

# Contents

---

<b>Preface .....</b>	<b>xxix</b>
Goals .....	xxx
Philosophy .....	xxxii
Organization .....	xxxiii
Roadmap .....	xxxiv
Dependencies .....	xxxiv
Background .....	xxxv
Undergraduate Level .....	xxxvi
Graduate Level .....	xxxvi
Practitioners .....	xxxviii
Special Acknowledgment .....	xxxviii
Acknowledgments .....	xxxviii

<b>PART 1:INTRODUCTION</b>	<b>1</b>
----------------------------	----------

<b>Chapter 1 An Overview of Computer Security .....</b>	<b>3</b>
1.1 The Basic Components .....	3
1.1.1 Confidentiality.....	4
1.1.2 Integrity.....	5
1.1.3 Availability .....	6
1.2 Threats .....	6
1.3 Policy and Mechanism .....	9
1.3.1 Goals of Security.....	10
1.4 Assumptions and Trust .....	11
1.5 Assurance .....	12
1.5.1 Specification .....	13
1.5.2 Design .....	14
1.5.3 Implementation .....	14
1.6 Operational Issues .....	16
1.6.1 Cost-Benefit Analysis .....	16
1.6.2 Risk Analysis.....	17
1.6.3 Laws and Customs .....	18

vi Contents

1.7 Human Issues .....	19
1.7.1 Organizational Problems .....	20
1.7.2 People Problems.....	21
1.8 Tying It All Together .....	22
1.9 Summary .....	23
1.10 Research Issues .....	24
1.11 Further Readings .....	24
1.12 Exercises .....	25

**PART 2: FOUNDATIONS** **29**

**Chapter 2 Access Control Matrix** ..... **31**

2.1 Protection State .....	31
2.2 Access Control Matrix Model .....	32
2.2.1 Access Control by Boolean Expression Evaluation.....	35
2.2.2 Access Controlled by History.....	36
2.3 Protection State Transitions .....	37
2.3.1 Conditional Commands .....	40
2.4 Copying, Owning, and the Attenuation of Privilege .....	41
2.4.1 Copy Right .....	42
2.4.2 Own Right .....	42
2.4.3 Principle of Attenuation of Privilege .....	43
2.5 Summary .....	43
2.6 Research Issues .....	44
2.7 Further Reading .....	44
2.8 Exercises .....	44

**Chapter 3 Foundational Results** ..... **47**

3.1 The General Question .....	47
3.2 Basic Results .....	48
3.3 The Take-Grant Protection Model .....	53
3.3.1 Sharing of Rights .....	55
3.3.2 Interpretation of the Model.....	58
3.3.3 Theft in the Take-Grant Protection Model.....	60
3.3.4 Conspiracy .....	63
3.3.5 Summary .....	65
3.4 Closing the Gap .....	65
3.4.1 Schematic Protection Model .....	66
3.4.1.1 <i>Link Predicate</i> .....	66
3.4.1.2 <i>Filter Function</i> .....	68

3.4.1.3	<i>Putting It All Together</i>	68
3.4.1.4	<i>Demand and Create Operations</i>	69
3.4.1.5	<i>Safety Analysis</i>	72
3.5	Expressive Power and the Models	78
3.5.1	Brief Comparison of HRU and SPM	78
3.5.2	Extending SPM	79
3.5.3	Simulation and Expressiveness	83
3.5.4	Typed Access Matrix Model	88
3.6	Summary	90
3.7	Research Issues	90
3.8	Further Reading	91
3.9	Exercises	91

**PART 3: POLICY** **93**

<b>Chapter 4 Security Policies</b>	<b>95</b>
4.1 Security Policies	95
4.2 Types of Security Policies	99
4.3 The Role of Trust	101
4.4 Types of Access Control	103
4.5 Policy Languages	104
4.5.1 High-Level Policy Languages	104
4.5.2 Low-Level Policy Languages	109
4.6 Example: Academic Computer Security Policy	111
4.6.1 General University Policy	111
4.6.2 Electronic Mail Policy	112
4.6.2.1 <i>The Electronic Mail Policy Summary</i>	112
4.6.2.2 <i>The Full Policy</i>	113
4.6.2.3 <i>Implementation at UC Davis</i>	114
4.7 Security and Precision	114
4.8 Summary	119
4.9 Research Issues	119
4.10 Further Reading	120
4.11 Exercises	120

**Chapter 5 Confidentiality Policies** **123**

5.1 Goals of Confidentiality Policies	123
5.2 The Bell-LaPadula Model	124
5.2.1 Informal Description	124
5.2.2 Example: The Data General B2 UNIX System	128

5.2.2.1	<i>Assigning MAC Labels</i>	128
5.2.2.2	<i>Using MAC Labels</i>	131
5.2.3	Formal Model	132
5.2.3.1	<i>Basic Security Theorem</i>	134
5.2.3.2	<i>Rules of Transformation</i>	136
5.2.4	Example Model Instantiation: Multics	139
5.2.4.1	<i>The get-read Rule</i>	140
5.2.4.2	<i>The give-read Rule</i>	141
5.3	Tranquility	142
5.4	The Controversy over the Bell-LaPadula Model	143
5.4.1	McLean's $\dagger$ -Property and the Basic Security Theorem	143
5.4.2	McLean's System Z and More Questions	146
5.4.3	Summary	148
5.5	Summary	148
5.6	Research Issues	148
5.7	Further Reading	149
5.8	Exercises	150
<b>Chapter 6 Integrity Policies</b>		<b>151</b>
6.1	Goals	151
6.2	Biba Integrity Model	153
6.2.1	Low-Water-Mark Policy	154
6.2.2	Ring Policy	155
6.2.3	Biba's Model (Strict Integrity Policy)	155
6.3	Lipner's Integrity Matrix Model	156
6.3.1	Lipner's Use of the Bell-LaPadula Model	156
6.3.2	Lipner's Full Model	158
6.3.3	Comparison with Biba	160
6.4	Clark-Wilson Integrity Model	160
6.4.1	The Model	161
6.4.1.1	<i>A UNIX Approximation to Clark-Wilson</i>	164
6.4.2	Comparison with the Requirements	164
6.4.3	Comparison with Other Models	165
6.5	Summary	166
6.6	Research Issues	166
6.7	Further Reading	167
6.8	Exercises	167
<b>Chapter 7 Hybrid Policies</b>		<b>169</b>
7.1	Chinese Wall Model	169
7.1.1	Informal Description	170
7.1.2	Formal Model	172

7.1.3	Bell-LaPadula and Chinese Wall Models . . . . .	175
7.1.4	Clark-Wilson and Chinese Wall Models . . . . .	177
7.2	Clinical Information Systems Security Policy . . . . .	177
7.2.1	Bell-LaPadula and Clark-Wilson Models . . . . .	179
7.3	Originator Controlled Access Control . . . . .	180
7.4	Role-Based Access Control . . . . .	182
7.5	Summary . . . . .	184
7.6	Research Issues . . . . .	184
7.7	Further Reading . . . . .	184
7.8	Exercises . . . . .	185
<b>Chapter 8 Noninterference and Policy Composition . . . . .</b>		<b>187</b>
8.1	The Problem . . . . .	187
8.1.1	Composition of Bell-LaPadula Models . . . . .	188
8.2	Deterministic Noninterference . . . . .	191
8.2.1	Unwinding Theorem . . . . .	195
8.2.2	Access Control Matrix Interpretation . . . . .	197
8.2.3	Security Policies That Change over Time . . . . .	200
8.2.4	Composition of Deterministic Noninterference-Secure Systems . . . . .	201
8.3	Nondeducibility . . . . .	202
8.3.1	Composition of Deducibly Secure Systems . . . . .	204
8.4	Generalized Noninterference . . . . .	205
8.4.1	Composition of Generalized Noninterference Systems . . . . .	206
8.5	Restrictiveness . . . . .	208
8.5.1	State Machine Model . . . . .	208
8.5.2	Composition of Restrictive Systems . . . . .	209
8.6	Summary . . . . .	210
8.7	Research Issues . . . . .	211
8.8	Further Reading . . . . .	211
8.9	Exercises . . . . .	212

**PART 4: IMPLEMENTATION I: CRYPTOGRAPHY** **215**

<b>Chapter 9 Basic Cryptography . . . . .</b>		<b>217</b>
9.1	What Is Cryptography? . . . . .	217
9.2	Classical Cryptosystems . . . . .	218
9.2.1	Transposition Ciphers . . . . .	219
9.2.2	Substitution Ciphers . . . . .	220
9.2.2.1	<i>Vigenère Cipher</i> . . . . .	221
9.2.2.2	<i>One-Time Pad</i> . . . . .	227

x Contents

9.2.3 Data Encryption Standard .....	228
9.2.4 Other Classical Ciphers .....	232
9.3 Public Key Cryptography .....	233
9.3.1 Diffie-Hellman .....	233
9.3.2 RSA .....	234
9.4 Cryptographic Checksums .....	237
9.4.1 HMAC .....	239
9.5 Summary .....	239
9.6 Research Issues .....	240
9.7 Further Reading .....	240
9.8 Exercises .....	241
<b>Chapter 10 Key Management .....</b>	<b>245</b>
10.1 Session and Interchange Keys .....	246
10.2 Key Exchange .....	246
10.2.1 Classical Cryptographic Key Exchange and Authentication .....	247
10.2.2 Kerberos .....	250
10.2.3 Public Key Cryptographic Key Exchange and Authentication .....	251
10.3 Key Generation .....	252
10.4 Cryptographic Key Infrastructures .....	254
10.4.1 Merkle's Tree Authentication Scheme .....	255
10.4.2 Certificate Signature Chains .....	256
10.4.2.1 X.509: Certification Signature Chains .....	256
10.4.2.2 PGP Certificate Signature Chains .....	258
10.4.3 Summary .....	260
10.5 Storing and Revoking Keys .....	261
10.5.1 Key Storage .....	261
10.5.1.1 Key Escrow .....	262
10.5.1.2 Key Escrow System and the Clipper Chip .....	263
10.5.1.3 The Yaksha Security System .....	264
10.5.1.4 Other Approaches .....	265
10.5.2 Key Revocation .....	265
10.6 Digital Signatures .....	266
10.6.1 Classical Signatures .....	267
10.6.2 Public Key Signatures .....	267
10.6.2.1 RSA Digital Signatures .....	267
10.6.2.2 El Gamal Digital Signature .....	269
10.7 Summary .....	270
10.8 Research Issues .....	271
10.9 Further Reading .....	272
10.10 Exercises .....	272

<b>Chapter 11 Cipher Techniques .....</b>	<b>275</b>
11.1 Problems .....	275
11.1.1 Precomputing the Possible Messages.....	275
11.1.2 Misordered Blocks .....	276
11.1.3 Statistical Regularities .....	276
11.1.4 Summary .....	277
11.2 Stream and Block Ciphers .....	277
11.2.1 Stream Ciphers .....	277
11.2.1.1 <i>Synchronous Stream Ciphers</i> .....	278
11.2.1.2 <i>Self-Synchronous Stream Ciphers</i> .....	280
11.2.2 Block Ciphers .....	281
11.2.2.1 <i>Multiple Encryption</i> .....	282
11.3 Networks and Cryptography .....	283
11.4 Example Protocols .....	286
11.4.1 Secure Electronic Mail: PEM.....	286
11.4.1.1 <i>Design Principles</i> .....	287
11.4.1.2 <i>Basic Design</i> .....	288
11.4.1.3 <i>Other Considerations</i> .....	289
11.4.1.4 <i>Conclusion</i> .....	290
11.4.2 Security at the Transport Layer: SSL.....	291
11.4.2.1 <i>Supporting Cryptographic Mechanisms</i> .....	292
11.4.2.2 <i>Lower Layer: SSL Record Protocol</i> .....	294
11.4.2.3 <i>Upper Layer: SSL Handshake Protocol</i> .....	295
11.4.2.4 <i>Upper Layer: SSL Change Cipher Spec Protocol</i> .....	297
11.4.2.5 <i>Upper Layer: SSL Alert Protocol</i> .....	297
11.4.2.6 <i>Upper Layer: Application Data Protocol</i> .....	298
11.4.2.7 <i>Summary</i> .....	298
11.4.3 Security at the Network Layer: IPsec.....	298
11.4.3.1 <i>IPsec Architecture</i> .....	299
11.4.3.2 <i>Authentication Header Protocol</i> .....	303
11.4.3.3 <i>Encapsulating Security Payload Protocol</i> .....	304
11.4.4 Conclusion .....	305
11.5 Summary .....	306
11.6 Research Issues .....	306
11.7 Further Reading .....	306
11.8 Exercises .....	307
<b>Chapter 12 Authentication .....</b>	<b>309</b>
12.1 Authentication Basics .....	309
12.2 Passwords .....	310
12.2.1 Attacking a Password System .....	312

12.2.2	Countering Password Guessing.....	313
12.2.2.1	<i>Random Selection of Passwords</i> .....	314
12.2.2.2	<i>Pronounceable and Other Computer-Generated Passwords</i> .....	315
12.2.2.3	<i>User Selection of Passwords</i> .....	316
12.2.2.4	<i>Reusable Passwords and Dictionary Attacks</i> .....	320
12.2.2.5	<i>Guessing Through Authentication Functions</i> .....	321
12.2.3	Password Aging.....	322
12.3	Challenge-Response .....	324
12.3.1	Pass Algorithms.....	324
12.3.2	One-Time Passwords.....	325
12.3.3	Hardware-Supported Challenge-Response Procedures.....	326
12.3.4	Challenge-Response and Dictionary Attacks .....	327
12.4	Biometrics .....	328
12.4.1	Fingerprints .....	328
12.4.2	Voices .....	329
12.4.3	Eyes .....	329
12.4.4	Faces .....	329
12.4.5	Keystrokes.....	330
12.4.6	Combinations.....	330
12.4.7	Caution .....	330
12.5	Location .....	331
12.6	Multiple Methods .....	331
12.7	Summary .....	333
12.8	Research Issues .....	334
12.9	Further Reading .....	335
12.10	Exercises .....	335

**PART 5: IMPLEMENTATION II: SYSTEMS** 339

<b>Chapter 13 Design Principles</b> .....	<b>341</b>
13.1 Overview .....	341
13.2 Design Principles .....	343
13.2.1 Principle of Least Privilege .....	343
13.2.2 Principle of Fail-Safe Defaults .....	344
13.2.3 Principle of Economy of Mechanism .....	344
13.2.4 Principle of Complete Mediation .....	345
13.2.5 Principle of Open Design .....	346
13.2.6 Principle of Separation of Privilege .....	347
13.2.7 Principle of Least Common Mechanism.....	348
13.2.8 Principle of Psychological Acceptability .....	348

13.3	Summary .....	349
13.4	Research Issues .....	350
13.5	Further Reading .....	350
13.6	Exercises .....	351
<b>Chapter 14 Representing Identity .....</b>		<b>353</b>
14.1	What Is Identity? .....	353
14.2	Files and Objects .....	354
14.3	Users .....	355
14.4	Groups and Roles .....	356
14.5	Naming and Certificates .....	357
14.5.1	Conflicts .....	360
14.5.2	The Meaning of the Identity .....	363
14.5.3	Trust .....	364
14.6	Identity on the Web .....	366
14.6.1	Host Identity .....	366
14.6.1.1	<i>Static and Dynamic Identifiers</i> .....	367
14.6.1.2	<i>Security Issues with the Domain Name Service</i> .....	368
14.6.2	State and Cookies .....	369
14.6.3	Anonymity on the Web .....	371
14.6.3.1	<i>Anonymity for Better or Worse</i> .....	375
14.7	Summary .....	377
14.8	Research Issues .....	378
14.9	Further Reading .....	378
14.10	Exercises .....	379
<b>Chapter 15 Access Control Mechanisms .....</b>		<b>381</b>
15.1	Access Control Lists .....	381
15.1.1	Abbreviations of Access Control Lists .....	382
15.1.2	Creation and Maintenance of Access Control Lists .....	384
15.1.2.1	<i>Which Subjects Can Modify an Object's ACL?</i> .....	385
15.1.2.2	<i>Do the ACLs Apply to a Privileged User?</i> .....	385
15.1.2.3	<i>Does the ACL Support Groups and Wildcards?</i> .....	386
15.1.2.4	<i>Conflicts</i> .....	386
15.1.2.5	<i>ACLs and Default Permissions</i> .....	387
15.1.3	Revocation of Rights .....	387
15.1.4	Example: Windows NT Access Control Lists .....	388
15.2	Capabilities .....	390
15.2.1	Implementation of Capabilities .....	391
15.2.2	Copying and Amplifying Capabilities .....	392
15.2.3	Revocation of Rights .....	393
15.2.4	Limits of Capabilities .....	394

15.2.5	Comparison with Access Control Lists . . . . .	395
15.3	Locks and Keys . . . . .	396
15.3.1	Type Checking . . . . .	397
15.3.2	Sharing Secrets . . . . .	399
15.4	Ring-Based Access Control . . . . .	400
15.5	Propagated Access Control Lists . . . . .	402
15.6	Summary . . . . .	404
15.7	Research Issues . . . . .	404
15.8	Further Reading . . . . .	405
15.9	Exercises . . . . .	405
<b>Chapter 16 Information Flow . . . . .</b>		<b>407</b>
16.1	Basics and Background . . . . .	407
16.1.1	Entropy-Based Analysis . . . . .	408
16.1.2	Information Flow Models and Mechanisms . . . . .	409
16.2	Nonlattice Information Flow Policies . . . . .	410
16.2.1	Confinement Flow Model . . . . .	411
16.2.2	Transitive Nonlattice Information Flow Policies . . . . .	412
16.2.3	Nontransitive Information Flow Policies . . . . .	413
16.3	Compiler-Based Mechanisms . . . . .	415
16.3.1	Declarations . . . . .	416
16.3.2	Program Statements . . . . .	418
16.3.2.1	<i>Assignment Statements</i> . . . . .	418
16.3.2.2	<i>Compound Statements</i> . . . . .	419
16.3.2.3	<i>Conditional Statements</i> . . . . .	419
16.3.2.4	<i>Iterative Statements</i> . . . . .	420
16.3.2.5	<i>Goto Statements</i> . . . . .	421
16.3.2.6	<i>Procedure Calls</i> . . . . .	424
16.3.3	Exceptions and Infinite Loops . . . . .	424
16.3.4	Concurrency . . . . .	426
16.3.5	Soundness . . . . .	428
16.4	Execution-Based Mechanisms . . . . .	429
16.4.1	Fenton's Data Mark Machine . . . . .	430
16.4.2	Variable Classes . . . . .	432
16.5	Example Information Flow Controls . . . . .	433
16.5.1	Security Pipeline Interface . . . . .	434
16.5.2	Secure Network Server Mail Guard . . . . .	434
16.6	Summary . . . . .	436
16.7	Research Issues . . . . .	436
16.8	Further Reading . . . . .	437
16.9	Exercises . . . . .	437

**Chapter 17 Confinement Problem ..... 439**

17.1	The Confinement Problem .....	439
17.2	Isolation .....	442
17.2.1	Virtual Machines .....	442
17.2.2	Sandboxes.....	444
17.3	Covert Channels .....	446
17.3.1	Detection of Covert Channels .....	448
17.3.1.1	<i>Noninterference</i> .....	448
17.3.1.2	<i>The Shared Resource Matrix Methodology</i> .....	450
17.3.1.3	<i>Information Flow Analysis</i> .....	453
17.3.1.4	<i>Covert Flow Trees</i> .....	454
17.3.2	Analysis of Covert Channels .....	462
17.3.2.1	<i>Covert Channel Capacity and Noninterference</i> .....	462
17.3.2.2	<i>Measuring Covert Channel Capacity</i> .....	464
17.3.2.3	<i>Analyzing a Noisy Covert Channel's Capacity</i> .....	465
17.3.3	Mitigation of Covert Channels.....	467
17.4	Summary .....	470
17.5	Research Issues .....	471
17.6	Further Reading .....	472
17.7	Exercises .....	472

**PART 6: ASSURANCE ..... 475****Chapter 18 Introduction to Assurance ..... 477**

18.1	Assurance and Trust .....	477
18.1.1	<i>The Need for Assurance</i> .....	479
18.1.2	<i>The Role of Requirements in Assurance</i> .....	481
18.1.3	<i>Assurance Throughout the Life Cycle</i> .....	482
18.2	Building Secure and Trusted Systems .....	484
18.2.1	<i>Life Cycle</i> .....	484
18.2.1.1	<i>Conception</i> .....	485
18.2.1.2	<i>Manufacture</i> .....	486
18.2.1.3	<i>Deployment</i> .....	487
18.2.1.4	<i>Fielded Product Life</i> .....	488
18.2.2	<i>The Waterfall Life Cycle Model</i> .....	488
18.2.2.1	<i>Requirements Definition and Analysis</i> .....	488
18.2.2.2	<i>System and Software Design</i> .....	489
18.2.2.3	<i>Implementation and Unit Testing</i> .....	489
18.2.2.4	<i>Integration and System Testing</i> .....	490
18.2.2.5	<i>Operation and Maintenance</i> .....	490
18.2.2.6	<i>Discussion</i> .....	490

18.2.3	Other Models of Software Development .....	491
18.2.3.1	<i>Exploratory Programming</i> .....	491
18.2.3.2	<i>Prototyping</i> .....	491
18.2.3.3	<i>Formal Transformation</i> .....	491
18.2.3.4	<i>System Assembly from Reusable Components</i> .....	492
18.2.3.5	<i>Extreme Programming</i> .....	492
18.3	Summary .....	492
18.4	Research Issues .....	493
18.5	Further Reading .....	494
18.6	Exercises .....	494
<b>Chapter 19 Building Systems with Assurance .....</b>		<b>497</b>
19.1	Assurance in Requirements Definition and Analysis .....	497
19.1.1	<i>Threats and Security Objectives</i> .....	498
19.1.2	<i>Architectural Considerations</i> .....	499
19.1.2.1	<i>Security Mechanisms and Layered Architecture</i> .....	500
19.1.2.2	<i>Building Security in or Adding Security Later</i> .....	501
19.1.3	<i>Policy Definition and Requirements Specification</i> .....	505
19.1.4	<i>Justifying Requirements</i> .....	508
19.2	Assurance During System and Software Design .....	510
19.2.1	<i>Design Techniques That Support Assurance</i> .....	510
19.2.2	<i>Design Document Contents</i> .....	512
19.2.2.1	<i>Security Functions Summary Specification</i> .....	513
19.2.2.2	<i>External Functional Specification</i> .....	513
19.2.2.3	<i>Internal Design Description</i> .....	515
19.2.2.4	<i>Internal Design Specification</i> .....	520
19.2.3	<i>Building Documentation and Specifications</i> .....	521
19.2.3.1	<i>Modification Specifications</i> .....	521
19.2.3.2	<i>Security Specifications</i> .....	522
19.2.3.3	<i>Formal Specifications</i> .....	523
19.2.4	<i>Justifying That Design Meets Requirements</i> .....	523
19.2.4.1	<i>Requirements Tracing and Informal Correspondence</i> .....	523
19.2.4.2	<i>Informal Arguments</i> .....	526
19.2.4.3	<i>Formal Methods: Proof Techniques</i> .....	527
19.2.4.4	<i>Review</i> .....	528
<i>Example: Setting up the Review</i> .....	529	
<i>Example: The Technical Review</i> .....	529	
<i>Example: The Review Meeting</i> .....	530	
<i>Example: Completion of the Review</i> .....	531	
19.3	Assurance in Implementation and Integration .....	531
19.3.1	<i>Implementation Considerations That Support Assurance</i> .....	531

19.3.2	Assurance Through Implementation Management .....	532
19.3.3	Justifying That the Implementation Meets the Design.....	533
	19.3.3.1 <i>Security Testing</i> .....	533
	19.3.3.2 <i>Security Testing Using PGWG</i> .....	536
	19.3.3.2 <i>Test Matrices</i> .....	536
	<i>Example: Test Assertions</i> .....	538
	<i>Example: Test Specifications</i> .....	539
	19.3.3.3 <i>Formal Methods: Proving That Programs Are Correct</i>	541
19.4	Assurance During Operation and Maintenance .....	541
19.5	Summary .....	541
19.6	Research Issues .....	542
19.7	Further Reading .....	542
19.8	Exercises .....	543
<b>Chapter 20 Formal Methods .....</b>		<b>545</b>
20.1	Formal Verification Techniques .....	545
20.2	Formal Specification .....	548
20.3	Early Formal Verification Techniques .....	551
	20.3.1 The Hierarchical Development Methodology .....	551
	20.3.1.1 <i>Verification in HDM</i> .....	553
	20.3.1.2 <i>The Boyer-Moore Theorem Prover</i> .....	555
	20.3.2 Enhanced HDM .....	556
	20.3.3 The Gypsy Verification Environment .....	557
	20.3.3.1 <i>The Gypsy Language</i> .....	557
	20.3.3.2 <i>The Bledsoe Theorem Prover</i> .....	558
20.4	Current Verification Systems .....	559
	20.4.1 The Prototype Verification System .....	559
	20.4.1.1 <i>The PVS Specification Language</i> .....	559
	20.4.1.2 <i>The PVS Proof Checker</i> .....	561
	20.4.1.3 <i>Experience with PVS</i> .....	562
	20.4.2 The Symbolic Model Verifier .....	562
	20.4.2.1 <i>The SMV Language</i> .....	562
	20.4.2.2 <i>The SMV Proof Theory</i> .....	564
	20.4.2.3 <i>SMV Experience</i> .....	566
	20.4.3 The Naval Research Laboratory Protocol Analyzer.....	566
	20.4.3.1 <i>NPA Languages</i> .....	566
	20.4.3.2 <i>NPA Experience</i> .....	567
20.5	Summary .....	567
20.6	Research Issues .....	568
20.7	Further Reading .....	568
20.8	Exercises .....	569

<b>Chapter 21 Evaluating Systems .....</b>	<b>571</b>
21.1 Goals of Formal Evaluation .....	571
21.1.1 Deciding to Evaluate .....	572
21.1.2 Historical Perspective of Evaluation Methodologies .....	573
21.2 TCSEC: 1983–1999 .....	574
21.2.1 TCSEC Requirements .....	575
<i>21.2.1.1 TCSEC Functional Requirements</i> .....	575
<i>21.2.1.2 TCSEC Assurance Requirements</i> .....	576
21.2.2 The TCSEC Evaluation Classes .....	577
21.2.3 The TCSEC Evaluation Process .....	578
21.2.4 Impacts .....	578
<i>21.2.4.1 Scope Limitations</i> .....	579
<i>21.2.4.2 Process Limitations</i> .....	579
<i>21.2.4.3 Contributions</i> .....	580
21.3 International Efforts and the ITSEC: 1991–2001 .....	581
21.3.1 ITSEC Assurance Requirements .....	582
<i>21.3.1.1 Requirements in the TCSEC Not Found in the ITSEC</i> .....	582
<i>21.3.1.2 Requirements in the ITSEC Not Found in the TCSEC</i> .....	583
21.3.2 The ITSEC Evaluation Levels .....	583
21.3.3 The ITSEC Evaluation Process .....	584
21.3.4 Impacts .....	585
<i>21.3.4.1 Vendor Provided Security Targets</i> .....	585
<i>21.3.4.2 Process Limitations</i> .....	585
21.4 Commercial International Security Requirements: 1991 .....	586
21.4.1 CISR Requirements .....	586
21.4.2 Impacts .....	587
21.5 Other Commercial Efforts: Early 1990s .....	587
21.6 The Federal Criteria: 1992 .....	587
21.6.1 FC Requirements .....	588
21.6.2 Impacts .....	588
21.7 FIPS 140: 1994–Present .....	589
21.7.1 FIPS 140 Requirements .....	589
21.7.2 FIPS 140-2 Security Levels .....	590
21.7.3 Impact .....	591
21.8 The Common Criteria: 1998–Present .....	591
21.8.1 Overview of the Methodology .....	592
21.8.2 CC Requirements .....	596
21.8.3 CC Security Functional Requirements .....	597
21.8.4 Assurance Requirements .....	599
21.8.5 Evaluation Assurance Levels .....	599
21.8.6 Evaluation Process .....	601

21.8.7	Impacts . . . . .	602
21.8.8	Future of the Common Criteria . . . . .	602
21.8.8.1	<i>Interpretations</i> . . . . .	602
21.8.8.2	<i>Assurance Class AMA and Family ALC_FLR</i> . . . . .	603
21.8.8.3	<i>Products Versus Systems</i> . . . . .	603
21.8.8.4	<i>Protection Profiles and Security Targets</i> . . . . .	603
21.8.8.5	<i>Assurance Class AVA</i> . . . . .	603
21.8.8.6	<i>EAL5</i> . . . . .	604
21.9	SSE-CMM: 1997–Present . . . . .	604
21.9.1	The SSE-CMM Model . . . . .	604
21.9.2	Using the SSE-CMM . . . . .	606
21.10	Summary . . . . .	607
21.11	Research Issues . . . . .	608
21.12	Further Reading . . . . .	608
21.13	Exercises . . . . .	609

## PART 7: SPECIAL TOPICS 611

<b>Chapter 22 Malicious Logic . . . . .</b>		<b>613</b>
22.1	Introduction . . . . .	613
22.2	Trojan Horses . . . . .	614
22.3	Computer Viruses . . . . .	615
22.3.1	Boot Sector Infectors . . . . .	617
22.3.2	Executable Infectors . . . . .	618
22.3.3	Multipartite Viruses . . . . .	619
22.3.4	TSR Viruses . . . . .	620
22.3.5	Stealth Viruses . . . . .	620
22.3.6	Encrypted Viruses . . . . .	620
22.3.7	Polymorphic Viruses . . . . .	621
22.3.8	Macro Viruses . . . . .	622
22.4	Computer Worms . . . . .	623
22.5	Other Forms of Malicious Logic . . . . .	624
22.5.1	Rabbits and Bacteria . . . . .	624
22.5.2	Logic Bombs . . . . .	625
22.6	Theory of Malicious Logic . . . . .	626
22.6.1	Theory of Computer Viruses . . . . .	626
22.7	Defenses . . . . .	630
22.7.1	Malicious Logic Acting as Both Data and Instructions . . . . .	630
22.7.2	Malicious Logic Assuming the Identity of a User . . . . .	631
22.7.2.1	<i>Information Flow Metrics</i> . . . . .	631

xx      Contents

22.7.2.2 Reducing the Rights .....	632
22.7.2.3 Sandboxing .....	635
22.7.3 Malicious Logic Crossing Protection Domain Boundaries by Sharing .....	636
22.7.4 Malicious Logic Altering Files .....	637
22.7.5 Malicious Logic Performing Actions Beyond Specification. 22.7.5.1 Proof-Carrying Code .....	638
22.7.6 Malicious Logic Altering Statistical Characteristics.....	639
22.7.7 The Notion of Trust.....	640
22.8 Summary .....	640
22.9 Research Issues .....	640
22.10 Further Reading .....	641
22.11 Exercises .....	642
<b>Chapter 23 Vulnerability Analysis .....</b>	<b>645</b>
23.1 Introduction .....	645
23.2 Penetration Studies .....	647
23.2.1 Goals .....	647
23.2.2 Layering of Tests.....	648
23.2.3 Methodology at Each Layer .....	649
23.2.4 Flaw Hypothesis Methodology .....	649
23.2.4.1 Information Gathering and Flaw Hypothesis .....	650
23.2.4.2 Flaw Testing .....	651
23.2.4.3 Flaw Generalization .....	651
23.2.4.4 Flaw Elimination .....	652
23.2.5 Example: Penetration of the Michigan Terminal System .....	652
23.2.6 Example: Compromise of a Burroughs System .....	654
23.2.7 Example: Penetration of a Corporate Computer System.....	655
23.2.8 Example: Penetrating a UNIX System .....	656
23.2.9 Example: Penetrating a Windows NT System .....	658
23.2.10 Debate .....	659
23.2.11 Conclusion.....	660
23.3 Vulnerability Classification .....	660
23.3.1 Two Security Flaws.....	661
23.4 Frameworks .....	662
23.4.1 The RISOS Study .....	662
23.4.1.1 The Flaw Classes .....	664
23.4.1.2 Legacy.....	665
23.4.2 Protection Analysis Model .....	665
23.4.2.1 The Flaw Classes .....	666
23.4.2.2 Analysis Procedure.....	668
23.4.2.3 Legacy.....	670

23.4.3	The NRL Taxonomy .....	671
23.4.3.1	<i>The Flaw Classes</i> .....	671
23.4.3.2	<i>Legacy</i> .....	672
23.4.4	Aslam's Model .....	673
23.4.4.1	<i>The Flaw Classes</i> .....	673
23.4.4.2	<i>Legacy</i> .....	673
23.4.5	Comparison and Analysis.....	674
23.4.5.1	<i>The xterm Log File Flaw</i> .....	674
23.4.5.2	<i>The fingerd Buffer Overflow Flaw</i> .....	676
23.4.5.3	<i>Summary</i> .....	678
23.5	Gupta and Gligor's Theory of Penetration Analysis .....	678
23.5.1	The Flow-Based Model of Penetration Analysis .....	679
23.5.2	The Automated Penetration Analysis Tool .....	682
23.5.3	Discussion .....	682
23.6	Summary .....	683
23.7	Research Issues .....	683
23.8	Further Reading .....	684
23.9	Exercises .....	685
<b>Chapter 24 \Auditing .....</b>		<b>689</b>
24.1	Definitions .....	689
24.2	Anatomy of an Auditing System .....	690
24.2.1	Logger .....	690
24.2.2	Analyzer.....	692
24.2.3	Notifier.....	693
24.3	Designing an Auditing System .....	693
24.3.1	Implementation Considerations .....	696
24.3.2	Syntactic Issues .....	696
24.3.3	Log Sanitization .....	698
24.3.4	Application and System Logging.....	700
24.4	A Posteriori Design .....	701
24.4.1	Auditing to Detect Violations of a Known Policy .....	702
24.4.1.1	<i>State-Based Auditing</i> .....	702
24.4.1.2	<i>Transition-Based Auditing</i> .....	703
24.4.2	Auditing to Detect Known Violations of a Policy .....	704
24.5	Auditing Mechanisms .....	705
24.5.1	Secure Systems.....	706
24.5.2	Nonsecure Systems.....	707
24.6	Examples: Auditing File Systems .....	708
24.6.1	Audit Analysis of the NFS Version 2 Protocol .....	709
24.6.2	The Logging and Auditing File System (LAFS) .....	713
24.6.3	Comparison .....	714

24.7	Audit Browsing .....	715
24.8	Summary .....	718
24.9	Research Issues .....	718
24.10	Further Reading .....	719
24.11	Exercises .....	720
<b>Chapter 25 Intrusion Detection .....</b>		<b>723</b>
25.1	Principles .....	723
25.2	Basic Intrusion Detection .....	724
25.3	Models .....	727
25.3.1	Anomaly Modeling .....	727
25.3.1.1	<i>Derivation of Statistics</i> .....	730
25.3.2	Misuse Modeling .....	733
25.3.3	Specification Modeling .....	738
25.3.4	Summary .....	740
25.4	Architecture .....	742
25.4.1	Agent .....	742
25.4.1.1	<i>Host-Based Information Gathering</i> .....	744
25.4.1.2	<i>Network-Based Information Gathering</i> .....	744
25.4.1.3	<i>Combining Sources</i> .....	745
25.4.2	Director .....	746
25.4.3	Notifier .....	747
25.5	Organization of Intrusion Detection Systems .....	748
25.5.1	Monitoring Network Traffic for Intrusions: NSM .....	749
25.5.2	Combining Host and Network Monitoring: DIDS .....	750
25.5.3	Autonomous Agents: AAFID .....	752
25.6	Intrusion Response .....	754
25.6.1	Incident Prevention .....	754
25.6.2	Intrusion Handling .....	755
25.6.2.1	<i>Containment Phase</i> .....	756
25.6.2.2	<i>Eradication Phase</i> .....	757
25.6.2.3	<i>Follow-Up Phase</i> .....	760
25.7	Summary .....	765
25.8	Research Issues .....	765
25.9	Further Reading .....	767
25.10	Exercises .....	767
<b>PART 8: PRACTICUM</b>		<b>771</b>
<b>Chapter 26 Network Security .....</b>		<b>773</b>
26.1	Introduction .....	773

26.2	Policy Development .....	774
26.2.1	Data Classes .....	775
26.2.2	User Classes .....	776
26.2.3	Availability.....	778
26.2.4	Consistency Check.....	778
26.3	Network Organization .....	779
26.3.1	Firewalls and Proxies .....	780
26.3.2	Analysis of the Network Infrastructure .....	782
26.3.2.1	<i>Outer Firewall Configuration</i> .....	783
26.3.2.2	<i>Inner Firewall Configuration</i> .....	785
26.3.3	In the DMZ.....	786
26.3.3.1	<i>DMZ Mail Server</i> .....	786
26.3.3.2	<i>DMZ WWW Server</i> .....	787
26.3.3.3	<i>DMZ DNS Server</i> .....	789
26.3.3.4	<i>DMZ Log Server</i> .....	789
26.3.3.5	<i>Summary</i> .....	790
26.3.4	In the Internal Network .....	790
26.3.5	General Comment on Assurance .....	792
26.4	Availability and Network Flooding .....	793
26.4.1	Intermediate Hosts .....	793
26.4.2	TCP State and Memory Allocations.....	794
26.5	Anticipating Attacks .....	796
26.6	Summary .....	798
26.7	Research Issues .....	798
26.8	Further Reading .....	799
26.9	Exercises .....	799
<b>Chapter 27 System Security .....</b>		<b>805</b>
27.1	Introduction .....	805
27.2	Policy .....	806
27.2.1	The Web Server System in the DMZ.....	806
27.2.2	The Development System .....	807
27.2.3	Comparison .....	810
27.2.4	Conclusion .....	811
27.3	Networks .....	811
27.3.1	The Web Server System in the DMZ.....	812
27.3.2	The Development System .....	814
27.3.3	Comparison .....	816
27.4	Users .....	817
27.4.1	The Web Server System in the DMZ.....	817
27.4.2	The Development System .....	819
27.4.3	Comparison .....	822

xxiv      Contents

27.5	Authentication .....	822
27.5.1	The Web Server System in the DMZ .....	823
27.5.2	Development Network System .....	823
27.5.3	Comparison .....	825
27.6	Processes .....	825
27.6.1	The Web Server System in the DMZ .....	825
27.6.2	The Development System .....	829
27.6.3	Comparison .....	830
27.7	Files .....	831
27.7.1	The Web Server System in the DMZ .....	831
27.7.2	The Development System .....	833
27.7.3	Comparison .....	835
27.8	Retrospective .....	837
27.8.1	The Web Server System in the DMZ .....	837
27.8.2	The Development System .....	838
27.9	Summary .....	838
27.10	Research Issues .....	839
27.11	Further Reading .....	840
27.12	Exercises .....	840
<b>Chapter 28 User Security .....</b>		<b>845</b>
28.1	Policy .....	845
28.2	Access .....	846
28.2.1	Passwords .....	846
28.2.2	The Login Procedure.....	848
28.2.2.1	<i>Trusted Hosts</i> .....	850
28.2.3	Leaving the System.....	850
28.3	Files and Devices .....	852
28.3.1	Files .....	852
28.3.1.1	<i>File Permissions on Creation</i> .....	853
28.3.1.2	<i>Group Access</i> .....	854
28.3.1.3	<i>File Deletion</i> .....	855
28.3.2	Devices .....	857
28.3.2.1	<i>Writable Devices</i> .....	857
28.3.2.2	<i>Smart Terminals</i> .....	857
28.3.2.3	<i>Monitors and Window Systems</i> .....	859
28.4	Processes .....	860
28.4.1	Copying and Moving Files .....	860
28.4.2	Accidentally Overwriting Files .....	861
28.4.3	Encryption, Cryptographic Keys, and Passwords .....	861
28.4.4	Start-up Settings .....	863

28.4.5	Limiting Privileges . . . . .	863
28.4.6	Malicious Logic . . . . .	864
28.5	Electronic Communications . . . . .	865
28.5.1	Automated Electronic Mail Processing . . . . .	865
28.5.2	Failure to Check Certificates . . . . .	865
28.5.3	Sending Unexpected Content . . . . .	866
28.6	Summary . . . . .	866
28.7	Research Issues . . . . .	867
28.8	Further Reading . . . . .	867
28.9	Exercises . . . . .	868
<b>Chapter 29 Program Security . . . . .</b>		<b>869</b>
29.1	Introduction . . . . .	869
29.2	Requirements and Policy . . . . .	870
29.2.1	Requirements . . . . .	870
29.2.2	Threats . . . . .	871
29.2.2.1	<i>Group 1: Unauthorized Users</i>	
	<i>Accessing Role Accounts</i> . . . . .	871
29.2.2.1	<i>Group 2: Authorized Users</i>	
	<i>Accessing Role Accounts</i> . . . . .	872
29.2.2.1	<i>Summary</i> . . . . .	873
29.3	Design . . . . .	873
29.3.1	Framework . . . . .	874
29.3.1.1	<i>User Interface</i> . . . . .	874
29.3.1.2	<i>High-Level Design</i> . . . . .	874
29.3.2	Access to Roles and Commands . . . . .	875
29.3.2.1	<i>Interface</i> . . . . .	876
29.3.2.2	<i>Internals</i> . . . . .	876
29.3.2.3	<i>Storage of the Access Control Data</i> . . . . .	877
29.4	Refinement and Implementation . . . . .	880
29.4.1	First-Level Refinement . . . . .	880
29.4.2	Second-Level Refinement . . . . .	881
29.4.3	Functions . . . . .	884
29.4.3.1	<i>Obtaining Location</i> . . . . .	884
29.4.3.2	<i>The Access Control Record</i> . . . . .	885
29.4.3.3	<i>Error Handling in the Reading and Matching Routines</i> . . . . .	886
29.4.4	Summary . . . . .	887
29.5	Common Security-Related Programming Problems . . . . .	887
29.5.1	Improper Choice of Initial Protection Domain . . . . .	888
29.5.1.1	<i>Process Privileges</i> . . . . .	888
29.5.1.1	<i>Access Control File Permissions</i> . . . . .	890

xxvi Contents

29.5.1.3	<i>Memory Protection</i> .....	891
29.5.1.4	<i>Trust in the System</i> .....	892
29.5.2	Improper Isolation of Implementation Detail .....	893
29.5.2.1	<i>Resource Exhaustion and User Identifiers</i> .....	893
29.5.2.2	<i>Validating the Access Control Entries</i> .....	894
29.5.2.3	<i>Restricting the Protection Domain of the Role Process</i> 894	
29.5.3	Improper Change.....	895
29.5.3.1	<i>Memory</i> .....	895
29.5.3.2	<i>Changes in File Contents</i> .....	898
29.5.3.3	<i>Race Conditions in File Accesses</i> .....	898
29.5.4	Improper Naming .....	899
29.5.5	Improper Deallocation or Deletion .....	901
29.5.6	Improper Validation .....	902
29.5.6.1	<i>Bounds Checking</i> .....	902
29.5.6.2	<i>Type Checking</i> .....	903
29.5.6.3	<i>Error Checking</i> .....	904
29.5.6.4	<i>Checking for Valid, not Invalid, Data</i> .....	904
29.5.6.5	<i>Checking Input</i> .....	905
29.5.6.6	<i>Designing for Validation</i> .....	907
29.5.7	Improper Indivisibility.....	907
29.5.8	Improper Sequencing.....	908
29.5.9	Improper Choice of Operand or Operation .....	909
29.5.10	Summary .....	911
29.6	Testing, Maintenance, and Operation .....	913
29.6.1	Testing .....	913
29.6.1.1	<i>Testing the Module</i> .....	914
29.6.2	Testing Composed Modules .....	916
29.6.3	Testing the Program .....	917
29.7	Distribution .....	917
29.8	Conclusion .....	918
29.9	Summary .....	919
29.10	Research Issues .....	919
29.11	Further Reading .....	919
29.12	Exercises .....	920
<b>PART 9: END MATTER</b>		<b>923</b>
<b>Chapter 30 Lattices .....</b>		<b>925</b>
30.1	Basics .....	925
30.2	Lattices .....	926
30.3	Exercises .....	927

<b>Chapter 31 The Extended Euclidean Algorithm .....</b>	<b>929</b>
31.1 The Euclidean Algorithm .....	929
31.2 The Extended Euclidean Algorithm .....	930
31.3 Solving $ax \bmod n = 1$ .....	932
31.4 Solving $ax \bmod n = b$ .....	932
31.5 Exercises .....	933
<b>Chapter 32 Entropy and Uncertainty .....</b>	<b>935</b>
32.1 Conditional and Joint Probability .....	935
32.2 Entropy and Uncertainty .....	937
32.3 Joint and Conditional Entropy .....	938
32.3.1 Joint Entropy .....	938
32.3.2 Conditional Entropy .....	939
32.3.3 Perfect Secrecy .....	940
32.4 Exercises .....	940
<b>Chapter 33 Virtual Machines .....</b>	<b>941</b>
33.1 Virtual Machine Structure .....	941
33.2 Virtual Machine Monitor .....	942
33.2.1 Privilege and Virtual Machines .....	943
33.2.2 Physical Resources and Virtual Machines .....	944
33.2.3 Paging and Virtual Machines .....	945
33.3 Exercises .....	946
<b>Chapter 34 Symbolic Logic .....</b>	<b>947</b>
34.1 Propositional Logic .....	947
34.1.1 Natural Deduction in Propositional Logic .....	948
34.1.1.1 Rules .....	949
34.1.1.2 Derived Rules .....	950
34.1.2 Well-Formed Formulas .....	950
34.1.3 Truth Tables .....	950
34.1.4 Mathematical Induction .....	951
34.2 Predicate Logic .....	952
34.2.1 Natural Deduction in Predicate Logic .....	953
34.3 Temporal Logic Systems .....	954
34.3.1 Syntax of CTL .....	954
34.3.2 Semantics of CTL .....	955
34.4 Exercises .....	956
<b>Chapter 35 Example Academic Security Policy .....</b>	<b>959</b>
35.1 University of California E-mail Policy .....	959

35.1.1	Summary: E-mail Policy Highlights . . . . .	959
35.1.1.1	<i>Cautions</i> . . . . .	959
35.1.1.2	<i>Do</i> . . . . .	960
35.1.1.3	<i>Do Not</i> . . . . .	961
35.1.1.4	<i>Does This Policy Apply to You?</i> . . . . .	961
35.1.2	University of California Electronic Mail Policy . . . . .	961
35.1.2.1	<i>Introduction</i> . . . . .	961
35.1.2.2	<i>Purpose</i> . . . . .	963
35.1.2.3	<i>Definitions</i> . . . . .	963
35.1.2.4	<i>Scope</i> . . . . .	964
35.1.2.5	<i>General Provisions</i> . . . . .	965
35.1.2.6	<i>Specific Provisions</i> . . . . .	967
35.1.2.7	<i>Policy Violations</i> . . . . .	971
35.1.2.8	<i>Responsibility for Policy</i> . . . . .	971
35.1.2.9	<i>Campus Responsibilities and Discretion</i> . . . . .	971
35.1.2.10	<i>Appendix A—Definitions</i> . . . . .	972
35.1.2.11	<i>Appendix B—References</i> . . . . .	975
35.1.2.12	<i>Appendix C—Policies Relating to Nonconsensual Access</i> . . . . .	976
35.1.3	UC Davis Implementation of the Electronic Mail Policy . . . . .	977
35.1.3.1	<i>Purpose and Scope</i> . . . . .	978
35.1.3.2	<i>Definitions</i> . . . . .	978
35.1.3.3	<i>Policy</i> . . . . .	978
35.1.4	References and Related Policy . . . . .	988
35.2	The Acceptable Use Policy for the University of California, Davis . . . . .	989
35.2.1	Part I . . . . .	989
35.2.1.1	<i>Introduction</i> . . . . .	989
35.2.1.2	<i>Rights and Responsibilities</i> . . . . .	989
35.2.1.3	<i>Existing Legal Context</i> . . . . .	989
35.2.1.4	<i>Enforcement</i> . . . . .	990
35.2.2	Part 2 . . . . .	990
	<b>Bibliography</b> . . . . .	<b>993</b>
	<b>Index</b> . . . . .	<b>1063</b>