robot control. Figure 5.8 illustrates the general system architecture and its connection to the robotic platform. At the centre of the architecture lies a shared dialogue state to which multiple system components are attached. These components monitor the dialogue state for relevant changes and read/write to it as they process their data flow. The dialogue manager is replaced by the wizard during data collection.

The modules used for the experiments include in particular an off-the-shelf speech recogniser connected to four microphones placed on the robot head. The language model of the speech recogniser is encoded with a small hand-crafted recognition grammar shown in Table 5.3.

The user dialogue acts are then derived from the ASR hypotheses via a template-based model. On the generation side, a shallow generation model is in charge of the linguistic realisation of the verbal actions which is then sent to the speech synthesis engine. Finally, the execution of physical

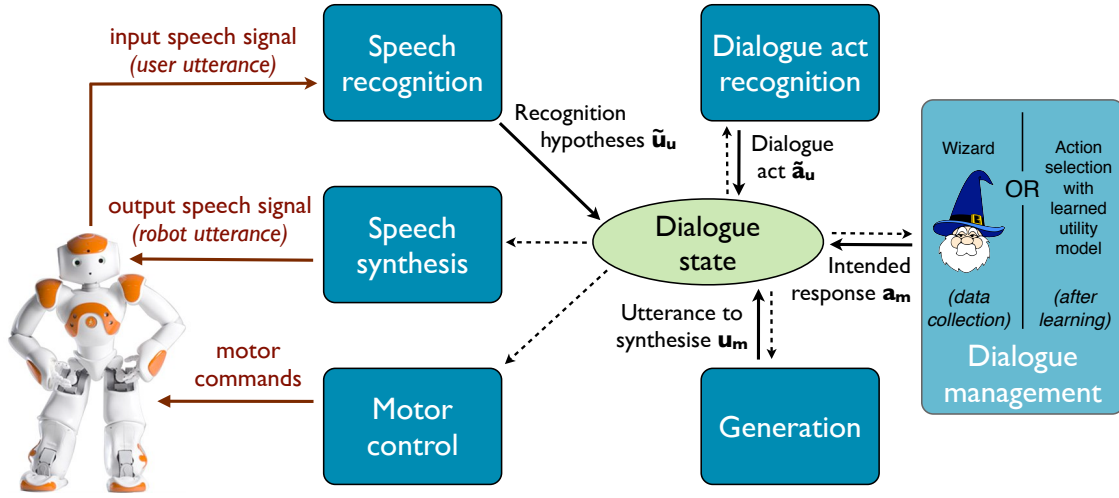


Figure 5.8: System architecture used for the experiment.

$\langle \text{TopRule} \rangle$::= $\langle \text{Movement} \rangle \langle \text{Timing} \rangle? \langle \text{Grounding} \rangle \langle \text{Engagement} \rangle \langle \text{Sequence} \rangle \text{stop}$
$\langle \text{Movement} \rangle$::= $\langle \text{ArmMove} \rangle \langle \text{HeadMove} \rangle \langle \text{FootMove} \rangle \langle \text{OtherMove} \rangle$
$\langle \text{ArmMove} \rangle$::= $(\text{lift} \text{move} \text{lower} \text{raise} \text{fold}) \langle \text{Arm} \rangle (\text{move} \text{put}) \langle \text{Arm} \rangle \langle \text{ArmDirection} \rangle \text{move} \langle \text{ArmDirection} \rangle \langle \text{Arm} \rangle$
$\langle \text{Arm} \rangle$::= $(\text{the} \text{your}) (\text{left} \text{right}) \text{arm} \text{both arms}$
$\langle \text{ArmDirection} \rangle$::= $\text{up} \text{down} \text{forward} \text{in front of you} \text{to the side} \text{laterally}$
$\langle \text{HeadMove} \rangle$::= $\text{move} (\text{the} \text{your}) \text{head} (\text{to the} (\text{left} \text{right}) \text{up} \text{down})$
$\langle \text{FootMove} \rangle$::= $(\text{do one})? \text{step} \langle \text{FootDirection} \rangle \text{move} \langle \text{Foot} \rangle \langle \text{FootDirection} \rangle$
$\langle \text{FootDirection} \rangle$::= $\text{forward} \text{forwards} \text{backward} \text{backwards}$
$\langle \text{Foot} \rangle$::= $(\text{the} \text{your}) (\text{left} \text{right}) \text{foot}$
$\langle \text{OtherMove} \rangle$::= $\text{go back to initial position} \text{kneel} \text{sit down} \text{stand up} \text{turn} (\text{left} \text{right})$
$\langle \text{Sequence} \rangle$::= $\text{repeat} (\text{all} \text{everything} \text{from the start}) \text{forget everything}$
$\langle \text{Timing} \rangle$::= $\text{in parallel} \text{at the same time} \text{in sequence} \text{after that} \text{at the end}$
$\langle \text{Grounding} \rangle$::= $\text{yes} \text{sure} \text{ok} \text{correct} \text{exactly} \text{no} \text{wrong} \text{thanks} \text{thank you} \text{great}$
$\langle \text{Engagement} \rangle$::= $\text{hello (Lenny)?} \text{goodbye (Lenny)?}$

Table 5.3: Speech recognition grammar (in Bachus-Naur form) employed for the experiment.

actions is delegated to a separate component, responsible for planning the robot movements and controlling its motors in real-time. Chapter 7 discusses in more detail the architectural design of the dialogue system as well as the configuration of each component.

Data collection procedure

Each recorded dialogue involved one human subject interacting with the Nao robot in a shared visual scene. The dialogues were relatively short, with an average duration of about four minutes. We collected a total of 20 interactions with 7 distinct users, for a total of 1020 system turns, summing to around one hour of interaction. The users were recruited amongst students and researchers in the Department of Informatics at the University of Oslo, while the role of the wizard was taken by the author of the present thesis. All the interactions were performed in English. All but one user were non-native speakers of English.⁵ As the speech recogniser relied on a language model of limited coverage, the users were briefed before each experiment about the comprehension capabilities of the robot in order to adjust their expectations about what the robot could and could not understand, and thereby limit the number of out-of-coverage utterances.

Wizard-of-Oz experiments should ideally place the wizard in the same types of decision contexts as the ones encountered by the dialogue manager. To this end, the wizard was prevented from listening directly to the spoken utterances of the user and was instead provided with the N-best list generated by the speech recogniser. The N-best lists appeared on the control screen of the wizard as hypotheses accompanied with their respective probabilities. On the basis of these inputs, the wizard could then select the action to perform from a list of alternatives.

Transcripts 1 and 2 present two recorded excerpts of Wizard-of-Oz interactions. The user utterances are displayed as N-best lists of speech recognition hypotheses.

Dialogue state

Each selected action a_m was recorded along with the complete dialogue state \mathcal{B} in effect at the time of the selection. The dialogue state consisted of five independent variables:

1. The last user dialogue act a_u (with the values given in Table 5.1)
2. The last system action a_m (with the values given in Table 5.2)
3. The recorded sequence of (confirmed) movements, encoded as a list
4. The last physical movement demonstrated by the robot
5. Finally, a periodically updated variable expressing the number of seconds elapsed since the last user or system action. This variable is used to determine when the system should ask for an explicit confirmation from the user.

The state variables are represented with their full probability distributions. The dialogue state recorded right before the registration of the first movement in Transcript 1 corresponds for instance

⁵This mismatch between the acoustic model trained on native U.S. English data and the foreign accents of the participants may partly explain the relatively high level of speech recognition errors.

Transcript 1 User interaction with wizard-controlled robot, first excerpt

HUMAN: $\begin{bmatrix} \text{hello Lenny} & 0.22 \\ \text{follow me} & 0.20 \\ \text{hi Lenny} & 0.53 \end{bmatrix}$

ROBOT: Hello there!

HUMAN: $\begin{bmatrix} \text{move your left arm up} & 0.41 \\ \text{move the left arm up} & 0.27 \\ \text{put your left arm up} & 0.30 \end{bmatrix}$

ROBOT: Sure!

[ROBOT *executes the movement* MoveArm(Left, Up)]

[ROBOT *waits a few seconds*]

ROBOT: Was that correct?

HUMAN: $\begin{bmatrix} \text{yes} & 0.88 \\ \text{thanks} & 0.10 \end{bmatrix}$

[ROBOT *registers the movement as confirmed*]

ROBOT: Great

HUMAN: $\begin{bmatrix} \text{move your right arm up at the same time} & 0.26 \\ \text{put the right arm up at the same time} & 0.32 \\ \text{move the right arm up at the same time} & 0.38 \end{bmatrix}$

ROBOT: Let's see

[ROBOT *executes movement* MoveArm(Both, Up)]

ROBOT: Was that correct?

HUMAN: $\begin{bmatrix} \text{kneel} & 0.25 \\ \text{thanks} & 0.14 \\ \text{no} & 0.57 \end{bmatrix}$

[ROBOT *discards last movement and goes back to previous position*]

ROBOT: What should I do then?

[...]

[...]

HUMAN: $\begin{bmatrix} \text{stop} & 0.25 \\ \text{stand up} & 0.41 \\ \text{no} & 0.25 \end{bmatrix}$

ROBOT: Let's see

[ROBOT *executes movement* StandUp]

HUMAN: $\begin{bmatrix} \text{put your right arm forward} & 0.31 \\ \text{move your right arm forward} & 0.36 \\ \text{move the right arm forward} & 0.30 \end{bmatrix}$

ROBOT: Let's see

[ROBOT *registers movement* StandUp *as implicitly confirmed*]

[ROBOT *executes movement* MoveArm(Right, Forward)]

HUMAN: $\begin{bmatrix} \text{move forward the left arm} & 0.31 \\ \text{lower the left arm} & 0.35 \\ \text{lower both arms} & 0.29 \end{bmatrix}$

ROBOT: Sorry, could you repeat?

HUMAN: $\begin{bmatrix} \text{raise your left arm} & 0.28 \\ \text{lift your right arm} & 0.31 \\ \text{lift your left arm} & 0.37 \end{bmatrix}$

ROBOT: Sure

[ROBOT *executes movement* MoveArm(Left, Up)]

[ROBOT *waits a few seconds*]

ROBOT: Should I do it like this?

HUMAN: $\begin{bmatrix} \text{kneel} & 0.23 \\ \text{wrong} & 0.22 \\ \text{no} & 0.47 \end{bmatrix}$

[ROBOT *discards last movement and goes back to previous position*]

ROBOT: What should I do then?

HUMAN: $\begin{bmatrix} \text{move your left arm up} & 0.29 \\ \text{move the left arm up} & 0.34 \\ \text{move the left arm down} & 0.28 \end{bmatrix}$

[...]

to the following specification:

$$\mathcal{B} = \begin{cases} a_u = [(\text{Confirm}, p=0.88), (\text{Say}(\text{ThankYou}), p=0.10), (\text{None}, p=0.02)] \\ a_m = \langle (\text{AskConfirm}, p=1) \rangle \\ \text{moveSequence} = [(\emptyset, p=1)] \\ \text{lastMove} = [(\text{MoveArm}(\text{Left}, \text{Up}), p=1)] \\ \text{silence} = [(2 \text{ seconds}, p=1)] \end{cases}$$

5.3.3 Experimental setup

The central question investigated in this experiment is the following: Does the encoding of dialogue management models in terms of probabilistic rules improve the efficiency of the parameter estimation process compared to more traditional representations? If yes, how significant is the difference? The experiment focused therefore on the learning performance of two competing utility models based on limited amounts of training data gathered from Wizard-of-Oz interactions. The parameters correspond here to the utilities of the various system actions depending on the current state.

Baseline models

The experiment relied on two distinct baselines that express the utility model of the domain via traditional representations:

1. The first baseline is a plain utility table that maps every combination of state values and actions to a particular utility. For a set of state variables X_1, \dots, X_n , the utility for the system action a'_m is therefore defined by:

$$U(a'_m \mid X_1=x_1, \dots, X_n=x_n) = \theta_{a'_m(x_1, \dots, x_n)} \quad (5.11)$$

where the $\theta_{a'_m(x_1, \dots, x_n)}$ value corresponds to the utility encoded in the table for the state-action pair. The number of required parameters is thus $|Val(X_1)| \times \dots \times |Val(X_n)| \times |Val(a'_m)|$. In order to keep the model tractable, the utility table was factored in the experiments in three parts, each responsible for a subset of the possible system actions. These utility tables comprised a total of 8962 independent parameters.

2. The second baseline defines the utility of a given action as a linear combination of values – one for each state variable. The total utility is thus determined as:

$$U(a'_m \mid X_1=x_1, \dots, X_n=x_n) = \sum_{i=1}^n \theta_{a'_m(x_i)} \quad (5.12)$$

where $\theta_{a'_m(x_i)}$ corresponds to the utility weight of the variable value x_i for the action a'_m . Note that the weights are specific to a given action value. The number of required parameters is here $|Val(a'_m)| \times (|Val(X_1)| + \dots + |Val(X_n)|)$. As a consequence, the size of the linear model is reduced to 581 independent parameters. However, this baseline hinges on the

assumption that the total utility of a given action can be decomposed as a linear combination of weights for each state variable value.

Rule-structured model

The two baselines were compared to a utility model structured with 15 utility rules. The interested reader is invited to browse the specification of these rules in Appendix B (Section B.1). The rule structure was designed by hand, while the parameters (in this case, the utility values) remained unknown. The rules were associated with a total of 24 parameters.

Parameter estimation

Figure 5.9 offers a graphical comparison of the utility models produced for the two baselines and the rule-structured approach. The two baselines are essentially “flattened” or unstructured versions of the rule-based model. The input and output variables remain identical in all three models. However, the two baselines directly associate each state–action combination to a single utility value, while the rule-structured approach defines this overall utility in a more indirect manner, through the instantiation of multiple utility rules.

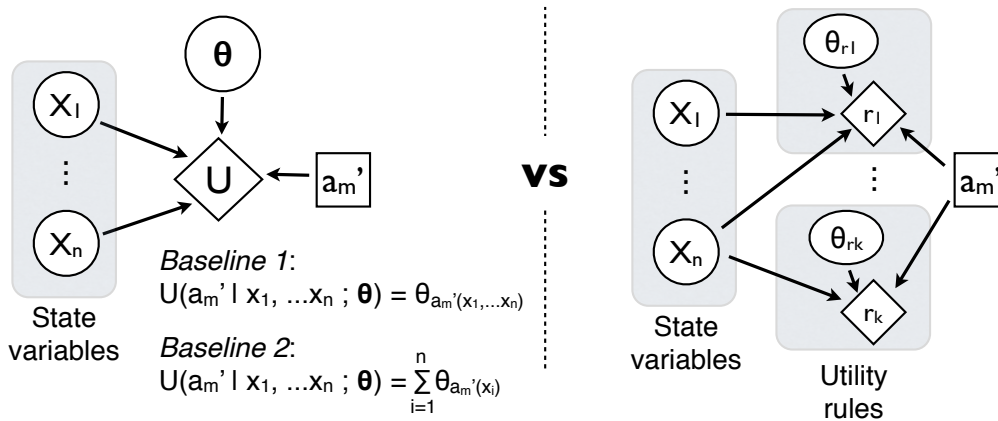


Figure 5.9: Baseline utility models (left) compared to the rule-structured utility model (right).

The parameter estimation procedure followed the Bayesian learning approach detailed in Section 5.2.2. The prior distributions on the utility values were initialised with uniform priors on the interval $[-1, 6]$ in all three utility models.

Evaluation of learning performance

Given the utility models defined above, the selected action simply corresponds to the action associated with the maximum utility in the current state. In this particular experiment, utility maximisation only considered the current (immediate) utility and did not perform forward planning.

The data collected from the Wizard-of-Oz interactions was split into a training set composed of 765 state–action pairs (75 % of the gathered data) and a held-out test set with 255 actions (remaining 25 %). The same training set was used to estimate the utility parameters for the three models. The resulting utility models were then evaluated on the basis of their agreement with the wizard actions in the held-out test set. This agreement is determined to be the proportion of

system-selected actions that are identical to the action chosen by the wizard. The agreement results for the three models were evaluated at regular intervals in the course of the estimation process. The results were practically calculated by sampling over the parameters, performing inference over the resulting models, and finally averaging over the inference results.

5.3.4 Empirical results and analysis

Table 5.4 presents the agreement results for the three utility models. The differences between the rule-structured model and the two baselines are statistically significant using Bonferroni-corrected paired t -tests, with p -value < 0.0001 .

We performed an error analysis on the 17% of actions that deviate from the wizard behaviour.⁶ The analysis revealed that the discrepancy is mainly due to two factors. The first factor is the lack of complete consistency on the part of the wizard, who occasionally decided to follow different strategies in similar situations (especially regarding the use of clarification requests). The second factor is the presence of a non-negligible number of spurious and noisy data points, notably caused by interruptions and technical issues with the robotic platform (e.g. movements that had to be repeated due to motor failures).

<i>Type of model</i>	<i>Agreement (in %)</i>
Plain utility table	67.35
Linear model	61.85
Rule-structured model	82.82

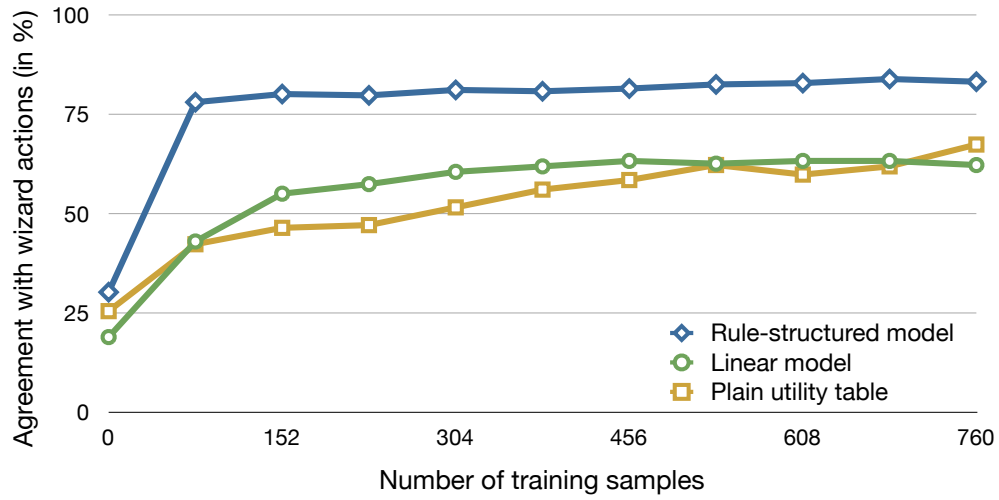
Table 5.4: Agreement results for the three models on a held-out test set.

The learning curves for the three models are shown in Figure 5.10. Note that since the parameters are initially uniformly distributed, the agreement is already non-zero before learning, since a random assignment of parameters has a low but non-zero chance of leading to the right action.

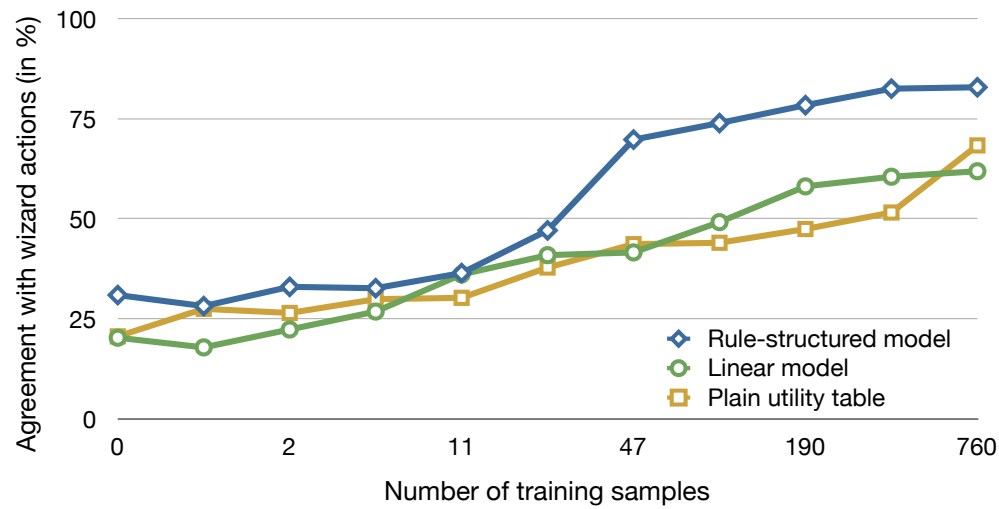
Thanks to its considerably reduced number of parameters, the rule-structured model is able to converge to a high-quality policy after observing only a small fraction of the training set. The incorporation of domain knowledge via the rule structure has a clearly beneficial effect on the learning performance and on the generalisation capacity of the model. As the figure shows, the two baseline models do also improve their accuracies over time, but at a much slower rate. The linear model is comparatively faster than the plain model, but levels off towards the end. The suboptimal learning performance of the linear model is most likely due to the non-linearity of some dialogue strategies. The plain model continues its convergence and would probably reach an agreement level similar to the rule-structured model if given much larger amounts of training data.

The learning results are in line with our expectations based on the respective sizes of the parameter space for the three utility models, and are not *per se* highly surprising. The main lesson to draw from this experiment is, however, not the exact difference in agreement or learning rates for each particular model, but the demonstration that probabilistic rules can be successfully applied to

⁶One should be wary of labelling these actions as “incorrect”, since they are in most cases relevant dialogue moves, but simply result from slightly different decision strategies than the one followed by the wizard.



(a) Linear scale



(b) Logarithmic scale (base 2)

Figure 5.10: Learning curves for the three utility models on the test set as a function of the number of processed data points. The agreement results are given for the plain, linear and rule-structured utility models, using both linear (top) and logarithmic scales (bottom).

structure a small but non-trivial dialogue domain and derive its parameters from collected interaction data. Through the use of abstraction mechanisms such as partitioning and quantification, the experiment shows that the utility rules specified for the domain can cover large regions of the problem space without degrading the accuracy of the model. The utility model can hence be optimised with only modest amounts of in-domain data.

5.4 Conclusion

The present chapter has described how parameters could be included in the specification of probabilistic rules and estimated via Bayesian learning techniques. Rule parameters can represent either probability or utility values. The estimation process operates by calculating posterior probability distributions over possible parameter values given the observed data set. The process is initiated with prior distributions such as Dirichlet priors for probability values and Gaussian or uniform priors for utilities.

The main focus of the chapter was on supervised learning of rule parameters based on Wizard-of-Oz training data. We described how Wizard-of-Oz data can be practically collected and processed to yield data points encoded as pairs $\langle \text{dialogue state } \mathcal{B}_i, \text{ wizard action } a_i \rangle$. These data points are used to progressively narrow down the spread of the posterior distributions to the values that provide the best fit for the observed wizard actions.

This learning approach has been implemented in an end-to-end spoken dialogue system for human–robot interaction and validated in a proof-of-concept experiment. The goal of the experiment was to estimate the utility values of various actions on the basis of a Wizard-of-Oz data set. Three utility models were compared: a plain utility table, a linear model, and a model structured with utility rules. The analysis of the empirical results shows that the rule-structured model outperforms the two baselines in regards to learning rate and generalisation performance with limited amounts of training data.

The outcome of the experiment corroborates one of the central claims of this thesis – namely, that hybrid approaches to dialogue modelling (and in particular the formalism of probabilistic rules developed in this thesis) are well suited to model dialogue domains that must simultaneously confront high levels of uncertainty and limited availability of in-domain dialogue data. In such situations, which are commonplace in the field of spoken dialogue systems, neither purely symbolic nor purely data-driven approaches are alone sufficient to harness the complex and stochastic nature of the interactions. Hybrid approaches to dialogue modelling provide ways to combine expert knowledge and statistically optimised parameters in a single, unified framework, thereby allowing the domain models to be tuned from even small amounts of training data.

As shown in the experiments, Wizard-of-Oz interaction data can be a useful and interesting source of domain knowledge for the estimation of probabilistic models of dialogue. The data collection procedure can, however, be a tedious endeavour, as it requires:

1. The availability of an expert (the wizard) that can control the system and provide examples of appropriate behaviour for the domain.
2. The technical setup of a Wizard-of-Oz environment from which the wizard can perceive the user inputs, monitor contextual features, select possible actions to execute, and get all relevant information recorded and stored in a generic format.

A natural alternative to supervised learning from Wizard-of-Oz data is to let the dialogue system learn the best conversational behaviour via trial and error from its own interaction experience (that is, through reinforcement learning), without relying on the provision of external examples. The next chapter demonstrates how such a strategy can be practically implemented, based once again on the formalism of probabilistic rules.

Chapter 6

Learning from interactions

This chapter extends the parameter estimation approach developed in the previous chapter to a reinforcement learning context. As explained in the first part of this thesis, a reinforcement learning agent learns how to act through a process of trial and error in a given environment. In our case, the environment is represented by verbal interactions with human users, and the system behaviour to learn corresponds to dialogue policies mapping dialogue states to relevant system responses.

The optimisation process is in many respects similar to the one already outlined in the previous chapter. Bayesian inference remains the basic instrument for updating distributions over the model parameters on account of the collected evidence. However, the evidence is no longer represented by examples of expert behaviour as in supervised learning. The learning agent instead actively gathers experience through repeated interactions with (real or simulated) users, and receives feedback on its actions in the form of new observations and rewards. The parameter distributions are gradually refined on the basis of this feedback and subsequently employed to select the next actions to execute. As we shall see in this chapter, the use of probabilistic rules helps the learning agent to escape the “curse of dimensionality” that often characterises dialogue domains. As a consequence, the number of interactions required for the optimisation can be greatly reduced.

The chapter is divided in three sections. After a survey of the core concepts of Bayesian reinforcement learning in Section 6.1, we define in Section 6.2 our own reinforcement learning approach to the estimation of rule parameters. More specifically, we present how the parameters of probabilistic rules can be automatically optimised from interactions using either model-based or model-free strategies. Finally, Section 6.3 reports on a learning experiment carried out in a human–robot interaction domain. The purpose of the experiment was to analyse the performance of rule-structured models compared to standard factored distributions. Empirical results on a simulator indicate that rule-structured models can converge to near-optimal parameters – and hence achieve higher returns – in a much shorter time than unstructured representations.

6.1 Bayesian reinforcement learning

Bayesian reinforcement learning has recently emerged as a generic framework for learning and acting in uncertain environments (Poupart and Vlassis, 2008; Ross et al., 2011; Vlassis et al., 2012). As in other types of Bayesian learning methods, the core idea of Bayesian reinforcement learning is to maintain explicit probability distributions over the domain parameters and gradually narrow down the spread of these distributions as more experience is collected. However, in contrast to

supervised approaches, the learning agent is no longer a mere passive observer in the interaction, as it must actively decide how to act after each turn in order to move the interaction forward.

As explained in Section 3.2, the actions selected by the agent must strike a balance between exploration (trying out new actions) and exploitation (preferring actions that are most likely to yield higher rewards). Bayesian reinforcement learning can offer principled solutions to the exploration–exploitation dilemma, as model uncertainty is explicitly accounted for in the action selection process (Duff, 2002; Ross et al., 2011). A Bayesian agent will therefore select actions that are expected to provide the highest long-term return given the current model uncertainty. When the uncertainty is high, information-gathering actions are preferred since they lead to a better understanding of the environment dynamics and are therefore more likely to result in higher future rewards. This inclination to explore gradually fades away as the learning agent develops a better grasp of its domain and becomes more confident about the relative merits of its own actions.

As for other families of reinforcement learning methods, Bayesian reinforcement learning can be divided in model-based and model-free methods.

Model-based methods

Model-based methods estimate an explicit model of the domain in the form of transition, observation and reward models. One advantage of model-based approaches is the relative simplicity of parameter estimation, as the model parameters can be directly updated upon the reception of each observation and reward using standard Bayesian inference. The policy is, however, complex to optimise, due to the combination of three types of uncertainty: state uncertainty, stochastic action effects, and model uncertainty. The result is an augmented POMDP where the state also includes random variables expressing the model parameters in addition to traditional state variables (Duff, 2002; Ross et al., 2011).

For domains of small to medium size, approximate dynamic programming methods such as point-based solvers (Shani et al., 2013) can be applied to generate the α -vectors for this augmented POMDP. These solution methods are, however, difficult to scale to more complex models due to the computational intractability of the optimisation process.

An alternative to offline approaches is online planning. Instead of compiling a policy for all possible states (as done in dynamic programming), online planning concentrates on selecting the best action for the current state at runtime. This selection is typically implemented through the construction of a lookahead search tree representing possible actions and their effects in terms of rewards and new observations. This tree is gradually expanded until a particular planning horizon is reached. Several approximate methods have recently been developed, based on e.g. point-based value iterations (Ross et al., 2008) and Monte Carlo tree search (Silver and Veness, 2010). The action leading to the highest return on the search tree is then executed by the agent.

One important benefit of online approaches is the possibility to dynamically adapt the domain models at runtime. This characteristic is useful for dialogue domains where the domain models can vary in the course of the interaction – for instance, in order to adapt to shifting user preferences. Offline approaches must in comparison recalculate their policies after every modification or extension of the internal models for the domain. However, this advantage comes at a price, namely the fact that planning must be performed at execution time, while the interaction is taking place. Planning must therefore meet real-time constraints.

Interestingly, offline and online approaches are not mutually exclusive, but can be combined together to take full advantage of both strategies. The idea is to perform offline planning to pre-compute a rough initial policy, and use this policy as a heuristic approximation to guide the search of an online planner (Ross and Chaib-draa, 2007). These approximations can for instance provide lower and upper bounds on the values associated with the dialogue states of the search tree. Based on these bounds, the planning algorithm can concentrate its computational efforts in the most fruitful regions of the search space and quickly discard irrelevant actions.

Model-based Bayesian reinforcement learning has been applied to dialogue management in several recent papers. Png et al. (2012) describe a Bayes-Adaptive POMDP framework and illustrate its use in simulated interactions. Doshi and Roy (2008) present a related POMDP framework with model uncertainty combined with active learning. Action selection is formalised in their paper by sampling possible POMDP models and extracting a solution for each sample. A similar strategy is employed by Atrash and Pineau (2009). Finally, Chinaei and Chaib-draa (2012) and Chinaei et al. (2012) demonstrate the estimation of observation and reward models for dialogue POMDPs in a healthcare application. One interesting aspect of their work is the use of inverse reinforcement learning to automatically derive a reward model from expert policies.

Model-free methods

Model-free methods adopt a different learning strategy and directly optimise a dialogue policy from experience, without attempting to construct explicit internal models of the domain. One simple method, first formalised by Dearden et al. (1998), is to assign prior distributions to the Q value estimates associated with state-action pairs, and iteratively refine these distributions upon the completion of each action. This update generally relies on Bellman's equation, since the Q values are never directly observed (only the observations and rewards are available to the agent). The best action is then simply defined as the one that maximises the Q values for the current state, modulo an "exploration bonus" added at learning time to favour exploratory strategies.

Gaussian processes can be used to extend model-free approaches to problems with continuous state and action spaces (Engel et al., 2005). Gašić et al. (2013) present a framework for model-free dialogue policy optimisation based on such processes. Their optimisation strategy relies on an extension of the SARSA algorithm for Gaussian Processes (Engel et al., 2005). One of the main benefits of their approach is the tremendous acceleration of the optimisation procedure. As a result, the dialogue policy can be optimised via live interactions with human users instead of being confined to simulation. Daubigney et al. (2012a) present a related line of work based on Kalman Temporal Differences. Their approach being grounded in Kalman filtering rather than full Bayesian filtering, only the first and second moments (mean and variance) of the parameter distributions are estimated instead of the full posterior distributions. Finally, Thomson et al. (2010) show how to apply Bayesian learning to the model-based estimation of the transition model while simultaneously optimising the dialogue policy in a model-free manner.

Scalability

Bayesian reinforcement learning has been the subject of much recent research in the last decade, based on both model-based and model-free paradigms. This research focus led to the development of powerful optimisation methods (see e.g. Vlassis et al., 2012, for a detailed survey). Nevertheless,

scalability remains an important concern when porting these methods to real applications, as the sizes of the parameter and action spaces can constitute major bottlenecks for many learning methods. This problem is especially acute in partially observable domains, as the dialogue policies are in such cases defined on a continuous and high-dimensional belief space (as explained in Chapter 3, the belief space is a simplex in $\mathbb{R}^{|\mathcal{S}|-1}$, where $|\mathcal{S}|$ is the size of the state space).

As shall be argued in the next section, probabilistic rules can contribute to addressing this scalability problem by reducing the dimensionality of the parameter space and filtering out irrelevant actions from the planning process.

6.2 Optimisation of rule parameters

This thesis develops two distinct approaches to the optimisation of rule parameters from direct interactions. Both employ Bayesian reinforcement learning as theoretical framework and probabilistic rules as representation formalism, but rely on distinct optimisation strategies:

- The first approach follows a model-based strategy. In this approach, the rule-structured models \mathcal{M} of the domain correspond to transition, observation and reward models. The models are associated with a collection of parameters θ with prior distribution $P(\theta)$. These parameter distributions are updated on the basis of the observations and rewards received by the system during the interactions. Forward planning is employed at runtime to calculate the expected cumulative utilities of possible actions and select the one yielding the maximum utility given the current dialogue state and rule parameters.
- The second approach is a model-free strategy with parametrised utility rules representing the estimated Q -value for the system actions. In contrast to the model-based strategy, the utility parameters are here updated via a temporal-difference learning method. The actions to execute are determined through an ϵ -greedy policy that seeks to strike a balance between the selection of known high-utility actions and the exploration of new actions.

The two sections below flesh out these two approaches in more detail.

6.2.1 Model-based approach

The model-based approach relies on the specification of probabilistic rules that capture:

- the *transition model* for the domain, which describes how the dialogue state is likely to change as a result of the system actions,
- the *observation model* for the domain, which describes the likely observations associated with a given dialogue state,
- the *reward model* for the domain, which describes the immediate rewards (reflecting the system objectives) that result from the execution of particular system actions.

Figure 6.1 depicts a dynamic decision network corresponding to the above definition. The transition model is encoded as a probability distribution $P(s_t | s_{t-1}, a_{t-1}; \theta_T)$, the observation model by a probability distribution $P(o_t | s_t; \theta_O)$ and the reward model by the utility distribution

$R_t(s_t, a_t; \theta_R)$. For the sake of clarity, the figure abstracts away from the rule nodes mediating between the variables in the network, and upon which the parameters are attached.

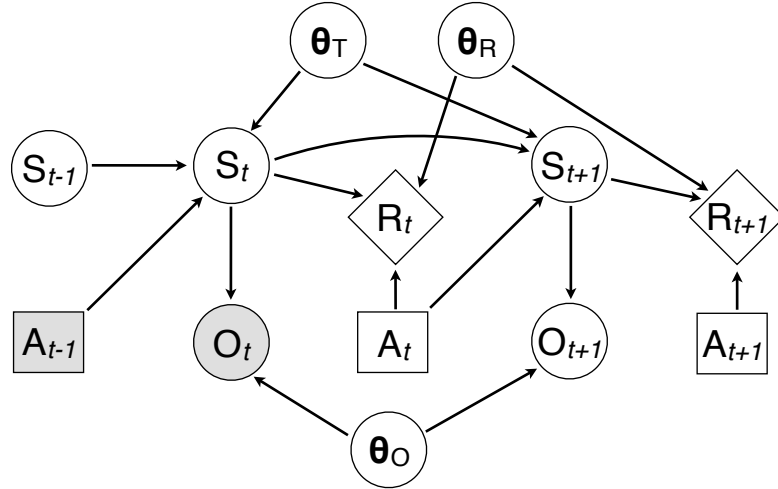


Figure 6.1: Dynamic decision network for a model-based learning strategy.

Parameter estimation

The probabilistic rules corresponding to these three models may all include unknown parameters that must be estimated from data. Fortunately, this worst case scenario where θ_T , θ_R and θ_O must all be learned from scratch rarely happens in practice. As evidenced in the experiment described at the end of this chapter, the reward and observation models can indeed often be defined by the system designer prior to learning.

Two types of information sources are available to the agent to refine its parameters during the interaction: the observations and the rewards. In the model-based setting, parameter update is relatively straightforward. The key idea is to include the parameter variables as part of the dialogue state. The probability distributions of these parameters are automatically updated as part of the state update process (see Algorithm 6 in Section 4.4). There is therefore no need for special purpose mechanisms beyond standard Bayesian inference.

Example of parameter update

Let us illustrate this process on the dialogue example already discussed in Section 4.4.3, reproduced here for convenience:

USER : Now move forward

Hypotheses for $\tilde{a}_u = [(Request(Forward), 0.6), (Request(Backward), 0.4)]$

SYSTEM : Could you please repeat?

USER : Please move forward!

Hypotheses for $\tilde{a}_u = [(Request(Forward), 0.7), (Other, 0.3)]$

However, contrary to the example in Chapter 4, we now assume that the effect distribution associated with the predictive rule r_{11} is initially unknown and is therefore replaced by parameters,

leading to the following rule:

$$\begin{aligned}
 r_{11} : & \forall y, \\
 & \mathbf{if} (a_m = AskRepeat \wedge a_u = y) \mathbf{then} \\
 & \quad \begin{cases} P(a_u^{p'} = y) = \theta_{r_{11}(1,1)} \\ P(\{\cdot\}) = \theta_{r_{11}(1,2)} \end{cases}
 \end{aligned}$$

Figure 6.2 illustrates how the distribution over the parameter values for $\theta_{r_{11}(1)}$ is automatically modified as part of the state update operation. To keep the example as simple as possible, the figure ignores the steps related to action selection and concentrates on the application of rule r_{11} . The initial prior distribution $P(\theta_{r_{11}(1)})$ is arbitrarily set in this example to $\sim \text{Dirichlet}(2, 1)$.

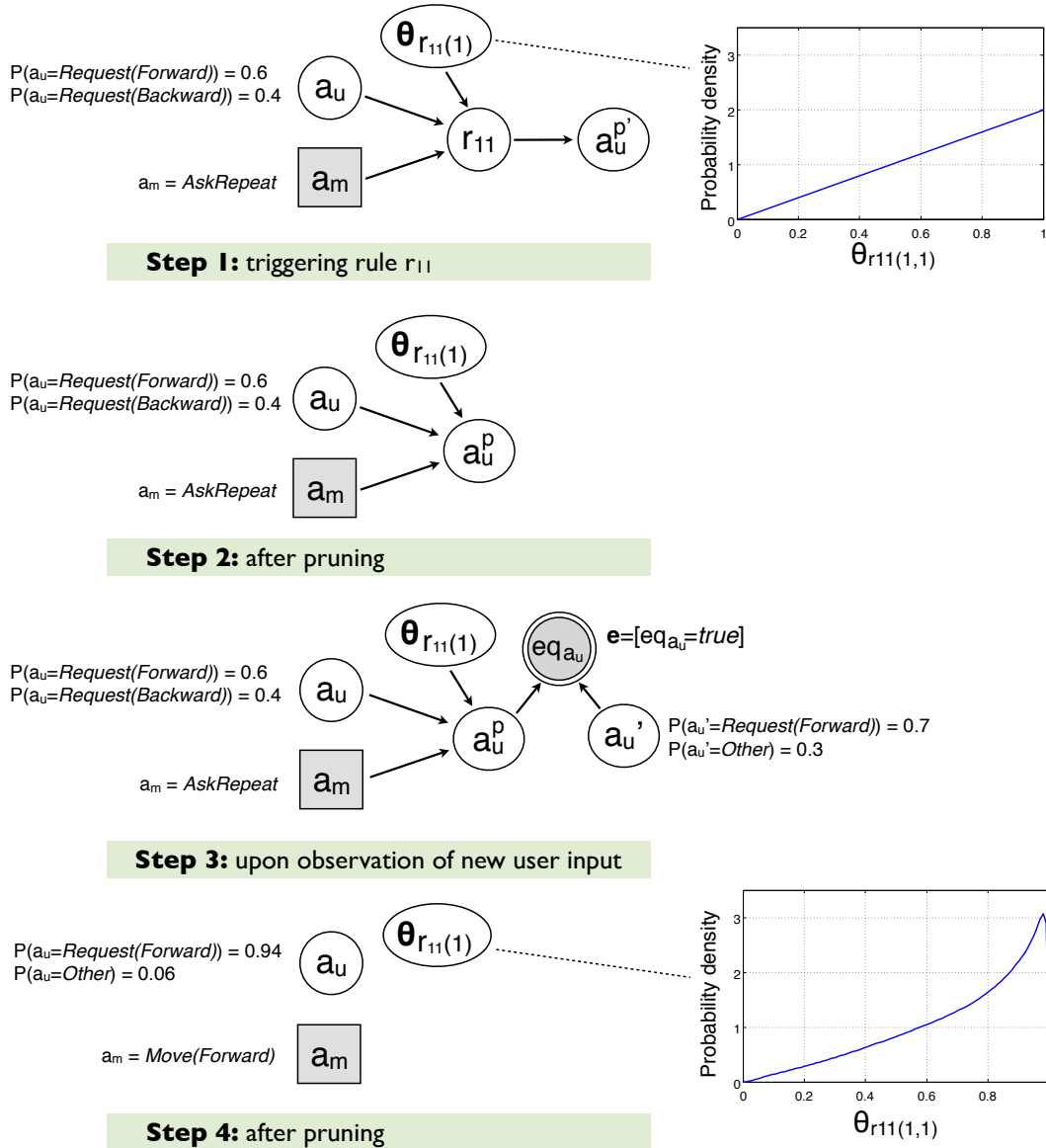


Figure 6.2: Parameter update for $\theta_{r_{11}(1)}$ after the reception of a new user input.

Step 1 corresponds to the instantiation of the rule. After the instantiation, the dialogue state is pruned, leading in Step 2 to the deletion of the rule node r_{11} . Step 3 shows the reception of the second user dialogue act a'_u and its inclusion in the dialogue state, with the equivalence node eq_{a_u} in charge of connecting the predicted and actual value for the dialogue act. Finally, Step 4 illustrates the results after pruning the dialogue state and integrating the (soft) evidence expressed by the last dialogue act. We notice that the parameter distribution $P(\theta_{r_{11}(1)})$ has shifted part of its probability mass further to the right. In other words, the probability of the user repeating their last utterance becomes somewhat more likely. The posterior distribution $P(\theta_{r_{11}(1)})$ after the update is constructed using kernel density estimation.

Action selection

As the Q -values are not directly accessible in model-based approaches, action selection must resort to either dynamic programming or forward planning to calculate the expected future rewards of each action. Action selection is the computational bottleneck in model-based Bayesian reinforcement learning, since the agent needs to reason not only over all the current and future states, but also over all possible models (parametrised by the θ variables). The high dimensionality of the task often prevents the use of offline solution techniques. We apply in our implementation a simple forward planning algorithm shown in Algorithm 12. The selection procedure relies on the recursive function $\text{CALCULATE-Q-VALUES}(\mathcal{B}, \mathbf{e}, h)$ to compute the Q -values of possible actions given a current state \mathcal{B} , evidence \mathbf{e} and planning horizon h .

Algorithm 12 : PLANACTION ($\mathcal{B}, \mathbf{e}, h$)

Input: Dialogue state \mathcal{B}

Input: Evidence \mathbf{e}

Input: Planning horizon h

Output: Selected action \mathbf{a}^*

- 1: $Q_{\mathcal{B}} \leftarrow \text{CALCULATE-Q-VALUES}(\mathcal{B}, \mathbf{e}, h)$
 - 2: Find value $\mathbf{a}^* = \arg\max_{\mathbf{a}} Q_{\mathcal{B}}(\mathbf{a})$
 - 3: **return** \mathbf{a}^*
-

The Q -value of an action is the discounted sum of its immediate reward (line 3 in Algorithm 13) and the expected future reward following its execution (line 4-11). Line 6 loops on possible observations. For efficiency reasons, only a limited number of high-probability observations are selected. For each observation, the dialogue state is updated (line 7) and the Q -values for the resulting state \mathcal{B}'' are computed (line 8). The maximum Q -value for this future state is then added to the Q -value for the current state, weighted by the discount factor γ and the probability $P_{\mathcal{B}'}(\mathbf{o})$ of the observation. The procedure stops when the planning horizon has been reached, or the algorithm has run out of time. The planner then simply selects the action with maximum expected cumulative utility, as shown in line 2 of Algorithm 12.

Algorithm 13 contains two loops: one cycling over the possible actions, and one cycling over the possible observations following the system action. This process can be represented in an AND-OR search tree anchored in the current state. The OR branches denote the system actions along with their respective rewards, while the AND branches denote the observations weighted by their likelihood. An example of such an AND-OR search tree is provided in Figure 6.1.

Algorithm 13 : CALCULATE-Q-VALUES (\mathcal{B} , \mathbf{e} , h)

Input: (see above)

- 1: Let \mathbf{A} be the set of all decision variables in \mathcal{B}
 - 2: **for all** actions $\mathbf{a} \in \text{Val}(\mathbf{A})$ **do**
 - 3: $Q_{\mathcal{B}}(\mathbf{a}) \leftarrow U_{\mathcal{B}}(\mathbf{a} | \mathbf{e})$
 - 4: **if** $h > 1$ **then**
 - 5: $\mathcal{B}' \leftarrow$ dialogue state updated from \mathcal{B} after action \mathbf{a}
 - 6: **for all** observations \mathbf{o} **do**
 - 7: $\mathcal{B}'' \leftarrow$ dialogue state updated from \mathcal{B}' after observation \mathbf{o}
 - 8: $Q_{\mathcal{B}''} \leftarrow \text{CALCULATE-Q-VALUES}(\mathcal{B}'', \mathbf{e}, h - 1)$
 - 9: $Q_{\mathcal{B}}(\mathbf{a}) \leftarrow Q_{\mathcal{B}}(\mathbf{a}) + \gamma P_{\mathcal{B}'}(\mathbf{o}) \max_{\mathbf{a}'} Q_{\mathcal{B}''}(\mathbf{a}')$
 - 10: **end for**
 - 11: **end if**
 - 12: **end for**
 - 13: **return** $Q_{\mathcal{B}}$
-

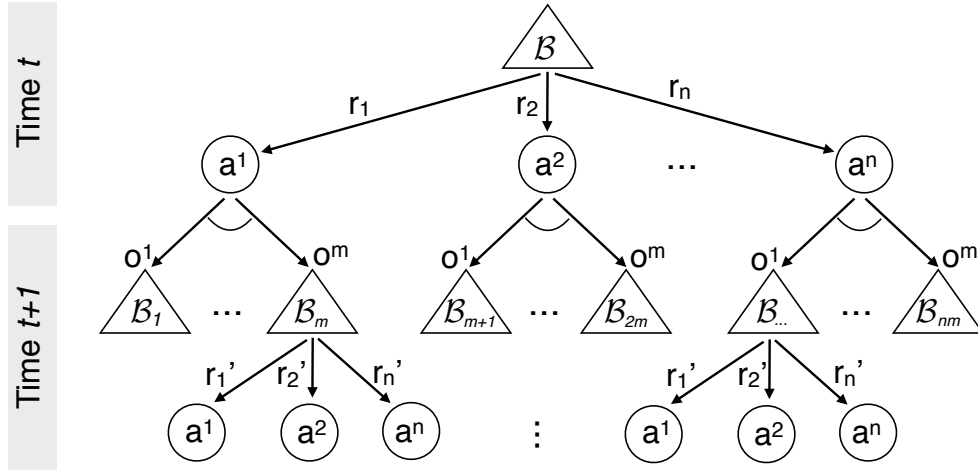


Figure 6.3: AND-OR search tree constructed through forward planning for $h = 2$.

Our implementation of Algorithms 12 and 13 expands the search tree by gradually adding new observations and actions in a breadth-first manner. This gradual expansion allows the planner to return a solution at any point in time (such types of processes are called *anytime* algorithms). The quality of the solution will of course depend on the accuracy of the search tree, which itself depends on the number of sampled actions and observations – more trajectories leading to a more accurate plan, but at a higher computational cost. The anytime nature of the algorithm is important since the planner operates online.

As argued in Lison (2012b), the reliance on utility rules to encode the reward model can help in making the planning process more tractable. In addition to assigning utilities to system actions, utility rules also implicitly define the set of action values that are relevant at a given time.¹ In other words, actions that are not deemed relevant in a particular state are automatically filtered out from the planning process. Instead of searching through the whole space of possible actions, the planning

¹Recall that in Algorithm 5 from Section 4.3, the set of possible values of an action node is directly derived from the values listed in the utility nodes connected to it.

algorithm is thus limited to a subset of actions that are locally relevant. One interesting aspect of this approach is that the filtering of relevant actions is done solely on the basis of the provided reward model and does not require the integration of additional constraints or ad-hoc mechanisms. This stands in contrast with most existing work in dialogue management, where constraints on possible actions are typically enforced through external filtering techniques defined on the basis of e.g. information-state update rules (Heeman, 2007), finite-state automata (Williams, 2008b), or – in our own previous work on this problem – high-level constraints encoded in Markov Logic formulae (Lison, 2010b).

Learning cycle

The model-based learning cycle is detailed in Algorithm 14. The learning agent incrementally updates its model parameters θ by running a number of interactions, either with a real user or in simulation. Starting with an initial dialogue state, the interaction alternates between the reception of new observations (in the form of e.g. user inputs or contextual changes in the environment) and the execution of system actions following these observations. The dialogue state is updated after each observation (line 5), using the procedure outlined in Section 4.4, with the action selection method replaced by Algorithm 12. The selected actions are then executed (line 7). If the reward model is unknown, the reward resulting from the system actions can be integrated in the set of observations and used to update the reward parameters accordingly.

Algorithm 14 : MODEL-BASED-RL ($\mathcal{M}, \mathcal{B}_0, \theta, N$)

Input: Initial dialogue state \mathcal{B}_0
Input: Rule-structured models \mathcal{M} with parameters θ
Input: Number N of interactions to collect
Output: Posterior distribution $P(\theta)$ for the parameters

```

1: for  $i = 0 \rightarrow N$  do
2:   Start new interaction with initial state  $\mathcal{B} = \mathcal{B}_0 \cup \theta$ 
3:   while interaction is active do
4:     Get new observations  $\mathbf{O}$ 
5:     UPDATESTATE( $\mathcal{B}, \mathbf{O}$ )
6:     if new action  $a$  is selected then
7:       Execute action  $a$  and get resulting reward  $r$ 
8:     end if
9:   end while
10: end for
11: return  $P(\theta)$ 

```

6.2.2 Model-free approach

In addition to the model-based learning strategy described above, we also developed an alternative Bayesian model-free approach to the estimation of rule parameters. In this approach, the core model that is to be estimated is the *action-value model* which specifies the expected cumulative reward Q of the system actions depending on the current state.

Besides this action–value model, the domain may also rely on transition and observation models. However, the transition and observation models are in model-free approaches only used for state updates (if the dialogue state contains hidden state variables that are indirectly inferred from observations, such as the user intentions) and are not exploited in the action selection. This stands in contrast with model-based approaches to reinforcement learning where transition and observation models are directly employed to plan the next action.

Figure 6.4 illustrates how these distributions combine to form a dynamic decision network. As for the model-based approach, all domain models are specified with probabilistic rules (which are again abstracted away from the simplified diagram in the figure). The transition and observation models are encoded by probability rules and the action–value model by utility rules.

In the worst case, all models may include unknown parameters. The transition model is thus defined as a probability distribution $P(s_t | s_{t-1}, a_{t-1}; \theta_T)$, the observation model by a distribution $P(o_t | s_t; \theta_O)$ and the Q -value model by a distribution $Q(s_t, a_t; \theta_Q)$.

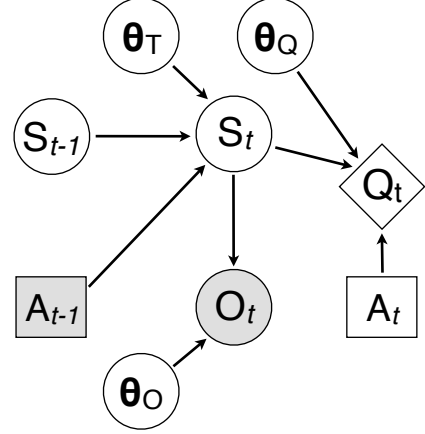


Figure 6.4: Dynamic decision network for a model-free strategy.

Parameter estimation

The model-free approach developed in this thesis rests on a simple Bayesian extension of the SARSA algorithm already presented in Section 3.2.1. The posterior parameter distribution is here computed on the basis of the evidence provided by the reward r_{t+1} and next system action a_{t+1} . Given a sequence $\langle \mathcal{B}_t, a_t, r_{t+1}, \mathcal{B}_{t+1}, a_{t+1} \rangle$, the likelihood distribution $P(r_{t+1}, a_{t+1}; \theta)$ is defined as:

$$P(r_{t+1}, a_{t+1}; \theta) = \phi \left(\frac{r_{t+1} + \gamma Q_{\mathcal{B}_{t+1}}(a_{t+1}; \theta) - Q_{\mathcal{B}_t}(a_t; \theta)}{\sigma} \right) \quad (6.1)$$

where $\phi(\cdot)$ is the density function for the standard normal distribution $\mathcal{N}(0, 1)$. The standard normal distribution has its peak around the value 0 and decreases exponentially with the distance to this mean. The likelihood distribution will therefore be proportional to the proximity between the initial estimate $Q_{\mathcal{B}_t}(a_t; \theta)$ calculated at time t and the updated estimate $[r_{t+1} + \gamma Q_{\mathcal{B}_{t+1}}(a_{t+1}; \theta)]$ calculated at time $t + 1$. The variance σ encodes the spread of the bell curve and controls as a consequence the learning rate.

Based on the likelihood distribution in Equation (6.1), the posterior distribution over the parameters is calculated as:

$$P(\theta | r_{t+1}, a_{t+1}) = \eta P(r_{t+1}, a_{t+1}; \theta) P(\theta) \quad (6.2)$$

Action selection

The above section described how the parameter distributions for the Q -model are updated on the basis of the received rewards and executed actions, but did not explain how the system actions were selected at runtime. For the practical purpose of our experiments, we have opted for a simple

action selection strategy that mixes the selection of high-utility actions with a small amount of exploration. This approach is known as a ϵ -greedy strategy (Sutton and Barto, 1998). In contrast with pure greedy strategies that directly select the action yielding the maximum Q -value, ϵ -greedy strategies allow the agent to explore other actions once in a while. The relative frequency of these exploration actions compared to the “greedy” actions is expressed by the probability ϵ , which is usually small. The strategy is illustrated in Algorithm 15.

Algorithm 15 : ϵ -GREEDY-POLICY (\mathcal{B} , \mathbf{e})

Input: Dialogue state \mathcal{B} and evidence \mathbf{e}

Output: Selected action \mathbf{a}^*

1: **return** $\mathbf{a}^* = \begin{cases} \operatorname{argmax}_{\mathbf{a}} Q_{\mathcal{B}}(\mathbf{a} | \mathbf{e}) & \text{with probability } (1 - \epsilon) \\ \text{another action} & \text{with probability } \epsilon \end{cases}$

Learning cycle

The model-free learning cycle is mostly similar to the one defined in the model-based setting. As shown in Algorithm 16, the agent optimises its rule parameters by collecting a number of interactions and gradually refining their estimates on the basis of the received feedback.

Algorithm 16 MODEL-FREE-RL (\mathcal{M} , \mathcal{B}_0 , $\boldsymbol{\theta}$, N)

Input: Rule-structured models \mathcal{M} for the domain

Input: Initial dialogue state \mathcal{B}_0

Input: Model parameters $\boldsymbol{\theta}$ with prior distribution $P(\boldsymbol{\theta})$

Input: Number N of interactions to collect

Output: Posterior distribution $P(\boldsymbol{\theta})$ for the parameters

```

1: for  $i = 0 \rightarrow N$  do
2:   Start new interaction with initial state  $\mathcal{B} = \mathcal{B}_0 \cup \boldsymbol{\theta}$ 
3:   while interaction is active do
4:     Get new observations  $\mathbf{O}$ 
5:     UPDATESTATE( $\mathcal{B}$ ,  $\mathbf{O}$ )
6:     if new action  $a$  is selected then
7:       Update posterior  $P(\boldsymbol{\theta} | r, a)$  based on Equation (6.2)
8:       Execute action  $a$  and get resulting reward  $r$ 
9:     end if
10:  end while
11: end for
12: return  $P(\boldsymbol{\theta})$ 

```

Each interaction starts from the initial dialogue state \mathcal{B}_0 and unfolds as a sequence of observations and actions. The dialogue state contains both traditional state variables and parameters. After perceiving new observations, the dialogue state is updated and the next system action selected according to the ϵ -greedy strategy. The posterior distributions over the rule parameters are correspondingly updated via SARSA (line 7). The action is then executed and the resulting reward is retrieved (line 8). The process is repeated for each interaction.

6.3 Experiments

We performed an empirical evaluation of the two approaches based on a user simulator for a human–robot interaction domain. The evaluation is divided in two parts:

1. The goal of the first experiment was to determine whether the use of probabilistic rules could be shown to improve the performance of a reinforcement learning agent. More specifically, the experiment compared two alternative formalisations of a transition model for a human–robot interaction scenario: one encoded with traditional factored distributions, and one encoded with probability rules.
2. The goal of the second experiment focused on the comparison between model-based and model-free approaches in Bayesian reinforcement learning. The evaluation compared a model-based learner with an unknown transition model (identical to the one used in the first experiment) to a model-free learner with an unknown action–value model. Both strategies relied on probabilistic rules to capture their respective models and were evaluated on the basis of their average rewards when interacting with the user simulator.

We first describe in this section the dialogue domain and user simulator used in both experiments, and then detail the evaluation setups and empirical results for each experiment.

6.3.1 Dialogue domain

As in the previous chapter, the dialogue domain chosen for the experiments is a human–robot interaction scenario with a Nao robot. conversing with a human user in a shared visual scene, as illustrated in Figure 6.5.

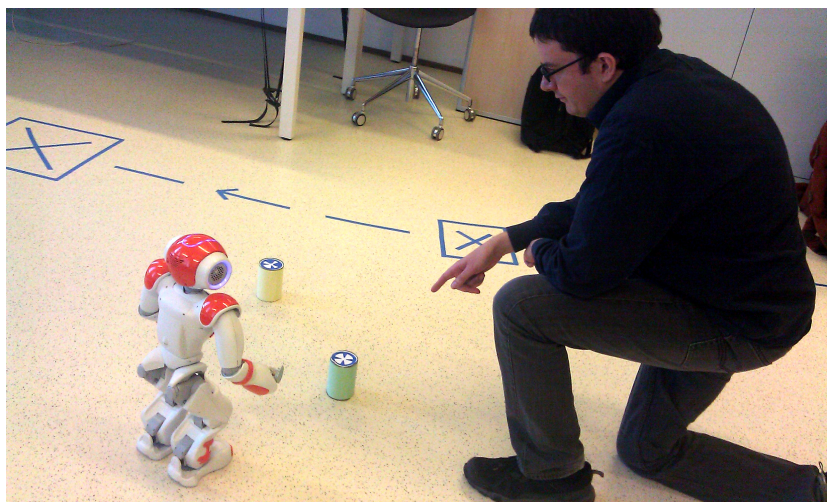


Figure 6.5: Human user interacting with the Nao robot in a shared visual scene with two objects.

The users were instructed to command the robot to carry the objects from one place to another. The users were free to decide which object(s) to pick up, where to place them on the floor, and what kinds of navigation commands to utter. The objects in the scene consisted of coloured metallic cylinders with a special marking on their top to facilitate the robot’s visual servoing during grasping

tasks. As the version of the Nao robot employed in our experiments did not include actuated fingers, the grasping operation employed permanent magnets attached to the robot hands to grasp and carry the cylinders. In addition to following the human instructions, the robot could also answer factual questions from the user regarding its own perception of the environment such as “do you see a blue cylinder?” or “what can you see now?”. Transcript 3 provides a detailed example of recorded interaction between a human user and the (wizard-controlled) robot.

Each (physical or information-gathering) sub-task is represented as a distinct user intention. As the human users could only instruct the robot to perform one sub-task at a time, the user intention is represented by a single variable denoting the current sub-task that the user wishes to see fulfilled. The user intentions for the domain are listed in Table 6.1.

Besides following the user commands related to spatial navigation and object manipulation, the robot could also perform grounding actions such as clarification requests and acknowledgements. In total, the domain included 9 user dialogue templates. The robot has a repertoire of 8 possible action templates that can be executed. For a dialogue domain with two objects, the user actions a_u and system actions a_m will thus expand into respectively 15 and 37 actions. Tables 6.2 and 6.3 list the possible user and system actions.

The reward model was defined by hand, using standard schemes: The execution of correct actions leads to large positive values (+6 in this particular case) while the execution of wrong or irrelevant actions leads to large negative values (-6) and the use of clarification or confirmation requests to small negative values (from -0.5 to -1.5, depending on the type of request). Table 6.4 presents the reward model defined for the domain.

6.3.2 Simulator

Methodology

In order to draw meaningful and reliable comparisons between reinforcement learning approaches, the user behaviours must be made fully consistent across interactions. This consistency must be enforced on both the conversational choices of the user and the average amount of noise and errors that characterise them. Needless to say, this criteria is hard to satisfy when working with human participants. The comparative evaluation of learning approaches was thus conducted with the help of a simulator. However, it should be emphasised that the reliance on user simulators to conduct the comparative evaluation of our learning approaches does not in any way imply that simulators are a necessary component of the learning approach presented in this chapter.²

The purpose of the simulator is to emulate the typical dialogue behaviour of a human user, and generate relevant user responses to the system actions. The simulator also maintains a virtual representation of the environment during the interaction (represented in our case by the physical objects) and updates this representation as a function of the system actions.

Wizard-of-Oz study

In order to build a user simulator that matches as closely as possible the behaviour of actual human subjects, we recorded a set of Wizard-of-Oz interactions in the human–robot dialogue domain

²In fact, probabilistic rules are expected to be well suited for optimisation from live interactions, as they require substantially less training data than traditional approaches (as evidenced by the empirical results in this section).

Transcript 3 User interaction (with wizard-controlled robot)

ROBOT: Hello human

HUMAN: Hi, hello Lenny!

[ROBOT *stands up*]

HUMAN: Would you please move forward

ROBOT: OK, moving forward

[ROBOT *steps forward*]

HUMAN: Would you please move a bit more forward

ROBOT: Should I move backward

HUMAN: No, a bit more forward

ROBOT: OK, forward then

[ROBOT *steps forward*]

HUMAN: Do you see any object?

ROBOT: Sorry I do not understand

HUMAN: Do you see any object?

ROBOT: I see a blue cylinder

HUMAN: Can you pick it up please?

ROBOT: Should I pick up the object?

HUMAN: Yes please

ROBOT: OK, thanks

[ROBOT *moves in direction of the blue cylinder*]

[ROBOT *picks up the object*]

ROBOT: Done

HUMAN: Now turn right

[ROBOT *turns right while holding the object*]

HUMAN: Move forward

[ROBOT *moves forward while holding the object*]

HUMAN: And then move two steps backward

ROBOT: OK, moving forward

[ROBOT *starts movement*]

HUMAN: No please move backward

[ROBOT *stops*]

[...]

· Move(x) where $x = \{\text{Left, Right, Forward, Backward}\}$	· Release(x) where x is an object identifier
· PickUp(x) where x is an object identifier	· WhatDoYouSee
	· DoYouSee(x) where x is an object identifier

Table 6.1: List of user intentions i_u .

· Ask(Move(x)) where $x = \{\text{Left, Right, Forward, Backward}\}$	· RepeatLast
· Ask(PickUp(x)) where x is an object identifier	· Ask(WhatDoYouSee)
· Ask(Release(x)) where x is an object identifier	· Ask(DoYouSee(x)) where x is an object identifier
	· Confirm
	· Disconfirm
	· Other

Table 6.2: List of user actions a_u .

· Do(x) where $x = \{\text{Move}(y), \text{PickUp}(z), \text{Release}(z)\}$ and $y = \{\text{Left, Right, Forward, Backward}\}$ and $z =$ an object identifier	· Ground(x) where $x = \{\text{Move}(y), \text{PickUp}(z), \text{Release}(z)\}$ and $y = \{\text{Left, Right, Forward, Backward}\}$ and $z =$ an object identifier
· Excuse(x) where $x = \{\text{DoNotSeeObject}, \text{DoNotCarryObject}, \text{AlreadyCarryObject}\}$	· AskRepeat
· Describe(x) where $x =$ a (possibly empty) list of object identifiers	· AskConfirm(x) where $x = \{\text{Move}(y), \text{PickUp}(z), \text{Release}(z), \text{DoYouSee}(z), \text{WhatDoYouSee}\}$ and $y = \{\text{Left, Right, Forward, Backward}\}$ and $z =$ an object identifier
· ConfirmDetection	
· DisconfirmDetection	

Table 6.3: List of system actions a_m .

Action	Reward
Execution of correct physical action $a_m = \text{Do}(i_u)$	+6
Execution of wrong physical action $a_m = \text{Do}(x)$ with $x \neq i_u$	-6
Declare $a_m = \text{Excuse}(\text{DoNotSeeObject})$ when $i_u = \text{PickUp}(x)$ and x is not perceived	+6
Declare $a_m = \text{Excuse}(\text{DoNotCarryObject})$ when $i_u = \text{Release}(x)$ and x is not carried	+6
Declare $a_m = \text{Excuse}(\text{AlreadyCarryObject})$ when $i_u = \text{PickUp}(x)$ and x is carried	+6
Declare $a_m = \text{Excuse}(\ast)$ in other circumstances	-6
Correct answer $a_m = \text{Describe}(x)$ when $i_u = \text{WhatDoYouSee}$ and x are the perceived objects	+6
Wrong answer $a_m = \text{Describe}(\ast)$ when $i_u \neq \text{WhatDoYouSee}$	-6
Correct answer $a_m = \text{ConfirmDetection}$ when $i_u = \text{DoYouSee}(x)$ and x is perceived	+6
Wrong answer $a_m = \text{ConfirmDetection}$ when $i_u \neq \text{DoYouSee}(x)$ or x is not perceived	-6
Correct answer $a_m = \text{DisconfirmDetection}$ when $i_u = \text{DoYouSee}(x)$ and x is not perceived	+6
Wrong answer $a_m = \text{DisconfirmDetection}$ when $i_u \neq \text{DoYouSee}(x)$ or x is perceived	-6
Grounding of correct intention $a_m = \text{Ground}(i_u)$	+2
Grounding of wrong intention $a_m = \text{Ground}(x)$ with $x \neq i_u$	-6
Request to confirm correct intention $a_m = \text{AskConfirm}(i_u)$	-0.5
Request to confirm wrong intention $a_m = \text{AskConfirm}(x)$ with $x \neq i_u$	-1.5
Request to clarify $a_m = \text{AskRepeat}$	-1
Ignore user act $a_m = \text{None}$ when $a_u \neq \text{None}$	-1.5

Table 6.4: Reward model for the domain.

chosen for the experiments.

The technical setup employed for the Wizard-of-Oz data collection was mostly similar to the one described in the previous chapter, with one notable difference: While the Wizard-of-Oz interactions described in Section 5.3.2 served to determine the most appropriate *system* actions depending on the situation, the present Wizard-of-Oz study aims to collect empirical data about the most likely *user* actions in their context. As the wizard behaviour was not the focus of the study, the wizard had a direct access to the user utterances, without relying on the speech recogniser as an intermediary. The wizard controlled the verbal and physical actions via a remote screen coupled to the robotic platform. Various types of errors and misunderstandings were artificially introduced by the wizard in the course of the interaction in order to gather data about the user responses to such comprehension errors.

A total of eight interactions was recorded, each with a different speaker (5 males and 3 females), totalling about 50 minutes divided in 486 turns. The interactions were performed in English. The users were again recruited amongst the local group of students and employees in the Department of Informatics at the University of Oslo and were (with one exception) non-native English speakers. The author of the present thesis served as the wizard.

After the recording, the dialogues were segmented and annotated by hand (with one single annotator). The first layer of annotation encodes the user dialogue acts a_u and system actions a_m listed in Tables 6.2 and 6.3. The user intentions underlying the user commands are annotated on top of this sequence of turns.³ The annotation also includes two contextual variables expressing the

³Although the user intentions are in principle hidden “mentalist” entities, they can in our domain be easily determined by a human annotator from the dialogue transcript.

objects perceived and carried by the robot at a given time. Transcript 4 provides a concrete example of annotation for the first part of the interaction in Transcript 3.

User and context modelling

After collecting and annotating the Wizard-of-Oz interactions, the next step in the development of the simulator is to design the transition model that determines how the user and the environment are to respond to the system actions. This statistical model is used at runtime to sample possible responses and feed them back to the dialogue system.

The transition model employed for the simulator is factored into four components:

1. A user goal model $P(i'_u | i_u, a_m, perceived', carried')$ describing the probability of the next user intention i'_u as a function of the current intention i_u , the last system action a_m and the two contextual variables *perceived* and *carried*. The dependence on the contextual variables can for instance express that the user is more likely to ask the robot to grasp an object if it sees it, and less likely to ask the same request if the robot already carries an object.
2. A user action model $P(a'_u | i'_u, a_m)$ describing the probability of the new user action a'_u as a function of the new user intention and last system action.
3. A contextual model $P(perceived' | perceived, a_m)$ describing how the set of objects perceived by the robot evolves as a function of the system action (since a movement may result in the detection of new objects or make other objects fall from view).
4. A contextual model $P(carried' | carried, a_m)$ describing how the set of objects carried by the robot can change due to grasping and releasing actions.

The resulting probabilistic model that combines these four distributions is depicted in Figure 6.6. The current state variables at time t are greyed out, signifying that their values are observed. It should be stressed that the knowledge of these values is limited to the simulator (since the user is aware of its own intentions and dialogue acts, and the environment “knows” its own state). The robot has, however, no access to the internal state of the simulator.

The transition model was practically designed with a set of probability rules expressing the four distributions based on a small number of common sense assumptions about the user behaviour. The probabilities associated with the rule effects were then estimated by maximum likelihood on the basis of the annotated dialogues.

Error modelling

In real interactions, user inputs are not directly observed by the dialogue manager but must first be processed by the speech recognition and understanding modules. These modules are prone to

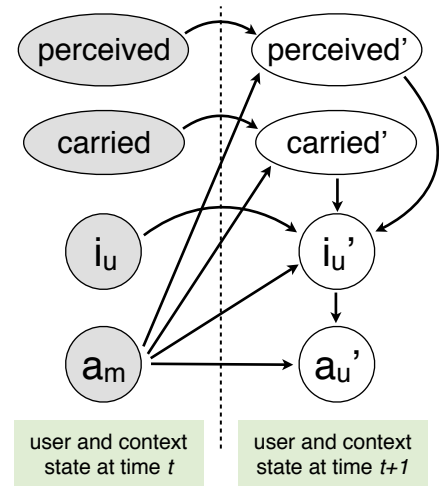


Figure 6.6: User and context models employed by the simulator.

Transcript 4 Annotated dialogue excerpt

HUMAN: Would you please move forward

Annotation: $a_u = \text{Ask}(\text{Move}(\text{Forward}))$
 $i_u = \text{Move}(\text{Forward}), \text{carried} = [], \text{perceived} = []$

ROBOT: OK, moving forward

Annotation: $a_m = \text{Ground}(\text{Move}(\text{Forward}))$ followed by $a_m = \text{Do}(\text{Move}(\text{Forward}))$

HUMAN: Would you please move a bit more forward

Annotation: $a_u = \text{Ask}(\text{Move}(\text{Forward}))$
 $i_u = \text{Move}(\text{Forward}), \text{carried} = [], \text{perceived} = [\text{object}_1]$

ROBOT: Should I move backward

Annotation: $a_m = \text{AskConfirm}(\text{Move}(\text{Backward}))$

HUMAN: No, a bit more forward

Annotation: $a_u = \text{Disconfirm}$ followed by $a_m = \text{Ask}(\text{Move}(\text{Forward}))$,
 $i_u = \text{Move}(\text{Forward}), \text{carried} = [], \text{perceived} = [\text{object}_1]$

ROBOT: OK, forward then

Annotation: $a_m = \text{Ground}(\text{Move}(\text{Forward}))$ followed by $a_m = \text{Do}(\text{Move}(\text{Forward}))$

HUMAN: Do you see any object?

Annotation: $a_u = \text{Ask}(\text{WhatDoYouSee}),$
 $i_u = \text{WhatDoYouSee}, \text{carried} = [], \text{perceived} = [\text{object}_1]$

ROBOT: Sorry I do not understand

Annotation: $a_m = \text{AskRepeat}$

HUMAN: Do you see any object?

Annotation: $a_u = \text{Ask}(\text{WhatDoYouSee}),$
 $i_u = \text{WhatDoYouSee}, \text{carried} = [], \text{perceived} = [\text{object}_1]$

ROBOT: I see a blue cylinder

Annotation: $a_m = \text{Describe}([\text{object}_1])$

various failures and frequently distort or misinterpret the actual user utterance. The user simulator should account for this fact by explicitly modelling errors and uncertainties arising from speech recognition and natural language understanding (Schatzmann et al., 2007b).

In order to reproduce the imperfect nature of the communication channel, the simulator wraps every user input in an N-best list of the following form:

$$\tilde{a}_u = \begin{cases} P(\text{correct } a_u) = p_1 \\ P(\text{another randomly selected value for } a_u) = p_2 \\ P(\text{spurious recognition}) = p_3 \end{cases}$$

where $\langle p_1, p_2, p_3 \rangle$ are probability values sampled at runtime from a three-dimensional Dirichlet distribution. The distribution $P(p_1, p_2, p_3)$ is estimated in an empirical manner based on actual speech recognition results for the domain. We first applied the off-the-shelf speech recogniser installed on the robot to the audio segments corresponding to the user utterances collected in the Wizard-of-Oz study. The recognition results were then processed in order to extract from each audio segment the three probabilities $\langle p_1, p_2, p_3 \rangle$, where p_1 stands for the probability of the correct utterance (which can be zero if the utterance does not appear in the N-Best list), p_2 to the total probability of incorrect utterances, and p_3 to the probability of no recognition. We finally derived a Dirichlet distribution based on these observed probabilities using the estimation method developed in Minka (2003). The particular Dirichlet distribution resulting from the recognition results was $\sim \text{Dirichlet}(5.4, 0.52, 1.6)$

At runtime, the probabilities for the N-best list elements are drawn from the Dirichlet distribution. Probability values falling below a minimum threshold are automatically pruned from the N-Best list. The method has been found to match reasonably well the actual recognition results produced by the speech recogniser, although one could naturally refine the approach by e.g. explicitly modelling confusion probabilities between individual inputs.

Simulation procedure

The simulation procedure takes the form of an interaction loop between the simulator and the dialogue system, as shown in Figure 6.7. Two separate dialogue systems are active: the simulator on the one hand and the robot's dialogue system on the other hand. However, the two systems operate differently, as the simulator has a fully observable state while the system state is only partially observable and contains unknown parameters.

Contrary to the experiments presented in the previous chapter, the dialogue architecture used in this learning experiment is essentially reduced to the dialogue management module, since the simulator and the dialogue system directly exchange their dialogue actions without needing to express them in actual spoken utterances.

An example of interaction generated when coupling the simulator to the dialogue system is provided in Transcript 5. The excerpt is taken at the onset of the learning cycle, when the system's estimation of the model parameters is still rudimentary, which explains the prevalence of information-gathering actions.

Transcript 5 Example of simulated interaction

[Initial context: perceived = [object₁, object₂], carried = []]

SIMULATOR: $\begin{bmatrix} \text{Ask(PickUp(object}_2)) & 0.06 \\ \text{Ask(PickUp(object}_1)) & 0.42 \end{bmatrix}$

ROBOT: AskRepeat \rightarrow Reward = -1

SIMULATOR: $\begin{bmatrix} \text{Ask(DoYouSee(object}_2)) & 0.01 \\ \text{Ask(PickUp(object}_1)) & 0.77 \end{bmatrix}$

ROBOT: Ground(PickUp(object₁)) \rightarrow Reward = 2

ROBOT: Do(PickUp(object₁)) \rightarrow Reward = 6, carried = [object₁]

SIMULATOR: $\begin{bmatrix} \text{Ask(DoYouSee(object}_2)) & 0.05 \end{bmatrix}$

ROBOT: AskRepeat \rightarrow Reward = -1

SIMULATOR: $\begin{bmatrix} \text{Ask(DoYouSee(object}_2)) & 0.87 \end{bmatrix}$

ROBOT: AskConfirm(DoYouSee(object₂)) \rightarrow Reward = -0.5

SIMULATOR: $\begin{bmatrix} \text{RepeatLast} & 0.05 \\ \text{Confirm} & 0.63 \end{bmatrix}$

ROBOT: ConfirmDetection \rightarrow Reward = 6

SIMULATOR: $\begin{bmatrix} \text{Ask(Move(Forward))} & 0.73 \\ \text{Ask(PickUp(object}_2)) & 0.03 \end{bmatrix}$

ROBOT: AskRepeat \rightarrow Reward = -1

SIMULATOR: $\begin{bmatrix} \text{Ask(Move(Forward))} & 0.92 \\ \text{Ask(Move(Left))} & 0.04 \end{bmatrix}$

ROBOT: Ground(Move(Forward)) \rightarrow Reward = 2

ROBOT: Do(Move(Forward)) \rightarrow Reward = 6

[...]

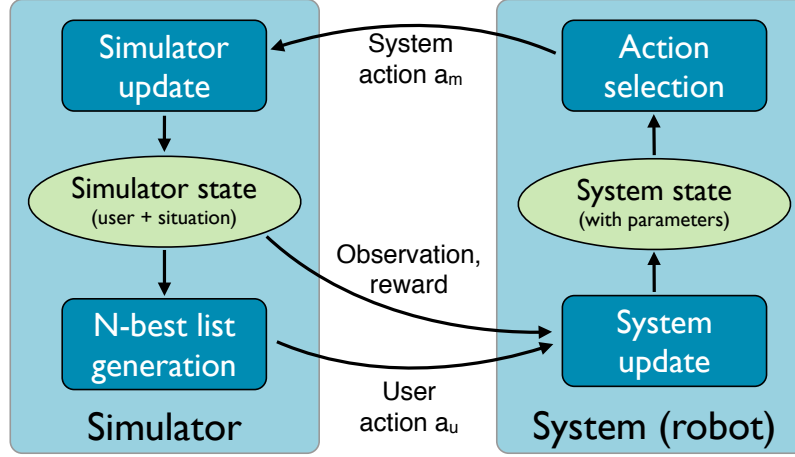


Figure 6.7: Processing workflow for the simulated interaction.

6.3.3 First experiment

The goal of the first experiment is to determine whether the use of probabilistic rules has a beneficial influence on the learning performance of the agent. The motivation is similar to the one put forward in the experiment of the previous chapter, with the notable difference that the estimation procedure is here based on model-based Bayesian reinforcement learning techniques instead of supervised learning.

The experiment focuses more specifically on the statistical estimation of the transition model for the human–robot interaction domain described in Section 6.3.1. Based on the simulator presented in the previous pages, the experiment compares two alternative representations of the transition model: one baseline model encoded via standard categorical distributions, and one equivalent model encoded via probability rules. The relative performance of these two representations is measured by the average return – i.e. the sum of rewards – per interaction.

The reward model was held fixed and identical in both cases (cf. Table 6.4). Online planning was used for action selection and operated with a horizon of length 2. In other words, the planner looked ahead one step into the future to determine the effects of its actions.

Baseline model

The transition model is represented in the baseline approach through traditional factored categorical distributions. More precisely, the transition model is divided into a user goal model $P(i'_u | i_u, a_m)$ and a user action model $P(a'_u | i'_u, a_m)$.⁴ The user goal model is defined in the following manner:

$$P(i'_u | i_u, a_m) = \begin{cases} P(i'_u) & \text{if } a_m \text{ fulfils the intention } i_u \\ 1 & \text{if above condition does not hold and } i'_u = i_u \\ 0 & \text{otherwise} \end{cases}$$

⁴The two contextual variables perceived and carried are not included in the transition model since their values do not need to be predicted in advance in this scenario.

where $P(i'_u)$ is a categorical distribution that expresses the prior probability of a new user intention i'_u . The user action model $P(a'_u | i'_u, a_m)$ is for its part constructed as a plain probability table where each possible assignment of values for the parent variables i'_u and a_m is assigned a distinct categorical distribution on the values of a'_u .

The resulting parameters for these categorical distributions are encoded with Dirichlet priors. The baseline model employed for this experiment contains a total of 229 Dirichlet parameters, divided into 228 Dirichlets with 16 dimensions (for the user action model) and one Dirichlet with 12 dimensions (for the user goal model). Weakly informative priors are used to initialise the prior distributions.

A linear model has also been constructed for this experiment but is not shown in the results as its parameter estimation systematically diverged and fared much worse than the classical factored distributions, most likely due to the non-linearity of the underlying domain models.

Rule-structured model

The rule-structured model is encoded with parametrised probability rules. A total of six rules with 13 corresponding Dirichlet parameters (of varying dimensions) are used to define the transition model. As for the baseline model, the rule parameters are initially associated with weakly informative Dirichlet priors. The rules designed for the experiment are listed in Appendix B.

Empirical results

The performance of the two competing approaches was first measured in terms of average return per simulated interaction, as shown in Figure 6.8.

To analyse the accuracy of the transition model, we also derived the Kullback–Leibler divergence between the next user act distribution $P(a'_u)$ predicted by the learned model and the actual distribution followed by the simulator at a given time, as shown in Figure 6.9. The Kullback–Leibler divergence (Kullback and Leibler, 1951) is a measure of the difference between two probability distributions. Some residual discrepancy is to be expected between these two distributions, the latter being based on the actual user intention (known to the simulator) while the former must infer the intention from the current belief state.

The results in both figures are averaged on 100 simulations.

Analysis of results

The empirical results illustrate that both models are able to capture at least some of the interaction dynamics and achieve higher returns as the number of turns increases, but they do so at different learning rates. In our view, this difference is to be explained by the higher generalisation capacity of the probabilistic rules compared to the unstructured categorical distributions.

One can observe from the empirical results that the Dirichlet parameters associated with the probabilistic rules converge to their final values very rapidly, after a handful of episodes. This is a promising result, since it implies that the learning approach presented in this chapter could in principle optimise dialogue policies from live interactions, without resorting to a user simulator.

One caveat is nevertheless worth mentioning. As described in the previous section, the simulation model used to sample the user intentions and actions is built on a number of structural assumptions to allow for its statistical estimation on a limited amount of Wizard-of-Oz data. The

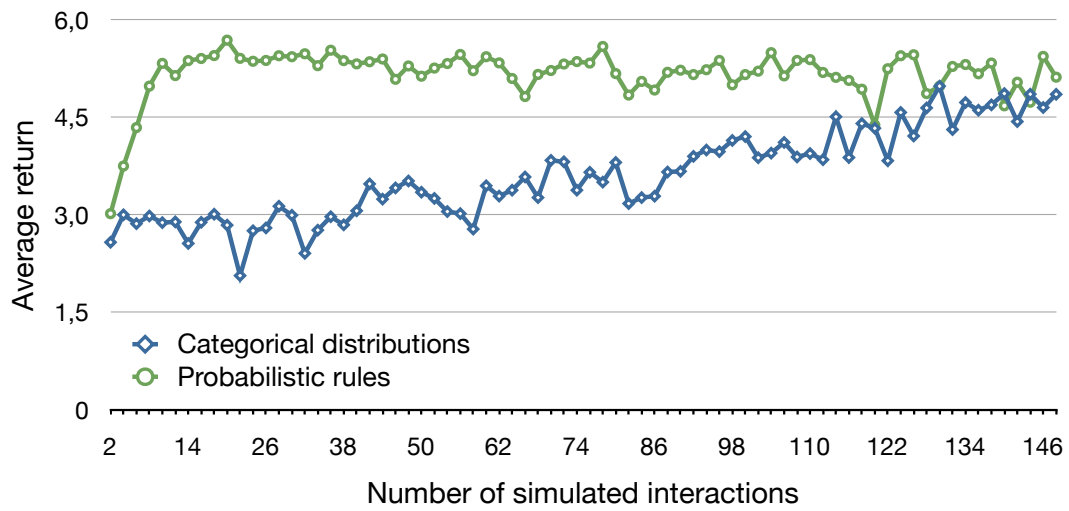


Figure 6.8: Average return as a function of the number of simulated interactions.

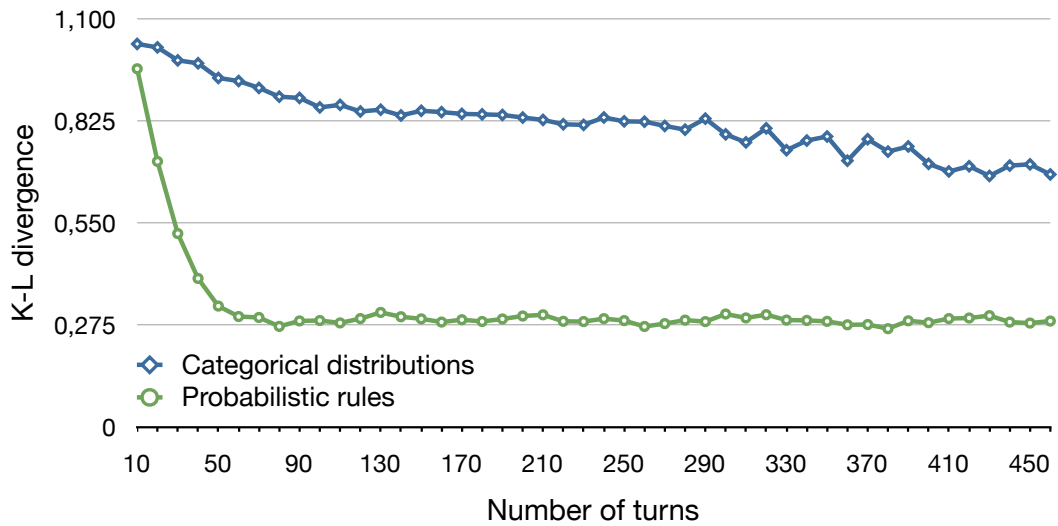


Figure 6.9: Kullback–Leibler divergence between the distribution $P(a'_u)$ estimated from the current model and the actual distribution followed by the simulator.

learning results must therefore be interpreted with caution, as one could reasonably object that the good learning performance of the rule-structured model is an artefact of the regular behaviour exhibited by the simulator, and that such regularities may not be found in genuine, real-world dialogues. This is a valid objection, although the posited assumptions on the user behaviour are relatively conservative and backed by a preliminary analysis of the actual user responses in the Wizard-of-Oz studies. However, we shall see in Chapter 8 that the performance gains demonstrated in this simulated experiment here also carry over to genuine interactions conducted without a simulator.

6.3.4 Second experiment

The first experiment was confined to the analysis of model-based methods to reinforcement learning and did not compare the performance of model-based and model-free approaches to the estimation of rule parameters. This second experiment remedies this shortcoming. As in the previous experiment, the reward model is provided but the transition model is unknown. Both approaches are encoded in this experiment with probabilistic rules.

In the model-free case, the rule parameters encode the action–value model $Q(s, a)$ over the return of state–action pairs, while the model-based case focuses on the transition model $P(s' | a, s)$. Figure 6.10 illustrates these two learning strategies.

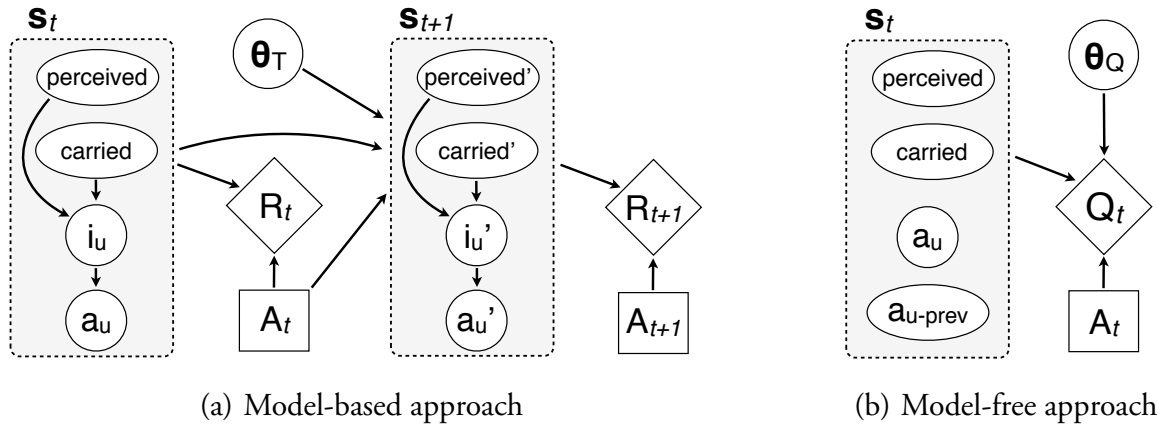


Figure 6.10: Model-based (left) and model-free (right) approaches compared in the experiment.

Model-based approach

The model-based approach is identical to the one presented in the previous experiment. The transition model is thus structured with six rules associated with 13 corresponding Dirichlet parameters of varying dimensions. The Dirichlet parameters are again initialised with weakly informative Dirichlet priors. As for the first experiment, the action selection was performed with an online planner operating with a horizon of 2.

Model-free approach

The model-free approach relied on a utility model structured with 11 probabilistic rules associated with 26 Gaussian parameters. As the model-free approach does not estimate an explicit transition

model of the domain, the user intention is derived via a deterministic rule on the basis of the recent history of dialogue acts. The utility rules stipulate the Q -values of all possible system actions on the basis of this user intention and the general dialogue context. Appendix B (Section B.2) details the content of these rules. The utility parameters are optimised using the SARSA-based reinforcement learning method outlined in this chapter.

Empirical results

The simulator was coupled to the dialogue system to compare the learning performance of the two methods. Figure 6.11 shows the average returns over 100 iterations.

Analysis of results

We can notice in Figure 6.11 that the model-based approach converges to a high-quality policy in fewer episodes than its model-free counterpart. However, this performance comes at the cost of higher computational demands brought about by the need to perform online planning, as evidenced in Figure 6.12 by the roughly similar times required for convergence (around 50 min.). We can also observe that the model-based approach yields slightly higher returns in this experiment, although this difference is harder to explain. One hypothesis is that the model-based approach can accumulate evidence about the underlying user intention in its belief state, while its model-free equivalent lacks an explicit transition model and can therefore only ground its decisions on the history of dialogue acts and objects perceived by the robot.

The results suggest that the model-based approach outperforms the model-free variant in this type of learning contexts. However, this conclusion warrants some cautionary remarks. First, the tractability of the model-based approach is directly dependent on the length of the planning horizon. Domains which call for longer horizons might be better addressed with a model-free strategy due to the exponential growth of the search tree. It should also be noted that the model-based method could rely in this work on the availability of a manually designed reward model. This is not an unreasonable assumption for dialogue domains, as the reward model is often a reflection of the application objectives as specified by the system designer. It may nevertheless be difficult to specify all aspects of the reward model at design time. Whether the results carry over to cases where the reward model must also be (partially or fully) estimated remains an open question.

The model-free approach presented in this experiment only focused on the estimation of the action-value model and did not include a transition model. An interesting idea for future work would be to blend the two optimisation methods and simultaneously estimate a transition model together with the action-value model. Such a hybrid approach would combine the advantages of model-free and model-based strategies. A mixture of offline and online planning (as demonstrated by e.g. Ross and Chaib-draa, 2007) could be used for the action selection.

6.4 Conclusion

This chapter has introduced two alternative Bayesian reinforcement learning techniques to the optimisation of parameters associated with probabilistic rules.

The first technique is a model-based approach that explicitly estimates statistical models of the domain in the form of transition, observation and reward models. The range of possible values

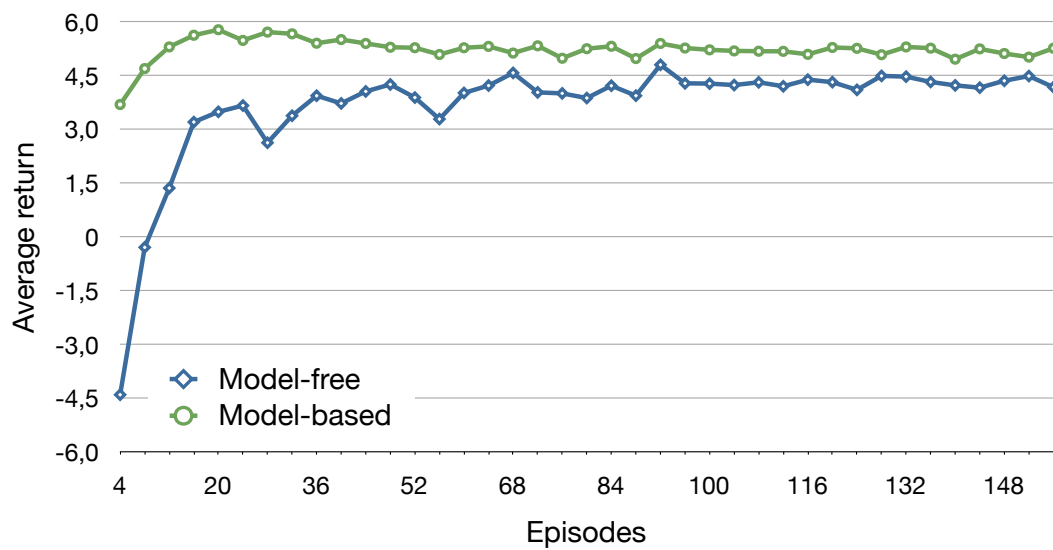


Figure 6.11: Average return as a function of the number of episodes.

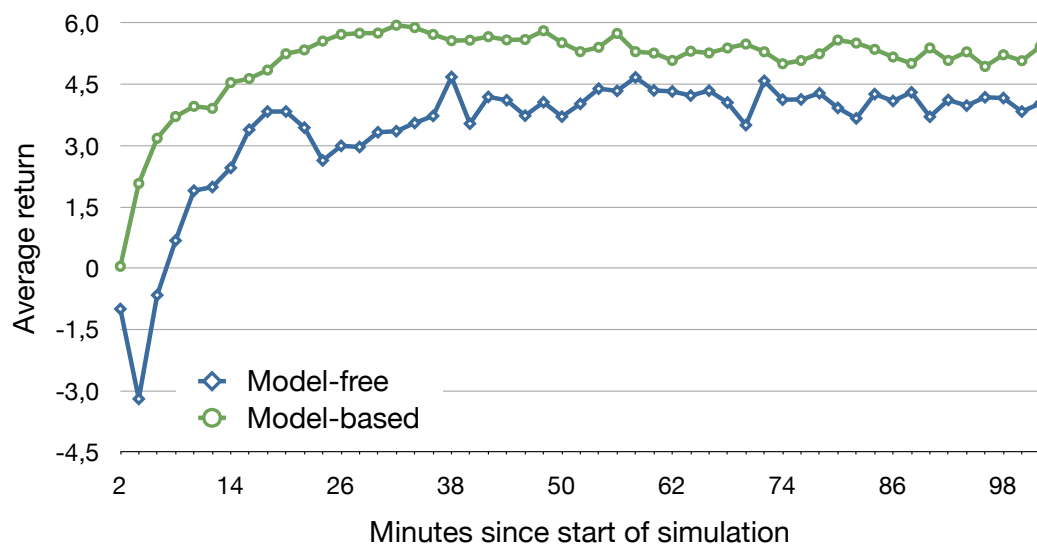


Figure 6.12: Average return as a function of the elapsed time.

for the domain parameters are represented as prior probability distributions that are incrementally updated based on the observations and rewards perceived during the interactions. Action selection is achieved through forward planning on the basis of the current dialogue state and domain parameters. Probabilistic rules are employed to structure the domain models and thereby reduce the number of parameters to optimise.

The second technique is a model-free approach that skips the estimation of the domain models in order to directly construct an action–value model expressing the Q -values of state–action pairs. We described how the action–value model could also be structured with utility rules and optimised through a Bayesian variant of the SARSA learning algorithm combined with ϵ -greedy action selection.

The last section presented two learning experiments conducted in a simulated environment. The simulator was common to both experiments and constructed on the basis of a preliminary Wizard-of-Oz study carried out in a human–robot interaction domain. The simulator included three distinct models, all estimated from the collected Wizard-of-Oz data: a *user model* expressing how the user intentions and dialogue acts are likely to evolve as a function of the system actions, a *context model* expressing the objects in the visual field of the robot as well as the ones carried by the robot, and an *error model* introducing errors and inaccuracies into the generated user input in order to mimic the imperfect nature of speech recognition.

On the basis of this simulator, the first experiment compared the performance of model-based Bayesian reinforcement learning on two alternative formalisations of the transition model. The first formalisation relied on traditional factored distributions, while the second represented the transition model through probability rules. The empirical results showed that the rule-structured model could converge to a high-performing dialogue behaviour – as measured by the average return per interaction – much faster than the baseline.

The second experiment examined the relative performance of model-based and model-free approaches. The two models compared in this experiment were structured with probabilistic rules. The results showed that the model-based approach fared slightly better than its model-free counterpart in terms of average return per interaction. However, we noted that this difference was contingent on particular aspects of the experimental setup such as the length of the planning horizon and the prior availability of a reward model.

The previous and present chapter demonstrated how probabilistic rules can facilitate the optimisation of dialogue policies both in supervised learning and in reinforcement learning. Our experiments have nevertheless so far concentrated on the *learning performance* of rule-structured approaches, and have not yet evaluated the effects of probabilistic rules on practical measures of interaction quality and user satisfaction. Chapter 8 will address this important question. But before doing so, we first discuss the technical implementation of the data structures and algorithms exposed in this thesis. This is the subject of the next chapter.

Chapter 7

Implementation

This chapter outlines the architecture and most important features of the OpenDial toolkit.¹ OpenDial is a Java-based software toolkit developed to construct and evaluate dialogue systems based on probabilistic rules. The toolkit aims to be fully generic and domain-independent, since all domain-specific knowledge is captured in the declarative specification of the dialogue domain.

The toolkit implements all the data structures and algorithms detailed in this thesis and served as our experimental platform to carry out the empirical studies presented in Chapters 5, 6 and 8. Dedicated components have been developed to interface OpenDial with the Nao robotic platform and adapt the architecture to human–robot interaction settings.

The chapter is divided in two sections. The first section focuses on the design of the OpenDial toolkit and describes its general workflow, the specification of dialogue domains in XML, and the concrete implementation of the algorithms employed for approximate inference, sampling and forward planning. We also briefly compare the toolkit to other types of dialogue architectures and discuss its current technical limitations. The second section goes on to explain how the toolkit is integrated and extended into a full-fledged dialogue system for human–robot interaction, describing both the general system structure as well as the individual components developed to control the verbal and non-verbal behaviour of the robot.

7.1 Toolkit design

7.1.1 Generalities

The OpenDial toolkit relies on an event-driven blackboard architecture. Blackboard architectures are widely used in spoken dialogue systems for their ability to handle flexible workflows where multiple modules “cooperate” to interpret the user inputs, maintain a representation of the dialogue state, and decide on the action(s) to perform. In spoken dialogue systems, the blackboard corresponds to the system state, while the modules attached to this blackboard are in charge of specific processing tasks such as speech recognition and understanding, dialogue management, natural language generation and speech synthesis.

¹The name of the toolkit was chosen because of the open design that characterises the framework, and more particularly its extensible, domain-independent architecture with a declarative domain specification.

System scheduling

The modules read and write to the dialogue state in an event-driven manner. After each change, the dialogue state sends an event message to all its attached modules to inform them of the state update. When appropriate, the modules can react to such events and further modify the dialogue state, thereby generating new updates. The process continues until the dialogue state is stabilised.² The OpenDial toolkit allows system modules to run in parallel via multi-threading. The possibility to execute modules in parallel is particularly useful in dialogue systems, as the agent must be able to react to new inputs and contextual changes occurring at any time – even while other modules are still busy processing a previous update. Many of the algorithms developed in the toolkit – such as the ones used for planning and probabilistic inference – also operate in anytime mode, which implies that they can be gracefully interrupted and deliver their outputs at any time.

At the time of writing, the implementation of OpenDial is optimised to run on a single platform.³ Should such a need arise, the framework could be extended to run on multiple platforms, as the blackboard paradigm generally lends itself well to distributed architectures (Corkill, 1989).

Components

The modules connected to the dialogue state in the OpenDial toolkit can be divided into two categories. The first type of module is the rule-structured model already outlined in Section 4.4. A rule-structured model is simply defined as a collection of probabilistic rules together with a list of trigger variables. The update of (at least) one of these trigger variables in the dialogue state results in the instantiation of the probabilistic rules in the dialogue state. In addition to these rule-structured models, the OpenDial toolkit also includes external components such as the speech recogniser, text-to-speech engine and processes for robot perception and control. Given the blackboard architecture of the toolkit, modules can be easily plugged in and out of the system without affecting the rest of the processing pipeline. Similarly to the rule-structured models, external components operate by monitoring the dialogue state and updating it when relevant changes are detected.

In the experiments carried out in this thesis, we found it useful to encode not only dialogue management models with the help of probabilistic rules, but also tasks related to natural language understanding and generation. As argued in Lison (2012a), the expressive power of probabilistic rules allows them to capture the structure of many dialogue processing tasks, not necessarily confined to dialogue management. However, the parameters of the NLU and NLG models are hand-crafted since they do not directly constitute the focus of our work.

Compared to traditional architectures in which the components are developed separately and rely on ad hoc representation formats, the use of a shared description formalism (probabilistic rules) to encode multiple reasoning tasks offers several advantages:

- *Transparency*: The reliance on a common representation format provides a unified, transparent semantics for the dialogue state, since all state variables are described and related to one another through a principled framework grounded in probabilistic modelling. This makes it possible to derive a semantic interpretation for the dialogue state as a whole, in terms of a joint probability distribution over the state variables.

²Recall that a model can only be applied once per update to avoid infinite cycles (cf. Algorithm 6).

³System modules can, however, remotely connect to external resources on the robotic platform to perform tasks related to robot perception and motor control, as explained in Section 7.2.

- *Domain portability*: As most domain-specific knowledge is declaratively specified in the rules, the system architecture is essentially reduced to a generic platform for rule instantiation and probabilistic inference. This declarative design greatly enhances the system portability across domains, since adapting a system to a new domain only requires a rewrite or extension of the domain-specific rules, without having to reconfigure or re-develop other components. This stands in sharp contrast with “black-box” types of architectures where much of the task- and domain-specific knowledge is encoded in procedural form buried inside the implementation of the system components.
- *Flexible workflow*: Probabilistic rules allow for very flexible processing pipelines where state variables are allowed to depend or influence each other in any order and direction. New rule-structured models can be easily inserted or extended without requiring any change to the underlying platform. Furthermore, several models can be triggered concurrently on the same input/output variables. As we have seen in Section 4.3.1, output distributions can indeed depend on an arbitrary number of rule nodes and handle effects arising from multiple, sometimes conflicting sources. This allows the system to take advantage of multiple, complementary processing strategies while ensuring that the representation of the dialogue state as a whole remains consistent.
- *Joint optimisation*: Finally, the use of a unified formalism allows domain models to be optimised jointly instead of being tuned in isolation from one another. Joint optimisation has recently gained much attention in the dialogue systems community to overcome the fragmentation of current system architectures and attempt to directly optimise the end-to-end conversational behaviour of the system (see also Lemon, 2011).

Despite these merits, probabilistic rules cannot naturally model all dialogue reasoning tasks. Modules such as speech recognition or speech synthesis depend in particular on external resources and processes and must be integrated separately in the system. The OpenDial toolkit is designed to incorporate both rule-structured models and external components in its architecture.

7.1.2 Specification of dialogue domains

Dialogue domains

As already mentioned in Section 4.4, a dialogue domain is represented in OpenDial by a pair $\langle \mathcal{B}_0, \mathcal{M} \rangle$ defined by an initial dialogue state \mathcal{B}_0 and a set of models \mathcal{M} , each model being itself composed of a collection of probability or utility rules. Dialogue domains are encoded in an XML format⁴ with a syntax specifically designed for the toolkit.

In practice, the specification of a dialogue domain in XML takes the following form:

```
<domain>
  <initialstate>
    <!-- initial state variable values -->
  </initialstate>
```

⁴XML (Extensible Markup Language) is a general-purpose markup language for encoding and exchanging documents, as specified by the World Wide Web Consortium (W3C), cf. <http://w3.org/xml>.

```

<model trigger="trigger variable(s) for model 1">
  <!-- rules for model 1 -->
</model>

...

<model trigger="trigger variable(s) for model n">
  <!-- rules for model n -->
</model>

</domain>

```

The initial dialogue state is represented as a list of state variables, each being associated with a particular probability distribution. Most state variables are defined by a categorical distribution, according to the following skeleton:

```

<variable id="variable name">
  <value prob="probability for first value">first value</value>
  <value prob="probability for second value">second value</value>
  ...
  <value prob="probability for nth value">nth value</value>
</variable>

```

State variables defined over continuous ranges can also be encoded with probability density functions. In such a case, the state variable is defined by a particular distribution family and a specification of parameters associated with that family.

Probabilistic rules

Each model specification encompasses a number of probability or utility rules. Listing 7.1 illustrates an example of an XML specification for a probability rule. The rule expresses the probability of the user intention *Release*(X), which corresponds to the action of putting down a carried object X onto the ground. The probability of this user intention is naturally dependent on the completion status of the previous task and on whether the object X is currently carried by the robot.

Each rule is divided in a number of cases, each containing a (possibly empty) condition and a set of (possibly empty) effects. Conditions can include several sub-conditions combined by conjunction or disjunction operators (the default operator being a conjunction). Each basic condition is denoted by an “if” element and is composed of three attributes: a variable label, a value, and a binary relation that must hold between the variable and the value. The default relation is equality, but relations may also correspond to inequalities (\neq , $<$ and $>$), set inclusion (\in and \notin) or string matching operations. More complex logical constructions with nested conjunctions, disjunctions and negation operators are encoded via additional XML markup (not shown in the example).

Effects are associated with probabilities that can either be fixed or correspond to parameters to learn such as the Dirichlet distributions θ_{release1} and θ_{release2} in the example. Although the effects in the example only have one single output variable, rules are allowed to include multiple “set” elements to express complex effects ranging over more than one output variable. Universally quantified variables such as X are wrapped in curly brackets $\{ \}$ to distinguish them from the rest of the text. These variables can occur in both the conditions and effects of the rule.

Utility rules are defined in the same manner. An example of a utility rule specified in XML is given in Listing 7.2. The rule defines the utility of asking the user to confirm the last system

action *Demonstrate*(X) after a certain amount of silence, divided here in three cases (between one and two seconds, between two and three seconds, and after three seconds). Three utility parameters θ_{confirm1} , θ_{confirm2} and θ_{confirm3} are associated with the utility rule. A universally quantified variable X is also employed here to generalise the rule to arbitrary arguments for the system action $a_m = \text{Demonstrate}(X)$.

Parameters

When operating in learning mode, dialogue domains must be associated with parameter variables defined together with their prior probability distribution. This prior can take the form of a categorical, Dirichlet, Gaussian or uniform distribution. As an illustration, the prior distribution for the parameter variable $\theta_{\text{release1}} \sim \text{Dirichlet}(1, 2)$ is specified as:

```
<variable id="theta_release1">
  <distrib type="dirichlet">
    <alpha>1</alpha>
    <alpha>2</alpha>
  </distrib>
</variable>
```

Other types of prior distributions are defined in a similar manner.

7.1.3 Core algorithms

We survey below a number of technical aspects related to the OpenDial implementation of the core algorithms presented through this thesis.

Inference

Probabilistic inference forms a key element in the state update process. Two distinct types of inference algorithms are implemented in OpenDial:

1. The first is variable elimination, which is an exact inference method initially developed by Zhang and Poole (1996). The algorithm operates by manipulating matrices through summation and pointwise products. The particular implementation of this algorithm in OpenDial follows the method presented in (Koller and Friedman, 2009, p. 1101), which generalises classical variable elimination to decision networks.
2. The second inference algorithm is likelihood weighting, which is an approximate inference method relying on importance sampling. As explained in Section 3.1.2, likelihood weighting generates samples based on the topological ordering of the graphical model. Each sample is associated with a particular weight that represents its likelihood in the light of the provided evidence. The final estimates correspond to the weighted averages of the samples.

Each inference algorithm has its own strengths and weaknesses. Variable elimination is able to deliver provably exact results and is often the most efficient inference method for small graphical models. However, variable elimination suffers from scalability problems when applied to models that are densely interconnected and/or include continuous variables. Likelihood weighting is easier

```

<rule>
  <case>
    <condition>
      <if var="completed-task" value="true" />
      <if var="carried" value="{X}" relation="contains" />
    </condition>
    <effect prob="theta_release1[0]">
      <set var="i_u" value="Release({X})" />
    </effect>
    <effect prob="theta_release1[1]" />
  </case>
  <case>
    <condition>
      <if var="completed-task" value="true" />
    </condition>
    <effect prob="theta_release2[0]">
      <set var="i_u" value="Release({X})" />
    </effect>
    <effect prob="theta_release2[1]" />
  </case>
</rule>

```

Listing 7.1: Example of probability rule in XML format.

```

<rule>
  <case>
    <condition>
      <if var="silence" value="3" relation=">" />
      <if var="a_m" value="Demonstrate({X})" />
    </condition>
    <effect utility="theta_confirm1">
      <set var="a_m" value="AskConfirmation" />
    </effect>
  </case>
  <case>
    <condition>
      <if var="silence" value="2" relation=">" />
      <if var="a_m" value="Demonstrate({X})" />
    </condition>
    <effect utility="theta_confirm2">
      <set var="a_m" value="AskConfirmation" />
    </effect>
  </case>
  <case>
    <condition>
      <if var="silence" value="1" relation=">" />
      <if var="a_m" value="Demonstrate({X})" />
    </condition>
    <effect utility="theta_confirm2">
      <set var="a_m" value="AskConfirmation" />
    </effect>
  </case>
</rule>

```

Listing 7.2: Example of utility rule in XML format.

to scale to larger networks and can be straightforwardly applied to hybrid models with both discrete and continuous variables. However, large numbers of samples are required to reach reasonably accurate estimates.

In order to bring together the best of both approaches, a switching mechanism has been integrated to OpenDial to automatically select the inference method that is best suited to each probabilistic query. The mechanism proceeds as follows. For each probabilistic query, three elements are extracted: the maximum branching factor of the network, the number of continuous variables, and the number of variables specified in the query. These elements are then matched against predefined thresholds. If at least one threshold is exceeded, likelihood weighting is selected to perform the inference, while variable elimination is chosen in the remaining cases.

Sampling techniques

The use of likelihood weighting necessitates the implementation of efficient sampling techniques for each possible probability distribution. We describe below the sampling methods employed in OpenDial to efficiently draw values from both discrete and continuous distributions:

- *Categorical distributions*: Sampling a categorical distribution is done through inverse random sampling, following the method described in Koller and Friedman (2009, p. 489). When constructing the distribution, the variable values are sorted according to lexicographic order, and a cumulative density function (CDF) calculated relative to this order. Sample values are then extracted at runtime by (1) generating a pseudo-random float number between 0 and 1 and (2) locating the greatest number in the CDF that is less than or equal to the number just generated. Operation (2) is done via binary search. The value indexed by this number is then selected as the sample.
- *Uniform distributions*: Uniform distributions are directly sampled as $g(b - a) + a$, where g is a pseudo-random number between 0 and 1, and a, b are the distribution boundaries.
- *Normal distributions*: Normal distributions are sampled in OpenDial via the well-known Box-Muller method (Box and Muller, 1958), which derives two sample values for a given normal distribution based on two pseudo-random numbers.
- *Dirichlet distributions*: Sampling Dirichlet distributions relies on a slightly more intricate procedure based on Gamma sampling. The first step is to derive K samples from $\text{Gamma}(\alpha_i, 1)$ with K denoting the dimension of the Dirichlet and $1 \leq i \leq K$. This sampling procedure is implemented in OpenDial using the method presented in Cheng and Feast (1979). The sampled Dirichlet value is then defined as $[x_1, \dots, x_K]$ where $x_i = \frac{y_i}{\sum_{j=1}^K y_j}$ and y_i is the sampled Gamma value for dimension i .
- *Kernel distributions*: We sample non-parametric distributions defined via kernel density estimation (KDE) in two steps. The first is to draw at random one point x_i from the set of points x_1, \dots, x_n included in the KDE. A value is then drawn from the kernel associated with the point. In our case, this corresponds to drawing a sample from the normal distribution $\mathcal{N}(x_i, h)$ centred at x_i and of variance h (the bandwidth).

Online planning

The implementation of the forward planning algorithm closely follows the procedure outlined in Section 6.2.1. The search tree is constructed in a breadth-first manner, until either the planning horizon has been reached or the planner has run out of time. The latter condition relies on a time-out function to ensure that the planner does not exceed specific time limits.

In order to generate a set of possible observations in a given state \mathcal{B} (line 6 of Algorithm 12), the planner locates all predictive state variables (denoted with a superscript p) currently present in the dialogue state and draws a sample value for each. In the experiment presented in Section 6.3, the predictive variable corresponds to the next user action, and the generated observations will therefore reflect possible values for this user action.

For tractability reasons, OpenDial limits the maximum number of actions and observations that are branched out at each point in the search tree. The actions are selected on the basis of their reward values in the current state – i.e. only the n actions with highest reward are selected, with n corresponding to an arbitrary threshold. The observations are filtered based on their likelihood of occurrence. The planner thus only expands the tree with the m most likely observations, where m is another threshold. The two thresholds are currently manually tuned, but could in principle correspond to additional parameters to optimise during learning.

7.1.4 Comparison with other architectures

The construction of generic, domain-independent architectures is a recurring theme in dialogue systems research, and there is a clear trend towards the development of platforms composed of more generic or reusable components. We present below the most important architectures currently deployed and contrast their design with the one followed in the OpenDial toolkit. Finally, we discuss the current limitations of the presented framework.

Existing software frameworks

Information state approaches are closely related to the framework presented in this thesis. The TrindiKit architecture presented by Larsson and Traum (2000) relies on a shared information state accessed by various system modules and a rich repository of rules. A control module is in charge of the system scheduling for the whole architecture. The system modules can also connect to external resources such as databases and plan libraries. The TrindiKit is a platform for constructing and evaluating dialogue engines and is designed to be fully domain-independent. The related DIPPER architecture described in Bos et al. (2003) is built on similar principles as the TrindiKit, but simplifies the architecture and the encoding format for the update rules. DIPPER employs the Open Agent Architecture as its communication protocol.

The idea of domain independence is also taken up by plan-based approaches such as TRIPS (The Rochester Interactive Planning System, cf. Allen et al., 2000). TRIPS uses an agent-oriented architecture comprising multiple modules working together to recognise the intentions of the human user and fulfilling the system goals. Most reasoning tasks are explicitly cast as planning problems, from high-level planning to response planning and surface realisation.

One of the most mature platforms for prototyping dialogue systems is Olympus and its associated dialogue management framework, called Ravenclaw (Bohus et al., 2007; Bohus and Rudnicky,

2009). The Olympus architecture is built on top of a centralised message-passing infrastructure in which modules can be plugged in and out to suit the needs of the application. Ravenclaw is a plan-based, task-independent dialogue engine which is fully integrated in Olympus. Ravenclaw supports mixed-initiative interaction and integrates dedicated functions for error handling, timing and turn-taking. Action selection is based on a hierarchical decomposition of tasks whose execution is sequentially ordered using an agenda structure.

The agent-based Jaspis architecture (Turunen, 2004) also has multiple points of contact with the OpenDial toolkit, as it similarly revolves around a shared representation of the system state. Jaspis components are themselves split into agents (in charge of decision-making), evaluators (in charge of selecting the most suitable agent in a particular situation) and managers (in charge of the general coordination of the components). Jaspis is designed to allow for distributed processing with dedicated mechanisms for the coordination and synchronisation of concurrent modules. The architecture also aims to facilitate system-level adaptivity. Compared to the OpenDial toolkit, Jaspis offers more advanced support for distributed and parallel setups, but at the cost of an increased system complexity.

Most MDP and POMDP-based dialogue architectures line up system components in a single processing sequence. The prototype systems developed for the TALK and CLASSIC projects (Henderson et al., 2008; Lemon and Pietquin, 2012) and the related BUDS POMDP system⁵ are structured into pipelines where each component takes a probability distribution over input hypotheses and generates another distribution over possible outputs.

Comparison and discussion

The OpenDial toolkit can be seen as an attempt to combine the flexibility of information state architectures with the robustness and adaptivity of statistically optimised dialogue systems. In line with logic-based approaches (e.g. TrindiKit, DIPPER, TRIPS, Olympus/Ravenclaw, and Jaspis), the workflow of OpenDial is designed to allow for multiple processing paths and context-sensitive reasoning strategies. And in line with MDP and POMDP-based approaches, the toolkit is also able to explicitly handle uncertain knowledge and stochastic relations between variables thanks to its probabilistic representation of the system state, as well as its ability to optimise domain models from interaction data via statistical inference.

The idea of combining statistical and symbolic approaches to dialogue processing is certainly not novel in the literature on spoken dialogue systems. In many of the aforementioned dialogue architectures, probabilistic reasoning techniques already coexist with classical symbolic components operating with deterministic inputs. Very often, this integration of heterogeneous statistical and symbolic components is achieved by reducing N-best lists to their single most likely hypothesis. However, an important drawback of such an approach is the substantial loss of information that results from this reduction. For instance, speech recognition typically provides explicit measures of uncertainty in the form of e.g. confidence scores, but these confidence measures are often lost at higher reasoning stages such as syntactic parsing, semantic interpretation and dialogue management.

One can also observe some design differences in the representation of the action selection process. Many dialogue architectures indeed decompose dialogue management into two or more dis-

⁵Bayesian Update of Dialogue State, cf. <http://mi.eng.cam.ac.uk/~mh521/nipsdemo12/>

tinct behavioural layers. The Olympus framework incorporates for instance both an interaction manager in charge of the low-level control of the conversational floor, and a dialogue manager in charge of higher-level dialogue decisions. The TRIPS architecture similarly divides dialogue management in a cluster of modules encompassing discourse management, discourse context management, plan management, and a behavioural agent in charge of controlling the overall behaviour. The OpenDial toolkit leaves by comparison the system designer free to frame decision-making in one, two or more layers, depending on the particular needs of the domain.⁶

The declarative specification of the dialogue domain in terms of rule-structured models facilitates a modular design of the system's internal knowledge base. The formalism of probabilistic rules is sufficiently general to encode a broad range of dialogue models, from highly domain-specific constraints and heuristics to more generic conversational skills. However, in contrast to frameworks such as Olympus/Ravenclaw, OpenDial leaves the distinction between domain-specific and domain-independent models entirely into the hands of the system designer and does not enforce a particular decomposition between these two types of specifications at the architectural level. Similarly, OpenDial does not commit to a particular encoding of the common ground or to a specific grounding strategy. However, the expressive power of probabilistic rules (and their support of logical operators) allows them to capture rich representations of the interaction dynamics – including grounding phenomena – and their effects on the dialogue state.

Limitations

One important aspect of dialogue architectures that has not really been covered in this work is the question of incremental processing. As explained in the background chapter, dialogue processing should ideally be performed incrementally and output partial hypotheses as early as possible in the system workflow. The InproTK architecture presented by Baumann and Schlangen (2012) and Baumann (2013) is specifically designed to support across-the-board incremental processing, from speech recognition to dialogue management and speech synthesis. Although the current implementation of OpenDial cannot claim to be incremental, we do nevertheless hypothesise that the formalism of probabilistic rules could be extended to allow for incremental processing without major difficulties, since the chain of related hypotheses is already explicitly captured in the conditional dependencies generated by the instantiated rules. An update in the probability distribution over some observations (e.g. the user utterance) is therefore automatically reflected in all hypotheses that depend on it (e.g. the corresponding user intention). Modifying the state update algorithm to run in a fully incremental manner without hampering the system performance is, however, a non-trivial engineering task, which could constitute an interesting topic for future work. Similarly, the turn-taking behaviour integrated in OpenDial remains relatively rudimentary and could certainly be improved to allow for e.g. interruptions and fragmented utterances.

While the dialogue system employed for our experiments does include several modules for robot perception and control (cf. next section), the toolkit does not yet support full-scale multi-modal processing, as such extensions would require the integration of dedicated mechanisms for information fusion and fission in the architecture. Our own previous work on situated human-robot interaction (Kruijff et al., 2010) illustrates how dialogue processing can be coupled to sensorimotor

⁶This can be practically realised by creating distinct utility models for action selection. Hierarchical decision policies can notably be captured by lining up utility models in a top-down cascade of triggers.

components in a bidirectional manner.

On a more practical note, it should finally be pointed out that OpenDial is at the time of writing at an early stage of development and does not benefit from the years of incremental refactoring and testing shown by more mature architectures such as TrindiKit or Olympus/Ravenclaw. Further development work is certainly needed to move OpenDial from being an advanced research prototype to a stable, robust platform capable of being deployed in any application domain. Of special importance is the integration of user-friendly authoring tools to allow human designers to write, organise and evaluate rule-structured dialogue domains without having to delve into the technical intricacies of XML syntax. OpenDial would also certainly benefit from more advanced performance tuning to enhance the system reactivity and scalability to larger domains.

7.2 System integration

The OpenDial toolkit was used as a software foundation to construct a concrete, end-to-end dialogue system for human–robot interaction. We detail in the next pages the practical design of this dialogue system as well as the graphical user interface implemented to monitor and control the system behaviour (and its internal dialogue state) in real-time.

7.2.1 Architecture

In addition to the OpenDial core components, the dialogue system employed in our experiments also included specific modules for speech recognition and synthesis, robot perception and motor control. The generic architecture for the system is shown in Figure 7.1.

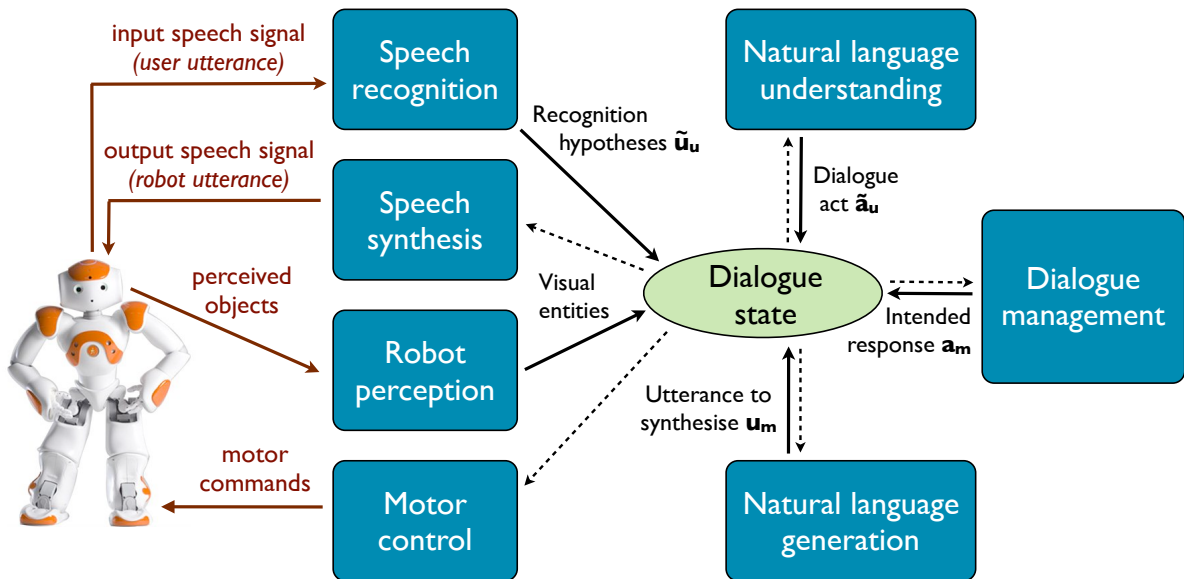


Figure 7.1: Generic system architecture employed in the experiments. The dialogue state serves as a central hub for the various modules reading and writing to it upon relevant changes.

The system modules can operate in either synchronous or asynchronous mode:

- Synchronous modules continuously monitor the dialogue state for relevant changes. Their activation is thus performed in synchrony with the update events generated by the dialogue state.
- Asynchronous modules run independently of the dialogue state. They typically relate to visual or speech perception tasks. Asynchronous modules update the dialogue state as soon as new observations are made available.

All modules have access to the complete dialogue state and can therefore exploit the full set of state variables (including generic contextual information) in their processing.

7.2.2 Individual modules

We describe below the modules shown in Figure 7.1 and explain their role and internal structure. It should be emphasised that the focus of the present thesis is on dialogue management. The other system modules are therefore deliberately limited to simple, “shallow” processing methods in order to concentrate the implementation efforts on the dialogue manager.

Speech recognition

Speech recognition is performed on the robot platform, using a commercial, off-the-shelf speech recognition engine (Vocon 3200 from Nuance). Four microphones placed on the robot head are used for the sound capture. The placement of the microphones on the robot allows the user to interact with the robot in a natural manner, without needing to resort to head-mounted microphones. This advantage comes, however, at the price of a lower sound quality due to the larger (and varying) distance between the sound source and the microphones. This distance between source and receiver is indeed a major degradation factor in speech recognition (Wölfel and McDonough, 2009). Moreover, the microphones are also adjacent to a number of mechanical motors that may disturb the sound signal and lead to spurious detections.

The acoustic model employed in all experiments is based on U.S. English. The language model takes the form of context-free recognition grammars in Bachus-Naur Form. Distinct grammars were used to cover the domain of discourse of each experiment. The grammars were designed by hand, based on the Wizard-of-Oz transcripts collected in our empirical studies (cf. previous chapters). Grammars can be dynamically attached or removed from the engine at runtime, thereby allowing the system to adapt the language model of the recogniser to the current dialogue context. Although this functionality is not directly exploited in the current implementation, we have shown in previous work (see Lison, 2010a) that such a dynamic model adaptation could lead to significant improvements in recognition accuracy for human–robot interaction settings, and would therefore constitute an interesting direction for the future development of the system. As the recognition engine only generates hypotheses with raw, unnormalised confidence scores, a normalisation routine is used to convert them to well-formed probability distributions.⁷

⁷The conversion between confidence scores and proper probabilities is manually tuned in the current setup. Future work may rely on more principled estimation techniques such as the ones outlined in Williams (2008a).

Natural language understanding

The goal of natural language understanding (NLU) is to map a collection of utterance hypotheses \tilde{u}_u to a corresponding set of dialogue act hypotheses \tilde{a}_u expressing the semantic and pragmatic content of the user input. This understanding step is decomposed in our implementation in two tasks, dialogue act recognition and visual reference resolution.

The goal of dialogue act recognition is to construct the logical form representing the pragmatic meaning of the utterance. One should note that user utterances may contain more than one dialogue act, as for instance in “yes and now pick the blue object” including both a backward-looking function (a confirmation) and a forward-looking function (a new instruction). A collection of domain-specific templates was designed by hand to convert surface forms into logical representations of dialogue acts. Although this approach does not allow for “deep” semantic extraction, it was shown to perform well in our dialogue domains. Future work may replace this template-based method with a data-driven semantic parser based on e.g. dependency parsing (Nivre et al., 2007).

Reference resolution is used to map linguistic expressions referring to objects in the visual context to their corresponding object identifier. The properties stated in the linguistic expressions are first matched against the set of possible references. If the description remains ambiguous (i.e. more than one object matches the linguistic expression), the references can be further ranked according to their visual saliency, defined in terms of their physical distance to the robot. The pronoun “it” is resolved by searching for the closest object reference in the dialogue history.

Natural language understanding is practically implemented in OpenDial via probability rules. As seen in Section 4.5, the formalism of probabilistic rules already includes special-purpose operators for string manipulation and can thus readily encode the shallow templates used for dialogue act recognition. Rule r_{15} below is an example of such a rule. The rule lists three regular expression patterns associated with the dialogue act MoveArm(Left, Down). If the value for the user utterance variable u_u matches at least one of the patterns, the dialogue act a_u is classified as MoveArm(Left, Down):

$$\begin{aligned} r_{15} : & \text{if } (u_u \text{ matches “(*) left arm down”}) \\ & \vee (u_u \text{ matches “(*) lower (the | your) left arm”}) \\ & \vee (u_u \text{ matches “(*) down (the | your) left arm”}) \text{ then} \\ & \left\{ P(a'_u = \text{MoveArm(Left, Down)}) = 1.0 \right. \end{aligned}$$

Dialogue management

Dialogue management follows the procedure outlined in the previous chapters and will not be repeated here. For each update of the dialogue state, the dialogue manager triggers the corresponding rule-structured models, and selects the next action to perform (if any).

Natural language generation

If the system action selected by the dialogue manager is non-empty and denotes a verbal action, the natural language generation module is triggered. As for natural language understanding, the generation component of OpenDial is based on a manually designed collection of templates. The

processing direction is the reverse of natural language understanding, as the templates are applied to convert a logical representation of the communicative goal into a surface form.

The generation templates are also encoded with a rule-structured model. The rules correspond here to utility rules, since natural language generation is at its core a decision-making task corresponding to the choice of a particular linguistic realisation for the intended communicative goal. As an example, rule r_{16} generates the system response u_m given the system act $a_m = \text{Acknowledgement}$. The rule specifies in this case three alternatives with equal utility:

$$r_{16} : \text{if } (a_m = \text{Acknowledgement}) \text{ then} \\ \left\{ \begin{array}{l} U(u'_m = \text{"ok"}) = 1 \\ U(u_m = \text{"great"}) = 1 \\ U(u'_m = \text{"thanks"}) = 1 \end{array} \right.$$

The presence of multiple realisations allows for some variation in the system behaviour, since the system will automatically select one realisation at random due to the uniform utility assigned to the alternative realisations.

Speech synthesis

Speech synthesis is performed on the robot, using an off-the-shelf speech synthesis engine developed by Acapela⁸. The synthesis engine is based on unit selection. The output speech signal is then sent to two speakers placed on the robot head. To avoid spurious recognition results, speech recognition is automatically disabled when the robot is speaking.

Robot perception

The robot can detect simple physical objects present in the visual scene. The object detection is done based on the vision libraries bundled with the robotic platform. Special markings are placed on top of the objects to facilitate the object recognition and the visual servoing.

Robot motion control

Various types of physical movements were engineered for the purpose of our experiments, including:

- generic body movements: rotating the arms and the head in various directions,
- spatial navigation: moving forward and backward, turning left and right,
- object manipulation: grasping and releasing objects.

All the movements were programmed using the motion control libraries available on the robot. The object manipulation relies on the use of permanent magnets attached to the robot hands.

⁸<http://www.acapela-group.com>

7.2.3 Graphical interface

The graphical user interface developed for the OpenDial toolkit enables the system designer to monitor and control in real-time the state of the system. The interface is divided in two views, shown as distinct tabs in the application window: the chat window and the dialogue state monitor.

Chat window

The main user interface displays the interaction history as a chat window, as illustrated by the screen capture in Figure 7.2.

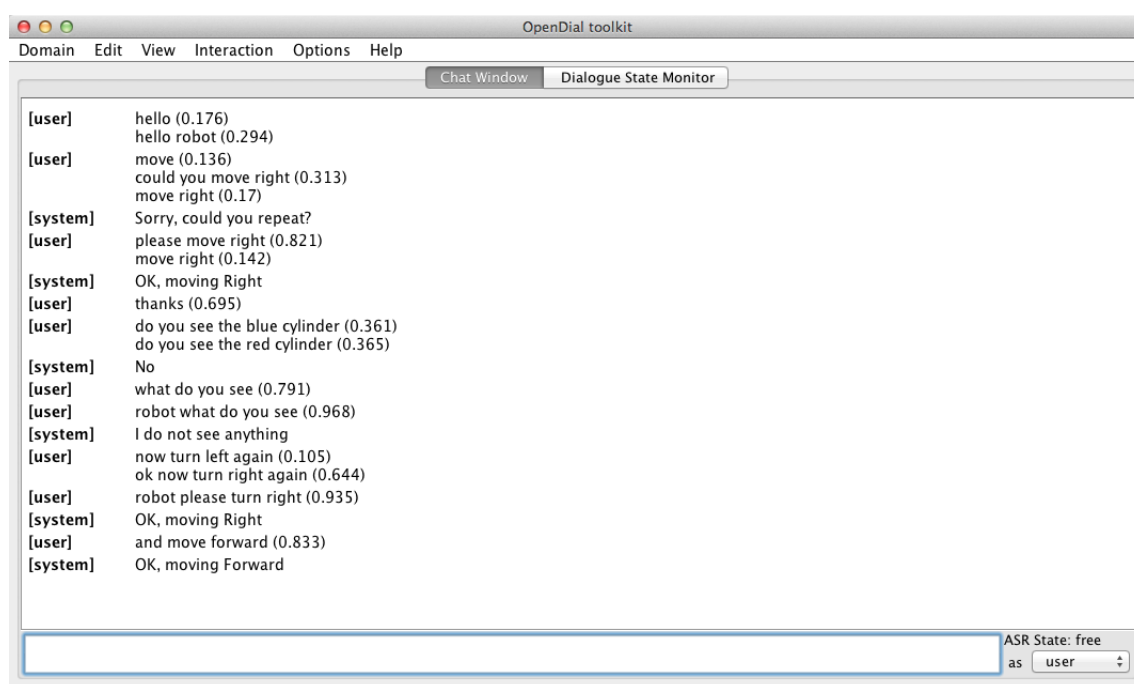


Figure 7.2: Graphical user interface showing the interaction history.

The user inputs are displayed as N-best lists together with their corresponding probabilities. In addition to monitoring the interaction, the chat window can also be used to test the dialogue system by typing new user and system inputs in the input field at the bottom of the window. A drop-down field in the bottom right corner is used to switch the agent role (e.g. for Wizard-of-Oz experiments).

Dialogue state monitor

To allow the system designer to easily inspect the content of the dialogue state, a state visualisation tool has also been integrated into OpenDial. The monitor provides a visual representation of the dialogue state in the form of a directed graph with nodes corresponding to the state variables and directed edges corresponding to conditional dependencies.⁹ An example of a graph layout is shown in Figure 7.3. The graph is dynamically refreshed after each update of the dialogue state, using graph drawing algorithms to optimise the layout of nodes on the screen.

⁹The graphs are rendered with JUNG, an open source toolkit for drawing graphs: <http://jung.sourceforge.net>.

In addition to depicting the current dialogue state, the monitor also records and stores previous dialogue states. The dialogue state to visualise can be selected among the list on the left side of the window. This functionality is particularly useful to compare dialogue states with one another and analyse how the dialogue state is evolving over time.

The user can manipulate the graph in multiple ways in order to e.g. analyse the content of specific state variables, add or remove evidence, or request the calculation of marginal distributions on a selected set of variables. The inference results are in this case shown in the text area at the bottom of the window. In addition, the system designer can also zoom in on selected probability distributions using the distribution viewer tool illustrated in Figure 7.4. Discrete probability distributions are shown as histograms, while continuous probability distributions are represented by their probability density functions.¹⁰

7.3 Conclusion

This chapter exposed the practical integration of our structured modelling framework in the OpenDial toolkit and its instantiation in a spoken dialogue system for human–robot interaction. The first section presented the general architecture of the toolkit, the declarative specification of dialogue domains in an XML format, and the implementation of efficient algorithms for inference, sampling and planning. We discussed the benefits of using a shared description formalism in terms of transparency, portability, flexibility and adaptivity over traditional “black-box” architectures. We also compared OpenDial to other existing architectures and pointed out a number of limitations in the current implementation of the toolkit, such as its lack of incremental processing and its limited turn-taking behaviour.

The OpenDial toolkit is inspired by both symbolic and statistical approaches to dialogue, and combines an information state architecture with probabilistic reasoning based on rule-structured models. As stated in the introduction chapter, the long-term goal of the OpenDial framework is to bridge the gap between symbolic approaches to dialogue management, which usually concentrate on capturing rich interaction patterns, and probabilistic approaches, more focused on aspects related to noise, uncertainty, and adaptivity.

The hybrid design of OpenDial allows system designers to exploit powerful generalisations in the dialogue domain specification without sacrificing the probabilistic nature of the model. Another important side benefit of probabilistic rules is their improved readability for human experts, which are able to leverage their domain knowledge in the form of pragmatic rules, common sense assumptions, or task-specific constraints. Furthermore, the internal organisation of rules into models enables dialogue domains to be specified in a modular fashion, by clustering rules into distinct models. Some models may therefore reflect highly domain-specific knowledge while others encode generic interaction patterns that can easily be ported to other applications.

The last section described the integrated dialogue system used to carry out the practical experiments presented in Chapters 5, 6 and 8. The system comprised both synchronous and asynchronous components and included dedicated modules for speech recognition, speech synthesis, robot perception and motor control. Natural language understanding, dialogue management and natural language generation were encoded with models structured with probability rules.

¹⁰The probability distributions are rendered with the open source toolkit JFreeChart: <http://jfreechart.sourceforge.net>.

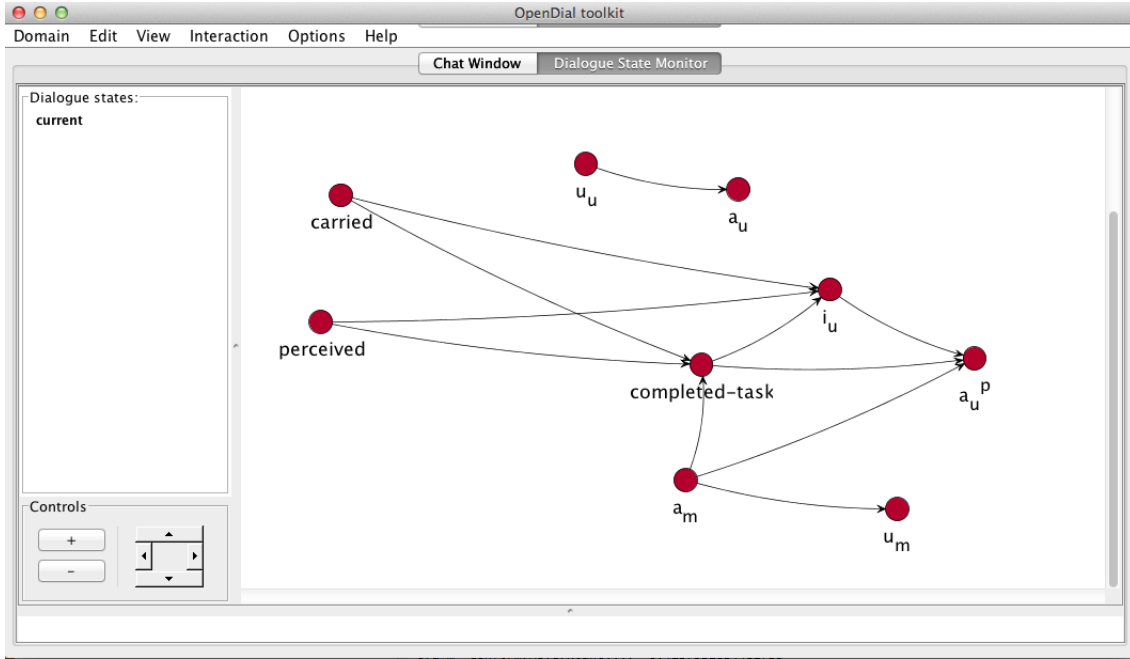


Figure 7.3: Visualisation of the current dialogue state.

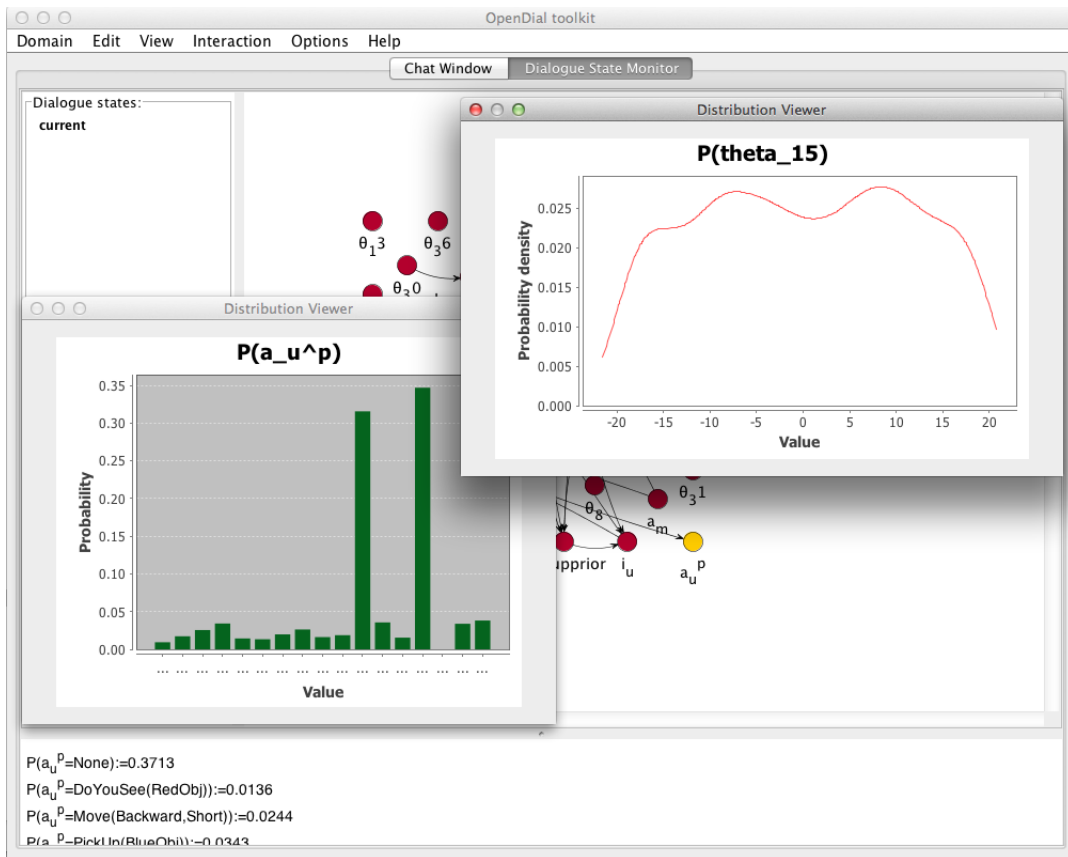


Figure 7.4: Visualisation of a discrete probability distribution $P(a_u^p)$ and a continuous probability distribution $P(\theta_{15})$ in the dialogue state monitor.

The next chapter demonstrates the practical deployment of this system in a full-scale user evaluation study.

Chapter 8

User evaluation

This chapter presents the last (and most extensive) experiment carried out in this thesis. The empirical studies described so far in Chapters 5 and 6 essentially focused on the learning performance of rule-structured models compared to more classical representations. However, although such experiments can provide useful insights about the model adequacy for various dialogue domains, they are not by themselves sufficient to assess the suitability of a particular modelling approach and its practical effects on the quality of the produced interactions.

In order to corroborate our claims regarding the benefits of probabilistic rules in dialogue management and contrast them with traditional methods, we conducted a user evaluation experiment with a total of 37 users. The aim of the experiment was to compare three alternative approaches to dialogue management (two baselines and our own approach) in a human–robot interaction domain. The three approaches respectively correspond to a purely hand-crafted approach, a purely statistical approach, and a hybrid approach based on probabilistic rules. The empirical results collected via this experiment indicate that the hybrid, rule-structured approach is able to outperform the two baselines on most of the metrics defined for the domain. The metrics include not only objective metrics extracted from the interaction logs but also subjective metrics of user satisfaction, based on a survey completed by the participants after each interaction.

The chapter is structured into three sections. The first section describes the human–robot interaction scenario within which the experiment is carried out, and details both the state variables, system architecture, and training data made available for the domain. The second section exposes the three alternative dialogue management approaches developed for the experiment, with a particular emphasis on the design choices that characterise each strategy. Finally, the third section presents the user evaluation itself, and surveys the experimental setup, quality metrics, and of course the empirical results and their detailed analysis.

8.1 Interaction scenario

The interaction scenario employed for the user evaluation is similar in most respects to the one presented in Section 6.3, modulo some minor adaptations to circumscribe more precisely the task to be performed.¹ The interactions revolve around a human user and a Nao robot standing on a large table, as illustrated in Figure 8.1. The purpose of the interaction is to instruct the robot to (1)

¹This change was suggested by several participants in the previous study.

walk to the other end of the table without bumping into the imaginary walls placed in the middle of the scene, (2) pick up the designated object, (3) bring it back to the left side of the table, and (4) release it on a yellow landmark. The robot is able to perceive the presence, colour and location of each physical object thanks to visual markings placed at their top. It can also grasp each object with the help of permanent magnets fixed inside the hands of the robot.

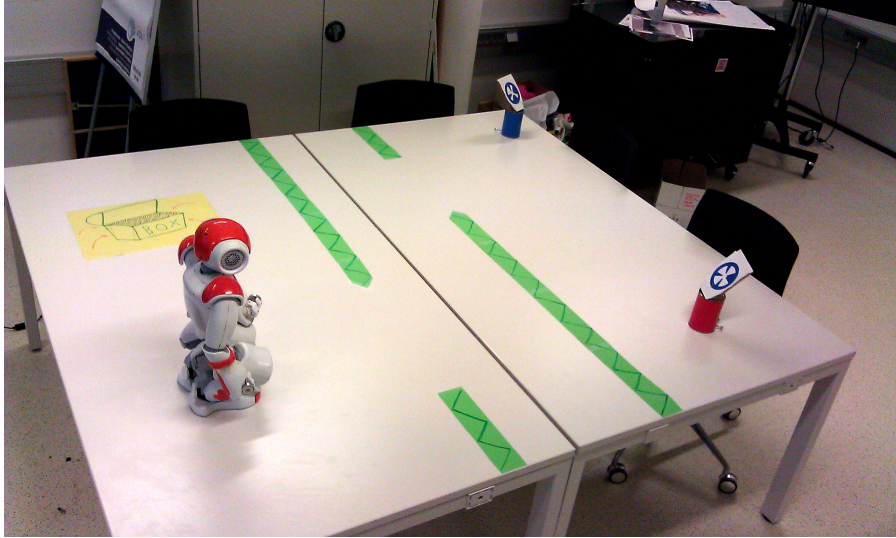


Figure 8.1: Interaction scenario for the experiment. Two graspable objects (one red and one blue) stand on the right side of the table. Imaginary walls (in green) are also placed on the table, as well as a yellow landmark depicting the final destination of the robot.

8.1.1 Dialogue domain

User intentions and actions

As in the previous experiment, we represent each basic instruction (such as moving forward, turning left, picking up an object, etc.) as a distinct user intention i_u . The possible user intentions for the domain are shown in Table 8.1.

We introduced a few minor changes compared to the Wizard-of-Oz study presented in Section 6.3. The basic movements are now augmented with a second argument specifying the duration of the movement (short or long). A new type of movement has also been added, Move(Turn) to make the robot turn around by 180 degrees. Finally, specific intentions are used to capture the opening (engagement) and closing (disengagement) phases of the dialogue.

The possible user actions a_u , listed in Table 8.2, correspond to the verbal realisations of these user intentions. The user can directly utter an instruction, ask the robot to repeat its last movement, or respond to a clarification or confirmation request. The user action Ask(Stop) can also be used to command the robot to stop its current movement, while grounding actions represent explicit feedback provided by the user on the robot behaviour.

System actions

As shown in Table 8.3, the system actions a_m include:

- Physical movements to move around in various directions and lengths, pick up or put down physical objects on the table, or stop the current move.
- Verbal responses to describe the robot's current perception or tell the user that it cannot perform a requested movement due to some impeding factor (e.g. not being able to pick up an object whose location is currently unknown).
- Clarification and confirmation requests, such as asking the users to repeat their last utterance, or confirming a particular intention.

The system's acknowledgements of the user instructions are coupled to the execution of the physical actions. Selecting the system action $\text{Do}(X)$ thus triggers both a positive feedback (“*Ok, now doing X*”) and the simultaneous execution of the corresponding physical movement.

Dialogue state

The dialogue state \mathcal{B} designed for the dialogue domain is factored into eleven distinct state variables, encoding both the user intentions and actions, the external context, the recent interaction history, and the physical status of the robot. Table 8.4 details the name, purpose, range of possible values, observability and dependencies of each state variable. As evidenced in the table, the dialogue state contains both fully and partially observed variables.

Even when ignoring the two variables u_u and u_m (which have a virtually infinite set of possible values, as they accept arbitrary strings) and assuming the presence of only two objects, the total size of the joint state space is non-trivial to tackle:

$$\begin{aligned}
 |\mathcal{S}| &= && 4 && [\text{size of } \text{Val}(\textit{perceived})] \\
 &&& \times 3 && [\text{size of } \text{Val}(\textit{carried})] \\
 &&& \times 18 && [\text{size of } \text{Val}(i_u)] \\
 &&& \times 26 && [\text{size of } \text{Val}(a_u)] \\
 &&& \times 26 && [\text{size of } \text{Val}(a_{u\text{-prev}})] \\
 &&& \times 41 && [\text{size of } \text{Val}(a_m)] \\
 &&& \times 2 && [\text{size of } \text{Val}(\textit{motion})] \\
 &&& \times 14 && [\text{size of } \text{Val}(\textit{lastMove})] \\
 &&& \times 2 && [\text{size of } \text{Val}(\textit{completed-task})] \\
 &= && 335\,252\,736
 \end{aligned}$$

8.1.2 System architecture

The dialogue system employed for the experiment follows the architecture described in the previous chapter (Section 7.2). We briefly describe below the configuration of each component. It should be stressed that the only component that varies across the three evaluated approaches is the dialogue manager. All other modules are fixed and remain identical for all interactions.

Speech recognition: The speech recognition engine relies on a hand-written recognition grammar of limited coverage. The grammar used for the experiment is shown in Table 8.5. The speech

· Move(x, y) where $x = \{\text{Left, Right, Forward, Backward}\}$ and $y = \{\text{Short, Long}\}$	· ReleaseObject
· Move(Turn)	· WhatDoYouSee
· Pickup(x) where x is AtFeet or an object identifier	· DoYouSee(x) where x is an object identifier
	· Greeting
	· Closing

Table 8.1: List of user intentions i_u .

· Ask(Move(x, y)) where $x = \{\text{Left, Right, Forward, Backward}\}$ and $y = \{\text{Short, Long}\}$	· Ask(WhatDoYouSee)
· Ask(Move(Turn))	· Ask(DoYouSee(x)) where x is an object identifier or Other if the reference is not resolved
· Ask(PickUp(x)) where x is AtFeet, an object identifier, or Other if the reference is not resolved	· Confirm
· Ask(ReleaseObject)	· Disconfirm
· RepeatLast	· Grounding
· Ask(Stop)	· Greet
	· Close
	· Other

Table 8.2: List of user actions a_u .

· Do(x) where $x = \{\text{Move}(y, z), \text{Move}(\text{Turn}), \text{PickUp}(a), \text{ReleaseObject}, \text{Stop}\}$ and $y = \{\text{Left, Right, Forward, Backward}\}$ and $z = \{\text{Short, Long}\}$ and $a = \text{AtFeet or an object identifier}$	· Describe(x) where $x =$ a (possibly empty) list of object identifiers
· Excuse(x) where $x = \{\text{UnseenObject, UnresolvedReference, NoCarriedObject, AlreadyCarryObject}\}$	· ConfirmDetection
· Greet	· DisconfirmDetection
· Goodbye	· AskRepeat
	· AskConfirm(x) where $x = \{\text{Move}(y, z), \text{Move}(\text{Turn}), \text{PickUp}(a), \text{ReleaseObject}, \text{Stop}\}$ and $y = \{\text{Left, Right, Forward, Backward}\}$ and $z = \{\text{Short, Long}\}$ and $a =$ an object identifier

Table 8.3: List of system actions a_m .

Variable label:	Description:	Range of values:	Observability:	Dependencies:
<i>perceived</i>	(Possibly empty) set of perceived objects	Object identifiers	Partial	\emptyset
<i>carried</i>	(Possibly empty) set of carried objects	Object identifiers	Full	\emptyset
i_u	Current user intention	cf. Table 8.1	Partial	<i>completed-task, perceived, carried</i>
u_u	Last user utterance	ASR hypotheses	Partial	\emptyset
a_u	Last dialogue act from the user	cf. Table 8.2	Partial	$u_u, i_u, a_m, lastMove$
a_{u-prev}	Next-to-last dialogue act from the user	cf. Table 8.2	Partial	\emptyset
a_m	Last system action	cf. Table 8.3	Full	$i_u, a_u, motion, perceived, carried$
<i>motion</i>	Activity status of the robot (denoting whether the robot is currently moving)	<i>true</i> or <i>false</i>	Full	\emptyset
<i>lastMove</i>	Last physical movement executed by robot	System actions of the form $Do(x)$	Full	a_m
u_m	Last system utterance	NLG outputs	Full	a_m
<i>completed-task</i>	Completion status of the user intention (denoting whether the current intention i_u has been fulfilled by the last action)	<i>true</i> or <i>false</i>	Partial	i_u, a_m

Table 8.4: List of state variables defined for the domain.

recognition engine runs directly on the robot platform based on the audio signals captured by four microphones on the robot head.

Natural language understanding: Natural language understanding is implemented in the dialogue system through probability rules. A total of 17 rules (of varying size) have been written for the domain, based on simple template-matching methods. One rule is specifically responsible for the resolution of referring expressions based on the current visual context. The probability rules are listed in Appendix B (Section B.3).

Dialogue management: Three distinct types of dialogue managers have been developed for this experiment: a finite-state automaton, a purely statistical dialogue manager, and a dialogue manager based on probabilistic rules. The design of these three dialogue management strategies is presented in Section 8.2.

Generation and synthesis: The natural language generation is realised through the application of one single rule in charge of mapping between the selected system action and its verbal realisation. The rule is also detailed in Appendix B. The generated sentence is then converted to a speech signal using the speech synthesis module.

Other components: As detailed in the previous chapter, the integrated dialogue system also comprises specific modules dedicated to object detection and motor control. The detection and localisation of the physical objects is facilitated by the use of visual markings on top of the objects. The robot relies on permanent magnets to pick up and hold objects in its hands.

8.1.3 Wizard-of-Oz data collection

We started our experimental study by collecting a small corpus of Wizard-of-Oz interactions for the dialogue domain. As shall be explained in the next section, this Wizard-of-Oz data set served to estimate the dialogue management models employed in the user evaluation. We recorded a total of 10 interactions, each with a distinct participant. All interactions were performed in English. The participants to the Wizard-of-Oz study (5 males and 5 females) were selected amongst students and employees working at the Department of Informatics. All but one participant were non-native speakers of English. The author of the present thesis served as the wizard.

The interactions were once again encoded as a sequence of pairs $\langle \mathcal{B}_i, a_i \rangle$, where each system turn i is represented by the selected wizard action a_i and the dialogue state \mathcal{B}_i in effect at the time the selection was made. The interactions had on average 84.2 system turns. 39 % of these turns resulted in a void action (i.e. no action at all), 40 % in a physical action (complemented by a feedback describing the action being performed), and the remaining 21 % in a verbal response such as a factual answer or a clarification request.

The variables expressed in the dialogue states \mathcal{B}_i of the collected data are directly extracted from the interaction logs. As a consequence, the recorded dialogue state \mathcal{B}_i includes only variables that are observed by the system during the interaction: the last and next-to-last user actions a_u and a_{u-prev} (as provided by the ASR and NLU modules), the last system action a_m , the set of objects currently perceived and carried by the robot, the last physical movement of the robot, and the *motion* variable denoting whether the robot is currently in movement.

$\langle \text{TopRule} \rangle$::= $\langle \text{Move-1} \rangle \mid \langle \text{Move-2} \rangle \mid \langle \text{PickUp} \rangle \mid \langle \text{Release} \rangle \mid \langle \text{Perception-1} \rangle \mid \langle \text{Perception-2} \rangle$ $\mid \langle \text{Confirmation} \rangle \mid \langle \text{Grounding} \rangle \mid \langle \text{Repeat} \rangle \mid \langle \text{Opening} \rangle \mid \langle \text{Closing} \rangle \mid \langle \text{Stop} \rangle$
$\langle \text{Move-1} \rangle$::= $\langle \text{Front} \rangle$ (walk go move continue)? $\langle \text{Translation} \rangle$ $\langle \text{Back} \rangle$
$\langle \text{Move-2} \rangle$::= $\langle \text{Front} \rangle$ (go move turn rotate)? $\langle \text{Rotation} \rangle$ $\langle \text{Back} \rangle$
$\langle \text{Translation} \rangle$::= $\langle \text{Modifier} \rangle?$ (forward backward back straight (forward ahead)?) $\langle \text{Modifier} \rangle?$
$\langle \text{Rotation} \rangle$::= $\langle \text{Modifier} \rangle?$ (to the)? (left right) $\langle \text{Modifier} \rangle?$ around 180 degrees
$\langle \text{Modifier} \rangle$::= (just)? a (little)? bit (more)?
$\langle \text{PickUp} \rangle$::= $\langle \text{Front} \rangle$ ((take pick up grasp) $\langle \text{Object} \rangle$) pick it up take it) $\langle \text{Back} \rangle$
$\langle \text{Release} \rangle$::= $\langle \text{Front} \rangle$ ((release put down drop) $\langle \text{Object} \rangle$) (put $\langle \text{Object} \rangle$ down)) $\langle \text{Back} \rangle$
$\langle \text{Perception-1} \rangle$::= what (can do) you (see perceive)
$\langle \text{Perception-2} \rangle$::= (can do) you (see perceive) ($\langle \text{Object} \rangle$ something anything)
$\langle \text{Object} \rangle$::= (the a) $\langle \text{Colour} \rangle?$ (object cylinder food can) (at your feet)?
$\langle \text{Colour} \rangle$::= red blue green yellow white black
$\langle \text{Confirmation} \rangle$::= yes (please)? no exactly ok
$\langle \text{Grounding} \rangle$::= (that is this is)? (correct incorrect wrong right perfect great good)
$\langle \text{Repeat} \rangle$::= $\langle \text{Front} \rangle$ (do (it that) (again once more one more time) repeat that)
$\langle \text{Opening} \rangle$::= (hi hello) $\langle \text{Name} \rangle$
$\langle \text{Closing} \rangle$::= (bye goodbye) $\langle \text{Name} \rangle?$
$\langle \text{Stop} \rangle$::= stop (it that)?
$\langle \text{Front} \rangle$::= (and)? (could you)? (now)? (please)?
$\langle \text{Back} \rangle$::= (please)? (again)?
$\langle \text{Name} \rangle$::= robot nao lenny

Table 8.5: Speech recognition grammar (in Bachus-Naur form) employed for the experiment.

Here is an example of a data point extracted from the collected data, corresponding to the user utterance “yes” after a confirmation request, followed by the system action $\text{Do}(\text{Move}(\text{Right}))$:

$$\mathcal{B} = \left\{ \begin{array}{l} u_u = \langle (\text{“yes”}, p=.95), (\text{None}, p=.05) \rangle \\ a_u = \langle (\text{Confirm}, p=.95), (\text{None}, p=.05) \rangle \\ a_{u\text{-prev}} = \langle (\text{Ask}(\text{Move}(\text{Right})), p=.63), (\text{None}, p=.37) \rangle \\ a_m = \langle (\text{AskConfirm}(\text{Move}(\text{Right})), p=1) \rangle \\ u_m = \langle (\text{“should I move right?”}, p=1) \rangle \\ perceived = \langle ([\text{RedObj}], p=1) \rangle \\ carried = \langle ([], p=1) \rangle \\ motion = \langle (\text{false}, p=1) \rangle \end{array} \right. \Rightarrow a'_m = \text{Do}(\text{Move}(\text{Right}))$$

8.2 Dialogue management models

In order to evaluate how the choice of a modelling framework affects the interaction quality, we developed three competing dialogue management approaches for the domain:

- The first approach is a purely hand-crafted dialogue manager using a finite-state automaton to process the user inputs and determine the corresponding responses.
- The second approach is a purely statistical dialogue manager that encodes the transition and utility model of the domain based on classical, factored probabilistic models.
- Finally, the third approach relies on a hybrid modelling strategy and uses the formalism of probabilistic rules to structure the domain models.

We detail below the exact design of each approach.

8.2.1 Approach 1: hand-crafted model

The first approach relies on a traditional finite-state automaton to determine the current conversational situation and its corresponding system action. Although more complex logic- or plan-based methods (such as the ones described in Section 2.3.1) could in principle also be applied, a finite-state automaton augmented with a basic support for logical reasoning was in practice found to be sufficient to capture the key characteristics of the dialogue domain.

The finite-state automaton is triggered upon each new user dialogue act a_u . Attached to each edge is a logical condition that determines when the edge can be traversed. The conditions are defined on the basis of the current dialogue act a_u , previous dialogue act $a_{u\text{-prev}}$, and contextual variables *perceived* and *carried*. The finite-state automaton directly operates at the level of the user dialogue acts a_u and $a_{u\text{-prev}}$ without explicitly computing the underlying user intention i_u , since the user intention corresponds in this domain to a hidden variable and cannot be adequately modelled by purely symbolic (i.e. non-probabilistic) representations.

Finite-state automaton

The automaton constructed for the domain operates on the basis of three specified threshold values T_1 , T_2 and T_3 (whose estimation is described shortly):

1. If the incoming dialogue act contains a hypothesis whose probability is higher than a given threshold T_3 , the system action associated with the user request is directly selected. For instance, if the new user act contains a hypothesis $a_u = \text{Ask}(\text{Move}(\text{Left}))$ with probability $p > T_3$, the action $a_m = \text{Do}(\text{Move}(\text{Left}))$ will be executed.
2. If the probability of the top hypothesis for a_u lies between T_2 and T_3 and corresponds to a request for a physical movement, the system will ask the users to confirm their intention. The system response to a user act $a_u = \text{Ask}(\text{Move}(\text{Left}))$ with probability $T_2 < p < T_3$ will hence be set to $a_m = \text{AskConfirm}(\text{Move}(\text{Left}))$.
3. If the probability of the top hypothesis lies between T_1 and T_2 , the system will ask the users to repeat their utterance by triggering the action $a_m = \text{AskRepeat}$.
4. Finally, if no hypothesis reaches the minimal threshold T_1 , the user action is assumed to correspond to a spurious recognition result and is simply ignored.

A graphical representation of the finite-state automaton is provided in Figure 8.2. The automaton contains 16 distinct states. Depending on the probability of the top hypothesis in the user dialogue act a_u , the automaton will either directly transit from the state s_1 to the states s_4, \dots, s_{15} or be redirected to state s_2 or s_3 for clarification. After each system action in the states s_4, \dots, s_{14} , the current state is re-initialised to state s_1 via empty transitions.

Since spurious speech recognition results are often produced when the robot is executing physical movements, the finite-state automaton employs a higher threshold ($P(a_u) > T_2$ instead of T_1) for moving from state s_1 to s_3 whenever the variable *motion* is set to true.

Probability thresholds

The threshold values T_1 , T_2 and T_3 are determined empirically on the basis of the actual probability values generated by the speech recogniser and NLU module during the Wizard-of-Oz study. This estimation was achieved in two steps. The first step is to extract all probability values associated with the most likely hypothesis of the user dialogue act a_u in the recorded Wizard-of-Oz interactions and derive a probability density from these values through kernel density estimation. The resulting density function is shown in Figure 8.3. As a second step, we divided the distribution over probability values for the top user act hypothesis into four non-overlapping regions:

- Region 1 (cf. figure) corresponds to user actions that most likely arise from spurious recognition and should hence be ignored. Based on a detailed inspection of the wizard actions in such cases, we mapped this region to the lowest quintile of the distribution (that is, all values with a cumulative density between 0 and 0.2).
- Region 2 corresponds to user actions that are more likely to reflect real user inputs, but do not have sufficient confidence to be directly executed. This region was mapped to the second quintile of the distribution (values with a cumulative density between 0.2 and 0.4).

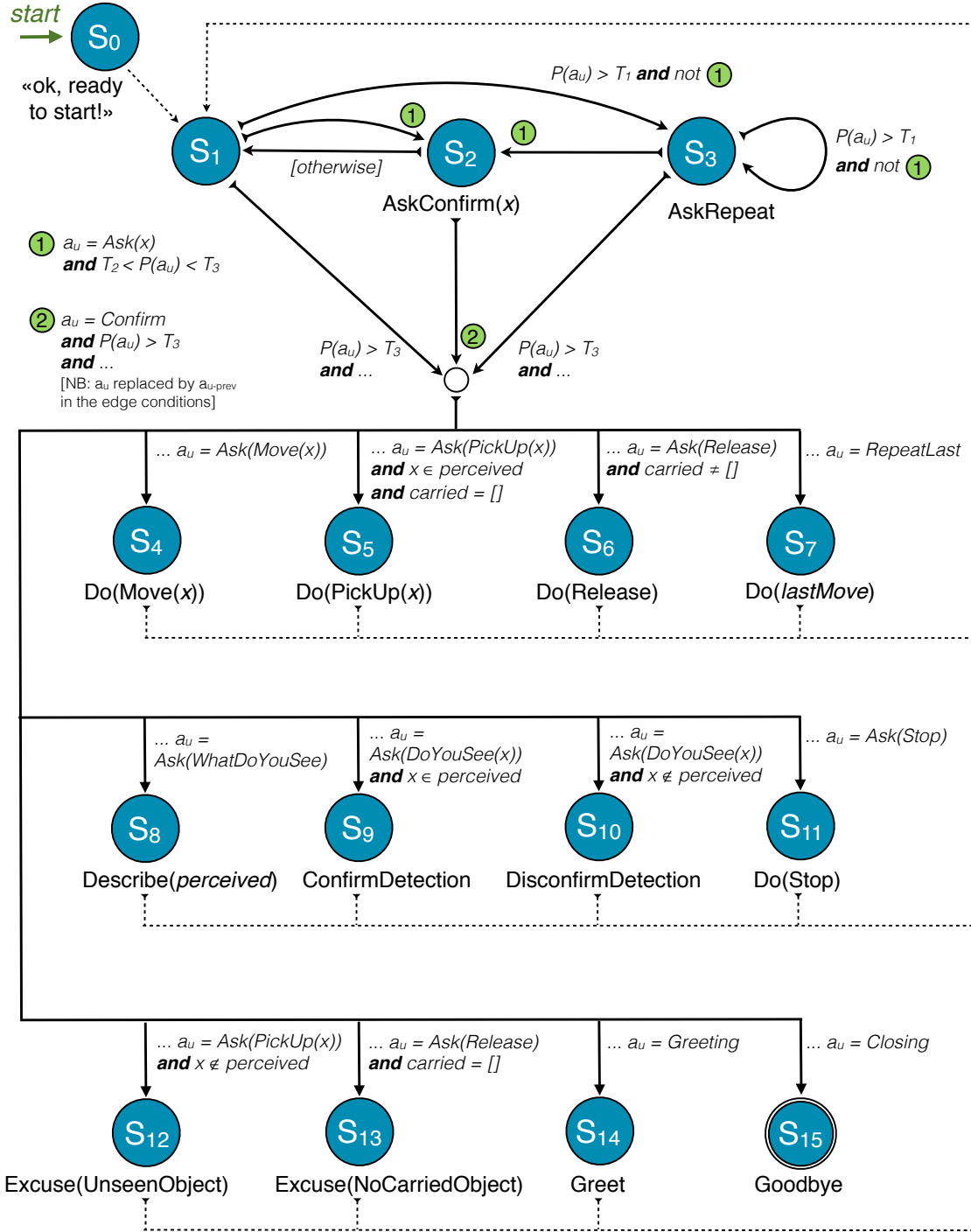


Figure 8.2: Finite-state automata designed for the domain (slightly simplified for the sake of exhibition). The dashed arrows denote empty transitions. For presentation purposes, the conditions applied to the edges going from s_1, s_2, s_3 to s_4, \dots, s_{15} are decomposed in two parts: the first part from the incoming node to the small white circle, and the second part from the circle to the outgoing node. T_1, T_2 and T_3 are threshold values determined empirically.

- Region 3 corresponds to user actions that have relatively high confidence, but should nevertheless be confirmed once before execution. This region was constrained to the third quintile of the distribution (values with a cumulative density between 0.4 and 0.6).
- Finally, Region 4 corresponds to user actions that have a sufficiently high confidence to be directly executed without user confirmation. This region defines the top 40 % of the probability mass, with cumulative densities between 0.6 and 1.0.

The mapping between the four regions and their associated system responses is substantiated by a manual analysis of the Wizard-of-Oz data set. The estimated thresholds for the density function shown in Figure 8.3 were derived to be $T_1 = 0.49$, $T_2 = 0.61$ and $T_3 = 0.73$. These values reflect the three thresholds employed in the finite-state automaton.

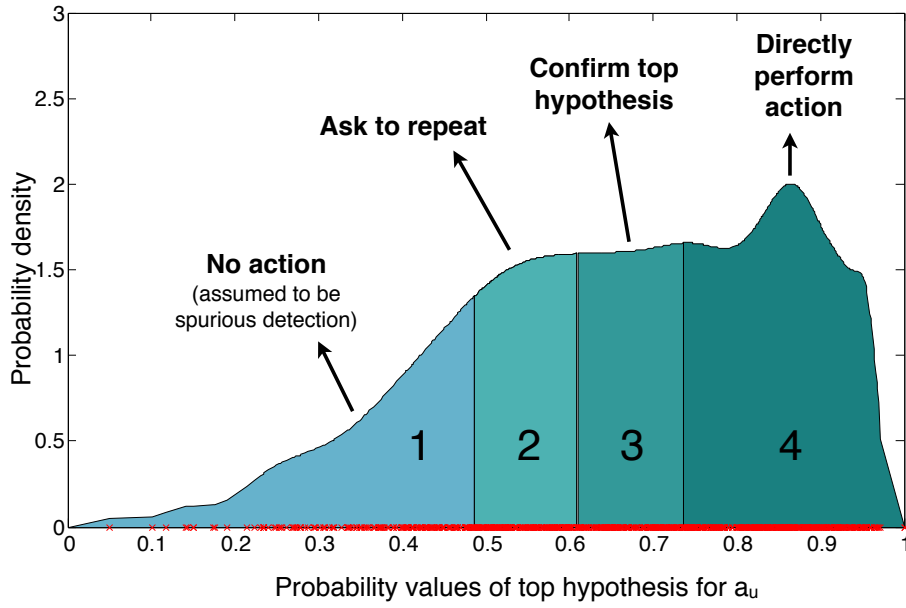


Figure 8.3: Probability density function for the probability values of the top hypothesis specified in the user dialogue act a_u , divided into four non-overlapping regions that respectively correspond to the first, second, third, and fourth+ fifth quintiles of the distribution. Red crosses on the X axis represent the actual probability values used to construct the kernel density function.

8.2.2 Approach 2: factored statistical model

The second approach developed for this experiment consists of a statistical model whose parameters are estimated from the Wizard-of-Oz data set collected for the experiment. We assume that both the transition model and utility model of the domain are initially unknown.

Both this approach and Approach 3 rely on a planning horizon limited to the present time step. In other words, the approaches do not use a forward planner (which has proven to be practically difficult to apply in live interactions) and directly selects the action yielding the highest utility in the current dialogue state.² The approach stands relatively close to the POMDP-based systems de-

²In other words, the utility model represents what is called a Q -value model in reinforcement learning.

scribed in Chapter 3, with the difference that the estimation of model parameters in this experiment is performed on the basis of Wizard-of-Oz data rather than through a simulator.

Domain modelling

Figure 8.4 illustrates the factored model employed to structure the dialogue domain of the experiment. As shown in the figure, the domain models are factored in four major distributions (the three first ones being part of the transition model, while the fourth one is a utility model):

- The task completion model $P(\text{completed-task} | i_u, a_m)$ describes the probability that the current intention i_u is fulfilled by the last system action a_m . The task completion model $P(\text{completed-task} | i_u, a_m)$ is essentially a deterministic distribution that marks the task as completed when the executed action a_m fulfils the user intention i_u , and as not completed in all other cases.
- The user goal model $P(i'_u | i_u, \text{completed-task}, \text{perceived}', \text{carried}')$ encodes the likelihood of a new user intention i'_u given the current intention i_u , task completion completed-task , as well as the two contextual variables $\text{perceived}'$ and $\text{carried}'$.
- The user action model $P(a'_u | i'_u, a_m)$ describes the probability of the next user dialogue act a'_u given the current user intention i'_u and the last system action a_m .
- Finally, the utility model $U(a'_m | i'_u, a'_u, \text{carried}', \text{perceived}', \text{motion}')$ describes the utility of a particular system action a'_m given the user intention i'_u , last user dialogue act a'_u , robot motion status motion' and contextual variables $\text{carried}'$ and $\text{perceived}'$.

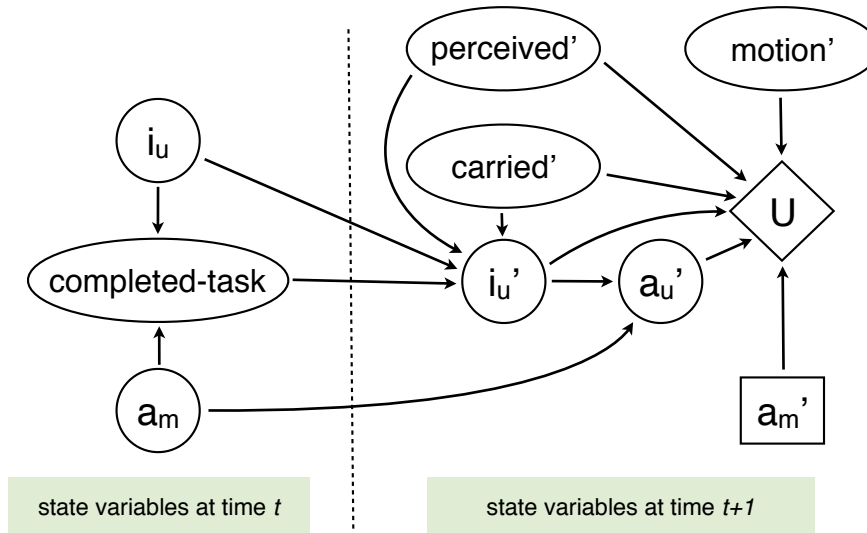


Figure 8.4: Factored transition and utility models for the dialogue domain.

Dimensionality reduction

Unfortunately, the four factored models listed above remain too large to be directly estimated from the limited amounts of data made available from the Wizard-of-Oz interactions. We therefore

introduced a number of additional heuristics and simplifying assumptions to further reduce the number of parameters associated with the model.

The first simplifying assumption pertains to the user goal model $P(i'_u | i_u, \text{completed-task}, \text{perceived}', \text{carried}')$, and rests on the idea that the user intention remains more or less constant – modulo a small probability of revision to account for sudden changes of mind on the part of the user – until the task is marked as completed. The values of the two contextual variables *perceived'* and *carried'* variables are furthermore grouped into two partitions: empty set or non-empty set. These two simplifications reduce the number of parameters required for the user goal model to four Dirichlet distributions, each with 18 dimensions (which is the number of possible user intentions).

We also compressed the size of the user action model $P(a'_u | i'_u, a_m)$ by exploiting the fact that only a fraction of user dialogue acts a'_u are locally relevant for a given user intention i'_u and last system action a_m . A manually specified function *relevant* : $Val(i'_u) \times Val(a_m) \rightarrow 2^{Val(a_u)}$ is used to derive the set of relevant user actions given a particular pair of user intention and system action. For instance, the relevant dialogue acts for the user intention Move(Left, Short) are Ask(Move(Left, Short)), RepeatLast, Confirm, Disconfirm, Stop and Grounding. The resulting set of parameters associated with the user action model contains 133 Dirichlet distributions, each with 6 dimensions (the number of relevant actions allowed per intention).

The third and final heuristic is to reduce the number of relevant system actions in the utility distribution $U(a'_m | i'_u, a'_u, \text{carried}', \text{perceived}', \text{motion}')$. Similarly to the user action model, we can exploit the fact that only a fraction of system actions are relevant in a given state, and that the non-relevant ones have a constant negative utility. In order to express this constraint, we first define a function *best* : $Val(i'_u) \times Val(\text{perceived}') \times Val(\text{carried}') \rightarrow Val(a_m)$ that maps each user intention and context to the “best” action that can be executed at that state if we were to assume no uncertainty. This best action is identical to the action selected by the finite-state automaton in Figure 8.2. In addition to this best action, we also allow the actions AskConfirm(i'_u), AskRepeat and *Do(Stop)* to be executed at any state. The utility distribution is then expressed as:

$$U(a'_m | i'_u, a'_u, \text{carried}', \text{perceived}', \text{motion}') = \begin{cases} \theta_{\text{best}(i'_u, \text{carried}', \text{perceived}')} & \text{if } a_m = \text{best}(i'_u, \text{carried}', \text{perceived}') \\ \theta_{\text{askConfirm}(i'_u, \text{carried}', \text{perceived}')} & \text{if } a_m = \text{Confirm}(i'_u) \\ \theta_{\text{askRepeat}(a_u, \text{motion}')} & \text{if } a_m = \text{AskRepeat} \\ \theta_{\text{stop}(a_u, \text{motion}')} & \text{if } a_m = \text{Stop} \\ -10 & \text{otherwise} \end{cases} \quad (8.1)$$

The factorisation of the utility model in Equation (8.1) results in 296 parameters. In total, the numbers of parameters associated with all factored models in this approach (including both univariate and multivariate parameters) equals 433.

Parameter estimation

The parameter estimation follows the Bayesian learning procedure presented in Chapter 5. The goal of the estimation process is to find the parameters for the domain models that provide the best fit for the Wizard-of-Oz data set. The learning algorithm operates by cycling through the Wizard-of-Oz training data and updating the parameter distributions after each data point using Bayesian

inference. The wizard is assumed to act rationally in most cases and select the action that yields the highest utility given the current dialogue state.

It should be noted that, in contrast to the experiment presented in Section 5.3 (which concentrated on the estimation of a single model), the parameters to estimate in this setting include both the transition model and the utility model. The learning algorithm is thus an instance of a joint optimisation problem, as the system must simultaneously optimise both models in order to find the parameters that provide the best fit for the Wizard-of-Oz dataset as a whole.

The parameters of categorical distributions are all encoded by Dirichlet distributions initialised with weakly informative priors, while the utility parameters are encoded by uniform distributions with a support range of $[-10, 30]$. The learning curve followed during the estimation process and the agreement results are provided in Section 8.2.4.

8.2.3 Approach 3: rule-structured model

The final dialogue management approach developed in this experiment is couched in the formalism of probabilistic rules presented in this thesis.

Domain modelling

The factorisation of the domain models remains identical to the one shown in Figure 8.4. As in the second approach, the models are decomposed into a task completion model, a user goal model, a user action model, and a utility model. Action selection is again formalised as a search for the highest-utility action in the current state (assuming a planning horizon limited to the current time step). However, in contrast to Approach 2, the internal structure of the domain models is here encoded through probabilistic rules instead of standard categorical distributions:

- The task completion model $P(\text{completed-task} \mid i_u, a_m)$ is encoded by one single deterministic rule that defines when the current intention i_u is fulfilled by the system action a_m .
- The user goal model $P(i'_u \mid i_u, \text{completed-task}, \text{perceived}', \text{carried}')$ consists of a small collection of rules that define the probability of the new user intention i'_u given the dialogue context. One rule defines the prior probability of the user intentions $\text{Move}(x)$, four rules specify the prior probability of $\text{PickUp}(x)$, WhatDoYouSee and $\text{DoYouSee}(x)$ depending on the value of the $\text{perceived}'$ variable, one rule specifies the prior probability of Release depending on the value of the $\text{carried}'$ variable, and one final rule specifies the probability of the Greeting and Closing intentions depending on the last system move.
- The user action model $P(a'_u \mid i'_u, a_m)$ is formalised with two rules that map user intentions to their potential verbal realisations in terms of user dialogue acts. The first rule expresses the likelihood of various user dialogue acts depending on the user intention and last system action (in particular, whether the system uttered a clarification or confirmation request). The second rule expresses the likelihood of the $\text{Ask}(\text{Stop})$ and Disconfirm actions during the execution of a physical movement.
- Finally, the utility model $U(a'_m \mid i'_u, a'_u, \text{carried}', \text{perceived}', \text{motion}')$ is encoded with a total of ten utility rules. The model contains one rule for each family of possible system actions. There is therefore one rule to define the relative utility of movement actions, one

rule for grasping actions, one rule for the release action, two rules for the Describe(x), ConfirmDetection and DisconfirmDetection actions, one rule to handle the Greet and Goodbye actions, two rules for the clarification and confirmation requests, and one rule to stop the current movement. The last rule fixes an initial, negative utility for all actions to ensure that non-relevant actions have a utility lower than zero.

The probability and utility models described by these rules include a total of 28 parameters, amongst which 15 are probability parameters and 13 utility parameters. The complete specification of the domain is provided in Appendix B (Section B.3).

Parameter estimation

The rule parameters are optimised on the basis of the collected Wizard-of-Oz data following the same procedure as for the second approach. The parameters of probability rules are all encoded by Dirichlet distributions of varying dimensions (from 2 to 10) initialised with weakly informative priors, while the parameters of utility rules are encoded by uniform distributions on the support range $[-10, 30]$.

8.2.4 Learning curves

Figure 8.5 presents the learning curves for the three dialogue management strategies presented on the previous pages. The Wizard-of-Oz data set described in Section 8.1.3 was first divided into a training set of 9 interactions (summing to 770 system turns) and a test set with one single interaction containing a total of 71 system turns. Based on this division, we measured the degree of agreement between the action selected by the system (on the basis of its model parameters) and the one selected by the wizard in the test set. This measurement is repeated at regular intervals during the parameter estimation process. As the finite-state approach is entirely hand-crafted and does not include any parameters to optimise, its agreement with the wizard actions remains constant.

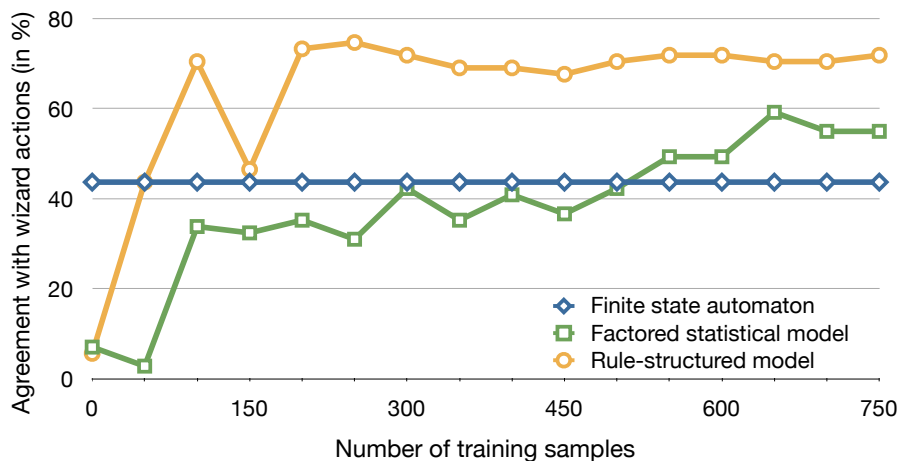


Figure 8.5: Learning curves for the three dialogue management approaches on the Wizard-of-Oz data set. The figure shows how the agreement between the best system action and the actual wizard action evolves as a function of the number of processed training samples. The agreement is calculated on a separate test set of 71 system turns.

The learning curves in Figure 8.5 illustrate the evolution of the degree of agreement as the function of the number of training samples processed by the learning algorithm. We can notice from the observation of the curves that both statistical approaches (Approach 2 and 3) do improve their agreement as they process more and more training samples, but do so at different learning speeds. While the rule-structured model is able to converge to a high-quality dialogue policy after observing only a fraction of the training data, the traditional, factored statistical model converges at a slower rate due to its larger set of parameters and weaker generalisation capacity.

The final agreement results obtained after processing the complete training set are shown in Table 8.6. As one can observe, the rule-structured approach is the one that is best able to imitate the conversational behaviour of the wizard.

<i>Type of model</i>	<i>Agreement with the wizard actions (in %)</i>
Finite-state automaton	43.66
Factored statistical model	54.93
Rule-structured model	71.83

Table 8.6: Agreement results on the test test for the three approaches.

It should be stressed once more that system actions that do not correspond to the ones selected by the wizard are not necessarily wrong or inappropriate, as they may reflect different but perfectly legitimate conversational strategies. The degree of agreement between the model and the wizard examples is, however, a good indication of the model ability to capture the dynamics of the interaction as well as the trade-offs of the action selection process.

8.3 User trials

In order to assess the relative performance of the three dialogue management approaches presented in the previous section, we conducted a total of 3×37 user trials (every participant carried out one separate interaction for each of the three approaches), which we now describe in detail. We start by laying out the experimental setup employed in the user trials, and then present and discuss the empirical results.

8.3.1 Experimental setup

Participants

The experiment was carried out with a total of 37 participants (16 males and 21 females). The average age of the participants was 30.6 years (standard deviation: 7.8). The participants were recruited amongst students and employees of the Department of Informatics at the University of Oslo. All participants were non-native speakers of English. To facilitate the recruitment of participants, a small monetary reward was offered to the participants upon the completion of the experiment.

Before the start of the experiment, we briefed the participants about the interaction scenario and the physical and conversational capabilities of the robot. To give the participants a better sense of what the robot can understand (and what falls outside the scope of the dialogue domain), we provided each participant with an instruction sheet detailing the different kinds of movements the robot can perform, as well as a few examples of verbal instructions for each.

User expectations

The participants were asked to fill out a short survey about their age, gender, and their expectations regarding the robot verbal behaviour. The user expectations were surveyed with a set of six multiple-answer questions as shown in Figure 8.6. The questions cover multiple aspects that may affect the interaction quality in the domain, such as the comprehension abilities of the robot (Q1), its ability to select appropriate reactions (Q2), its use of clarification requests (Q3), its ability to distinguish between noise and actual utterances (Q4 and Q5), and finally the overall naturalness of the interaction (Q6). One should note that the participants were told during the briefing phase to be aware of the technical limitations of the speech recogniser. The user responses must therefore be interpreted in the light of this cautionary statement.

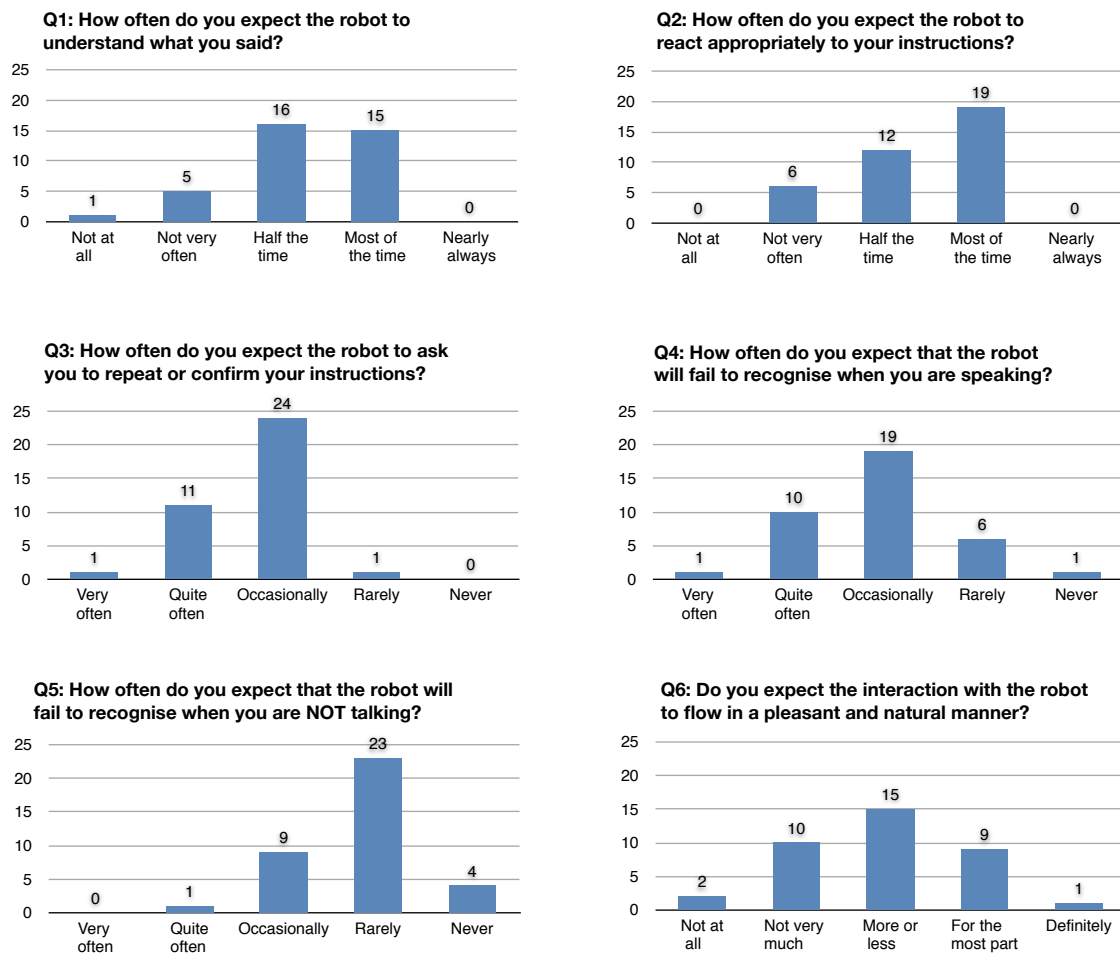


Figure 8.6: Prior user expectations about the robot's conversational abilities. The Y axis corresponds to the number of user responses (out of 37 participants).

The first and most evident purpose of this preliminary survey is to allow us to compare the prior expectations of the users with their actual experiences during the interactions. As shown by e.g. Jokinen and Hurtig (2006), such contrastive analysis can yield interesting insights on the factors that empirically influence user satisfaction and their variability amongst different groups of users. In addition, the survey also served as an indirect mean to direct the user attention towards the aspects of the robot behaviour that are of particular relevance for this study – namely, the robot’s choice of dialogue moves.

Trials

After completing the survey, each participant was requested to carry out three distinct dialogues (one for each dialogue management approach). We shuffled the order in which the three approaches were tested before each trial to mitigate the effects of the ordering sequence on the results. The interactions indeed become increasingly efficient as the user gets more accustomed to the robot and the task to perform. The average duration of the first dialogue amounts to 6:31 minutes, while the average duration of the second dialogue is reduced to 5:08 minutes, and the duration of the last dialogue goes down even further to 4:40.

The participants did not have a time limit to complete the task. Immediately after each dialogue, the participants were asked to fill out a small survey to determine how they subjectively perceived the interaction. The survey was once more divided into six multiple-answer questions, as explained in the next section.

All interactions were captured on video, totalling about 12 hours of footage. In addition to the videos, the dialogue system also logged every user and system turns occurring in the interaction along with their associated dialogue state.

8.3.2 Results

Objective metrics

In line with previous work on the evaluation of spoken dialogue systems (see e.g. Jokinen and McTear, 2009, ch. 6 for an overview), we defined a set of objective metrics aimed at measuring the quality and efficiency of the recorded dialogues. The defined metrics and their empirical values for three approaches are shown in Figure 8.7.

Although many evaluation schemes include explicit measures of task completion in their metrics, we found such measures to be difficult to incorporate in our experimental setup, as the participants did not really have the possibility to end a task before its conclusion. Some dialogues had to be terminated before the full completion of the task but these cases were due to external causes such as hardware failures (e.g. system crash or physical collapse of the robot).

The measures were extracted on the basis of the interaction logs produced by the dialogue system during the course of the dialogue. As the interaction logs are generated automatically, the counts of user turns correspond to the number of speech recognition results and do not necessarily correspond one-to-one to the actual user turns in the dialogue (due to spurious results caused by ambient noise). We can observe from Figure 8.7 that the rule-structured model produces on average shorter and more efficient dialogues than the two baselines (metrics M6-M9). In particular, on the basis of its parameter estimation on the Wizard-of-Oz training set, the rule-structured model

systematically assigned higher utilities to confirmation requests (“*should I do X?*”) in comparison to repetition requests (“*Sorry, could you repeat?*”) and consequently never asked the user to repeat the last utterance (metric M1). The number of system turns is also notably shorter than for the finite-state and factored statistical model, reflecting the fact that the rule-structured model is better able to filter out spurious recognition results based on the current context (metric M8).

Subjective metrics

The subjective metrics reflect the answers to the six multiple-answer questions specified in the user survey. Each question allows five alternative answers on a scale ranked from worst to best. The six questions and the responses they received from the participants are shown in Figure 8.8. As one can observe, the responses to the survey do seem to indicate that the rule-structured model was perceived as leading to more effective and natural conversational behaviours.

Summary of results

Table 8.7 summarises the results of both the objective and subjective metrics and specifies the statistical significance of each observed difference between measures. The results from the subjective metrics are calculated by mapping the qualitative answers to a scale from 1 to 5 (with 1 corresponding to the worst behaviour and 5 to the best) and averaging the results over all participants.

In order to analyse the statistical significance of the results obtained for each metric, the table indicates the p -values for two distinct test statistics:³

- The first p -value is derived via the ANOVA procedure (Analysis of Variance) with one single factor corresponding to the dialogue management approach selected for the interaction. The null hypothesis corresponds in this case to the assumption that the observed measures extracted with the three approaches (denoted below A_1 , A_2 and A_3) are drawn from populations with the same mean:

$$H_0 : \mu_{A_1} = \mu_{A_2} = \mu_{A_3} \quad (8.2)$$

- As we are more specifically interested in the difference between the rule-structured approach and the two baselines, we also calculated a second test statistic that compares for each metric the mean of the best approach against the second-best approach. The test statistic is in this case derived using Bonferroni-corrected Student’s paired t -tests. The null hypothesis corresponds to the assumption that the observed measures for the best approach and the second-best approach are drawn from populations with the same mean:

$$H_0 : \mu_{best} = \mu_{second} \quad \text{where} \quad \begin{cases} \mu_{best} = \max(\{\mu_{A_1}, \mu_{A_2}, \mu_{A_3}\}) \\ \mu_{second} = \max(\{\mu_{A_1}, \mu_{A_2}, \mu_{A_3}\} \setminus \mu_{best}) \end{cases} \quad (8.3)$$

Results for which a statistically significant difference is found (with $\alpha = 0.05$) are decorated in the table with a star sign. As one can observe from the results, 7 of the 15 metrics demonstrate

³A p -value corresponds to the probability of obtaining a test statistic at least as extreme as the one actually observed if we presuppose that the null hypothesis is true. We can therefore reject the null hypothesis whenever the derived p -value is lower than a certain significance level α (often set to 0.05 or 0.01). The hypothesis testing procedures applied in this section are discussed in detail in (Ross, 2009, chapter 8).

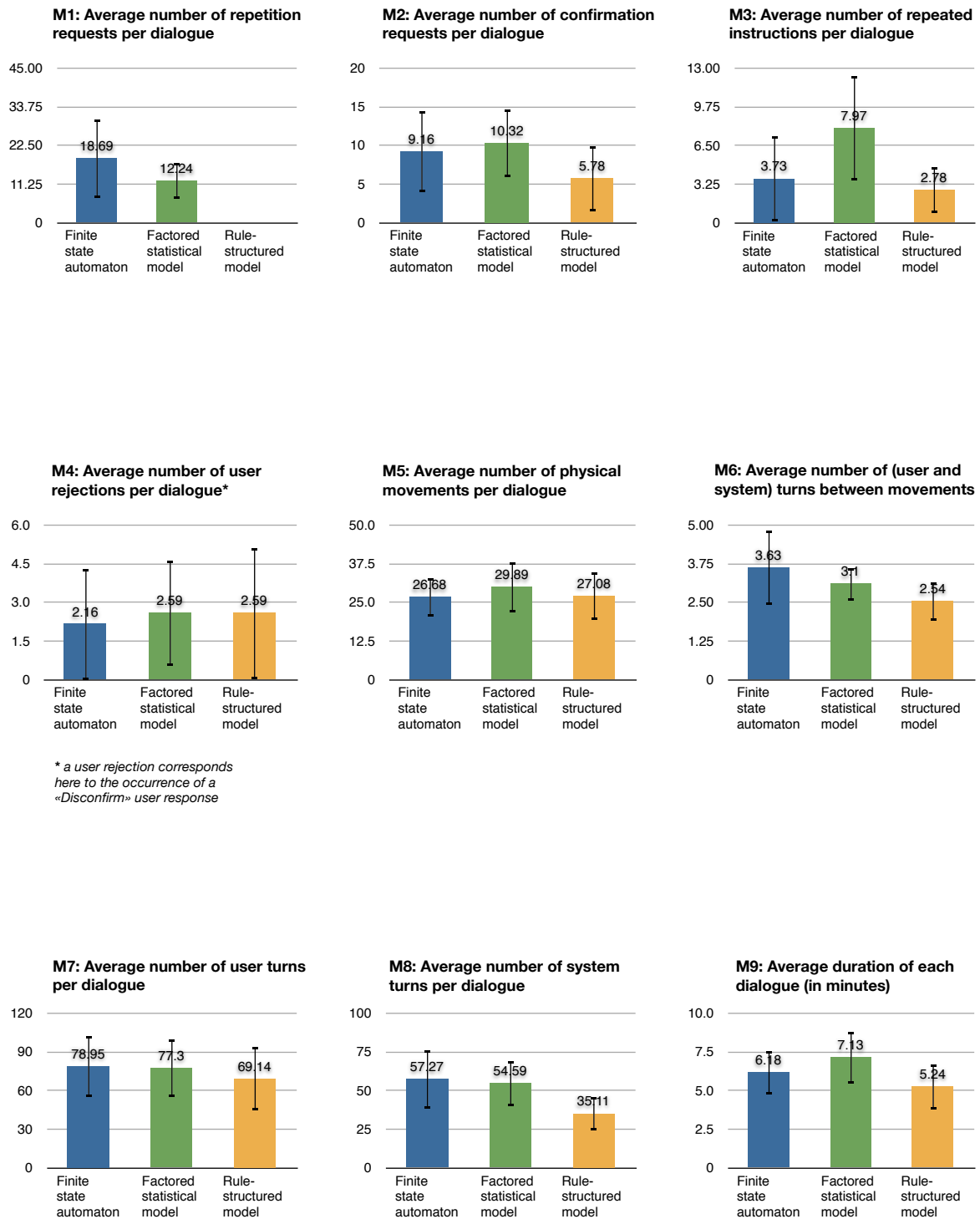


Figure 8.7: Objective metrics extracted from the collected dialogues.

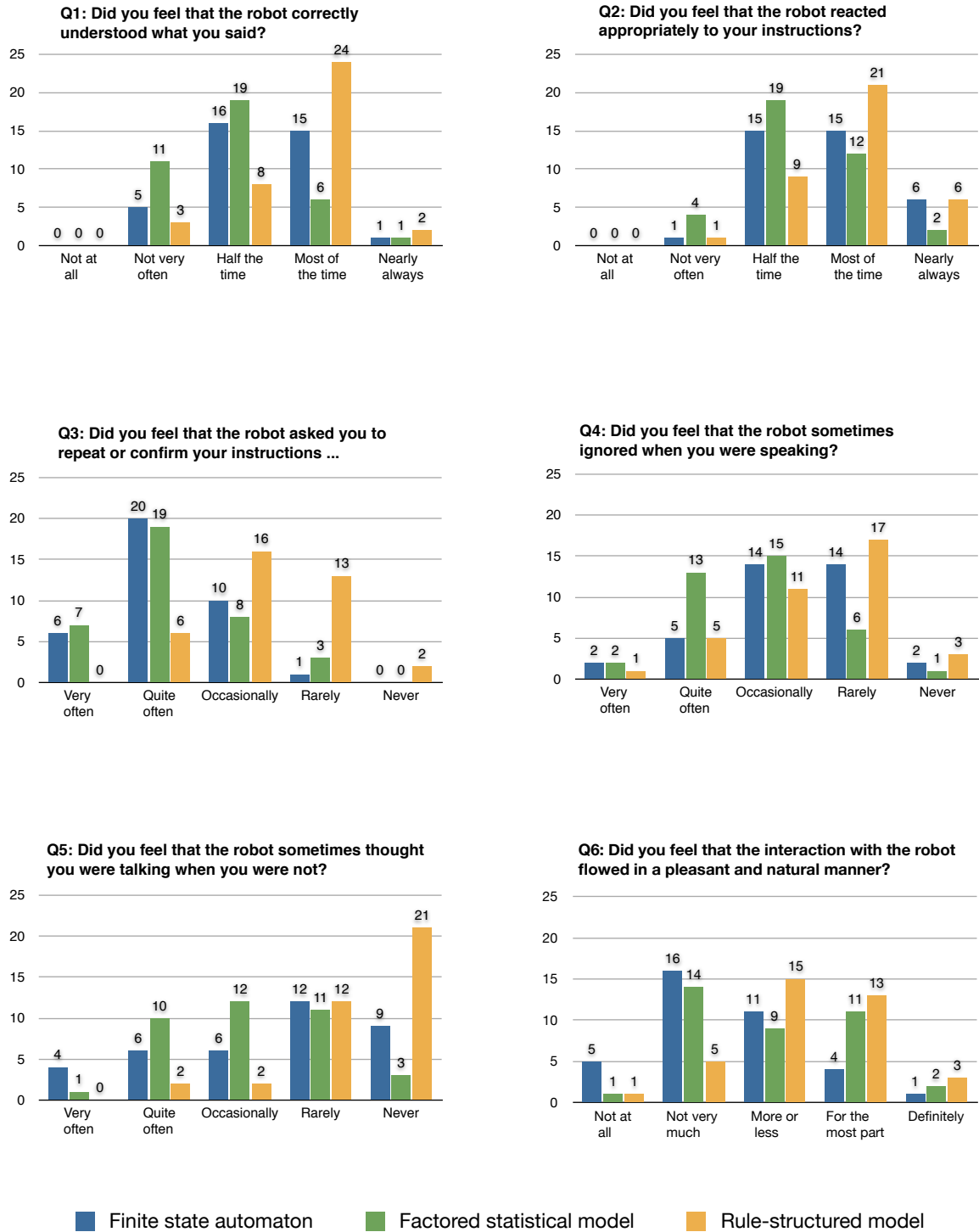


Figure 8.8: Survey responses obtained from the participants in the user trial after each interaction. The Y axis corresponds to the number of user responses (out of 37 participants).

Metrics	Approaches			p -values ANOVA	p -values 1 st vs. 2 nd (t -test)
	Finite- state automaton	Factored statistical model	Rule- structured model		
Objective metrics:					
M1. Average number of repetition requests per dialogue	18.68	12.24	0*	9×10^{-19}	1×10^{-16}
M2. Average number of confirmation requests per dialogue	9.16	10.32	5.78*	1.7×10^{-4}	0.001
M3. Average number of repeated instructions per dialogue	3.73	7.97	2.78	3.8×10^{-9}	0.18
M4. Average number of user rejections per dialogue	2.16	2.59	2.59	0.65	0.33
M5. Average number of physical movements per dialogue	26.68	29.89	27.08	0.13	0.80
M6. Average number of (user and system) turns between movements	3.63	3.10	2.54*	$4. \times 10^{-4}$	2.2×10^{-4}
M7. Average number of user turns per dialogue	78.95	77.30	69.14	0.17	0.11
M8. Average number of system turns per dialogue	57.27	54.59	35.11*	4.4×10^{-9}	5.6×10^{-8}
M9. Average duration of each dialogue (in minutes)	6:18	7:13	5.24*	1.4×10^{-4}	0.02
Subjective metrics:					
“Did you feel that ...					
Q1. ... the robot correctly understood what you said?”	3.32	2.92	3.68	1.3×10^{-4}	0.03
Q2. ... the robot reacted appropriately to your instructions?”	3.70	3.32	3.86	7.6×10^{-3}	0.23
Q3. ... the robot asked you to repeat or confirm your instructions?”	2.16	2.19	3.30*	1.7×10^{-9}	4.7×10^{-7}
Q4. ... the robot sometimes ignored when you were speaking?”	3.24	2.76	3.43	6.7×10^{-3}	0.21
Q5. ... the robot sometimes thought you were talking when you were not?”	3.43	3.14	4.41*	3.4×10^{-6}	4.7×10^{-5}
Q6. ... the interaction flowed in a pleasant and natural manner?”	2.97	2.46	3.32	8.6×10^{-4}	0.03

Table 8.7: Empirical results obtained for the user evaluation with a total of 37 participants, based on a set of 15 metrics (9 objective and 6 subjective). The * symbol indicates results that outperform the two other approaches with a level of statistical significance $\alpha = 0.05$ and Bonferroni correction.

statistically significant differences for the rule-structured model, while 6 metrics show higher means for the rule-structured model but without achieving full statistical significance, and 2 metrics yield slightly better results for the finite-state approach, although both without statistical significance.

It is also useful to contrast the results obtained from the survey with the initial user expectations, as shown in Table 8.8. We can observe that for all six questions, the actual system behaviour of the rule-structured approach exceeded the initial expectations of the user, while the two baseline models exhibit worse-than-expected performance on several metrics.

Survey questions: “Did you feel that ...”	Initial user expectations	Finite- state automaton	Factored statistical model	Rule- structured model
Q1. ... the robot correctly understood what you said?”	3.22	3.32	2.92	3.68*
Q2. ... the robot reacted appropriately to your instructions?”	3.35	3.70	3.32	3.86*
Q3. ... the robot asked you to repeat or confirm your instruction?”	2.68	2.16 [†]	2.19 [†]	3.30*
Q4. ... the robot sometimes ignored when you were speaking?”	2.89	3.24	2.76	3.43*
Q5. ... the robot sometimes thought you were talking when you were not?”	3.81	3.43	3.14 [†]	4.41*
Q6. ... the interaction flowed in a pleasant and natural manner?”	2.92	2.97	2.46 [†]	3.32*

Table 8.8: Comparison between the initial expectations and the actual performance of the three approaches. The * symbol indicates better-than-expected performance with $\alpha = 0.05$, and the [†] symbol worse-than-expected performance (also with $\alpha = 0.05$).

8.3.3 Discussion

Error analysis

The empirical results derived from the user trials highlight the benefits of a hybrid modelling framework based on probabilistic rules compared to traditional approaches. Through a follow-up error analysis, we found this difference to be imputable to several factors, which we now describe.

Although the finite-state automaton functioned well in most trials, it often required multiple repetitions in order to reach sufficient confidence regarding the instruction to perform. In comparison, the rule-structured model was able to accumulate evidence from several information sources (including the prior probabilities of the various instructions given the context) thanks to its explicit, probabilistic representation of the user intention. This possibility to accumulate evidence and exploit contextual knowledge enables the rule-structured model to zero in on the right instruction faster and more efficiently than the hand-crafted model. One can observe this difference in the metrics M1 (number of repetition requests), M6 (number of turns per instructions) and Q3 (frequency

of clarification requests) of the user trial.

Another interesting element we found in our analysis was that the factored statistical model operated well in the most common conversational situations, but was frequently led astray when encountering events that had not been observed in the Wizard-of-Oz training set. In particular, although the user action model $P(a'_u | i'_u, a_m)$ offered reasonable estimates for the most prevalent user intentions and dialogue acts, this was not the case for less common instructions which had few or no occurrences in the training set. This disparity in the estimated distributions often resulted in the dialogue system getting stuck in unseen dialogue states and selecting suboptimal actions. Although it was trained on the exact same data, the rule-structured approach did not suffer from this data sparsity in the same extent due to its more powerful generalisation abilities. This difference can be clearly noticed in the metrics M3 (number of repeated instructions), M9 (average duration), Q1 (quality of the robot's understanding) and Q2 (appropriateness of the robot's behaviour).

The finite-state automaton and the factored statistical model also encountered difficulties in filtering out spurious speech recognition hypotheses, especially the ones produced by the robot's own noise when executing physical movements. This often led the robot to request the user to repeat an instruction when no instruction was actually uttered. The rule-structured model proved to be better at filtering out these undesired inputs. The metrics M8 (number of system turns) and Q5 (ability of the robot to distinguish noise from speech) illustrate this discrepancy.

Finally, it is worth noting that the rule-structured model systematically assigned higher utilities to confirmation requests (“*should I do X?*”) than repetition requests (“*sorry, could you repeat?*”) when faced with unclear user instructions, as evidenced by the metric M1. While this characteristic of the estimated parameters for the rule-structured model initially came as a surprise (since the wizard did use some repetition requests in the Wizard-of-Oz interactions, although admittedly much fewer than confirmations), it proved to be an excellent conversational strategy for the domain, as participants perceived these confirmation requests to be much more natural and informative than repetitions. By contrast, the two baseline approaches relied much more heavily on repetition requests to elicit the user instructions, a strategy that many users found irritating.

Interpretation of the results

The empirical results obtained from the user trials demonstrate that the hybrid modelling framework presented in this thesis is a viable and competitive alternative to classical dialogue management approaches. Nevertheless, the results are subject to two cautionary remarks. Most importantly, the results obtained for the two baselines are contingent on the particular design choices described in Section 8.2.1 and 8.2.2. Although these design choices are in our view relatively uncontroversial and do follow standard practices in the field of dialogue modelling, there is no doubt that these approaches could be further optimised through the use of more advanced estimation methods and parameter tuning. The intended purpose of this user evaluation is, however, *not* to compare probabilistic rules with the “best possible” hand-crafted and statistical techniques, as such a characterisation would make little sense and remain impossible to prove in practice. Instead, the empirical results presented on the previous pages are best interpreted as a comparison between approaches featuring the same level of sophistication in their representation of the dialogue domain, but differing from one another along two dimensions:

- The finite-state automaton and the rule-structured model share the same domain knowledge

and mappings between user instructions and corresponding system actions. However, these two approaches diverge in their account of uncertainty: While the automaton relies on confidence thresholds, the rule-structured model employs probabilistic reasoning to infer the most likely instruction given the observed inputs, prior likelihoods and external context.

- Analogously, the factored statistical model and the rule-structured model share the same conditional dependencies between variables, domain-specific constraints, and training data. However, they differ in the amount of internal domain structure introduced into the probabilistic model, and therefore in the numbers of parameters to estimate.

Furthermore, we must also highlight the fact that the results were obtained in a context of a dialogue domain that exhibits three properties: (1) relatively high levels of noise and uncertainty, (2) a non-trivial relational structure to model and (3) a limited availability of in-domain training data. Although these properties are common to many dialogue domains, one should be wary of extrapolating these results to domains that do not share these properties. For instance, dialogue domains in which all state variables are fully observed and behave in a deterministic manner might be better addressed by purely symbolic techniques instead of adopting a hybrid approach. Similarly, dialogue domains that can draw on large amounts of training data (or can rely on a pre-existing user simulator)⁴ might not have a direct need for the kind of expert domain knowledge incorporated in probabilistic rules. In our experience, such cases constitute nevertheless the exception rather than the rule: Most dialogue domains *do* have substantial levels of uncertainty to confront, a rich internal structure, and only limited access to domain-specific interaction data (if any at all).

8.4 Conclusion

This chapter presented an extensive user evaluation of the hybrid dialogue modelling framework developed in this thesis. The experiment was designed to compare a dialogue manager relying on probabilistic rules against two baselines that respectively correspond to a purely hand-crafted dialogue manager (expressed as a finite-state automaton) and a purely statistical dialogue manager (based on factored models).

The experiment was again set up in a human–robot interaction domain. The participants were asked to instruct the robot to locate a given object, pick it up and bring it back to the starting position. Each of the 37 participants performed 3 dialogues (one for each dialogue management approach), thus amounting to 3×37 collected interactions. After each interaction, the participants completed a survey with 6 questions inquiring about their perception of the dialogue.

The three approaches were compared on the basis of 15 metrics with the aim to measure the quality and efficiency of the dialogues. The metrics comprised both the user answers to the survey as well as 9 objective metrics extracted from the interaction logs. The empirical results indicate that the rule-structured approach outperforms the two baselines on both objective and subjective metrics, with statistically significant differences for 7 metrics. The outcome of this user evaluation provides further empirical support for the central argument developed in this thesis, namely that the formalism of probabilistic rules is well-suited to capture the structure of dialogue domains and

⁴The current experiment focused on comparing dialogue managers tuned from Wizard-of-Oz data. An interesting direction for future work would be to evaluate the empirical effects of our modelling approach on measures of dialogue quality when the parameters are optimised from a simulator such as the one detailed in Chapter 6.

can contribute to the development of more robust and conversationally competent dialogue systems through a combination of expert domain knowledge and probabilistic reasoning.

Chapter 9

Concluding remarks

This final chapter summarises the main contributions of this thesis. We briefly review the theoretical underpinnings of our work, its practical implementation in the OpenDial software toolkit and its empirical validation in three consecutive experimental studies. In addition, we also enumerate a number of research themes that have not been directly addressed in this dissertation but constitute interesting and important topics for future work.

9.1 Summary of contributions

The introductory chapter listed three research questions at the core of this thesis:

1. How can we integrate prior domain knowledge into probabilistic models of dialogue?
2. How can the parameters of these structured probabilistic models be estimated from data, using methods from supervised and reinforcement learning?
3. What is the empirical effect of such modelling techniques on the quality and efficiency of verbal interactions?

The first question was addressed in Chapter 4, which presented the formalism of probabilistic rules and its application to dialogue management. We also showed in Chapters 5 and 6 how to optimise the parameters of these rules through a process of Bayesian inference. Finally, Chapter 8 described an empirical evaluation of our modelling approach based on user trials in a human–robot interaction domain.

A new, hybrid approach to dialogue management

The single most important scientific contribution made in this thesis is (in our view) the development of a new theoretical framework for dialogue modelling and control based on the notion of *probabilistic rules*. As we have seen, probabilistic rules are defined as structured mappings between conditions and effects and can encode both probability and utility distributions. The conditions and effects are encoded as arbitrarily complex logical formulae and can make use of universal quantification as well as special-purpose operators to manipulate strings and lists of elements. At runtime, these probabilistic rules are instantiated as latent nodes in the graphical model representing the current dialogue state.

The formalism allows the system designer to express the internal structure of a given dialogue domain in a compact set of rules. This modelling methodology offers two important benefits for dialogue management. The first benefit is a substantial reduction of the number of parameters associated with the model, thereby allowing probabilistic rules to be optimised from limited amounts of interactions. This advantage is in our opinion crucial for many application domains, as high-quality, in-domain interaction data is typically scarce and difficult to acquire.

In addition, probabilistic rules are also well-suited to capture the particular constraints, conventions and assumptions that characterise a given dialogue domain. Due to its combination of logical and probabilistic inference, we believe the formalism of probabilistic rules can serve as a useful bridge between symbolic and statistical approaches to dialogue management. The presented framework is very general and can express a wide spectrum of models, from classical probabilistic models fully estimated from data to manually designed models associated with only a handful of parameters. The choice of model within this spectrum boils down to a design decision based on the relative availabilities of training data and domain knowledge.

Estimation of rule parameters

Chapters 5 and 6 introduced a number of specialised learning algorithms employed to automatically estimate the parameter of probabilistic rules from data. We argued that the general skeleton of the rules – that is, the mapping between the conditions and their associated effects – is generally best structured by the system designer, while the numeric probabilities or utilities encoded in the rules are best estimated empirically on the basis of observed dialogue data.

We developed and discussed two complementary approaches to the statistical estimation of these rule parameters:

1. The first approach is a supervised learning approach in which the rule parameters are estimated from collected Wizard-of-Oz data. In this approach, the learning algorithm gradually adjusts the rule parameters in order to imitate the conversational behaviour of the wizard. The estimation procedure builds on the assumption that the wizard will tend in most cases to select the action that yields the highest utility in the current situation.
2. The second approach is couched in a reinforcement learning framework. In this setting, the learning agent is not provided with external examples of expert behaviour but optimises its parameters through repeated interactions with a real or simulated user. We reviewed both model-based and model-free reinforcement learning methods to this task. The model-based approach operates by estimating explicit models of the domain and subsequently selecting the system actions through online forward planning, while the model-free approach skips this intermediate estimation step in order to directly optimise a dialogue policy from interaction experience.

Both approaches are grounded in Bayesian inference. Each parameter is represented as a distinct random variable and associated with an initial prior distribution over a (usually continuous) range of possible values. This distribution is iteratively refined and narrowed down on the basis of the observed data points. The mathematical foundations for this process are directly derived from Bayes' rule. Assuming a set of parameters θ , some observed data \mathcal{D} and a prior distribution $P(\theta)$

over the parameter values, the posterior distribution $P(\boldsymbol{\theta} | \mathcal{D})$ over the parameters given the data set is calculated as:

$$P(\boldsymbol{\theta} | \mathcal{D}) = \eta P(\mathcal{D}; \boldsymbol{\theta}) P(\boldsymbol{\theta}) \quad (9.1)$$

where η is a normalisation factor. Depending on the rule type and availability of expert knowledge, the parameter priors can be encoded through multiple families of distributions such as Dirichlet, Gaussian or uniform distributions.

Experimental studies

We conducted a series of practical experiments to evaluate the practical viability of our modelling framework. All experiments took place in the context of a human–robot interaction domain and employed the Nao robot as our development and testing platform.

We carried out three distinct experimental studies. The first experiment, described in Section 5.3, sought to empirically analyse the learning performance of a rule-structured utility model compared to more weakly structured representations based on either plain utility tables or linear models. Using a small set of Wizard-of-Oz interactions as training data, the empirical results attested to the ability of the rule-structured model to quickly converge towards a high-quality policy and imitate the dialogue behaviour of the wizard.

The second experiment, outlined in Section 6.3, demonstrated how to transfer this learning method into a reinforcement learning context. The aim of the experiment was to automatically estimate the transition model of a human–robot interaction domain from repeated interactions with a user simulator bootstrapped from Wizard-of-Oz data. The experiment contrasted the learning performance of a rule-structured model with a classical factored baseline. A forward planning algorithm was used in both cases to select the next action to perform given all sources of uncertainty (i.e. state uncertainty, uncertain action effects, and model uncertainty). As in the first experiment, the results indicated that the rule-structured model could learn the interaction dynamics (and thus achieve higher rewards) much faster than its unstructured counterpart.

The third and final experiment, which we detailed in the previous chapter, evaluated the modelling framework through a full-scale user study. Instead of focusing on the learning performance, the objective of the experiment was to analyse the practical effects of the framework on measures of dialogue quality and efficiency. The interaction scenario consisted of a simple task in which the participants instructed the robot to pick up a designated object and bring it to another location. Three dialogue management approaches were developed: one hand-crafted finite-state automaton, one statistical dialogue manager with factored models, and one hybrid dialogue manager based on probabilistic rules. Each participant carried out three separate dialogues (one for each approach). The results obtained from this user evaluation showed that the rule-structured model outperformed the two baselines on a large range of objective and subjective metrics.

Development of the OpenDial toolkit

The final contribution of this thesis is the development of a new software toolkit for dialogue management called OpenDial. The toolkit implements all the algorithms and data structures described in this dissertation and can be used to develop various types of dialogue systems through probabilistic rules. Domain- and task-specific knowledge is captured in the declarative specification of the dialogue domain in an XML format, thereby reducing the dialogue architecture to a small set of

generic functions for state update and action selection. We showed in Chapter 7 that probabilistic rules could be employed to represent a large panel of dialogue processing tasks and argued that the reliance on such a shared modelling framework offers several advantages in terms of transparency, flexibility and portability across domains in comparison to black-box architectures.

9.2 Future work

The approach presented in this thesis can be extended in several important directions, which we describe below.

Reinforcement learning with live interactions

As demonstrated in Chapter 6, the parameters of probabilistic rules can be optimised from relatively small amounts of interactions. This characteristic opens up the possibility of directly estimating rule-structured domain models from live interactions with human users, without relying on a user simulator. However, although theoretically appealing, this possibility has not yet been validated experimentally and would certainly constitute an important direction for future work.

In practice, the conduct of such an experiment will require algorithmic improvements to the online planning algorithm in order to enhance its real-time performance. One possible solution, as already suggested in Section 6.3.4, would be to integrate model-based and model-free approaches and employ the model-free policy as a heuristic function to guide the forward search of the online planner. Such a mixture of offline and online planning has notably been investigated by Ross and Chaib-draa (2007) with promising results.

Combination of supervised learning and reinforcement learning

This thesis developed two distinct methods to the optimisation of rule parameters, respectively based on supervised learning and on reinforcement learning. Each method brings its own advantages and shortcomings: Supervised learning algorithms offer relatively straightforward methods for parameter estimation, but hinges on the availability of external examples of dialogue such as Wizard-of-Oz interactions. Furthermore, the estimated parameters may not always lead to optimal decisions when the wizard behaviour is inconsistent or difficult to reproduce. Reinforcement learning algorithms, for their part, can directly optimise parameters without having access to “gold standard” examples, but can be tedious to apply from scratch to live interactions.¹

As already shown by several authors (see e.g. Williams and Young, 2003; Rieser and Lemon, 2006; Henderson et al., 2008), supervised and reinforcement learning methods can be combined with one another in order to obtain the best of both worlds. This is often achieved by deriving initial estimates for the domain parameters via supervised learning and then refining these estimates through reinforcement learning. Such a combination of approaches would be facilitated in our framework by the fact that both learning techniques are already grounded in the same theoretical foundations, namely Bayesian inference.

¹In the absence of reasonable initial estimates for the domain models, the dialogue policy followed by the system runs the risk of being completely inadequate in the first round of interactions. While such a low starting point is not problematic in simulated interactions, it becomes a more serious issue when interacting with real users.

Joint optimisation of dialogue models

As noted in Chapter 7, probabilistic rules can be employed to structure many reasoning tasks and are not necessarily restricted to dialogue management. Indeed, the dialogue system developed for our experiments already relied on probability and utility rules for natural language understanding and generation tasks, although the parameters of these rules were hand-crafted. However, nothing prevents these parameters from also being estimated in parallel with the dialogue management models in order to jointly optimise the end-to-end behaviour of the dialogue agent. As argued by e.g. Lemon (2011), such joint optimisation of dialogue models brings several theoretical and practical advantages over isolated, component-by-component optimisations.

Incrementality and turn-taking

An important aspect of dialogue architectures that has not been covered in this dissertation is the question of incremental processing. As argued by several researchers (see for instance Schlangen and Skantze, 2011), conversationally competent dialogue systems should be able to process their inputs in a continuous manner, without having to wait for the end of an utterance to trigger the interpretation process. Extending the state update algorithm outlined in Section 4.4 to operate in an incremental manner would certainly constitute an important topic for future work.²

Similarly, the turn-taking functionalities integrated in the OpenDial toolkit are still rudimentary and would certainly benefit from a more principled account of the conversational floor in order to handle common dialogue phenomena such as interruptions and fragmented utterances.

Scaling up to more complex domains

Last but not least, the approach presented in this thesis should be evaluated in the context of larger and more realistic dialogue domains. While the human–robot interaction scenarios employed for the experiments presented a number of non-trivial challenges to address (notably regarding the high proportion of speech recognition errors and the necessity to perceive and act upon a real physical environment), they remained nevertheless restricted to a limited size. Scaling up the modelling framework to more complex domains with larger state–action spaces and more elaborate dialogue dynamics would allow us to cast a new light on the expressive power of the formalism and its suitability for practical dialogue applications.

²One suggestion would be to explicitly distinguish between the *insertion* of a new variable in the dialogue state and its *commitment*, as in the incremental units model of Schlangen and Skantze (2011). The pruning of the dialogue state would hence only be triggered when all its variables are committed.

Appendix A

Relevant probability distributions

This appendix details the most important probability distributions employed in this thesis. For each distribution, we provide its parameters, probability density or mass function (depending on whether the distribution has a discrete or continuous domain), mean and variance.

Continuous uniform distribution

Parameters: Continuous uniform distributions are described by two parameters a and b that define the range $[a, b]$ upon which the distribution is defined.

Density function: The density remains constant within $[a, b]$ and is 0 outside this range:

$$P(x; a, b) = \begin{cases} \frac{1}{b-a} & \text{for } x \in [a, b] \\ 0 & \text{otherwise} \end{cases} \quad (\text{A.1})$$

Mean: The mean of a continuous uniform distribution is simply equal to $\frac{a+b}{2}$

Variance: The distribution variance is $\frac{(b-a)^2}{12}$

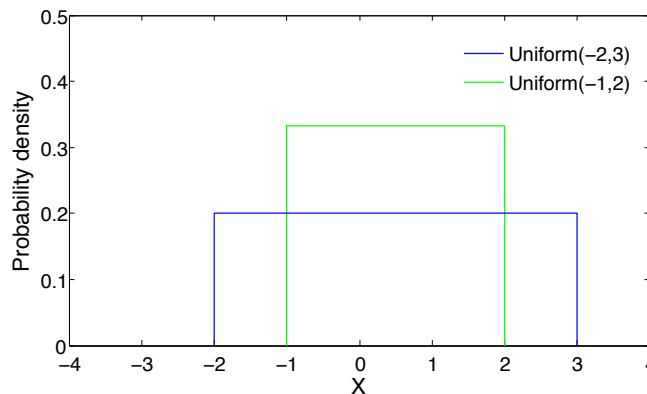


Figure A.1: Probability density functions for two continuous uniform distributions.

Discrete uniform distribution

Parameters: Discrete uniform distributions are also described by two parameters a and b , but are here constrained to integer values. The number n of values in the distribution is $b - a + 1$.

Probability mass function: The probability mass function is defined as:

$$P(X=i; a, b) = \begin{cases} \frac{1}{n} & \text{for } i \in \mathcal{Z} \text{ and } i \in [a, b] \\ 0 & \text{otherwise} \end{cases} \quad (\text{A.2})$$

Mean: The mean of a discrete uniform distribution is also $\frac{a+b}{2}$

Variance: The distribution variance is $\frac{(n^2 - 1)}{12}$

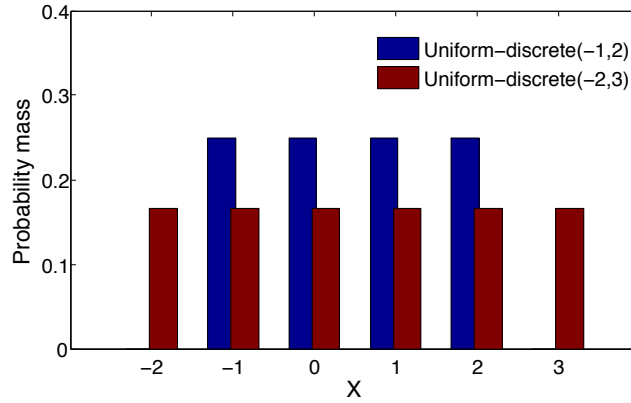


Figure A.2: Probability mass functions for two discrete uniform distributions.

Categorical distribution

A categorical distribution encodes the result of a random event that can take on one of K possible (and mutually exclusive) outcomes.

Parameters: A categorical distributions on K outcomes is defined by K parameters p_1, \dots, p_K representing the probabilities of each outcome.

Probability mass function: The probability mass function is simply defined as:

$$P(X = i; p_1, \dots, p_K) = p_i \quad (\text{A.3})$$

Mean: The expectation for a category i is p_i .

Variance: The variance for the category i is $p_i(1 - p_i)$.

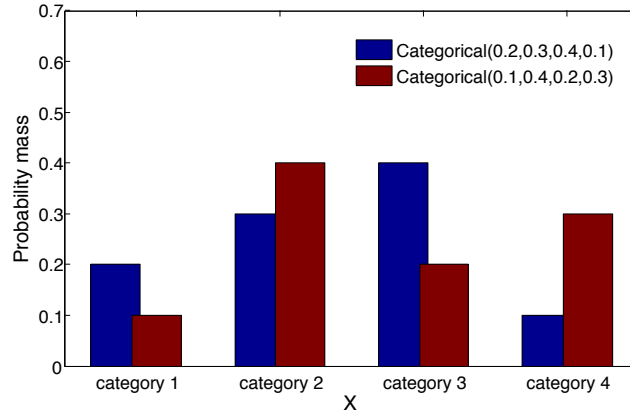


Figure A.3: Probability mass functions for two categorical distributions.

Multinomial distribution

Given the repetition of n independent trials where each trial leads to one of K possible outcomes (described by a categorical distribution), the multinomial distribution gives the probability of a particular combination of numbers of outcomes for the various categories.

Parameters: Multinomial distributions are parametrised with K probability values p_1, \dots, p_K expressing the likelihood of each outcome, and an integer n denoting the number of trials.

Probability mass function: For n trials, the probability of having x_1 outcomes for category 1, x_2 outcomes for category 2, \dots , and x_K outcomes for category K is:

$$P(X_1 = x_1, \dots, X_K = x_K) = \begin{cases} \frac{n!}{x_1! \dots x_K!} p_1^{x_1} \dots p_K^{x_K} & \text{when } \sum_{i=1}^K x_i = n \\ 0 & \text{otherwise} \end{cases} \quad (\text{A.4})$$

Mean: The expected number of outcomes for a category i is np_i .

Variance: The variance on the number of outcomes for a category i is $np_i(1 - p_i)$.

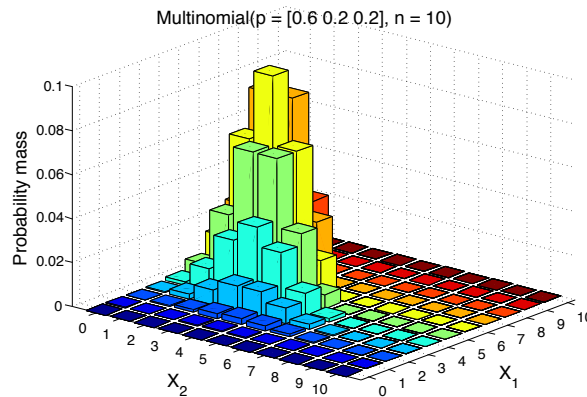


Figure A.4: Probability mass function for a multinomial distribution.

The binomial distribution is a special case of multinomial with only two categories. The binomial distribution expresses the number of successes associated with the repetition of n Bernoulli trials with a specific probability of success.

Normal distribution

The normal distribution (also called the Gaussian distribution or the bell curve) is the most well known probability distribution in the continuous domain. The central limit theorem states that, under mild conditions, the mean of many random variables drawn independently from the same (arbitrary) distribution is distributed according to a normal distribution in the large sample limit.

Parameters: A normal distribution is encoded by two parameters: the mean μ and variance σ^2 .

Probability density function: The density function of a normal distribution is defined as:

$$P(x; \mu, \sigma^2) = \frac{1}{\sqrt{2\pi\sigma^2}} \exp \left\{ -\frac{(x - \mu)^2}{2\sigma^2} \right\} \quad (\text{A.5})$$

Mean: The mean of the normal distribution corresponds to μ .

Variance: The variance of the distribution is σ^2 .

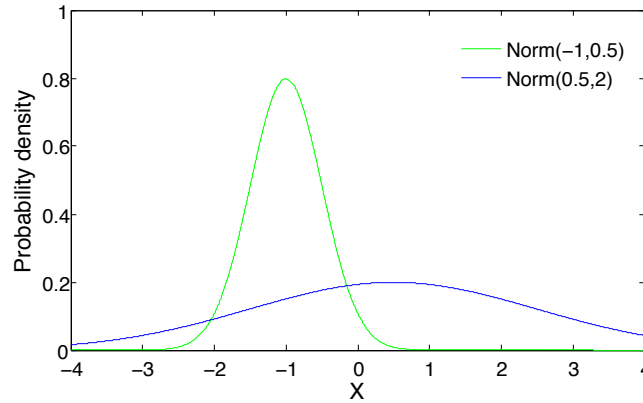


Figure A.5: Probability density functions for two normal distributions.

Multivariate normal distributions can be used to generalise one-dimensional normal distributions to higher dimensions. Multivariate normal distributions of dimensions K are parametrised by a K -dimensional mean vector μ and a $(K \times K)$ -dimensional covariance matrix Σ .

Dirichlet distribution

A Dirichlet is a continuous, multivariate probability distribution that is often used to describe the parameters of categorical or multinomial distributions. The Dirichlet distribution is indeed the conjugate prior of these distributions.

Parameters: A Dirichlet of dimension K is encoded by K parameters $\boldsymbol{\alpha} = \alpha_1, \dots, \alpha_K$.

Probability density function: The density function of a Dirichlet distribution is defined as:

$$P(x_1, \dots, x_K; \boldsymbol{\alpha}) = \frac{1}{B(\boldsymbol{\alpha})} \prod_{i=1}^K x_i^{\alpha_i-1} \quad \text{with } B(\boldsymbol{\alpha}) = \frac{\prod_{i=1}^K \Gamma(\alpha_i)}{\Gamma(\sum_{i=1}^K \alpha_i)} \quad (\text{A.6})$$

in which $B(\boldsymbol{\alpha})$ is a normalisation factor and Γ is the gamma function $\Gamma(z) = \int_0^\infty t^{z-1} e^{-t} dt$.

Mean: The mean of the i -th component of the Dirichlet distribution is $\frac{\alpha_i}{\sum_k \alpha_k}$.

Variance: The variance of the i -th component is $\frac{\alpha_i(\alpha_0 - \alpha_i)}{\alpha_0^2(\alpha_0 + 1)}$ with $\alpha_0 = \sum_{i=1}^K \alpha_i$.

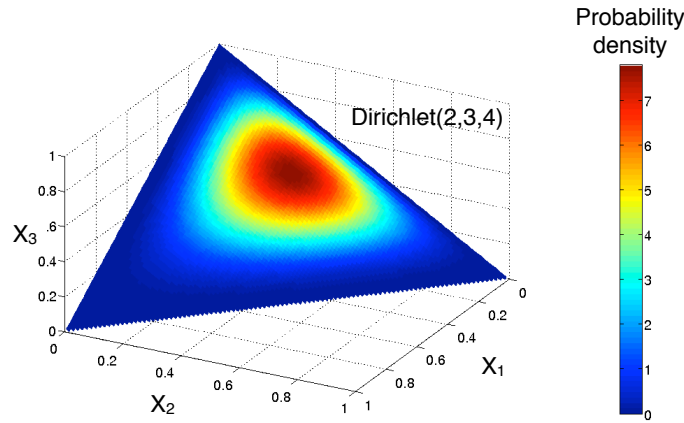


Figure A.6: Probability density function for a three-dimensional Dirichlet distribution.

Geometric distribution

A geometric distribution is a discrete probability distribution that describes the number of Bernoulli trials required to get one success.

Parameters: Geometric distributions are defined by the parameter p that encodes the probability of success for each Bernoulli trial.

Probability mass function: Given a constant probability p of success for each trial, the probability that the k th trial will result in the first success is:

$$P(X = k) = (1 - p)^{k-1} p \quad (\text{A.7})$$

Mean: The expected number of trials needed to get one success is $\frac{1}{p}$.

Variance: The variance on the numbers of trials to get the first success is $\frac{1-p}{p^2}$.

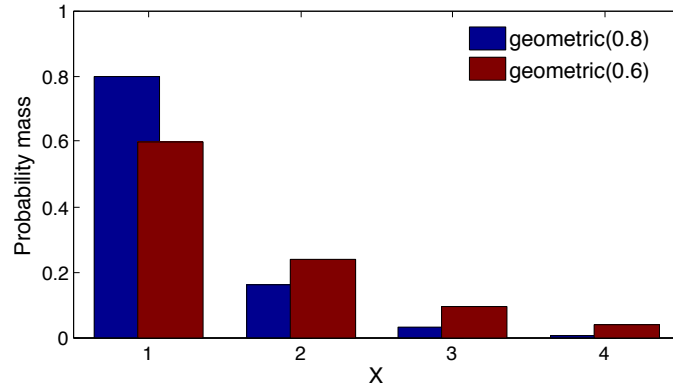


Figure A.7: Probability mass function for two geometric distributions.

Kernel distribution

Distributions can also be defined in a non-parametric manner using kernel density estimation (KDE). Such distributions are constructed on the basis of a set of sample points x_1, \dots, x_n .

Parameters: A kernel distribution is fully defined by its sample points, the kernel function $K(\cdot)$, and the smoothing bandwidth h . Multiple kernels are possible but a common choice is the Gaussian distribution.

Probability density function: The kernel density estimator for the points x_1, \dots, x_n is:

$$P(x) = \frac{1}{nh} \sum_{i=1}^n K\left(\frac{x - x_i}{h}\right) \quad (\text{A.8})$$

Mean: The mean of kernel density estimate is the average of the sample points: $\frac{\sum_{i=1}^n x_i}{n}$.

Variance: The variance of the estimate is $\sigma^2 + h^2\kappa$, where σ^2 is the variance of the sample points and κ corresponds to the variance of the kernel.

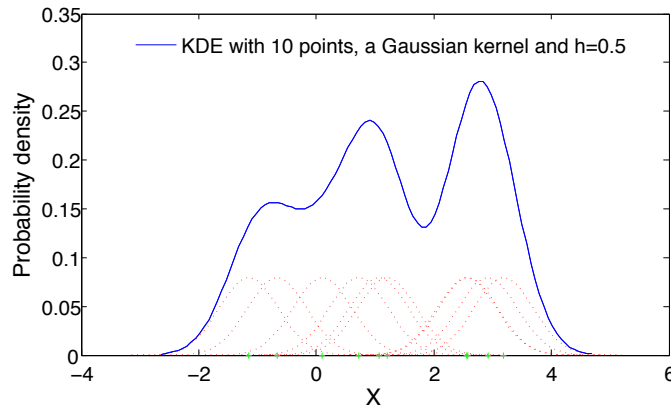


Figure A.8: Probability density function for a kernel density estimate with ten points. The Gaussian distributions making up the estimate are shown with red dashed lines.

Appendix B

Domain specifications

B.1 Experiments in Section 5.3

The dialogue policy is composed of a total of fifteen utility rules. The input variables of these rules are the user dialogue act a_u , the last system act a_m , the last physical movement $lastMove$, the recorded list of movements $sequence$, and a variable $silence$ expressing the amount of time elapsed since the last (user or system) action.

The variable a_u is encoded as a list of (one or more) dialogue acts. This encoding facilitates the processing of utterances containing more than one dialogue act.

- $r_1 :$ $\forall x,$
 if ($silence > 3 \wedge a_m = Demonstrate(x)$) **then**
 $\{U(a_m' = AskConfirm) = \theta_{confirm1}$
 else if ($silence > 2 \wedge a_m = Demonstrate(x)$) **then**
 $\{U(a_m' = AskConfirm) = \theta_{confirm2}$
 else if ($silence > 1 \wedge a_m = Demonstrate(x)$) **then**
 $\{U(a_m' = AskConfirm) = \theta_{confirm3}$
- $r_2 :$ **if** ($Confirm \in a_u \wedge lastMove \neq None$) **then**
 $\{U(a_m' = RegisterMove) = \theta_{registerExplicit}$
 else
 $\{U(a_m' = RegisterMove) = \theta_{registerExplicit2}$
- $r_3 :$ **if** ($Disconfirm \in a_u \wedge lastMove \neq None$) **then**
 $\{U(a_m' = UndoMove) = \theta_{undoMove}$
 else
 $\{U(a_m' = UndoMove) = \theta_{undoMove2}$
- $r_4 :$ **if** ($a_u \neq None \wedge lastMove \notin a_u \wedge Confirm \notin a_u$
 $\wedge Disconfirm \notin a_u \wedge lastMove \neq None$) **then**
 $\{U(a_m' = RegisterMove) = \theta_{registerImplicit}$
 else
 $\{U(a_m' = RegisterMove) = \theta_{registerImplicit2}$
- $r_5 :$ $\forall x, y, z,$
 if ($a_u = x \wedge lastMove \notin a_u \wedge (MoveArm(y, z) \in a_u$

$$\begin{aligned}
& \vee \text{MoveHead}(y) \in a_u \vee \text{Kneel} \in a_u \vee \text{MoveFoot}(x, y) \in a_u \\
& \vee \text{StandUp} \in a_u \vee \text{SitDown} \in a_u \vee \text{Turn}(y) \in a_u)) \text{ then} \\
& \quad \left\{ U(a_m' = \text{Demonstrate}(x)) = \theta_{\text{Demonstrate}} \right. \\
& \text{else} \\
& \quad \left\{ U(a_m' = \text{Demonstrate}(x)) = \theta_{\text{Demonstrate2}} \right. \\
r_6 : & \quad \text{if } (a_m \neq \text{AskRepeat}) \text{ then} \\
& \quad \left\{ U(a_m' = \text{AskRepeat}) = \theta_{\text{repeatFirst}} \right. \\
& \text{else} \\
& \quad \left\{ U(a_m' = \text{AskRepeat}) = \theta_{\text{repeatSecond}} \right. \\
r_7 : & \quad \text{if } (\text{Confirm} \in a_u \wedge |a_u| = 1) \text{ then} \\
& \quad \left\{ U(a_m' = \text{Acknowledgement}) = \theta_{\text{acknowledgement}} \right. \\
& \text{else} \\
& \quad \left\{ U(a_m' = \text{Acknowledgement}) = \theta_{\text{acknowledgement2}} \right. \\
r_8 : & \quad \text{if } (\text{Disconfirm} \in a_u \wedge |a_u| = 1) \text{ then} \\
& \quad \left\{ U(a_m' = \text{AskIntention}) = \theta_{\text{askIntention}} \right. \\
& \text{else} \\
& \quad \left\{ U(a_m' = \text{AskIntention}) = \theta_{\text{askIntention2}} \right. \\
r_9 : & \quad \text{if } (\text{RepeatAll} \in a_u \wedge \text{sequence} \neq \text{None}) \text{ then} \\
& \quad \left\{ U(a_m' = \text{DemonstrateAll}) = \theta_{\text{demonstrateAll}} \right. \\
r_{10} : & \quad \text{if } (\text{ForgetAll} \in a_u \wedge \text{sequence} \neq \text{None}) \text{ then} \\
& \quad \left\{ U(a_m' = \text{ForgetAll}) = \theta_{\text{forgetAll}} \right. \\
r_{11} : & \quad \text{if } (\text{Say}(\text{Compliment}) \in a_u \wedge a_m = \text{DemonstrateAll}) \text{ then} \\
& \quad \left\{ U(a_m' = \text{Say}(\text{ThankYou})) = \theta_{\text{sayThankYou}} \right. \\
r_{12} : & \quad \text{if } (\text{GoToInitPose} \in a_u) \text{ then} \\
& \quad \left\{ U(a_m' = \text{GoToInitPose}) = \theta_{\text{goToInitPose}} \right. \\
r_{13} : & \quad \text{if } (\text{Stop} \in a_u) \text{ then} \\
& \quad \left\{ U(a_m' = \text{Stop}) = \theta_{\text{stop}} \right. \\
r_{14} : & \quad \text{if } (\text{Say}(\text{Hello}) \in a_u) \text{ then} \\
& \quad \left\{ U(a_m' = \text{Say}(\text{Hello})) = \theta_{\text{sayHello}} \right. \\
r_{15} : & \quad \text{if } (\text{Say}(\text{Goodbye}) \in a_u) \text{ then} \\
& \quad \left\{ U(a_m' = \text{Say}(\text{Goodbye})) = \theta_{\text{sayGoodbye}} \right.
\end{aligned}$$

B.2 Experiments in Section 6.3

First experiment

The six rules below specify the transition model used in the first experiment of Section 6.3. The first rule expresses the probability of the current task being completed after the last system action.

If the task is completed, the user intention is reinitialised with a prior distribution given by rules r_3 , r_4 and r_5 . The user action model is represented by rule r_6 .

- r_1 : $\forall x$,
if ($a_m = Do(x) \wedge i_u = x$) **then**
 $\left\{ P(completed-task' = true) = 1.0 \right.$
else if ($a_m = Excuse(x)$) **then**
 $\left\{ P(completed-task' = true) = 1.0 \right.$
else if ($a_m = ConfirmDetection \wedge i_u = DoYouSee(x)$) **then**
 $\left\{ P(completed-task' = true) = 1.0 \right.$
else if ($a_m = DisconfirmDetection \wedge i_u = DoYouSee(x)$) **then**
 $\left\{ P(completed-task' = true) = 1.0 \right.$
else if ($a_m = Describe(x) \wedge i_u = WhatDoYouSee$) **then**
 $\left\{ P(completed-task' = true) = 1.0 \right.$
else if ($a_m = Do(x) \vee a_m = Excuse(x) \vee a_m = Describe(x)$
 $\vee a_m = DisconfirmDetection \vee a_m = ConfirmDetection$) **then**
 $\left\{ \begin{array}{l} P(completed-task' = true) = \theta_{changemind[0]} \\ P(completed-task' = false) = \theta_{changemind[1]} \end{array} \right.$
else if ($i_u = None$) **then**
 $\left\{ P(completed-task' = true) = 1.0 \right.$
else
 $\left\{ P(completed-task' = false) = 1.0 \right.$
- r_2 : $\forall x$,
if ($i_u = x \wedge completed-task = false$) **then**
 $\left\{ P(i_u' = x) = 1 \right.$
- r_3 : **if** ($completed-task = true$) **then**
 $\left\{ \begin{array}{l} P(i_u' = Move(Left)) = \theta_{baseprior[0]} \\ P(i_u' = Move(Forward)) = \theta_{baseprior[1]} \\ P(i_u' = Move(Backward)) = \theta_{baseprior[2]} \\ P(i_u' = Move(Right)) = \theta_{baseprior[3]} \\ P(i_u' = DoYouSee(object_1)) = \theta_{baseprior[4]} \\ P(i_u' = DoYouSee(object_2)) = \theta_{baseprior[5]} \\ P(i_u' = WhatDoYouSee) = \theta_{baseprior[6]} \\ P(\cdot) = \theta_{baseprior[7]} \end{array} \right.$
- r_4 : $\forall x$,
if ($completed-task = true \wedge x \in carried$) **then**
 $\left\{ \begin{array}{l} P(i_u' = Release(x)) = \theta_{releaseprior[0]} \\ P(\cdot) = \theta_{releaseprior[1]} \end{array} \right.$
else if ($completed-task = true$) **then**
 $\left\{ \begin{array}{l} P(i_u' = Release(x)) = \theta_{releaseprior2[0]} \\ P(\cdot) = \theta_{releaseprior2[1]} \end{array} \right.$
- r_5 : $\forall x$,
if ($completed-task = true \wedge carried = []$) **then**

$$\begin{aligned}
& \begin{cases} P(i_u' = \text{PickUp}(x)) = \theta_{\text{pickupprior}[0]} \\ P(\cdot) = \theta_{\text{pickupprior}[1]} \end{cases} \\
& \text{else if } (\text{completed-task} = \text{true}) \text{ then} \\
& \begin{cases} P(i_u' = \text{PickUp}(x)) = \theta_{\text{pickupprior2}[0]} \\ P(\cdot) = \theta_{\text{pickupprior2}[1]} \end{cases} \\
r_6: & \quad \forall x, \\
& \text{if } (a_m = \text{Ground}(x) \wedge i_u = x) \text{ then} \\
& \begin{cases} P(a_u^{p'} = \text{Confirm}) = \theta_{\text{groundpredict}[0]} \\ P(a_u^{p'} = \text{Other}) = \theta_{\text{groundpredict}[1]} \\ P(\cdot) = \theta_{\text{groundpredict}[2]} \end{cases} \\
& \text{else if } (a_m = \text{Ground}(x) \wedge i_u \neq x \wedge i_u \neq \text{None}) \text{ then} \\
& \begin{cases} P(a_u^{p'} = \text{Disconfirm}) = \theta_{\text{groundpredict2}[0]} \\ P(a_u^{p'} = \text{Ask}(x)) = \theta_{\text{groundpredict2}[1]} \\ P(a_u^{p'} = \text{Other}) = \theta_{\text{groundpredict2}[2]} \\ P(\cdot) = \theta_{\text{groundpredict2}[3]} \end{cases} \\
& \text{else if } (a_m = \text{AskConfirm}(x) \wedge i_u = x) \text{ then} \\
& \begin{cases} P(a_u^{p'} = \text{Confirm}) = \theta_{\text{confirmpredict}[0]} \\ P(a_u^{p'} = \text{Ask}(x)) = \theta_{\text{confirmpredict}[1]} \\ P(a_u^{p'} = \text{Other}) = \theta_{\text{confirmpredict}[2]} \\ P(\cdot) = \theta_{\text{confirmpredict}[3]} \end{cases} \\
& \text{else if } (a_m = \text{AskConfirm}(x) \wedge i_u \neq x \wedge i_u \neq \text{None}) \text{ then} \\
& \begin{cases} P(a_u^{p'} = \text{Disconfirm}) = \theta_{\text{disconfirmpredict}[0]} \\ P(a_u^{p'} = \text{Other}) = \theta_{\text{disconfirmpredict}[1]} \\ P(\cdot) = \theta_{\text{disconfirmpredict}[2]} \end{cases} \\
& \text{else if } (a_m = \text{Do}(x) \wedge i_u = x) \text{ then} \\
& \begin{cases} P(a_u^{p'} = \text{RepeatLast}) = \theta_{\text{samemove}[0]} \\ P(a_u^{p'} = \text{Ask}(x)) = \theta_{\text{samemove}[1]} \\ P(a_u^{p'} = \text{Other}) = \theta_{\text{samemove}[2]} \\ P(\cdot) = \theta_{\text{samemove}[3]} \end{cases} \\
& \text{else if } (a_m = \text{AskRepeat} \vee \text{completed-task} = \text{true}) \text{ then} \\
& \begin{cases} P(a_u^{p'} = \text{Ask}(x)) = \theta_{\text{intent}[0]} \\ P(a_u^{p'} = \text{Other}) = \theta_{\text{intent}[1]} \\ P(\cdot) = \theta_{\text{intent}[2]} \end{cases} \\
& \text{else if } (i_u = \text{None}) \text{ then} \\
& \begin{cases} P(a_u^{p'} = \text{Other}) = 1.0 \end{cases} \\
& \text{else} \\
& \begin{cases} P(a_u^{p'} = \text{Ask}(x)) = \theta_{\text{othercase}[0]} \\ P(a_u^{p'} = \text{Other}) = \theta_{\text{othercase}[1]} \\ P(\cdot) = \theta_{\text{othercase}[2]} \end{cases}
\end{aligned}$$

Second experiment

The second experiment focuses on the comparison of two rule-structured models: a transition model for the model-based approach, and an action-value model for the model-free approach. The

transition model is identical to the one described above and will hence not be repeated. The model-free approach is specified with a set of 11 rules. The rule r_0 first derives a simple representation of the user intention based on the last user dialogue act a_u , the next-to-last user dialogue act a_{u-prev} , last system act a_m and last system action $lastMove$. The 10 following rules r_1, \dots, r_{10} encode the action utilities based on this user intention and on the general context.

- $r_0 :$ $\forall x,$
 if ($a_u = Confirm \wedge a_{u-prev} = Ask(x)$) **then**
 $\{ P(i_u' = x) = 1$
 else if ($a_m = Ground(x) \wedge a_u \neq Disconfirm$) **then**
 $\{ P(i_u' = x) = 1$
 else if ($a_u = RepeatLast \wedge lastMove = x$) **then**
 $\{ P(i_u' = x) = 1$
 else if ($a_u = Ask(x)$) **then**
 $\{ P(i_u' = x) = 1$
- $r_1 :$ $\forall x,$
 if ($i_u = Move(x)$) **then**
 $\left\{ \begin{array}{l} U(a_m' = Do(Move(x))) = \theta_{movements1} \\ U(a_m' = Ground(Move(x))) = \theta_{movements2} \end{array} \right.$
- $r_2 :$ $\forall x,$
 if ($i_u = PickUp(x) \wedge x \in perceived \wedge carried = []$) **then**
 $\left\{ \begin{array}{l} U(a_m' = Do(PickUp(x))) = \theta_{pickup1} \\ U(a_m' = Ground(PickUp(x))) = \theta_{pickup2} \end{array} \right.$
 else if ($i_u = PickUp(x) \wedge x \in perceived \wedge carried \neq []$) **then**
 $\{ U(a_m' = Excuse(AlreadyCarryObject)) = \theta_{pickup3}$
 else if ($i_u = PickUp(x) \wedge x \notin perceived$) **then**
 $\{ U(a_m' = Excuse(DoNotSeeObject)) = \theta_{pickup4}$
- $r_3 :$ $\forall x,$
 if ($i_u = Release(x) \wedge x \in carried$) **then**
 $\left\{ \begin{array}{l} U(a_m' = Do(Release(x))) = \theta_{release1} \\ U(a_m' = Ground(Release(x))) = \theta_{release2} \end{array} \right.$
 else if ($i_u = Release(x) \wedge x \notin carried$) **then**
 $\{ U(a_m' = Excuse(DoNotCarryObject)) = \theta_{release3}$
- $r_4 :$ **if** ($i_u \neq None$) **then**
 $\{ U(a_m' = None) = \theta_{none}$
 else
 $\{ U(a_m' = None) = \theta_{none2}$
- $r_5 :$ $\forall x, y,$
 if ($i_u = x$) **then**
 $\left\{ \begin{array}{l} U(a_m' = Do(y) \wedge a_m' \neq Do(x)) = \theta_{wrong1} \\ U(a_m' = Ground(y) \wedge a_m' \neq Ground(x)) = \theta_{wrong2} \\ U(a_m' = Excuse(y)) = \theta_{wrong3} \end{array} \right.$

$r_6:$ **if** ($a_m \neq AskRepeat$) **then**
 $\left\{ U(a_m' = AskRepeat) = \theta_{repeat} \right.$

$r_7:$ **if** ($i_u = Disconfirm$) **then**
 $\left\{ U(a_m' = AskRepeat) = \theta_{repeat2} \right.$

$r_8:$ $\forall x, y,$
 if ($i_u = x$) **then**
 $\left\{ \begin{array}{l} U(a_m' = AskConfirm(x)) = \theta_{confirm1} \\ U(a_m' = AskConfirm(y) \wedge a_m' \neq AskConfirm(x)) = \theta_{confirm2} \end{array} \right.$

$r_9:$ $\forall x,$
 if ($i_u = DoYouSee(x) \wedge x \in perceived$) **then**
 $\left\{ \begin{array}{l} U(a_m' = Confirm) = \theta_{doyousee1} \\ U(a_m' = Disconfirm) = \theta_{doyousee2} \end{array} \right.$
 else if ($i_u = DoYouSee(x) \wedge x \notin perceived$) **then**
 $\left\{ \begin{array}{l} U(a_m' = Disconfirm) = \theta_{doyousee3} \\ U(a_m' = Confirm) = \theta_{doyousee4} \end{array} \right.$
 else
 $\left\{ \begin{array}{l} U(a_m' = Confirm) = \theta_{doyousee5} \\ U(a_m' = Disconfirm) = \theta_{doyousee6} \end{array} \right.$

$r_{10}:$ $\forall x,$
 if ($i_u = WhatDoYouSee \wedge x = perceived$) **then**
 $\left\{ U(a_m' = Describe(x)) = \theta_{whatdoyousee1} \right.$
 else
 $\left\{ U(a_m' = Describe(x)) = \theta_{whatdoyousee2} \right.$

B.3 Experiments in Chapter 8

We list below the collection of rule-structured models employed for the user evaluation experiment. The models for natural language understanding and generation are common to all three approaches, while the four other models are specific to Approach 3.

Natural language understanding model

The natural language understanding model is composed of a set of simple, deterministic template-matching rules. The rules map the presence of particular words or phrases in the user utterance u_u to specific user dialogue acts a_u .

The model is divided in two phases. Rules r_1 to r_{16} are responsible for defining the general structure of the dialogue acts. The last rule r_{17} builds on the results from the previous rules and refines the dialogue act representation through the resolution of references to visual objects and the distinction between short and long movements.

- r_1 : **if** ("forward" $\in u_u \vee$ "forwards" $\in u_u \vee$ "straight" $\in u_u$) **then**
 $\left\{ P(a_u^{\text{temp}'} = \text{Ask}(\text{Move}(\text{Forward}))) = 1 \right.$
- r_2 : **if** ("backward" $\in u_u \vee$ "backwards" $\in u_u \vee$ ("back" $\in u_u \wedge$ "turn" $\notin u_u$)) **then**
 $\left\{ P(a_u^{\text{temp}'} = \text{Ask}(\text{Move}(\text{Backward}))) = 1 \right.$
- r_3 : **if** ("left" $\in u_u$) **then**
 $\left\{ P(a_u^{\text{temp}'} = \text{Ask}(\text{Move}(\text{Left}))) = 1 \right.$
- r_4 : **if** ("go * right" $\in u_u \vee$ "turn * right" $\in u_u \vee$ "move * right" $\in u_u \vee$ "rotate * right" $\in u_u$) **then**
 $\left\{ P(a_u^{\text{temp}'} = \text{Ask}(\text{Move}(\text{Right}))) = 1 \right.$
- r_5 : **if** ("turn back" $\in u_u \vee$ "turn around" $\in u_u \vee$ "one hundred eighty degrees" $\in u_u \vee$ "U turn" $\in u_u$) **then**
 $\left\{ P(a_u^{\text{temp}'} = \text{Ask}(\text{Move}(\text{Turn}))) = 1 \right.$
- r_6 : $\forall x$,
if ("pick up {x}" $\in u_u \vee$ "pick {x} up" $\in u_u \vee$ "take {x}" $\in u_u \vee$ "grasp {x}" $\in u_u$) **then**
 $\left\{ P(a_u^{\text{temp}'} = \text{Ask}(\text{PickUp}(x))) = 1 \right.$
- r_7 : **if** ("release" $\in u_u \vee$ "put * down" $\in u_u \vee$ "put * on the floor" $\in u_u \vee$ "put * on the table" $\in u_u$) **then**
 $\left\{ P(a_u^{\text{temp}'} = \text{Ask}(\text{Release})) = 1 \right.$
- r_8 : **if** ("what * you see" $\in u_u \vee$ "what * you perceive" $\in u_u$) **then**
 $\left\{ P(a_u^{\text{temp}'} = \text{Ask}(\text{WhatDoYouSee})) = 1 \right.$
- r_9 : $\forall x$,
if ("you see {x}" $\in u_u \vee$ "you perceive {x}" $\in u_u$) **then**
 $\left\{ P(a_u^{\text{temp}'} = \text{Ask}(\text{DoYouSee}(x))) = 1 \right.$
- r_{10} : **if** ("yes" $\in u_u \vee$ "exactly" $\in u_u \vee$ "correct" $\in u_u$) **then**
 $\left\{ P(a_u^{\text{temp}'} = \text{Confirm}) = 1 \right.$
- r_{11} : **if** ("thanks" $\in u_u \vee$ "thank" $\in u_u \vee$ "correct" $\in u_u \vee$ "perfect" $\in u_u \vee$ "great" $\in u_u \vee$ "good" $\in u_u \vee$ "right" $\in u_u \vee$ "that's right" $\in u_u =$ "ok" $\in u_u$) **then**
 $\left\{ P(a_u^{\text{temp}'} = \text{Grounding}) = 1 \right.$
- r_{12} : **if** ("no" $\in u_u \vee$ "wrong" $\in u_u \vee$ "incorrect" $\in u_u$) **then**
 $\left\{ P(a_u^{\text{temp}'} = \text{Disconfirm}) = 1 \right.$
- r_{13} : **if** ("once more" $\in u_u \vee$ "one more time" $\in u_u \vee$ "repeat" $\in u_u \vee$ "again" $\in u_u$) **then**
 $\left\{ P(a_u^{\text{temp}'} = \text{RepeatLast}) = 1 \right.$
- r_{14} : **if** ("hi" $\in u_u \vee$ "hello" $\in u_u \vee$ "good afternoon" $\in u_u \vee$ "good morning" $\in u_u$) **then**
 $\left\{ P(a_u^{\text{temp}'} = \text{Greeting}) = 1 \right.$
- r_{15} : **if** ("bye" $\in u_u \vee$ "goodbye" $\in u_u$) **then**
 $\left\{ P(a_u^{\text{temp}'} = \text{Closing}) = 1 \right.$
- r_{16} : **if** ("stop" $\in u_u$) **then**
 $\left\{ P(a_u^{\text{temp}'} = \text{Ask}(\text{Stop})) = 1 \right.$

r_{17} :

$$\begin{aligned}
& \forall x, \\
& \mathbf{if} ("bit" \in u_u \wedge a_u^{\text{temp}} = \text{Move}(x)) \mathbf{then} \\
& \quad \left\{ P(a_u' = \text{Ask}(\text{Move}(x, \text{Short}))) = 1 \right. \\
& \mathbf{else if} (a_u^{\text{temp}} = \text{Move}(x) \wedge ("left" \in x \vee "right" \in x) \wedge "thirty degrees" \in u_u) \mathbf{then} \\
& \quad \left\{ P(a_u' = \text{Ask}(\text{Move}(x, \text{Short}))) = 1 \right. \\
& \mathbf{else if} (a_u^{\text{temp}} = \text{PickUp}(x) \wedge "feet" \in u_u) \mathbf{then} \\
& \quad \left\{ P(a_u' = \text{Ask}(\text{PickUp}(\text{AtFeet}))) = 1 \right. \\
& \mathbf{else if} (a_u^{\text{temp}} = \text{PickUp}(x) \wedge ("blue" \in x \vee ("it" = x \wedge (\text{BlueObj} \in a_u \vee \text{BlueObj} \in a_m)) \\
& \quad \vee ("the" \in x \wedge \text{perceived} = [\text{BlueObj}]))) \mathbf{then} \\
& \quad \left\{ P(a_u' = \text{Ask}(\text{PickUp}(\text{BlueObj}))) = 1 \right. \\
& \mathbf{else if} (a_u^{\text{temp}} = \text{PickUp}(x) \wedge ("red" \in x \vee ("it" = x \wedge (\text{RedObj} \in a_u \vee \text{RedObj} \in a_m)) \\
& \quad \vee ("the" \in x \wedge \text{perceived} = [\text{RedObj}]))) \mathbf{then} \\
& \quad \left\{ P(a_u' = \text{Ask}(\text{PickUp}(\text{RedObj}))) = 1 \right. \\
& \mathbf{else if} (a_u^{\text{temp}} = \text{PickUp}(x)) \mathbf{then} \\
& \quad \left\{ P(a_u' = \text{Ask}(\text{PickUp}(\text{Other}))) = 1 \right. \\
& \mathbf{else if} (a_u^{\text{temp}} = \text{DoYouSee}(x) \wedge "red" \in x) \mathbf{then} \\
& \quad \left\{ P(a_u' = \text{Ask}(\text{DoYouSee}(\text{RedObj}))) = 1 \right. \\
& \mathbf{else if} (a_u^{\text{temp}} = \text{DoYouSee}(x) \wedge "blue" \in x) \mathbf{then} \\
& \quad \left\{ P(a_u' = \text{Ask}(\text{DoYouSee}(\text{BlueObj}))) = 1 \right. \\
& \mathbf{else if} (a_u^{\text{temp}} = \text{DoYouSee}(x) \wedge "it" \notin x) \mathbf{then} \\
& \quad \left\{ P(a_u' = \text{Ask}(\text{WhatDoYouSee})) = 1 \right. \\
& \mathbf{else if} (a_u^{\text{temp}} = x) \\
& \quad \left\{ P(a_u' = x) = 1 \right.
\end{aligned}$$

Task completion model

The task completion model considers a task to be completed whenever the system performs an action that is not a clarification request. The probability of the user changing his mind before the completion of the task is defined by the parameter $\theta_{\text{changemind}}$.

r_1 :

$$\begin{aligned}
& \forall x, \\
& \mathbf{if} (a_m \neq \text{AskConfirm}(x) \wedge a_m \neq \text{AskRepeat} \wedge a_m \neq \text{None}) \mathbf{then} \\
& \quad \left\{ P(\text{completed-task}' = \text{true}) = 1 \right. \\
& \mathbf{else if} (i_u = \text{None}) \mathbf{then} \\
& \quad \left\{ P(\text{completed-task}' = \text{true}) = 1 \right. \\
& \mathbf{else} \\
& \quad \left\{ \begin{aligned} P(\text{completed-task}' = \text{false}) &= \theta_{\text{changemind}[0]} \\ P(\text{completed-task}' = \text{true}) &= \theta_{\text{changemind}[1]} \end{aligned} \right. \\
& \mathbf{if} (a_m = \text{Do}(x)) \mathbf{then} \\
& \quad \left\{ P(\text{lastMove}' = x) = 1 \right.
\end{aligned}$$

r_2 :

User goal model

The user goal model encodes how the user intention i_u is expected to evolve over time, given the current dialogue context. The intention is only assumed to change when the current task is completed. Rule r_2 defines the likelihood of instructions related to spatial movements, while r_3 and r_4 define the likelihood of user questions related to the robot perception, r_5 the likelihood of greeting and closing actions, r_6 the likelihood of releasing actions, and r_7 and r_8 the likelihood of grasping actions.

Rule r_3 and r_7 are used to increase the probability of grasping instructions and questions about visual objects whenever an object is actually perceived by the robot.

$$\begin{aligned}
r_1: & \quad \forall x, \\
& \quad \mathbf{if} (i_u = x \wedge \text{completed-task} = \text{false}) \mathbf{then} \\
& \quad \quad \left\{ P(i_u' = x) = 1 \right. \\
r_2: & \quad \mathbf{if} (\text{completed-task} = \text{true}) \mathbf{then} \\
& \quad \quad \left\{ \begin{array}{l} P(i_u' = \text{Move}(\text{Left})) = \theta_{\text{moveprior}[0]} \\ P(i_u' = \text{Move}(\text{Forward})) = \theta_{\text{moveprior}[1]} \\ P(i_u' = \text{Move}(\text{Backward})) = \theta_{\text{moveprior}[2]} \\ P(i_u' = \text{Move}(\text{Right})) = \theta_{\text{moveprior}[3]} \\ P(i_u' = \text{Move}(\text{Left}, \text{Short})) = \theta_{\text{moveprior}[4]} \\ P(i_u' = \text{Move}(\text{Forward}, \text{Short})) = \theta_{\text{moveprior}[5]} \\ P(i_u' = \text{Move}(\text{Backward}, \text{Short})) = \theta_{\text{moveprior}[6]} \\ P(i_u' = \text{Move}(\text{Right}, \text{Short})) = \theta_{\text{moveprior}[7]} \\ P(i_u' = \text{Move}(\text{Turn})) = \theta_{\text{moveprior}[8]} \\ P(\cdot) = \theta_{\text{moveprior}[9]} \end{array} \right. \\
r_3: & \quad \forall x, \\
& \quad \mathbf{if} (x \in \text{perceived} \wedge \text{completed-task} = \text{true}) \mathbf{then} \\
& \quad \quad \left\{ \begin{array}{l} P(i_u' = \text{Do You See}(x)) = \theta_{\text{perceive_see_prior}[0]} \\ P(i_u' = \text{What Do You See}) = \theta_{\text{perceive_see_prior}[1]} \\ P(\cdot) = \theta_{\text{perceive_see_prior}[2]} \end{array} \right. \\
r_4: & \quad \mathbf{if} (\text{completed-task} = \text{true}) \mathbf{then} \\
& \quad \quad \left\{ \begin{array}{l} P(i_u' = \text{Do You See}(\text{RedObj})) = \theta_{\text{perceive_nosee_prior}[0]} \\ P(i_u' = \text{Do You See}(\text{BlueObj})) = \theta_{\text{perceive_nosee_prior}[1]} \\ P(i_u' = \text{What Do You See}) = \theta_{\text{perceive_nosee_prior}[2]} \\ P(\cdot) = \theta_{\text{perceive_nosee_prior}[3]} \end{array} \right. \\
r_5: & \quad \mathbf{if} (\text{lastMove} = \text{None} \wedge \text{completed-task} = \text{true}) \mathbf{then} \\
& \quad \quad \left\{ \begin{array}{l} P(i_u' = \text{Greeting}) = \theta_{\text{openingprior}[0]} \\ P(\cdot) = \theta_{\text{openingprior}[1]} \end{array} \right. \\
& \quad \mathbf{else if} (\text{lastMove} = \text{Release}) \mathbf{then} \\
& \quad \quad \left\{ \begin{array}{l} P(i_u' = \text{Closing}) = \theta_{\text{closingprior}[0]} \\ P(\cdot) = \theta_{\text{closingprior}[1]} \end{array} \right. \\
r_6: & \quad \mathbf{if} (\text{completed-task} = \text{true} \wedge \text{carried} \neq [] \wedge \text{carried} \neq \text{None}) \mathbf{then}
\end{aligned}$$

$$\begin{aligned}
& \begin{cases} P(i_u' = Release) = \theta_{\text{releaseprior}[0]} \\ P(\cdot) = \theta_{\text{releaseprior}[1]} \end{cases} \\
r_7: & \quad \forall x, \\
& \quad \text{if } (completed_task = true \wedge carried = [] \wedge x \in perceived) \text{ then} \\
& \quad \quad \begin{cases} P(i_u' = PickUp(x)) = \theta_{\text{pickup_see_prior}[0]} \\ P(\cdot) = \theta_{\text{pickup_see_prior}[1]} \end{cases} \\
r_8: & \quad \text{if } (completed_task = true \wedge carried = []) \text{ then} \\
& \quad \quad \begin{cases} P(i_u' = PickUp(RedObj)) = \theta_{\text{pickup_nosee_prior}[0]} \\ P(i_u' = PickUp(BlueObj)) = \theta_{\text{pickup_nosee_prior}[1]} \\ P(i_u' = PickUp(AtFeet)) = \theta_{\text{pickup_nosee_prior}[2]} \\ P(\cdot) = \theta_{\text{pickup_nosee_prior}[3]} \end{cases}
\end{aligned}$$

User action model

The user action model derives the possible user actions a_u depending on the current user intention i_u and the last system action a_m .

$$\begin{aligned}
r_1: & \quad \forall x, y, \\
& \quad \text{if } (a_m = AskConfirm(x) \wedge i_u = x) \text{ then} \\
& \quad \quad \begin{cases} P(a_u' = Confirm) = \theta_{\text{confirmpredict}[0]} \\ P(a_u' = Ask(x)) = \theta_{\text{confirmpredict}[1]} \\ P(\cdot) = \theta_{\text{confirmpredict}[2]} \end{cases} \\
& \quad \text{else if } (a_m = AskConfirm(y) \wedge i_u = x \wedge x \neq y \wedge i_u \neq None) \text{ then} \\
& \quad \quad \begin{cases} P(a_u' = Disconfirm) = \theta_{\text{disconfirmpredict}[0]} \\ P(a_u' = Ask(x)) = \theta_{\text{disconfirmpredict}[1]} \\ P(\cdot) = \theta_{\text{disconfirmpredict}[2]} \end{cases} \\
& \quad \text{else if } (lastMove = i_u \wedge i_u = x) \text{ then} \\
& \quad \quad \begin{cases} P(a_u' = RepeatLast) = \theta_{\text{samemove}[0]} \\ P(a_u' = Ask(x)) = \theta_{\text{samemove}[1]} \\ P(\cdot) = \theta_{\text{samemove}[2]} \end{cases} \\
& \quad \text{else if } ((a_m = AskRepeat \vee completed_task = true) \wedge i_u = x) \text{ then} \\
& \quad \quad \begin{cases} P(a_u' = Ask(x)) = \theta_{\text{intent}[0]} \\ P(\cdot) = \theta_{\text{intent}[1]} \end{cases} \\
& \quad \text{else if } (i_u \neq None \wedge i_u = x) \text{ then} \\
& \quad \quad \begin{cases} P(a_u' = Ask(x)) = \theta_{\text{othercase}[0]} \\ P(\cdot) = \theta_{\text{othercase}[1]} \end{cases} \\
r_2: & \quad \forall x, \\
& \quad \text{if } (a_m = Do(x)) \text{ then} \\
& \quad \quad \begin{cases} P(a_u' = Stop) = \theta_{\text{aftermove}[0]} \\ P(a_u' = Disconfirm) = \theta_{\text{aftermove}[1]} \\ P(\cdot) = \theta_{\text{aftermove}[2]} \end{cases}
\end{aligned}$$

Utility model

The utility model captures the relative utility of various system actions depending on the current hypotheses about the user intention i_u , last user action a_u , and general dialogue context. Rule r_7 sets an initial negative value to all actions in order ensure that their base utility (in the absence of other information) remains lower than zero.

$r_1:$	$\forall x,$ if ($i_u = \text{Move}(x)$) then $\left\{ U(a_m' = \text{Do}(\text{Move}(x))) = \theta_{\text{move}} \right.$
$r_2:$	$\forall x,$ if ($i_u = \text{PickUp}(x) \wedge x \in \text{perceived} \wedge \text{carried} = []$) then $\left\{ U(a_m' = \text{Do}(\text{PickUp}(x))) = \theta_{\text{pickup}} \right.$ else if ($i_u = \text{PickUp}(\text{AtFeet}) \wedge \text{carried} = []$) then $\left\{ U(a_m' = \text{Do}(\text{PickUp}(\text{AtFeet}))) = \theta_{\text{pickup}} \right.$ else if ($i_u = \text{PickUp}(x) \wedge y \in \text{perceived} \wedge \text{carried} \neq []$) then $\left\{ U(a_m' = \text{Say}(\text{AlreadyCarryObject})) = \theta_{\text{excuse}} \right.$ else if ($i_u = \text{PickUp}(x) \wedge y = \text{Other}$) then $\left\{ U(a_m' = \text{Say}(\text{CannotResolve})) = \theta_{\text{excuse}} \right.$ else if ($i_u = \text{PickUp}(x) \wedge y \notin \text{perceived}$) then $\left\{ U(a_m' = \text{Say}(\text{DoNotSeeObject})) = \theta_{\text{excuse}} \right.$
$r_3:$	if ($i_u = \text{Release} \wedge \text{carried} \neq \text{None} \wedge \text{carried} \neq []$) then $\left\{ U(a_m' = \text{Do}(\text{Release})) = \theta_{\text{release}} \right.$ else if ($i_u = \text{Release} \wedge \text{carried} = []$) then $\left\{ U(a_m' = \text{Say}(\text{DoNotCarryObject})) = \theta_{\text{excuse}} \right.$
$r_4:$	$\forall x,$ if ($i_u = \text{DoYouSee}(x) \wedge x \in \text{perceived}$) then $\left\{ U(a_m' = \text{Say}(\text{Confirm})) = \theta_{\text{confirmpercept}} \right.$ else if ($i_u = \text{DoYouSee}(x) \wedge x \notin \text{perceived}$) then $\left\{ U(a_m' = \text{Say}(\text{Disconfirm})) = \theta_{\text{confirmpercept}} \right.$
$r_5:$	$\forall x,$ if ($i_u = \text{WhatDoYouSee} \wedge x = \text{perceived}$) then $\left\{ U(a_m' = \text{Describe}(x)) = \theta_{\text{describe}} \right.$
$r_6:$	if ($i_u = \text{Greeting}$) then $\left\{ U(a_m' = \text{Say}(\text{Greet})) = \theta_{\text{chitchat}} \right.$ else if ($i_u = \text{Closing}$) then $\left\{ U(a_m' = \text{Say}(\text{Goodbye})) = \theta_{\text{chitchat}} \right.$
$r_7:$	$\forall x,$ if (true) then $\left\{ \begin{array}{l} U(a_m' = \text{Do}(x)) = -10 \\ U(a_m' = \text{Say}(x)) = -10 \\ U(a_m' = \text{Describe}(x)) = -10 \end{array} \right.$

$r_8:$ **if** ($a_m \neq AskRepeat \wedge a_u \neq None \wedge a_u \neq Confirm$
 $\wedge a_u \neq Disconfirm \wedge a_u \neq Grounding$) **then**
 $\left\{ U(a_m' = AskRepeat) = \theta_{repeat1} \right\}$
else
 $\left\{ U(a_m' = AskRepeat) = \theta_{repeat2} \right\}$

$r_9:$ $\forall x, y,$
if ($i_u = x \wedge i_u \neq DoYouSee(y) \wedge i_u \neq WhatDoYouSee \wedge i_u \neq Greeting$
 $\wedge i_u \neq Closing \wedge i_u \neq None$) **then**
 $\left\{ U(a_m' = AskConfirm(x)) = \theta_{confirm1} \right\}$
else
 $\left\{ U(a_m' = AskConfirm(x)) = \theta_{confirm2} \right\}$

$r_{10}:$ **if** ($motion = true \wedge a_u = Ask(Stop)$) **then**
 $\left\{ U(a_m' = Do(Stop)) = \theta_{stop} \right\}$
else if ($motion = true \wedge a_u = Disconfirm$) **then**
 $\left\{ U(a_m' = Do(Stop)) = \theta_{stop} \right\}$
else if ($motion = true$) **then**
 $\left\{ U(a_m' \neq None) = \theta_{whilemove} \right\}$

Generation model

The generation model maps each selected system action a_m to its corresponding verbal realisation u_m . The surface form is then picked up by the speech synthesis module.

$r_1:$ $\forall x,$
if ($a_m = Do(Move(Turn))$) **then**
 $\left\{ U(u_m' = \text{"OK, now turning back"}) = 1 \right\}$
else if ($a_m = Do(Move(x, Short))$) **then**
 $\left\{ U(u_m' = \text{"OK, moving \{x\} a little bit"}) = 1 \right\}$
else if ($a_m = Do(Move(x))$) **then**
 $\left\{ U(u_m' = \text{"OK, moving \{x\}"}) = 1 \right\}$
else if ($a_m = Do(PickUp(RedObj))$) **then**
 $\left\{ U(u_m' = \text{"OK, picking up the red object"}) = 1 \right\}$
else if ($a_m = Do(PickUp(BlueObj))$) **then**
 $\left\{ U(u_m' = \text{"OK, picking up the blue object"}) = 1 \right\}$
else if ($a_m = Do(PickUp(AtFeet))$) **then**
 $\left\{ U(u_m' = \text{"OK, picking up the object at my feet"}) = 1 \right\}$
else if ($a_m = Do(Release)$) **then**
 $\left\{ U(u_m' = \text{"OK, putting down the object"}) = 1 \right\}$
else if ($a_m = Do(Stop)$) **then**
 $\left\{ U(u_m' = \text{"OK, stopping now"}) = 1 \right\}$
else if ($a_m = AskRepeat$) **then**

$\{U(u_m' = \text{"Sorry, could you repeat?"}) = 1$
else if ($a_m = \text{Say}(\text{AlreadyCarryObject})$) **then**
 $\{U(u_m' = \text{"Sorry, I cannot do that, I am already carrying an object"}) = 1$
else if ($a_m = \text{Say}(\text{DoNotCarryObject})$) **then**
 $\{U(u_m' = \text{"Sorry, I cannot do that, I am not carrying the object"}) = 1$
else if ($a_m = \text{Say}(\text{DoNotSeeObject})$) **then**
 $\{U(u_m' = \text{"Sorry, I cannot do that, I do not see the object"}) = 1$
else if ($a_m = \text{Say}(\text{CannotResolve})$) **then**
 $\{U(u_m' = \text{"Sorry, I don't know which object you are talking about"}) = 1$
else if ($a_m = \text{AskConfirm}(\text{Move}(\text{Left}))$) **then**
 $\{U(u_m' = \text{"Should I move left?"}) = 1$
else if ($a_m = \text{AskConfirm}(\text{Move}(\text{Left}, \text{Short}))$) **then**
 $\{U(u_m' = \text{"Should I move a bit to the left?"}) = 1$
else if ($a_m = \text{AskConfirm}(\text{Move}(\text{Right}))$) **then**
 $\{U(u_m' = \text{"Should I move right?"}) = 1$
else if ($a_m = \text{AskConfirm}(\text{Move}(\text{Right}, \text{Short}))$) **then**
 $\{U(u_m' = \text{"Should I move a bit to the right?"}) = 1$
else if ($a_m = \text{AskConfirm}(\text{Move}(\text{Forward}))$) **then**
 $\{U(u_m' = \text{"Should I move forward?"}) = 1$
else if ($a_m = \text{AskConfirm}(\text{Move}(\text{Forward}, \text{Short}))$) **then**
 $\{U(u_m' = \text{"Should I move a bit forward?"}) = 1$
else if ($a_m = \text{AskConfirm}(\text{Move}(\text{Backward}))$) **then**
 $\{U(u_m' = \text{"Should I move backward?"}) = 1$
else if ($a_m = \text{AskConfirm}(\text{Move}(\text{Backward}, \text{Short}))$) **then**
 $\{U(u_m' = \text{"Should I step a bit backward?"}) = 1$
else if ($a_m = \text{AskConfirm}(\text{Move}(\text{Turn}))$) **then**
 $\{U(u_m' = \text{"Should I turn 180 degrees?"}) = 1$
else if ($a_m = \text{AskConfirm}(\text{Stop})$) **then**
 $\{U(u_m' = \text{"Should I stop?"}) = 1$
else if ($a_m = \text{AskConfirm}(\text{Release})$) **then**
 $\{U(u_m' = \text{"Should I release the object?"}) = 1$
else if ($a_m = \text{AskConfirm}(\text{PickUp}(\text{RedObj}))$) **then**
 $\{U(u_m' = \text{"Should I pick up the red object?"}) = 1$
else if ($a_m = \text{AskConfirm}(\text{PickUp}(\text{BlueObj}))$) **then**
 $\{U(u_m' = \text{"Should I pick up the blue object?"}) = 1$
else if ($a_m = \text{AskConfirm}(\text{PickUp}(\text{AtFeet}))$) **then**
 $\{U(u_m' = \text{"Should I pick up the object at my feet?"}) = 1$
else if ($a_m = \text{Say}(\text{Confirm})$) **then**
 $\{U(u_m' = \text{"Yes"}) = 1$
else if ($a_m = \text{Say}(\text{Disconfirm})$) **then**
 $\{U(u_m' = \text{"No"}) = 1$

```

else if ( $a_m = Describe(x) \wedge x = []$ ) then
     $\{U(u_m' = "I do not see anything") = 1$ 
else if ( $a_m = Describe(x) \wedge RedObj \in x \wedge BlueObj \in x$ ) then
     $\{U(u_m' = "I see a red and a blue cylinder") = 1$ 
else if ( $a_m = Describe(x) \wedge RedObj \in x$ ) then
     $\{U(u_m' = "I see a red cylinder") = 1$ 
else if ( $a_m = Describe(x) \wedge BlueObj \in x$ ) then
     $\{U(u_m' = "I see a blue cylinder") = 1$ 
else if ( $a_m = Say(Greet)$ ) then
     $\{U(u_m' = "Hi there") = 1$ 
else if ( $a_m = Say(Goodbye)$ ) then
     $\{U(u_m' = "Bye, see you next time") = 1$ 

```

Bibliography

- J. Allen, D. Byron, M. Dzikovska, G. Ferguson, L. Galescu, and A. Stent. An architecture for a generic dialogue shell. *Natural Language Engineering*, 6:213–228, 2000.
- J. F. Allen and C. R. Perrault. Analyzing intention in utterances. *Artificial Intelligence*, 15:143–178, 1980.
- J. Allwood. *Linguistic communication as action and cooperation : A study in pragmatics*. PhD thesis, University of Göteborg, 1976.
- J. Allwood, J. Nivre, and E. Ahlsén. On the semantics and pragmatics of linguistic feedback. *Journal of Semantics*, 9:1–26, 1992.
- N. Asher and A. Lascarides. *Logics of Conversation*. Cambridge University Press, 2005.
- A. Atrash and J. Pineau. A Bayesian reinforcement learning approach for customizing human-robot interfaces. In *Proceedings of the 13th International Conference on Intelligent User Interfaces*, pages 355–360, Sanibel Island, USA, 2009.
- J. L. Austin. *How to do things with words*. Harvard University Press, 1962.
- F. Bacchus and A. Grove. Graphical models for preference and utility. In *Proceedings of the 11th conference on Uncertainty in Artificial Intelligence*, pages 3–10, Montréal, Canada, 1995.
- T. Baumann. *Incremental Spoken Dialogue Processing: Architecture and Lower-level Components*. PhD thesis, Universität Bielefeld, Germany, 2013.
- T. Baumann and D. Schlangen. The InproTK 2012 release. In *NAACL-HLT Workshop on Future Directions and Needs in the Spoken Dialog Community: Tools and Data*, pages 29–32, Montréal, Canada, 2012.
- J. B. Bavelas, A. Black, C. R. Lemery, and J. Mullett. “I show how you feel”: Motor mimicry as a communicative act. *Journal of Personality and Social Psychology*, 50(2):322–329, 1986.
- R.E. Bellman. *Dynamic programming*. Princeton University Press, 1957.
- Y. Bengio. Learning deep architectures for AI. *Foundations and Trends in Machine Learning*, 2(1): 1–127, 2009.
- C. L. Bennett and A. Rudnicky. The Carnegie Mellon COMMUNICATOR corpus. In *Proceedings of the 7th International Conference on Spoken Language Processing*, pages 341–344, Denver, USA, 2002.

- L. Benotti. *Implicature as an Interactive Process*. PhD thesis, Université Henri Poincaré, Nancy, 2010.
- D. P. Bertsekas and J. N. Tsitsiklis. *Neuro-Dynamic Programming*. Athena Scientific, 1996.
- T. W. Bickmore and T. Giorgino. Health dialog systems for patients and consumers. *Journal of Biomedical Informatics*, 39(5):556–571, 2006.
- J. Binder, D. Koller, S. Russell, and K. Kanazawa. Adaptive probabilistic networks with hidden variables. *Machine Learning*, 29(2-3):213–244, 1997.
- C. M. Bishop. *Pattern Recognition and Machine Learning*. Information Science and Statistics. Springer, 2006.
- D. Bohus and A. Rudnicky. The RavenClaw dialog management framework: Architecture and systems. *Computer Speech & Language*, 23(3):332–361, 2009.
- D. Bohus, A. Raux, T. K. Harris, M. Eskenazi, and A. Rudnicky. Olympus: an open-source framework for conversational spoken language interface research. In *Proceedings of the NAACL-HLT Workshop on Bridging the Gap: Academic and Industrial Research in Dialog Technologies*, pages 32–39, Rochester, USA, 2007.
- J. Bos, E. Klein, O. Lemon, and T. Oka. DIPPER: Description and formalisation of an information-state update dialogue system architecture. In *Proceedings of the 4th SIGDIAL Workshop on Discourse and Dialogue*, pages 115–124, Sapporo, Japan, 2003.
- A. Boularias, H. R. Chinaei, and B. Chaib-draa. Learning the reward model of dialogue POMDPs from data. In *Proceedings of the NIPS Workshop on Machine Learning for Assistive Technology*, Whistler, Canada, 2010.
- C. Boutilier, T. Dean, and S. Hanks. Decision-Theoretic Planning: Structural Assumptions and Computational Leverage. *Journal of Artificial Intelligence Research*, 11:1–94, 1999.
- G. E. P. Box and M. E. Muller. A note on the generation of random normal deviates. *Annals of Mathematical Statistics*, 29:610–611, 1958.
- H. P. Branigan, M. J. Pickering, and A. A. Cleland. Syntactic co-ordination in dialogue. *Cognition*, 75(2):B13–B25, 2000.
- S. E. Brennan and H. H. Clark. Conceptual pacts and lexical choice in conversation. *Journal of Experimental Psychology: Learning, Memory and Cognition*, 22(6):1482–1493, 1996.
- T. Brick and M. Scheutz. Incremental natural language processing for HRI. In *Proceedings of the 2nd International Conference on Human-Robot Interaction*, pages 263–270, Arlington, USA, 2007.
- T. H. Bui, M. Poel, A. Nijholt, and J. Zwiers. A tractable hybrid DDN-POMDP approach to affective dialogue modeling for probabilistic frame-based dialogue systems. *Natural Language Engineering*, 15(2):273–307, 2009.

- H. Bunt. The semantics of dialogue acts. In *Proceedings of the 9th International Conference on Computational Semantics*, pages 1–13, Oxford, UK, 2011.
- H. C. Bunt. Dynamic Interpretation and Dialogue Theory. In M. M. Taylor, F. Néel, and D. G. Bouwhuis, editors, *The Structure of Multimodal Dialogue, Volume 2*. John Benjamins, 1996.
- L. Burnard. Reference guide for the British National Corpus, 2007. URL <http://info.ox.ac.uk/bnc>.
- R. Cantrell, M. Scheutz, P. W. Schermerhorn, and X. Wu. Robust spoken instruction understanding for HRI. In *Proceedings of the 5th ACM/IEEE International Conference on Human–Robot Interaction*, pages 275–282, Osaka, Japan, 2010.
- S. Castronovo, A. Mahr, M. Pentcheva, and C. A. Müller. Multimodal dialog in the car: combining speech and turn-and-push dial to control comfort functions. In *Proceedings of the 11th Annual Conference of the International Speech Communication Association*, pages 510–513, Makuhari, Japan, 2010.
- L. Chen, A. Wang, and B. Di Eugenio. Improving pronominal and deictic co-reference resolution with multi-modal features. In *Proceedings of the 12th Annual SIGDIAL Meeting on Discourse and Dialogue*, pages 307–311, Portland, USA, 2011.
- S. F. Chen and J. Goodman. An empirical study of smoothing techniques for language modeling. *Computer Speech & Language*, 13(4):359–393, 1999.
- J. Cheng and M. J. Druzdzel. AIS-BN: An adaptive importance sampling algorithm for evidential reasoning in large Bayesian networks. *Journal of Artificial Intelligence Research*, 13(1):155–188, 2000.
- R. C. H. Cheng and G. M. Feast. Some simple gamma variate generators. *Journal of the Royal Statistical Society. Series C (Applied Statistics)*, 28(3):290–295, 1979.
- M. Chi, K. Van Lehn, D. J. Litman, and P. W. Jordan. An evaluation of pedagogical tutorial tactics for a natural language tutoring system: A reinforcement learning approach. *International Journal of Artificial Intelligence in Education*, 21(1-2):83–113, 2011.
- H. R. Chinaei and B. Chaib-draa. An inverse reinforcement learning algorithm for partially observable domains with application on healthcare dialogue management. In *Proceedings of the 11th International Conference on Machine Learning and Applications*, pages 144–149, Boca Raton, USA, 2012.
- H. R. Chinaei, B. Chaib-draa, and L. Lamontagne. Learning observation models for dialogue POMDPs. In *Proceedings of the 25th Canadian Conference on Artificial Intelligence*, pages 280–286, Toronto, Canada, 2012.
- J. Choi and K.-E. Kim. Inverse reinforcement learning in partially observable environments. *Journal of Machine Learning Research*, 12:691–730, 2011.
- H. H. Clark. *Using Language*. Cambridge University Press, 1996.

- H. H. Clark and E. F. Schaefer. Contributing to discourse. *Cognitive Science*, 13(2):259–294, 1989.
- P. R. Cohen and C. R. Perrault. Elements of a plan-based theory of speech acts. *Cognitive Science*, 3(3):177–212, 1979.
- G. F. Cooper. The computational complexity of probabilistic inference using Bayesian belief networks. *Artificial Intelligence*, 42(2-3):393–405, 1990.
- R. Cooper. Type theory and semantics in flux. In R. Kempson, T. Fernando, and N. Asher, editors, *Handbook of the Philosophy of Science, Volume 14: Philosophy of Linguistics*. Elsevier, 2012.
- B. Coppola, A. Moschitti, and G. Riccardi. Shallow semantic parsing for spoken language understanding. In *Proceedings of the Human Language Technology Conference of the North American Chapter of the Association for Computational Linguistics*, pages 85–88, Boulder, USA, 2009.
- J. G. Core and J. F. Allen. Coding dialogs with the DAMSL annotation scheme. In *Proceedings of the AAAI Fall Symposium on Communicative Action in Humans and Machines*, pages 28–35, Cambridge, USA, 1997.
- D. D. Corkill. Design alternatives for parallel and distributed blackboard systems. In *Blackboard Architectures and Applications*, pages 99–136. Academic Press, 1989.
- P. A. Crook and O. Lemon. Representing uncertainty about complex user goals in statistical dialogue systems. In *Proceedings of the 12th Annual SIGDIAL Meeting on Discourse and Dialogue*, pages 209–212, Tokyo, Japan, 2010.
- P. A. Crook and O. Lemon. Lossless value directed compression of complex user goal states for statistical spoken dialogue systems. In *Proceedings of the 12th Annual Conference of the International Speech Communication Association*, pages 1029–1032, Florence, Italy, 2011.
- H. Cuayáhuít. Learning Dialogue Agents with Bayesian Relational State Representations. In *Proceedings of the IJCAI Workshop on Knowledge and Reasoning in Practical Dialogue Systems*, pages 9–15, Barcelona, Spain, 2011.
- H. Cuayáhuít, S. Renals, O. Lemon, and H. Shimodaira. Evaluation of a hierarchical reinforcement learning spoken dialogue system. *Computer Speech & Language*, 24:395–429, 2010.
- P. Dagum and M. Luby. Approximating probabilistic inference in Bayesian belief networks is NP-hard. *Artificial Intelligence*, 60(1):141 – 153, 1993.
- N. Dahlbäck, A. Jönsson, and Lars Ahrenberg. Wizard of Oz studies: why and how. In *Proceedings of the 1st International Conference on Intelligent User Interfaces*, pages 193–200, Orlando, USA, 1993.
- L. Daubigny, M. Geist, S. Chandramohan, and O. Pietquin. A Comprehensive Reinforcement Learning Framework for Dialogue Management Optimisation. *IEEE Journal of Selected Topics in Signal Processing*, 6(8):891–902, 2012a.

- L. Daubigney, M. Geist, and O. Pietquin. Off-policy learning in large-scale POMDP-based dialogue systems. In *Proceedings of the 37th IEEE International Conference on Acoustics, Speech, and Signal Processing*, pages 4989–4992, Kyoto, Japan, 2012b.
- R. De Mori, F. Bechet, D. Hakkani-Tur, M. McTear, G. Riccardi, and G. Tur. Spoken language understanding. *IEEE Signal Processing Magazine*, 25(3):50–58, 2008.
- R. Dearden, N. Friedman, and S. Russell. Bayesian Q-learning. In *Proceedings of the 15th National Conference on Artificial intelligence*, pages 761–768, Madison, USA, 1998.
- R. Dearden, N. Friedman, and D. Andre. Model-based Bayesian Exploration. In *Proceedings of the 15th Conference on Uncertainty in Artificial Intelligence*, pages 150–159, Stockholm, Sweden, 1999.
- N. Dethlefs and H. Cuayáhuil. Hierarchical reinforcement learning and hidden Markov models for task-oriented natural language generation. In *Proceedings of the 49th Meeting of the Association for Computational Linguistics*, pages 654–659, Portland, USA, 2011.
- F. Doshi and N. Roy. Spoken language interaction with model uncertainty: an adaptive human–robot interaction system. *Connection Science*, 20(4):299–318, 2008.
- M. Duff. *Optimal learning: computational procedures for Bayes-Adaptive Markov Decision Processes*. PhD thesis, University of Massachusetts Amherst, 2002.
- S. Duncan. Some signals and rules for taking speaking turns in conversations. *Journal of Personality and Social Psychology*, 23:283–292, 1972.
- M. O. Dzikovska, A. Isard, P. Bell, J. D. Moore, N. B. Steinhauser, G. E. Campbell, L. S. Taylor, S. Caine, and C. Scott. Adaptive intelligent tutorial dialogue in the BEETLE II system. In *Proceedings of the 15th International Conference on Artificial Intelligence in Education*, pages 621–621, Auckland, New Zealand, 2011.
- M. Eckert and M. Strube. Dialogue acts, synchronizing units, and anaphora resolution. *Journal of Semantics*, 17(1):51–89, 2000.
- P. Ehlen and M. Johnston. A multimodal dialogue interface for mobile local search. In *Proceedings of the 18th International Conference on Intelligent User Interfaces*, pages 63–64, Santa Monica, USA, 2013.
- Y. Engel, S. Mannor, and R. Meir. Reinforcement learning with Gaussian processes. In *Proceedings of the 22nd International Conference on Machine Learning*, pages 201–208, Bonn, Germany, 2005.
- R. Fernández. *Non-Sentential Utterances in Dialogue: Classification, Resolution and Use*. PhD thesis, King’s College London, 2006.
- R. Fernández, J. Ginzburg, and S. Lappin. Classifying non-sentential utterances in dialogue: A machine learning approach. *Computational Linguistics*, 33(3):397–427, 2007.

- M. Frampton and O. Lemon. Recent research advances in reinforcement learning in spoken dialogue systems. *Knowledge Engineering Review*, 24(4):375–408, 2009.
- M. Frampton, R. Fernández, P. Ehlen, M. Christoudias, T. Darrell, and S. Peters. Who is "you"?: combining linguistic and gaze features to resolve second-person references in dialogue. In *Proceedings of the 12th Conference of the European Chapter of the Association for Computational Linguistics*, pages 273–281, Athens, Greece, 2009.
- R. Freedman. Plan-based dialogue management in a physics tutor. In *Proceedings of the 6th Conference on Applied Natural Language Processing*, pages 52–59, Seattle, USA, 2000.
- K. Funakoshi, M. Nakano, T. Tokunaga, and R. Iida. A unified probabilistic approach to referring expressions. In *Proceedings of the 13th Annual SIGDIAL Meeting on Discourse and Dialogue*, pages 237–246, Seoul, South Korea, 2012.
- R. M. Fung and K.-C. Chang. Weighing and integrating evidence for stochastic simulation in Bayesian networks. In *Proceedings of the 5th Conference on Uncertainty in Artificial Intelligence*, pages 209–220, Windsor, Canada, 1989.
- D. Gamerman and H. F. Lopes. *Markov Chain Monte Carlo: stochastic simulation for Bayesian inference*. Chapman & Hall/CRC, 2006.
- L. T. F. Gamut. *Logic, language, and meaning: Introduction to logic. Volume 1*. University of Chicago Press, 1991.
- S. Garrod and M. J. Pickering. Joint action, interactive alignment, and dialog. *Topics in Cognitive Science*, 1(2):292–304, 2009.
- S. Garrod and M.J. Pickering. Why is conversation so easy? *Trends in Cognitive Sciences*, 8:8–11, 2004.
- M. Gašić, C. Breslin, M. Henderson, D. Kim, M. Szummer, B. Thomson, P. Tsiakoulis, and S. Young. On-line policy optimisation of Bayesian spoken dialogue systems via human interaction. In *Proceedings of the 38th IEEE International Conference on Acoustics, Speech, and Signal Processing*, Vancouver, Canada, 2013.
- K. Georgila, J. Henderson, and O. Lemon. User simulation for spoken dialogue systems: learning and evaluation. In *Proceedings of the 9th International Conference on Spoken Language Processing*, Pittsburgh, USA, 2006.
- L. Getoor and B. Taskar. *Introduction to Statistical Relational Learning*. MIT Press, 2007.
- H. Giles, N. Coupland, and J. Coupland. Accommodation theory: Communication, context, and consequence. *Contexts of accommodation*, 1991.
- J. Ginzburg. *The Interactive Stance*. Oxford University Press, 2012.
- J. J. Godfrey, E. C. Holliman, and J. McDaniel. SWITCHBOARD: Telephone speech corpus for research and development. In *Proceedings of the 17th IEEE International Conference on Acoustics, Speech, and Signal Processing*, pages 517–520, San Francisco, USA, 1992.

- M. A. Goodrich and A. C. Schultz. Human–robot interaction: a survey. *Foundations and Trends in Human-Computer Interaction*, 1(3):203–275, 2007.
- A. L. Gorin, G. Riccardi, and J. H. Wright. How may I help you? *Speech Communication*, 23(1-2): 113–127, 1997.
- A. Gravano and J. Hirschberg. Turn-taking cues in task-oriented dialogue. *Computer Speech & Language*, 25(3):601 – 634, 2011.
- P. J. Green. On use of the EM algorithm for penalized likelihood estimation. *Journal of the Royal Statistical Society*, 52(3):443–452, 1990.
- H.P. Grice. *Studies in the Way of Words*. Harvard University Press, 1989.
- B. J. Grosz and C. L. Sidner. Attention, intentions, and the structure of discourse. *Computational Linguistics*, 12:175–204, 1986.
- A. Gruenstein, C. Wang, and S. Seneff. Context-sensitive statistical language modeling. In *Proceedings of the 9th European Conference on Speech Communication and Technology*, pages 17–20, Lisbon, Portugal, 2005.
- E. A. Hansen. Solving POMDPs by searching in policy space. In *Proceedings of the 14th Conference on Uncertainty in Artificial Intelligence*, pages 211–219, Madison, USA, 1998.
- J. H. L. Hansen, X. Zhang, M. Akbacak, U.H. Yapanel, B. Pellom, W. Ward, and P. Angkititrakul. CU-move: Advanced in-vehicle speech systems for route navigation. In H. Abut, J. H . L. Hansen, and K. Takeda, editors, *DSP for In-Vehicle and Mobile Systems*, pages 19–45. Springer, 2005.
- M. Hauskrecht, N. Meuleau, L. P. Kaelbling, T. Dean, and C. Boutilier. Hierarchical solution of Markov Decision Processes using macro-actions. In *Proceedings of the 14th Conference on Uncertainty in Artificial Intelligence*, pages 220–229, Madison, USA, 1998.
- Y. He and S. Young. Semantic processing using the hidden vector state model. *Computer Speech & Language*, 19(1):85 – 106, 2005.
- P. Heeman. Combining Reinforcement Learning with Information-State Update Rules. In *Proceedings of the Human Language Technology Conference of the North American Chapter of the Association for Computational Linguistics*, pages 268–275, Rochester, USA, 2007.
- M. Heldner and J. Edlund. Pauses, gaps and overlaps in conversations. *Journal of Phonetics*, 38(4): 555 – 568, 2010.
- J. Henderson, O. Lemon, and K. Georgila. Hybrid reinforcement/supervised learning of dialogue policies from fixed data sets. *Computational Linguistics*, 34:487–511, 2008.
- G. Herzog, A. Ndiaye, S. Merten, H. Kirchmann, T. Becker, and P. Poller. Large-scale software integration for spoken language and multimodal dialog systems. *Natural Language Engineering*, 10(3-4):283–305, 2004.

- J.-H. Hong, Y.-S. Song, and S.-B. Cho. Mixed-Initiative Human–Robot Interaction using Hierarchical Bayesian networks. *IEEE Transactions on Systems, Man, and Cybernetics*, 37(6):1158–1164, 2007.
- E. Horvitz. Principles of mixed-initiative user interfaces. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, pages 159–166, Pittsburgh, USA, 1999.
- A. J. Hunt and A. W. Black. Unit selection in a concatenative speech synthesis system using a large speech database. In *Proceedings of the 21st IEEE International Conference on Acoustics, Speech, and Signal Processing*, pages 373–376, Atlanta, USA, 1996.
- L. F. Hurtado, D. Griol, E. Sanchis, and E. Segarra. A stochastic approach to dialog management. In *Proceedings of the IEEE Workshop on Automatic Speech Recognition and Understanding*, pages 226–231, San Juan, Puerto Rico, 2005.
- M. Jaeger. Complex probabilistic modeling with recursive relational Bayesian networks. *Annals of Mathematics and Artificial Intelligence*, 32(1-4):179–220, 2001.
- D. Jan, E. Chance, D. Rajpurohit, D. DeVault, A. Leuski, J. Morie, and D. Traum. Checkpoint exercise: Training with virtual actors in virtual worlds. In *Proceedings of the 11th International Conference on Intelligent Virtual Agents*, pages 453–454, Reykjavík, Iceland, 2011.
- S. Janarthanam, O. Lemon, X. Liu, P. Bartie, W. Mackaness, T. Dalmas, and J. Goetze. Integrating location, visibility, and question-answering in a spoken dialogue system for pedestrian city exploration. In *Proceedings of the 13th Annual SIGDIAL Meeting on Discourse and Dialogue*, pages 134–136, Seoul, South Korea, 2012.
- F. Jelinek. *Statistical methods for speech recognition*. MIT Press, 1997.
- F. V. Jensen, K. G. Olesen, and S. K. Andersen. An algebra of Bayesian belief universes for knowledge-based systems. *Networks*, 20(5):637–659, 1990.
- M. Johnson and E. Charniak. A TAG-based noisy channel model of speech repairs. In *Proceedings of the 42nd Meeting of the Association for Computational Linguistics*, pages 33–39, Barcelona, Spain, 2004.
- K. Jokinen. *Constructive Dialogue Modelling: Speech Interaction and Rational Agents*. Wiley, 2009.
- K. Jokinen and T. Hurtig. User expectations and real experience on a multimodal interactive system. In *Proceedings of the 9th International Conference on Spoken Language Processing*, pages 1049–10523, Pittsburgh, USA, 2006.
- K. Jokinen and M. F. McTear. *Spoken Dialogue Systems*. Synthesis Lectures on Human Language Technologies. Morgan & Claypool Publishers, 2009.
- A. Jönsson and N. Dahlbäck. Talking to a computer is not like talking to your best friend. In *Proceedings of the First Scandinavian Conference on Artificial Intelligence*, pages 53–68, Tromsø, Norway, 1988.
- M. I. Jordan. *Learning in Graphical Models*. MIT Press, 1998.

- M. I. Jordan, Z. Ghahramani, T. S. Jaakkola, and L. K. Saul. An introduction to variational methods for graphical models. *Machine Learning*, 37(2):183–233, 1999.
- B. Juang and L. Rabiner. Hidden Markov models for speech recognition. *Technometrics*, 33:251–272, 1991.
- D. Jurafsky, L. Shriberg, and D. Biasca. Switchboard SWBD-DAMSL shallow-discourse-function annotation coders manual. Technical report, University of Colorado at Boulder, 1997.
- D. Jurafsky, E. Shriberg, B. Fox, and T. Curl. Lexical, prosodic, and syntactic cues for dialog acts. In *Proceedings of the ACL-COLING Workshop on Discourse Relations and Discourse Markers*, pages 114–120, Montréal, Canada, 1998.
- S. Keizer and R. op den Akker. Dialogue act recognition under uncertainty using Bayesian networks. *Natural Language Engineering*, 13:287–316, 2007.
- J. Kelleher and J. Van Genabith. Visual salience and reference resolution in simulated 3-D environments. *Artificial Intelligence Review*, 21(3-4):253–267, 2004.
- C. Kennington and D. Schlangen. Markov logic networks for situated incremental natural language understanding. In *Proceedings of the 13th Annual SIGDIAL Meeting on Discourse and Dialogue*, pages 314–323, Seoul, South Korea, 2012.
- K. Kersting and L. De Raedt. Logical Markov Decision Programs and the convergence of logical TD(λ). In *Proceedings of the 14th International Conference on Inductive Logic Programming*, pages 180–197, Porto, Portugal, 2004.
- S. Kok and P. Domingos. Learning Markov logic network structure via hypergraph lifting. In *Proceedings of the 26th International Conference on Machine Learning*, pages 505–512, Montréal, Canada, 2009.
- A. Koller and M. Stone. Sentence generation as a planning problem. In *Proceedings of the 45th Meeting of the Association for Computational Linguistics*, pages 336–343, Prague, Czech Republic, 2007.
- A. Koller, K. Garoufi, M. Staudte, and M. W. Crocker. Enhancing referential success by tracking hearer gaze. In *Proceedings of the 13th Annual SIGDIAL Meeting on Discourse and Dialogue*, pages 30–39, Seoul, South Korea, 2012.
- D. Koller and N. Friedman. *Probabilistic Graphical Models: Principles and Techniques*. MIT Press, 2009.
- K. Komatani, K. Tanaka, H. Kashima, and T. Kawahara. Domain-independent spoken dialogue platform using key-phrase spotting based on combined language model. In *Proceedings of the 7th European Conference on Speech Communication and Technology*, pages 1319–1322, Aalborg, Denmark, 2001.
- G.-J. M. Kruijff, P. Lison, T. Benjamin, H. Jacobsson, H. Zender, I. Kruijff-Korbayová, and N. Hawes. Situated dialogue processing for human–robot interaction. In H. Christensen, G.-J. M. Kruijff, and J. L. Wyatt, editors, *Cognitive Systems*, pages 311–364. Springer, 2010.

- G.-J. M. Kruijff, M. Janiček, and H. Zender. Situated communication for joint activity in human-robot teams. *IEEE Intelligent Systems*, 27(2):27–35, 2012.
- S. Kullback and R. A. Leibler. On Information and Sufficiency. *Annals of Mathematical Statistics*, 22(1):79–86, 1951.
- H. Kurniawati, D. Hsu, and W.S. Lee. SARSOP: Efficient point-based POMDP planning by approximating optimally reachable belief spaces. In *Proceedings of Robotics: Science and Systems*, Zurich, Switzerland, 2008.
- I. R. Lane, T. Kawahara, and S. Ueno. Example-based training of dialogue planning incorporating user and situation models. In *Proceedings of the 8th International Conference on Spoken Language Processing*, pages 2837–2840, Jeju Island, South Korea, 2004.
- T. Lang and M. Toussaint. Planning with noisy probabilistic relational rules. *Journal of Artificial Intelligence Research*, 39:1–49, 2010.
- S. Larsson. *Issue-based Dialogue Management*. PhD thesis, University of Göteborg, 2002.
- S. Larsson and D. R. Traum. Information state and dialogue management in the TRINDI dialogue move engine toolkit. *Natural Language Engineering*, 6(3-4):323–340, 2000.
- S. Lemaignan, R. Ros, E. A. Sisbot, R. Alami, and M. Beetz. Grounding the interaction: Anchoring situated discourse in everyday human–robot interaction. *International Journal of Social Robotics*, 4(2):181–199, 2012.
- O. Lemon. Learning what to say and how to say it: Joint optimisation of spoken dialogue management and natural language generation. *Computer Speech & Language*, 25:210–221, 2011.
- O. Lemon and O. Pietquin. Machine Learning for Spoken Dialogue Systems. In *Proceedings of the 8th Annual Conference of the International Speech Communication Association*, pages 2685–2688, Antwerp, Belgium, 2007.
- O. Lemon and O. Pietquin. *Data-Driven Methods for Adaptive Spoken Dialogue Systems: Computational Learning for Conversational Interfaces*. Springer, 2012.
- O. Lemon, K. Georgila, and J. Henderson. Evaluating effectiveness and portability of reinforcement learned dialogue strategies with real users: the TALK TownInfo evaluation. In *Proceedings of the IEEE Spoken Language Technology Workshop*, pages 178–181, Palm Beach, Aruba, 2006.
- E. Levin, R. Pieraccini, and W. Eckert. A stochastic model of human-machine interaction for learning dialog strategies. *IEEE Transactions on Speech and Audio Processing*, 8(1):11–23, 2000.
- L. Li, T. J. Walsh, and M. L. Littman. Towards a unified theory of state abstraction for MDPs. In *Proceedings of the 9th International Symposium on Artificial Intelligence and Mathematics*, Fort Lauderdale, USA, 2006.
- P. Lison. A salience-driven approach to speech recognition for human–robot interaction. In *Interfaces: Explorations in Logic, Language and Computation*, pages 102–113. Springer, 2010a.

- P. Lison. Towards relational POMDPs for adaptive dialogue management. In *Proceeding of the Student Research Workshop of the 48th Annual Meeting of the Association for Computational Linguistics*, Uppsala, Sweden, 2010b.
- P. Lison. Multi-policy dialogue management. In *Proceedings of the 12th Annual SIGDIAL Meeting on Discourse and Dialogue*, Portland, USA, 2011.
- P. Lison. Declarative design of spoken dialogue systems with probabilistic rules. In *Proceedings of the 16th Workshop on the Semantics and Pragmatics of Dialogue*, pages 97–106, Paris, France, 2012a.
- P. Lison. Towards online planning for dialogue management with rich domain knowledge. In *Towards Natural Interaction with Robots, Knowbots and Smartphones - Putting Spoken Dialog Systems into practice*, Paris, France, 2012b. Springer.
- P. Lison. Towards dialogue management in relational domains. In *Proceedings of the SLTC Workshop on Action, Perception and Language*, Lund, Sweden, 2012c.
- P. Lison. Probabilistic dialogue models with prior domain knowledge. In *Proceedings of the 13th Annual SIGDIAL Meeting on Discourse and Dialogue*, pages 179–188, Seoul, South Korea, 2012d.
- P. Lison. Model-based Bayesian reinforcement learning for dialogue management. In *Proceedings of the 14th Annual Conference of the International Speech Communication Association*, Lyon, France, 2013.
- D. J. Litman and J. F. Allen. A plan recognition model for subdialogues in conversations. *Cognitive Science*, 11(2):163–200, 1987.
- M. L. Littman, A. R. Cassandra, and L. P. Kaelbling. Learning policies for partially observable environments: scaling up. In *Proceedings of the 12th International Conference on Machine Learning*, pages 495–503, Tahoe City, USA, 1998.
- R. López-Cózar and Z. Callejas. Multimodal dialogue for ambient intelligence and smart environments. In H. Nakashima, H. Aghajan, and J.-C. Augusto, editors, *Handbook of Ambient Intelligence and Smart Environments*, pages 559–579. Springer, 2010.
- D. J.C. MacKay. Introduction to Monte Carlo methods. In *Learning in graphical models*, pages 175–204. Springer, 1998.
- C. Matheson, M. Poesio, and D. Traum. Modelling grounding and discourse obligations using update rules. In *Proceedings of the 1st Conference of the North American Chapter of the Association for Computational Linguistics*, pages 1–8, Seattle, USA, 2000.
- D. McDermott, M. Ghallab, A. Howe, C. Knoblock, A. Ram, M. Veloso, D. Weld, and D. Wilkins. PDDL - the planning domain definition language. Technical Report CVC TR98003 / DCS TR1165, Yale Center for Computational Vision and Control, 1998.
- M. F. McTear. *Spoken Dialogue Technology: Toward the Conversational User Interface*. Springer, 2004.

- N. Mehta, R. Gupta, A. Raux, D. Ramachandran, and S. Krawczyk. Probabilistic ontology trees for belief tracking in dialog systems. In *Proceedings of the 11th Annual SIGDIAL Meeting on Discourse and Dialogue*, pages 37–46, Tokyo, Japan, 2010.
- T. P. Minka. Estimating a Dirichlet distribution. *Annals of Physics*, 2000(8):1–13, 2003.
- N. Mirnig, A. Weiss, G. Skantze, S. Al Moubayed, J. Gustafson, J. Beskow, B. Granström, and M. Tscheligi. Face-to-face with a robot: What do we actually talk about? *International Journal of Humanoid Robotics*, 10(1):1350011, 2013.
- F. Morbini, E. Forbell, D. DeVault, K. Sagae, D. R. Traum, and A. A. Rizzo. A mixed-initiative conversational dialogue system for healthcare. In *Proceedings of the 13th Annual SIGDIAL Meeting on Discourse and Dialogue*, pages 137–139, Seoul, South Korea, 2012.
- K. P. Murphy, Y. Weiss, and M. I. Jordan. Loopy belief propagation for approximate inference: an empirical study. In *Proceedings of the 15th Conference on Uncertainty in Artificial Intelligence*, pages 467–475, Stockholm, Sweden, 1999.
- Y. I. Nakano, G. Reinstein, T. Stocky, and J. Cassell. Towards a model of face-to-face grounding. In *Proceedings of the 41st Meeting of the Association for Computational Linguistics*, pages 553–561, 2003.
- J. Nivre, J. Hall, J. Nilsson, A. Chanev, G. Eryigit, S. Kübler, S. Marinov, and E. Marsi. Malt-parser: A language-independent system for data-driven dependency parsing. *Natural Language Engineering*, 13(2):95–135, 2007.
- A. O’Hagan. *Uncertain Judgements : Eliciting Experts’ Probabilities*. Wiley, 2006.
- I. O’Neill, P. Hanna, A. Yue, and W. Liu. Using probabilistic logic for dialogue strategy selection. In *Proceedings of the Workshop on Paralinguistic Information and its Integration in Spoken Dialogue Systems*, pages 247–253, Granada, Spain, 2011. Springer.
- S. Oviatt, R. Coulston, and R. Lunsford. When do we interact multimodally? cognitive load and multimodal communication patterns. In *Proceedings of the 6th International Conference on Multimodal Interfaces*, pages 129–136, State College, USA, 2004.
- T. Paek. Reinforcement learning for spoken dialogue systems: Comparing strengths and weaknesses for practical deployment. In *Proceedings of the Interspeech Workshop on Multidisciplinary Evaluation of Advanced Speech-based Interactive System*, Pittsburgh, USA, 2006.
- T. Paek and D. M. Chickering. Evaluating the Markov assumption in Markov Decision Processes for spoken dialogue management. *Language Resources and Evaluation*, 40(1):47–66, 2006.
- T. Paek and R. Pieraccini. Automating spoken dialogue management design using machine learning: An industry perspective. *Speech Communications*, 50(8-9):716–729, 2008.
- R. Pan, Y. Peng, and Z. Ding. Belief update in Bayesian networks using uncertain evidence. In *Proceedings of the 18th IEEE International Conference on Tools with Artificial Intelligence*, pages 441–444, Washington, USA, 2006.

- C. Papadimitriou and J. N. Tsitsiklis. The complexity of Markov Decision Processes. *Mathematics of Operations Research*, 12(3):441–450, 1987.
- J. S. Pardo. On phonetic convergence during conversational interaction. *The Journal of the Acoustical Society of America*, 119:2382, 2006.
- R. J. Passonneau, S. L. Epstein, and T. Ligorio. Naturalistic dialogue management for noisy speech recognition. *IEEE Journal of Selected Topics in Signal Processing*, 6(8):928–942, 2012.
- H. M. Pasula, L. S. Zettlemoyer, and L. P. Kaelbling. Learning symbolic models of stochastic domains. *Journal of Artificial Intelligence Research*, 29:309–352, 2007.
- J. Pearl. Evidential reasoning using stochastic simulation of causal models. *Artificial Intelligence*, 32(2):245–257, 1987.
- O. Pietquin. Optimising spoken dialogue strategies within the reinforcement learning paradigm. In *Reinforcement Learning, Theory and Applications*, pages 239–256. I-Tech Education and Publishing, 2008.
- O. Pietquin and T. Dutoit. A probabilistic framework for dialog simulation and optimal strategy learning. *IEEE Transactions on Audio, Speech and Language Processing*, 14(2):589–599, 2006.
- J. Pineau. *Tractable planning under uncertainty: exploiting structure*. PhD thesis, Carnegie Mellon University, 2004.
- J. Pineau, G. Gordon, and S. Thrun. Point-based value iteration: An anytime algorithm for POMDPs. In *Proceedings of the 18th International Joint Conference on Artificial Intelligence*, pages 1025 – 1032, Acapulco, Mexico, 2003.
- S. Png and J. Pineau. Bayesian reinforcement learning for POMDP-based dialogue systems. In *Proceedings of the 36th IEEE International Conference on Acoustics, Speech, and Signal Processing*, pages 2156–2159, Prague, Czech Republic, 2011.
- S. Png, J. Pineau, and B. Chaib-draa. Building adaptive dialogue systems via Bayes-Adaptive POMDPs. *IEEE Journal of Selected Topics in Signal Processing*, 6(8):917–927, 2012.
- M. Poesio and H. Rieser. An incremental model of anaphora and reference resolution based on resource situations. *Dialogue & Discourse*, 2(1):235–277, 2011.
- M. Poesio and D. R. Traum. Conversational actions and discourse situations. *Computational Intelligence*, 13(3):309–347, 1997.
- D. Poole. The independent choice logic and beyond. In L. De Raedt, P. Frasconi, K. Kersting, and S. Muggleton, editors, *Probabilistic inductive logic programming*, pages 222–243. Springer, 2008.
- P. Poupart. *Exploiting structure to efficiently solve large scale Partially Observable Markov Decision Processes*. PhD thesis, University of Toronto, 2005.
- P. Poupart and N. A. Vlassis. Model-based Bayesian reinforcement learning in partially observable domains. In *Proceedings of the 10th International Symposium on Artificial Intelligence and Mathematics*, Fort Lauderdale, USA, 2008.

- P. Prodanov and A. Drygajlo. Bayesian networks for spoken dialogue management in multimodal systems of tour-guide robots. In *Proceedings of the 8th European Conference on Speech Communication and Technology*, pages 1057–1060, Geneva, Switzerland, 2003.
- M. Purver. *The Theory and Use of Clarification Requests in Dialogue*. PhD thesis, King’s College London, August 2004.
- A. Raux and M. Eskenazi. A finite-state turn-taking model for spoken dialog systems. In *Proceedings of the Human Language Technology Conference of the North American Chapter of the Association for Computational Linguistics*, pages 629–637, Boulder, USA, 2009.
- A. Raux and Y. Ma. Efficient probabilistic tracking of user goal and dialog history for spoken dialog systems. In *Proceedings of the 12th Annual Conference of the International Speech Communication Association*, pages 801–804, Florence, Italy, 2011.
- A. Raux, B. Langner, D. Bohus, A. W. Black, and M. Eskenazi. Let’s go public! Taking a spoken dialog system to the real world. In *Proceedings of the 9th European Conference on Speech Communication and Technology*, pages 885–888, Lisbon, Portugal, 2005.
- C. Rich and C. L. Sidner. COLLAGEN: A collaboration manager for software interface agents. *User Modeling and User-Adapted Interaction*, 8(3-4):315–350, 1998.
- M. Richardson and P. Domingos. Markov logic networks. *Machine Learning*, 62:107–136, 2006.
- V. Rieser and O. Lemon. Using logistic regression to initialise reinforcement-learning-based systems. In *Proceedings of the IEEE Spoken Language Technology Workshop*, pages 190–193, Palm Beach, Aruba, 2006.
- V. Rieser and O. Lemon. Natural language generation as planning under uncertainty for spoken dialogue systems. In E. Krahmer and M. Theune, editors, *Empirical methods in natural language generation*, pages 105–120. Springer, 2010a.
- V. Rieser and O. Lemon. Learning human multimodal dialogue strategies. *Natural Language Engineering*, 16:3–23, 2010b.
- V. Rieser and O. Lemon. *Reinforcement Learning for Adaptive Dialogue Systems*. Springer, 2011.
- V. Rieser and J. D. Moore. Implications for generating clarification requests in task-oriented dialogues. In *Proceedings of the 43rd Meeting of the Association for Computational Linguistics*, pages 239–246, Ann Arbor, USA, 2005.
- E. K. Ringger and J. F. Allen. Error correction via a post-processor for continuous speech recognition. In *Proceedings of the 21st IEEE International Conference on Acoustics, Speech, and Signal Processing*, pages 427–430, Atlanta, USA, 1996.
- S. Ross and B. Chaib-draa. AEMS: An anytime online search algorithm for approximate policy refinement in large POMDPs. In *Proceedings of the 20th International Joint Conference on Artificial Intelligence*, pages 2592–2598, Hyderabad, India, 2007.

- S. Ross, J. Pineau, S. Paquet, and B. Chaib-Draa. Online planning algorithms for POMDPs. *Journal of Artificial Intelligence Research*, 32:663–704, 2008.
- S. Ross, J. Pineau, B. Chaib-draa, and P. Kreitmann. A Bayesian Approach for Learning and Planning in Partially Observable Markov Decision Processes. *Journal of Machine Learning Research*, 12:1729–1770, 2011.
- S. M. Ross. *Introduction to Probability and Statistics for Engineers and Scientists*. Academic Press, 4th edition, 2009.
- D. Roy. Semiotic schemas: A framework for grounding language in action and perception. *Artificial Intelligence*, 167(1-2):170–205, 2005.
- N. Roy, J. Pineau, and S. Thrun. Spoken dialogue management using probabilistic reasoning. In *Proceedings of the 38th Meeting of the Association for Computational Linguistics*, pages 93–100, Hong Kong, China, 2000.
- N. Roy, G. Gordon, and S. Thrun. Finding approximate POMDP solutions through belief compression. *Journal of Artificial Intelligence Research*, 23(1):1–40, 2005.
- G. A. Rummery. *Problem Solving with Reinforcement Learning*. PhD thesis, Cambridge University, 1995.
- H. Sacks, E. A. Schegloff, and G. Jefferson. A simplest systematics for the organization of turn-taking for conversation. *Language*, 50(4):696–735, 1974.
- M. Salem, S. Kopp, I. Wachsmuth, K. Rohlfing, and F. Joublin. Generation and evaluation of communicative robot gesture. *International Journal of Social Robotics*, 4:201–217, 2012.
- S. Sanner. Relational Dynamic Influence Diagram Language (RDDL): Language description. 2010.
- S. Sanner and K. Kersting. Symbolic dynamic programming for first-order POMDPs. In *Proceedings of the 24th AAAI Conference on Artificial Intelligence*, Atlanta, USA, 2010.
- J. Schatzmann, B. Thomson, K. Weilhammer, H. Ye, and S. Young. Agenda-based user simulation for bootstrapping a POMDP dialogue system. In *Proceedings of the Human Language Technology Conference of the North American Chapter of the Association for Computational Linguistics*, pages 149–152, Rochester, USA, 2007a.
- J. Schatzmann, B. Thomson, and S. Young. Error simulation for training statistical dialogue systems. In *Proceedings of the IEEE Workshop on Automatic Speech Recognition & Understanding*, pages 526–531, Kyoto, Japan, 2007b.
- K. Scheffler and S. Young. Automatic learning of dialogue strategy using dialogue simulation and reinforcement learning. In *Proceedings of the 2nd International Conference on Human Language Technology Research*, pages 12–19, San Diego, USA, 2002.
- D. Schlangen. Towards finding and fixing fragments: Using ML to identify non-sentential utterances and their antecedents in multi-party dialogue. In *Proceedings of the 43rd Meeting of the Association for Computational Linguistics*, pages 247–254, Ann Arbor, USA, 2005.

- D. Schlangen and A. Lascarides. The interpretation of non-sentential utterances in dialogue. In *Proceedings of the 4th SIGDIAL Workshop on Discourse and Dialogue*, pages 62–71, Sapporo, Japan, 2003.
- D. Schlangen and G. Skantze. A general, abstract model of incremental dialogue processing. *Dialogue and Discourse*, 2(1):83–111, 2011.
- D. Schlangen, T. Baumann, and M. Atterer. Incremental reference resolution: The task, metrics for evaluation, and a Bayesian filtering model that is sensitive to disfluencies. In *Proceedings of the 10th Annual SIGDIAL Meeting on Discourse and Dialogue*, pages 30–37, London, UK, 2009.
- D. Schlangen, T. Baumann, H. Buschmeier, S. Kopp, G. Skantze, and R. Yaghoubzadeh. Middleware for incremental processing in conversational agents. In *Proceedings of the 11th Annual SIGDIAL Meeting on Discourse and Dialogue*, pages 51–54, Tokyo, Japan, 2010.
- J. Searle. *Speech Acts: An Essay in the Philosophy of Language*. Cambridge University Press, 1969.
- J. Searle. A taxonomy of illocutionary acts. In K. Gunderson, editor, *Language, Mind and Knowledge*, pages 344–369. University of Minnesota Press, 1975.
- S. Seneff and J. Polifroni. Dialogue Management in the Mercury Flight Reservation System. In *Proceedings of the ANLP-NAACL Workshop on Conversational Systems*, pages 11–16, Seattle, USA, 2000.
- G. Shani, J. Pineau, and R. Kaplow. A survey of point-based POMDP solvers. *Autonomous Agents and Multi-Agent Systems*, 27(1):1–51, 2013.
- E. Shriberg, A. Stolcke, D. Jurafsky, N. Coccaro, M. Meteer, R. Bates, P. Taylor, K. Ries, R. Martin, and C. Van Ess-Dykema. Can prosody aid the automatic classification of dialog acts in conversational speech? *Language and speech*, 41(3-4):443–492, 1998.
- D. Silver and J. Veness. Monte-carlo planning in large POMDPs. In *Proceedings of the 24th Conference on Neural Information Processing Systems*, pages 2164–2172, Vancouver, Canada, 2010.
- B. W. Silverman. *Density estimation: for statistics and data analysis*. Chapman and Hall, 1986.
- J. Sinclair and M. Coulthard. *Towards an Analysis of Discourse*. Oxford University Press, 1975.
- S. P. Singh, M. J. Kearns, D. J. Litman, and M. A. Walker. Empirical evaluation of a reinforcement learning spoken dialogue system. In *Proceedings of the 17th National Conference on Artificial Intelligence*, pages 645–651, Austin, USA, 2000.
- S. P. Singh, D. J. Litman, M. J. Kearns, and M. A. Walker. Optimizing dialogue management with reinforcement learning: Experiments with the NJFun system. *Journal of Artificial Intelligence Research*, 16:105–133, 2002.
- G. Skantze. *Error Handling in Spoken Dialogue Systems: Managing Uncertainty, Grounding and Miscommunication*. PhD thesis, Royal Institute of Technology (KTH), Stockholm, 2007.

- E. J. Sondik. *The Optimal Control of Partially Observable Markov Processes*. PhD thesis, Stanford University, 1971.
- O. Ståhl, B. Gambäck, M. Turunen, and J. Hakulinen. A mobile health and fitness companion demonstrator. In *Proceedings of the 12th Conference of the European Chapter of the Association for Computational Linguistics*, pages 65–68, Athens, Greece, 2009.
- M. Steedman and R. P. A. Petrick. Planning dialog actions. In *Proceedings of the 8th SIGDIAL Workshop on Discourse and Dialogue*, pages 265–272, Antwerp, Belgium, 2007.
- A. J. Stent and S. Bangalore. Interaction between dialog structure and coreference resolution. In *Proceedings of the IEEE Spoken Language Technology Workshop*, pages 342–347, Berkeley, USA, 2010.
- R. Stiefelhagen, C. Fugen, R. Giesermann, H. Holzapfel, K. Nickel, and A. Waibel. Natural human–robot interaction using speech, head pose and gestures. In *Proceedings of the IEEE-RSJ International Conference on Intelligent Robots and Systems*, pages 2422–2427, Sendai, Japan, 2004.
- T. Stivers, N. J. Enfield, P. Brown, C. Englert, M. Hayashi, T. Heinemann, G. Hoymann, F. Rossano, J. P. de Ruiter, K.-E. Yoon, and S. C. Levinson. Universals and cultural variation in turn-taking in conversation. *Proceedings of the National Academy of Sciences*, 106(26):10587–10592, 2009.
- A. Stolcke, K. Ries, N. Coccaro, E. Shriberg, R. Bates, D. Jurafsky, P. Taylor, R. Martin, C. Van Ess-Dykema, and M. Meteer. Dialogue act modeling for automatic tagging and recognition of conversational speech. *Computational linguistics*, 26(3):339–373, 2000.
- M. Stone, C. Doran, B. Webber, T. Bleam, and M. Palmer. Microplanning with communicative intentions: The SPUD system. *Computational Intelligence*, 19(4):311–381, 2003.
- M. Strube and C. Müller. A machine learning approach to pronoun resolution in spoken dialogue. In *Proceedings of the 41st Meeting of the Association for Computational Linguistics*, pages 168–175, Sapporo, Japan, 2003.
- N. Ström and S. Seneff. Intelligent barge-in in conversational systems. In *Proceedings of the 6th International Conference on Spoken Language Processing*, pages 652–655, Beijing, China, 2000.
- R. S. Sutton and A. G. Barto. *Reinforcement Learning: An Introduction*. MIT Press, 1998.
- J. Tetreault and D. Litman. Using reinforcement learning to build a better model of dialogue state. In *Proceedings of the 11th Conference of the European Chapter of the Association for Computational Linguistics*, Trento, Italy, 2006.
- R. H. Thomason and M. Stone. Enlightened update: A computational architecture for presupposition and other pragmatic phenomena. In *Presupposition Accommodation*. Ohio State Pragmatics Initiative, 2006.

- B. Thomson and S. Young. Bayesian update of dialogue state: A POMDP framework for spoken dialogue systems. *Computer Speech & Language*, 24:562–588, 2010.
- B. Thomson, F. Jurcícek, M. Gašić, S. Keizer, F. Mairesse, K. Yu, and S. Young. Parameter learning for POMDP spoken dialogue models. In *Proceedings of the IEEE Spoken Language Technology Workshop*, pages 271–276, Berkeley, USA, 2010.
- B. Thomson, M. Gašić, M. Henderson, P. Tsiakoulis, and S. Young. N-best error simulation for training spoken dialogue systems. In *Proceedings of the IEEE Spoken Language Technology Workshop*, pages 37–42, Miami, USA, 2012.
- M. Tomasello, M. Carpenter, J. Call, T. Behne, and H. Moll. Understanding and sharing intentions: The origins of cultural cognition. *Behavioral and Brain Sciences*, 28:675–691, 9 2005.
- D. R. Traum and J. F. Allen. Discourse obligations in dialogue processing. In *Proceedings of the 32nd Meeting of the Association for Computational Linguistics*, pages 1–8, Las Cruces, USA, 1994.
- D. R. Traum and E. A. Hinkelman. Conversation acts in task-oriented spoken dialogue. *Computational Intelligence*, 8:575–599, 1992.
- D. R. Traum, P. Aggarwal, R. Artstein, S. Foutz, J. Gerten, A. Katsamanis, A. Leuski, D. Noren, and W. R. Swartout. Ada and Grace: Direct Interaction with Museum Visitors. In *The 12th International Conference on Intelligent Virtual Agents*, pages 245–251, Santa Cruz, USA, 2012.
- M. Turunen. *Jaspis: A Spoken Dialogue Architecture and Its Applications*. PhD thesis, University of Tampere, Finland, 2004.
- G.-J. Van Noord, G. Bouma, R. Koeling, and M.-J. Nederhof. Robust grammatical analysis for spoken dialogue systems. *Natural Language Engineering*, 5:45–93, 2 1999.
- M. van Otterlo. A survey of reinforcement learning in relational domains. Technical report, University of Twente, 2006.
- M. van Otterlo. Solving relational and first-order logical Markov Decision Processes: A survey. In M. Wiering and M. van Otterlo, editors, *Reinforcement Learning*, volume 12 of *Adaptation, Learning, and Optimization*, pages 253–292. Springer, 2012.
- R. C. Vipperla, M. Wolters, K. Georgila, and S. Renals. Speech input from older users in smart environments: Challenges and perspectives. In *Universal Access in Human-Computer Interaction. Intelligent and Ubiquitous Interaction Environments*, pages 117–126, San Diego, USA, 2009.
- T. Visser, D. Traum, D. DeVault, and R. op den Akker. Toward a model for incremental grounding in spoken dialogue systems. In *Proceedings of the 12th International Conference on Intelligent Virtual Agents*, Santa Cruz, USA, 2012.
- N. Vlassis, M. Ghavamzadeh, S. Mannor, and P. Poupart. Bayesian reinforcement learning. In M. Wiering and M. van Otterlo, editors, *Reinforcement Learning*, volume 12 of *Adaptation, Learning, and Optimization*, pages 359–386. Springer, 2012.

- W. E. Wahlster. *SmartKom: Foundations of Multimodal Dialogue Systems*. Cognitive Technologies. Springer, 2006.
- M. Walker, B. Pellom, J. Polifroni, A. Potamianos, P. Prabhu, A. Rudnicky, S. Seneff, and D. Stallard. DARPA Communicator dialog travel planning systems: The June 2000 data collection. In *Proceedings of the 7th European Conference on Speech Communication and Technology*, pages 1371–1374, Aalborg, Denmark, 2001.
- M. A. Walker. An application of reinforcement learning to dialogue strategy selection in a spoken dialogue system for email. *Journal of Artificial Intelligence Research*, 12(1):387–416, 2000.
- C. Wang and R. Khordon. Relational Partially Observable MDPs. In *Proceedings of the 24th AAAI Conference on Artificial Intelligence*, pages 1153–1158, Atlanta, USA, 2010.
- C. Watkins and P. Dayan. Technical note: Q-learning. *Machine Learning*, 8(3-4):279–292, 1992.
- J. D. Williams. Exploiting the ASR N-best by tracking multiple dialog state hypotheses. In *Proceedings of the 9th Annual Conference of the International Speech Communication Association*, pages 191–194, Brisbane, Australia, 2008a.
- J. D. Williams. The best of both worlds: Unifying conventional dialog systems and POMDPs. In *Proceedings of the 9th Annual Conference of the International Speech Communication Association*, Brisbane, Australia, 2008b.
- J. D. Williams. Incremental partition recombination for efficient tracking of multiple dialog states. In *Proceedings of the 35th IEEE International Conference on Acoustics, Speech, and Signal Processing*, pages 5382–5385, Dallas, USA, 2010.
- J. D. Williams and S. Young. Using Wizard-of-Oz simulations to bootstrap Reinforcement- Learning based dialog management systems. In *Proceedings of the 4th SIGDIAL Workshop on Discourse and Dialogue*, Sapporo, Japan, 2003.
- J. D. Williams and S. Young. Scaling up POMDPs for dialog management: The “summary POMDP” method. In *Proceedings of the IEEE Workshop on Automatic Speech Recognition and Understanding*, pages 177–182, San Juan, Puerto Rico, 2005.
- J. D. Williams and S. Young. Partially Observable Markov Decision Processes for spoken dialog systems. *Computer Speech & Language*, 21:393–422, 2007.
- J. D. Williams, P. Poupart, and S. Young. Factored Partially Observable Markov Decision Processes for Dialogue Management. In *Proceedings of the 4th IJCAI Workshop on Knowledge and Reasoning in Practical Dialog Systems*, Edinburgh, UK, 2005.
- J. D. Williams, P. Poupart, and S. Young. Partially Observable Markov Decision Processes with continuous observations for dialogue management. In L. Dybkjær and W. Minker, editors, *Recent Trends in Discourse and Dialogue*, volume 39 of *Text, Speech and Language Technology*, pages 191–217. Springer, 2008.
- M. Wölfel and J. McDonough. *Distant speech recognition*. Wiley, 2009.

- F. Xu, S. Schmeier, R. Ai, and H. Uszkoreit. Yochina: Mobile multimedia and multimodal cross-lingual dialog system. In *Towards Natural Interaction with Robots, Knowbots and Smartphones - Putting Spoken Dialog Systems into practice*, Paris, France, 2012. Springer.
- H. L. S. Younes and M. L. Littman. PPDDL1.0: The language for the probabilistic part of IPC-4. In *Proceedings of the 4th International Planning Competition*, Whistler, Canada, 2004.
- S. Young, M. Gašić, S. Keizer, F. Mairesse, J. Schatzmann, B. Thomson, and K. Yu. The Hidden Information State model: A practical framework for POMDP-based spoken dialogue management. *Computer Speech & Language*, 24:150–174, 2010.
- S. Young, M. Gašić, B. Thomson, and J. D. Williams. POMDP-based statistical spoken dialog systems: A review. *Proceedings of the IEEE*, 101(5):1160–1179, 2013.
- H. Zender, G.-J. M. Kruijff, and I. Kruijff-Korbayová. Situated resolution and generation of spatial referring expressions for robotic assistants. In *Proceedings of the 21st International Joint Conference on Artificial Intelligence*, pages 1604–1609, Pasadena, USA, 2009.
- B. Zhang, Q. Cai, J. Mao, E. Chang, and B. Guo. Spoken Dialogue Management as Planning and Acting under Uncertainty. In *Proceedings of the 7th European Conference on Speech Communication and Technology*, pages 2169–2172, Aalborg, Denmark, 2001.
- N. L. Zhang and D. Poole. Exploiting causal independence in Bayesian network inference. *Journal of Artificial Intelligence Research*, 5:301–328, 1996.
- P. Zhang, Q. Zhao, and Y. Yan. A spoken dialogue system based on keyword spotting technology. In *Proceedings of the 12th International Conference on Human–Computer Interaction*, pages 253–261, Beijing, China, 2007.
- R. Zhou and R. A. Hansen. An improved grid-based approximation algorithm for POMDPs. In *Proceedings of the 17th International Joint Conference on Artificial Intelligence*, pages 707–714, Seattle, USA, 2001.
- V. Zue, S. Seneff, J.R. Glass, J. Polifroni, C. Pao, T.J. Hazen, and L. Hetherington. JUPITER: a telephone-based conversational interface for weather information. *IEEE Transactions on Speech and Audio Processing*, 8(1):85–96, 2000.

Index

- α -vectors, 48
- ϵ -greedy strategy, 124
- acoustic model, 19, 154
- action selection, 2, 21, 80, 121, 124
 - filtering of relevant actions, 123
- action space, 44
- action–value model, 123
- anaphora, 13
- AND-OR search tree, 121
- anytime algorithm, 122
- average return, 136
- backchannels, 15
- Bayes’ rule, 35, 42
- Bayes-Adaptive POMDP, 117
- Bayesian learning, 41, 119, 173, 188
- Bayesian network, 4, 34, 68
- Bayesian reinforcement learning, 115
 - model-based methods for, 116
 - model-free methods for, 117
- belief state, 27, 47
- belief update, 53
- belief-desire-intention model, 24
- Bellman’s equation, 45, 47, 117
- black-box architecture, 145
- blackboard architecture, 143
- categorical distribution, 35, 146, 149
- chat window, 157
- clarification strategy, 15
- common ground, 14
- conditional independence, 34
- conditional probability distribution, 34
- Constructive Dialogue Modelling, 24
- context modelling, 131
- contextual awareness, 17
- conversation analysis, 10
- conversational floor, 10
- conversational implicatures, 13
- curse of dimensionality, 52, 115
- data sparsity, 50
- database semantics, 68
- decision network, 37
- decision-theoretic planning, 86
- deictic marker, 13
- dependency parsing, 155
- dialogue acts, 11, 103, 127
 - annotation of, 11
 - backward-looking functions, 12
 - DAMSL annotation for, 11
 - forward-looking functions, 12
 - recognition of, 20, 155
- dialogue context, 54
- dialogue domain, 77, 103, 126, 145, 162
 - declarative design of, 143
- dialogue management, 2, 16, 20, 23, 155, 166
 - domain knowledge in, 4
 - hybrid approach to, 161, 174, 187
 - logic-based approaches to, 24
 - MDP approaches to, 50, 151
 - plan-based approaches to, 24
 - POMDP approaches to, 53, 151
 - statistical approaches to, 3, 25, 50, 171
 - symbolic approaches to, 3, 23, 168
- dialogue modelling, 4
- dialogue moves, *see* dialogue acts
- dialogue performance measures, 52
- dialogue policy, 25
 - integration of constraints in, 28
 - reinforcement learning of, 26, 50, 51, 55
 - supervised learning of, 25, 50

- dialogue state, 2, 20, 68, 98, 106, 163
 - factorisation of, 54
 - partial observability, 27, 46
 - pruning of, 80
 - representation of, 51, 53
 - update of, 53, 77
- dialogue state monitor, 157
- dialogue system architecture, 16, 104, 150, 163
- dialogue understanding, 16
- dimensionality reduction, 28, 88, 172
- DIPPER, 150
- Dirichlet distribution, 42, 93, 133, 149
- disfluencies, 20
- distributed architecture, 144
- domain authoring, 153
- domain modelling, 172, 174
- dynamic Bayesian network, 36
- dynamic decision network, 37, 44, 118, 124
- dynamic model adaptation, 154
- dynamic programming, 116
- equivalence node, 78
- error handling, 16
- error modelling, 131
- event-driven architecture, 144
- exploration–exploitation dilemma, 46, 116
- factored probabilistic model, 135
- finite-state automaton, 23, 168
- first-order logic, 62, 67, 87, 88
- frame-based dialogue management, 24
- Gaussian processes, 117
- generalisation capacity, 111, 136, 176
- geometric distribution, 100
- graphical models, 4, **33**, 33, 56
 - parameter estimation, 40
 - structure learning, 40
- graphical user interface, 157
- ground inference, 74
- grounding, **14**
- hidden Markov model, 19
- human–robot interaction, 6, 17, 22, 103, 126, 161, 189
- incremental processing, 18, 152, 191
- incrementality, *see* incremental processing
- influence diagram, *see* decision network
- information state, 15, 18, 24, 88, 150
- informative and non-informative prior, 94
- InproTK, 152
- interaction quality
 - objective metrics of, 178
 - subjective metrics of, 179
- inverse reinforcement learning, 56
- Jaspis, 151
- joint optimisation, 145, 191
- joint probability distribution, 34
- Kalman Temporal Differences, 117
- kernel density estimation, 35, 101, 149, 169
- kernel function, 101
- Kullback–Leibler divergence, 136
- language model, 19, 154
- latent variables, 60, 68
- learning curve, 111, 175
- learning performance, 103, 110, 135
- lexical entrainment, 15
- likelihood distribution, 99
- likelihood weighting, 38, 147
- linear model, 109, 136
- Markov assumption, 36
- Markov Decision Process, 26, **44**, 50
 - action–value function, 45
 - discount factor, 44
 - expected return, 27, 44
 - policy of, 27
- Markov logic network, 87, 123
- maximum likelihood estimation, 41
- MDP, *see* Markov Decision Process
- mixed initiative, 10
- motion control, 156
- multi-modal processing, 17, 152
- N-best list, 19
- Nao robot, 103, 126, 161
- natural language generation, 16, 21, 155, 166
- natural language understanding, 20, 155, 166

- non-parametric distribution, 101
- non-sentential utterance, 12
- normal distribution, 95, 124, 149
- observation model, 47, 54, 118
- observation space, 46
- Olympus/Ravenclaw, 150
- online planning, 48, 116, 121, 135, 150, 188
- OpenDial, 5, 38, 77, **143**, 189
- output distribution, 70
- parameter estimation, 92, 110, 119, 123–125, 173, 175
 - overfitting in, 41
 - with complete data, 41
 - with partial data, 41
- parameter priors, 136, 188
- parameter sharing, 67
- partial observability, 87
- Partially Observable Markov Decision Process, 27, **46**, 53
 - belief state of, 27, 47
 - dimensionality reduction of, 48
 - solution of, 48
 - value function of, 47
- pipeline architecture, 18
- plan recognition, 24
- Planning Domain Definition Language, 87
- planning horizon, 121
- POMDP, *see* Partially Observable Markov Decision Process
- posterior distribution, 38, 100
- posterior parameter distribution, 121, 124
- probabilistic inference, **38**, 147
 - approximate algorithms for, 38
 - exact algorithms for, 38
- probabilistic modelling, 3
- probabilistic rule, 4, **59**, 62, 115, 118, 124, 146, 174, 187
 - conditions of, 64
 - effects of, 64
 - grounding of, 74
 - instantiation of, 68
 - quantified variables in, 67
 - quantifiers in, 67, 74
- probability density function, 35
- probability distribution
 - conjugate prior, 42
 - discretisation of, 100
 - elicitation of, 39, 92
 - factored representation of, 49
 - marginalisation of, 34
- probability rule, 63, 146
 - instantiation of, 69
 - quantifiers in, 74
 - structure of, 63
- Q-learning, 46
- quantification, 61, 67
- random variable, 34
- reference resolution, 20, 155
- referring expression, 13
- reinforcement learning, 5, 26, **43**, 114
 - function approximation in, 52
 - hierarchical abstraction in, 53
 - model-based approaches to, 45
 - model-free approaches to, 46
 - with live interactions, 190
- repair strategy, 15
- reward model, 27, 44, 118, 127, 135
- robot perception, 156
- rule distribution, 70
- rule parameters
 - Bayesian learning of, 93
 - estimation of, 188
 - model-based RL of, 118, 138
 - model-free RL of, 123, 138
 - of probability rules, 93
 - of utility rules, 95
 - parameter estimation of, 4
 - prior distributions of, 93
 - reinforcement learning of, 118, 188
 - supervised learning of, 98, 188
- rule-structured model, 77, 110, 136, 144
 - instantiation of, 79
 - learning performance of, 189
- sampling techniques, 38, 100, 149
- SARSA, 46, 124

- Semi-Markov Decision Process, 53
- sequential decision-making under uncertainty, 3, 43
- shallow template, 155
- soft evidence, 78
- speech acts, *see* dialogue acts
- speech recognition, 16, 19, 154, 163
- speech synthesis, 16, 21, 156, 166
- spoken dialogue, **9**
 - alignment in, 15
 - ambiguities in, 20
 - as a collaborative activity, 9
 - disfluencies in, 20
 - feedback mechanisms in, 15
 - grounding in, 14
 - initiative in, 10
 - parsing of, 20
 - turn-taking in, 10
- spoken dialogue systems, 1, **16**, 153
 - applications of, 22
- state abstraction, 61
- state space, 44
 - partitioning of, 60, 88
- stationary process, 36
- statistical relational learning, 62, 86, 92
- supervised learning, 25, 50, 91, 98
 - as imitation, 99
- synchronous & asynchronous processing, 154
- system action, 162
- system modules, 144
- system portability, 145
- system transparency, 144
- system workflow, 145
- task completion model, 172, 174
- temporal abstraction, 53
- temporal-difference algorithms, 46
- temporal-difference methods, 46
- transition model, 27, 44, 54, 118, 131, 135
- TrindiKit, 150
- TRIPS, 150
- turn-taking, 10, 152, 191
- uniform distribution, 95, 149
- user action, 54, 162
- user action model, 54, 131, 172, 174
- user evaluation, 5, **161**, 189
- user expectations, 177
- user goal model, 54, 131, 172, 174
- user intention, 54, 162
- user model, 21
- user modelling, 131
- user simulator, 27, **52**, 126, 127, 133
- user trial, *see* user evaluation
- utility model, 172, 174
- utility rule, 65, 146
 - instantiation of, 71
 - quantifiers in, 75
 - structure of, 66
- utility table, 109
- value function, 44
- value iteration, 45
- variable elimination, 38, 147
- Wizard-of-Oz interaction, 5, 50, **98**, 127, 166, 173, 189
 - agreement measure, 102, 176
 - assumptions about, 98
 - data collection, 106, 127
- XML, 145