

---

# Contents

<b>I</b>	<b>PROBABILISTIC REASONING</b>	<b>1</b>
<b>1</b>	<b>Bayesian Reasoning</b>	<b>3</b>
1.1	Reasoning under uncertainty . . . . .	3
1.2	Uncertainty in AI . . . . .	4
1.3	Probability calculus . . . . .	5
1.3.1	Conditional probability theorems . . . . .	8
1.3.2	Variables . . . . .	9
1.4	Interpretations of probability . . . . .	10
1.5	Bayesian philosophy . . . . .	11
1.5.1	Bayes' theorem . . . . .	11
1.5.2	Betting and odds . . . . .	13
1.5.3	Expected utility . . . . .	14
1.5.4	Dutch books . . . . .	15
1.5.5	Bayesian reasoning examples . . . . .	17
1.6	The goal of Bayesian AI . . . . .	21
1.7	Achieving Bayesian AI . . . . .	22
1.8	Are Bayesian networks Bayesian? . . . . .	22
1.9	Summary . . . . .	23
1.10	Bibliographic notes . . . . .	23
1.11	Technical notes . . . . .	24
1.12	Problems . . . . .	25
<b>2</b>	<b>Introducing Bayesian Networks</b>	<b>29</b>
2.1	Introduction . . . . .	29
2.2	Bayesian network basics . . . . .	29
2.2.1	Nodes and values . . . . .	30
2.2.2	Structure . . . . .	31
2.2.3	Conditional probabilities . . . . .	32
2.2.4	The Markov property . . . . .	33
2.3	Reasoning with Bayesian networks . . . . .	33
2.3.1	Types of reasoning . . . . .	34
2.3.2	Types of evidence . . . . .	35
2.3.3	Reasoning with numbers . . . . .	36
2.4	Understanding Bayesian networks . . . . .	37
2.4.1	Representing the joint probability distribution . . . . .	37

2.4.2	Pearl's network construction algorithm . . . . .	37
2.4.3	Compactness and node ordering . . . . .	38
2.4.4	Conditional independence . . . . .	39
2.4.5	d-separation . . . . .	41
2.5	More examples . . . . .	43
2.5.1	Earthquake . . . . .	43
2.5.2	Metastatic cancer . . . . .	44
2.5.3	Asia . . . . .	44
2.6	Summary . . . . .	45
2.7	Bibliographic notes . . . . .	45
2.8	Problems . . . . .	47
<b>3</b>	<b>Inference in Bayesian Networks</b>	<b>53</b>
3.1	Introduction . . . . .	53
3.2	Exact inference in chains . . . . .	54
3.2.1	Two node network . . . . .	54
3.2.2	Three node chain . . . . .	55
3.3	Exact inference in polytrees . . . . .	56
3.3.1	Kim and Pearl's message passing algorithm . . . . .	57
3.3.2	Message passing example . . . . .	60
3.3.3	Algorithm features . . . . .	62
3.4	Inference with uncertain evidence . . . . .	62
3.4.1	Using a virtual node . . . . .	63
3.4.2	Virtual nodes in the message passing algorithm . . . . .	65
3.5	Exact inference in multiply-connected networks . . . . .	66
3.5.1	Clustering methods . . . . .	66
3.5.2	Junction trees . . . . .	68
3.6	Approximate inference with stochastic simulation . . . . .	72
3.6.1	Logic sampling . . . . .	72
3.6.2	Likelihood weighting . . . . .	74
3.6.3	Markov Chain Monte Carlo (MCMC) . . . . .	75
3.6.4	Using virtual evidence . . . . .	75
3.6.5	Assessing approximate inference algorithms . . . . .	76
3.7	Other computations . . . . .	77
3.7.1	Belief revision . . . . .	77
3.7.2	Probability of evidence . . . . .	78
3.8	Causal inference . . . . .	79
3.9	Summary . . . . .	80
3.10	Bibliographic notes . . . . .	81
3.11	Problems . . . . .	82

<b>4</b>	<b>Decision networks</b>	<b>89</b>
4.1	Introduction	89
4.2	Utilities	89
4.3	Decision network basics	91
4.3.1	Node types	91
4.3.2	Football team example	92
4.3.3	Evaluating decision networks	93
4.3.4	Information links	94
4.3.5	Fever example	95
4.3.6	Types of actions	97
4.4	Sequential decision making	98
4.4.1	Test-action combination	98
4.4.2	Real estate investment example	99
4.4.3	Evaluation using a decision tree model	101
4.4.4	Value of information	103
4.4.5	Direct evaluation of decision networks	104
4.5	Dynamic Bayesian networks	104
4.5.1	Nodes, structure and CPTs	105
4.5.2	Reasoning	107
4.5.3	Inference algorithms for DBNs	109
4.6	Dynamic decision networks	110
4.6.1	Mobile robot example	111
4.7	Summary	112
4.8	Bibliographic notes	113
4.9	Problems	114
<b>5</b>	<b>Applications of Bayesian Networks</b>	<b>117</b>
5.1	Introduction	117
5.2	A Brief Survey of BN Applications	118
5.2.1	Types of reasoning	118
5.2.2	BN structures for medical problems	118
5.2.3	Other medical applications	120
5.2.4	Non-medical applications	120
5.3	Bayesian Poker	122
5.3.1	Five-card stud poker.	123
5.3.2	A decision network for poker	124
5.3.3	Betting with randomization	127
5.3.4	Bluffing	128
5.3.5	Experimental evaluation	129
5.4	Ambulation monitoring and fall detection	129
5.4.1	The domain	129
5.4.2	The DBN model	130
5.4.3	Case-based evaluation	133
5.4.4	An Extended Sensor Model	135
5.5	A Nice Argument Generator (NAG)	136

5.5.1	NAG architecture . . . . .	136
5.5.2	Example: An asteroid strike . . . . .	138
5.5.3	The psychology of inference . . . . .	139
5.5.4	Example: The asteroid strike continues . . . . .	141
5.5.5	The future of argumentation . . . . .	141
5.6	Summary . . . . .	142
5.7	Bibliographic notes . . . . .	143
5.8	Problems . . . . .	143
<b>II LEARNING CAUSAL MODELS</b>		<b>147</b>
<b>6</b>	<b>Learning Linear Causal Models</b>	<b>151</b>
6.1	Introduction . . . . .	151
6.2	Path models . . . . .	153
6.2.1	Wright's first decomposition rule . . . . .	155
6.2.2	Parameterizing linear models . . . . .	159
6.2.3	Learning linear models is complex . . . . .	159
6.3	Conditional independence learners . . . . .	161
6.3.1	Markov equivalence . . . . .	164
6.3.2	PC algorithm . . . . .	167
6.3.3	Causal discovery versus regression . . . . .	169
6.4	Summary . . . . .	170
6.5	Bibliographic notes . . . . .	170
6.6	Technical notes . . . . .	170
6.7	Problems . . . . .	172
<b>7</b>	<b>Learning Probabilities</b>	<b>175</b>
7.1	Introduction . . . . .	175
7.2	Parameterizing discrete models . . . . .	176
7.2.1	Parameterizing a binomial model . . . . .	176
7.2.2	Parameterizing a multinomial model . . . . .	179
7.3	Incomplete data . . . . .	181
7.3.1	The Bayesian solution . . . . .	182
7.3.2	Approximate solutions . . . . .	182
7.3.3	Incomplete data: summary . . . . .	187
7.4	Learning local structure . . . . .	187
7.4.1	Causal interaction . . . . .	187
7.4.2	Noisy-or connections . . . . .	188
7.4.3	Classification trees and graphs . . . . .	189
7.4.4	Logit models . . . . .	191
7.4.5	Dual model discovery . . . . .	192
7.5	Summary . . . . .	192
7.6	Bibliographic notes . . . . .	193
7.7	Technical notes . . . . .	193
7.8	Problems . . . . .	194

<b>8</b>	<b>Learning Discrete Causal Structure</b>	<b>197</b>
8.1	Introduction . . . . .	197
8.2	Cooper & Herskovits' K2 . . . . .	198
8.2.1	Learning variable order . . . . .	200
8.3	MDL causal discovery . . . . .	201
8.3.1	Lam and Bacchus's MDL code for causal models . . . . .	202
8.3.2	Suzuki's MDL code for causal discovery . . . . .	205
8.4	Metric pattern discovery . . . . .	205
8.5	CaMML: Causal discovery via MML . . . . .	206
8.5.1	An MML code for causal structures . . . . .	207
8.5.2	An MML metric for linear models . . . . .	209
8.6	CaMML stochastic search . . . . .	210
8.6.1	Genetic algorithm (GA) search . . . . .	211
8.6.2	Metropolis search . . . . .	211
8.6.3	Prior constraints . . . . .	213
8.6.4	MML models . . . . .	214
8.6.5	An MML metric for discrete models . . . . .	215
8.7	Experimental evaluation . . . . .	215
8.7.1	Qualitative evaluation . . . . .	216
8.7.2	Quantitative evaluation . . . . .	216
8.8	Summary . . . . .	217
8.9	Bibliographic notes . . . . .	218
8.10	Technical notes . . . . .	218
8.11	Problems . . . . .	219
<b>III</b>	<b>KNOWLEDGE ENGINEERING</b>	<b>221</b>
<b>9</b>	<b>Knowledge Engineering with Bayesian Networks</b>	<b>225</b>
9.1	Introduction . . . . .	225
9.1.1	Bayesian network modeling tasks . . . . .	225
9.2	The KEBN process . . . . .	226
9.2.1	KEBN lifecycle model . . . . .	226
9.2.2	Prototyping and spiral KEBN . . . . .	227
9.2.3	Are BNs suitable for the domain problem? . . . . .	229
9.2.4	Process management . . . . .	229
9.3	Modeling and elicitation . . . . .	230
9.3.1	Variables and values . . . . .	230
9.3.2	Graphical structure . . . . .	233
9.3.3	Probabilities . . . . .	241
9.3.4	Local structure . . . . .	248
9.3.5	Variants of Bayesian networks . . . . .	251
9.3.6	Modeling example: Missing car. . . . .	251
9.3.7	Decision networks . . . . .	254
9.4	Adaptation . . . . .	257
9.4.1	Adapting parameters . . . . .	258

9.4.2	Structural adaptation . . . . .	260
9.5	Summary . . . . .	260
9.6	Bibliographic notes . . . . .	261
9.7	Problems . . . . .	261
<b>10</b>	<b>Evaluation</b>	<b>263</b>
10.1	Introduction . . . . .	263
10.2	Elicitation review . . . . .	263
10.3	Sensitivity analysis . . . . .	264
10.3.1	Sensitivity to evidence . . . . .	264
10.3.2	Sensitivity to changes in parameters . . . . .	271
10.4	Case-based evaluation . . . . .	272
10.4.1	Explanation methods . . . . .	273
10.5	Validation methods . . . . .	274
10.5.1	Predictive accuracy . . . . .	275
10.5.2	Expected value . . . . .	277
10.5.3	Kullback-Leibler divergence . . . . .	278
10.5.4	Information reward . . . . .	280
10.5.5	Bayesian information reward . . . . .	281
10.6	Summary . . . . .	282
10.7	Bibliographic notes . . . . .	283
10.8	Technical notes . . . . .	284
10.9	Problems . . . . .	286
<b>11</b>	<b>KEBN Case Studies</b>	<b>287</b>
11.1	Introduction . . . . .	287
11.2	Bayesian poker revisited . . . . .	287
11.2.1	The initial prototype . . . . .	287
11.2.2	Subsequent developments . . . . .	288
11.2.3	Ongoing Bayesian poker . . . . .	289
11.2.4	KEBN aspects . . . . .	290
11.3	An intelligent tutoring system for decimal understanding . . . . .	290
11.3.1	The ITS domain . . . . .	291
11.3.2	ITS system architecture . . . . .	293
11.3.3	Expert elicitation . . . . .	294
11.3.4	Automated methods . . . . .	301
11.3.5	Field trial evaluation . . . . .	303
11.3.6	KEBN aspects . . . . .	304
11.4	Seabreeze prediction . . . . .	305
11.4.1	The seabreeze prediction problem . . . . .	305
11.4.2	The data . . . . .	306
11.4.3	Bayesian network modeling . . . . .	307
11.4.4	Experimental evaluation . . . . .	309
11.4.5	Case study conclusions . . . . .	311
11.5	Summary . . . . .	312

<b>A</b>	<b>Notation</b>	<b>315</b>
<b>B</b>	<b>Software Packages</b>	<b>317</b>
B.1	Introduction	317
B.2	History	318
B.3	Murphy's Software Package Survey	318
B.4	BN software	322
B.4.1	Analytica	322
B.4.2	BayesiaLab	323
B.4.3	Bayes Net Toolbox (BNT)	324
B.4.4	GeNIe	325
B.4.5	Hugin	326
B.4.6	JavaBayes	327
B.4.7	MSBNx	328
B.4.8	Netica	328
B.5	Bayesian statistical modeling	329
B.5.1	BUGS	329
B.5.2	First Bayes	330
B.6	Causal discovery programs	330
B.6.1	Bayesware Discoverer	330
B.6.2	CaMML	331
B.6.3	TETRAD	331
B.6.4	WinMine	331