

---

# Contents

---

## Part I Planning Benchmarks

---

<b>1</b>	<b>The Role of Benchmarks</b> . . . . .	3
1.1	Evaluating Planner Performance . . . . .	3
1.1.1	Worst-Case Evaluation . . . . .	4
1.1.2	Average-Case Evaluation . . . . .	5
1.2	Planning Benchmarks Are Important . . . . .	7
1.3	Theoretical Analyses of Planning Benchmarks . . . . .	8
1.3.1	Why Theoretical Analyses Are Useful . . . . .	8
1.3.2	Published Results on Benchmark Complexity . . . . .	9
1.4	Standard Benchmarks . . . . .	9
1.5	Summary and Overview . . . . .	11
<b>2</b>	<b>Defining Planning Domains</b> . . . . .	13
2.1	Optimization Problems . . . . .	13
2.1.1	Minimization Problems . . . . .	14
2.1.2	Approximation Algorithms . . . . .	15
2.1.3	Approximation Classes . . . . .	16
2.1.4	Reductions . . . . .	18
2.2	Formalizing Planning Domains . . . . .	21
2.3	General Results and Reductions . . . . .	24
2.3.1	Upper Bounds . . . . .	24
2.3.2	Shortest Plan Length . . . . .	25
2.3.3	Approximation Classes of Limited Interest . . . . .	26
2.3.4	Relating Planning and (Bounded) Plan Existence . . . . .	28
2.3.5	Generalization and Specialization . . . . .	29
<b>3</b>	<b>The Benchmark Suite</b> . . . . .	31
3.1	Defining the Competition Domains . . . . .	31
3.2	The Benchmark Suite . . . . .	32
3.2.1	IPC1 Domains . . . . .	32

3.2.2	IPC2 Domains .....	34
3.2.3	IPC3 Domains .....	34
3.2.4	IPC4 Domains .....	35
3.3	Domains and Domain Families .....	36
<b>4</b>	<b>Transportation and Route Planning .....</b>	<b>39</b>
4.1	TRANSPORT and ROUTE .....	39
4.1.1	The TRANSPORT Domain .....	41
4.1.2	The ROUTE Domain .....	43
4.1.3	Special Cases and Hierarchy .....	44
4.2	General Results .....	46
4.3	Plan Existence .....	52
4.4	Hardness of Optimization .....	54
4.5	Constant Factor Approximation .....	59
4.6	Hardness of Constant Factor Approximation .....	62
4.7	Summary .....	68
4.8	Beyond TRANSPORT and ROUTE .....	71
<b>5</b>	<b>IPC Domains: Transportation and Route Planning .....</b>	<b>75</b>
5.1	GRIPPER .....	75
5.2	MYSTERY and MYSTERYPRIME .....	76
5.3	LOGISTICS .....	78
5.4	ZENOTRAVEL .....	83
5.5	DEPOTS .....	85
5.6	MICONIC-10 .....	88
5.7	ROVERS .....	93
5.8	GRID .....	98
5.9	DRIVERLOG .....	103
5.10	AIRPORT .....	108
5.11	Summary .....	111
<b>6</b>	<b>IPC Domains: Others .....</b>	<b>113</b>
6.1	ASSEMBLY .....	113
6.2	BLOCKSWORLD .....	117
6.3	FREECELL .....	117
6.4	MOVIE .....	126
6.5	PIPESWORLD .....	127
6.6	PROMELA .....	132
6.7	PSR .....	138
6.8	SATELLITE .....	142
6.9	SCHEDULE .....	145
6.10	Summary .....	149

<b>7</b>	<b>Conclusions</b> .....	151
7.1	Ten Conclusions.....	151
7.2	Going Further.....	154

---

## Part II Fast Downward

---

<b>8</b>	<b>Solving Planning Tasks Hierarchically</b> .....	157
8.1	Introduction .....	157
8.2	Related Work .....	163
8.2.1	Causal Graphs and Abstraction .....	164
8.2.2	Causal Graphs and Unary STRIPS Operators .....	165
8.2.3	Multi-Valued Planning Tasks .....	167
8.3	Architecture and Overview .....	168
<b>9</b>	<b>Translation</b> .....	171
9.1	PDDL and Multi-valued Planning Tasks.....	171
9.2	Translation Overview .....	175
9.3	Normalization.....	176
9.3.1	Compiling Away Types .....	177
9.3.2	Simplifying Conditions .....	177
9.3.3	Simplifying Effects .....	179
9.3.4	Normalization Result .....	179
9.4	Invariant Synthesis .....	180
9.4.1	Initial Candidates .....	182
9.4.2	Proving Invariance .....	183
9.4.3	Refining Failed Candidates .....	186
9.4.4	Examples .....	188
9.4.5	Related Work .....	188
9.5	Grounding.....	190
9.5.1	Overview of Horn Exploration .....	191
9.5.2	Generating the Logic Program .....	191
9.5.3	Translating the Logic Program to Normal Form .....	193
9.5.4	Computing the Canonical Model .....	195
9.5.5	Axiom and Operator Instantiation.....	197
9.6	Multi-valued Planning Task Generation .....	197
9.6.1	Variable Selection .....	198
9.6.2	Converting the Initial State.....	199
9.6.3	Converting Operator Effects .....	200
9.6.4	Converting Conditions .....	201
9.6.5	Computing Axiom Layers .....	202
9.6.6	Generating the Output.....	202
9.7	Performance Notes .....	203
9.7.1	Relative Performance Compared to MIPS Translator... ..	203
9.7.2	Absolute Performance.....	205

- 10 Knowledge Compilation** . . . . . 207
  - 10.1 Overview . . . . . 207
  - 10.2 Domain Transition Graphs . . . . . 208
  - 10.3 Causal Graphs . . . . . 213
    - 10.3.1 Acyclic Causal Graphs . . . . . 214
    - 10.3.2 Generating and Pruning Causal Graphs . . . . . 215
    - 10.3.3 Causal Graph Examples . . . . . 217
  - 10.4 Successor Generators and Axiom Evaluators . . . . . 220
    - 10.4.1 Successor Generators . . . . . 220
    - 10.4.2 Axiom Evaluators . . . . . 221
- 11 Search** . . . . . 223
  - 11.1 Overview . . . . . 223
  - 11.2 The Causal Graph Heuristic . . . . . 224
    - 11.2.1 Conceptual View of the Causal Graph Heuristic . . . . . 225
    - 11.2.2 Computation of the Causal Graph Heuristic . . . . . 226
    - 11.2.3 States with Infinite Heuristic Value . . . . . 228
    - 11.2.4 Helpful Transitions . . . . . 229
  - 11.3 The FF Heuristic . . . . . 230
  - 11.4 Greedy Best-First Search in Fast Downward . . . . . 231
    - 11.4.1 Preferred Operators . . . . . 231
    - 11.4.2 Deferred Heuristic Evaluation . . . . . 232
  - 11.5 Multi-heuristic Best-First Search . . . . . 233
  - 11.6 Focused Iterative-Broadening Search . . . . . 234
- 12 Experiments** . . . . . 239
  - 12.1 Experiment Design . . . . . 239
    - 12.1.1 Benchmark Set . . . . . 240
    - 12.1.2 Experiment Setup . . . . . 242
    - 12.1.3 Translation and Knowledge Compilation vs. Search . . . . . 243
  - 12.2 STRIPS Domains from IPC1–3 . . . . . 243
  - 12.3 ADL Domains from IPC1–3 . . . . . 246
  - 12.4 Domains from IPC4 . . . . . 248
  - 12.5 Conclusions from the Experiment . . . . . 251
- 13 Discussion** . . . . . 253
  - 13.1 Summary . . . . . 253
  - 13.2 Major Contributions . . . . . 254
    - 13.2.1 Multi-valued Representations . . . . . 254
    - 13.2.2 Task Decomposition Heuristics . . . . . 256
  - 13.3 Minor Contributions . . . . . 257
  - 13.4 Going Further . . . . . 258
- References** . . . . . 259
- Index** . . . . . 267