

CONTENTS

Preface	xi
Acknowledgments	xiii
1. Introduction	1
1.1 Overview	1
1.2 Organization	5
2. Parallel Systems and Programming	7
2.1 Parallel Architectures	7
2.1.1 Flynn's Taxonomy	7
2.1.2 Memory Architectures	9
2.1.3 Programming Paradigms and Models	11
2.2 Communication Networks	13
2.2.1 Static Networks	13
2.2.2 Dynamic Networks	18
2.3 Parallelization	22
2.4 Subtask Decomposition	24
2.4.1 Concurrency and Granularity	24
2.4.2 Decomposition Techniques	25
2.4.3 Computation Type and Program Formulation	27
2.4.4 Parallelization Techniques	28
2.4.5 Target Parallel System	28
2.5 Dependence Analysis	29
2.5.1 Data Dependence	29
2.5.2 Data Dependence in Loops	32
2.5.3 Control Dependence	35
2.6 Concluding Remarks	36
2.7 Exercises	37
3. Graph Representations	40
3.1 Basic Graph Concepts	40

viii CONTENTS

3.1.1	Computer Representation of Graphs	43
3.1.2	Elementary Graph Algorithms	46
3.2	Graph as a Program Model	49
3.2.1	Computation and Communication Costs	50
3.2.2	Comparison Criteria	50
3.3	Dependence Graph (DG)	51
3.3.1	Iteration Dependence Graph	53
3.3.2	Summary	55
3.4	Flow Graph (FG)	56
3.4.1	Data-Driven Execution Model	60
3.4.2	Summary	61
3.5	Task Graph (DAG)	62
3.5.1	Graph Transformations and Conversions	64
3.5.2	Motivations and Limitations	68
3.5.3	Summary	69
3.6	Concluding Remarks	69
3.7	Exercises	70
4.	Task Scheduling	74
4.1	Fundamentals	74
4.2	With Communication Costs	76
4.2.1	Schedule Example	81
4.2.2	Scheduling Complexity	82
4.3	Without Communication Costs	86
4.3.1	Schedule Example	87
4.3.2	Scheduling Complexity	88
4.4	Task Graph Properties	92
4.4.1	Critical Path	93
4.4.2	Node Levels	95
4.4.3	Granularity	101
4.5	Concluding Remarks	105
4.6	Exercises	105
5.	Fundamental Heuristics	108
5.1	List Scheduling	108
5.1.1	Start Time Minimization	111
5.1.2	With Dynamic Priorities	114
5.1.3	Node Priorities	115
5.2	Scheduling with Given Processor Allocation	118
5.2.1	Phase Two	119

5.3	Clustering	119
5.3.1	Clustering Algorithms	121
5.3.2	Linear Clustering	124
5.3.3	Single Edge Clustering	128
5.3.4	List Scheduling as Clustering	135
5.3.5	Other Algorithms	138
5.4	From Clustering to Scheduling	139
5.4.1	Assigning Clusters to Processors	139
5.4.2	Scheduling on Processors	141
5.5	Concluding Remarks	141
5.6	Exercises	142
6.	Advanced Task Scheduling	145
6.1	Insertion Technique	145
6.1.1	List Scheduling with Node Insertion	148
6.2	Node Duplication	150
6.2.1	Node Duplication Heuristics	153
6.3	Heterogeneous Processors	154
6.3.1	Scheduling	157
6.4	Complexity Results	158
6.4.1	$\alpha \beta \gamma$ Classification	158
6.4.2	Without Communication Costs	165
6.4.3	With Communication Costs	165
6.4.4	With Node Duplication	168
6.4.5	Heterogeneous Processors	170
6.5	Genetic Algorithms	170
6.5.1	Basics	171
6.5.2	Chromosomes	172
6.5.3	Reproduction	177
6.5.4	Selection, Complexity, and Flexibility	180
6.6	Concluding Remarks	182
6.7	Exercises	183
7.	Communication Contention in Scheduling	187
7.1	Contention Awareness	188
7.1.1	End-Point Contention	189
7.1.2	Network Contention	190
7.1.3	Integrating End-Point and Network Contention	192
7.2	Network Model	192
7.2.1	Topology Graph	192
7.2.2	Routing	198
7.2.3	Scheduling Network Model	202

x CONTENTS

7.3	Edge Scheduling	203
7.3.1	Scheduling Edge on Route	204
7.3.2	The Edge Scheduling	208
7.4	Contention Aware Scheduling	209
7.4.1	Basics	209
7.4.2	NP-Completeness	211
7.5	Heuristics	216
7.5.1	List Scheduling	216
7.5.2	Priority Schemes—Task Graph Properties	219
7.5.3	Clustering	220
7.5.4	Experimental Results	221
7.6	Concluding Remarks	223
7.7	Exercises	224
8.	Processor Involvement in Communication	228
8.1	Processor Involvement—Types and Characteristics	229
8.1.1	Involvement Types	229
8.1.2	Involvement Characteristics	232
8.1.3	Relation to LogP and Its Variants	236
8.2	Involvement Scheduling	238
8.2.1	Scheduling Edges on the Processors	240
8.2.2	Node and Edge Scheduling	246
8.2.3	Task Graph	247
8.2.4	NP-Completeness	248
8.3	Algorithmic Approaches	250
8.3.1	Direct Scheduling	251
8.3.2	Scheduling with Given Processor Allocation	254
8.4	Heuristics	257
8.4.1	List Scheduling	257
8.4.2	Two-Phase Heuristics	261
8.4.3	Experimental Results	263
8.5	Concluding Remarks	264
8.6	Exercises	265
	Bibliography	269
	Author Index	281
	Subject Index	285