

A vertical splash of water runs down the center of the cover, with numerous droplets and bubbles scattered around it against a light blue background.

INTRODUCTION TO

ENGINEERING

MODELING AND PROBLEM SOLVING

JAY B. BROCKMAN

Contents

Part I: THE ENGINEERING MINDSET 1

1 Engineering and Society 3

- 1.1 Introduction 3**
 - 1.2 The Engineering Method 5,**
 - 1.2.1 Science, Mathematics, and Engineering 5**
 - 1.2.2 Ingenuity: From Lifting Weights to Microelectronics 6**
 - 1.2.3 Engineering Models 9**
 - 1.3 Networks and Systems 10**
 - 1.3.1 Everything is Connected to Everything 10**
 - 1.3.2 A Web of Innovation 11**
 - 1.3.3 Systems 15**
 - 1.4 Engineering Disciplines and Majors 18**
 - 1.4.1 Introduction 18**
 - 1.4.2 Overview of Engineering Disciplines 19**
 - 1.4.3 Professional Organizations 27**
 - 1.4.4 Innovation at the Interfaces Between Disciplines 27**
 - 1.5 Engineering and Computing 31**
 - 1.5.1 Programming and Logical Thinking 31**
 - 1.5.2 Number Crunching 32**
- Problems 36

2 Organization and Representation of Engineering Systems 38

- 2.1 What We Think About How We Think 38**
 - 2.1.1 Example: Doing Math in Your Head 39**
 - 2.1.2 A Model for Cognitive Processing 40**
 - 2.1.3 “How To” Knowledge and Problem Solving 42**
 - 2.1.4 Mind and Brain 46**

- 2.2 Concept Maps 48**
 - 2.2.1 What Is a Concept Map? 48**
 - 2.2.2 How to Build a Good Concept Map 50**
 - 2.2.3 Hierarchies 54**
 - 2.3 Representation and Design 58**
 - 2.3.1 Purpose, Environment, and Form 58**
 - 2.3.2 Requirements, Specifications, and the Forces That Shape a Design 62**
 - 2.3.3 Design Hierarchies 65**
 - 2.4 Example: Water Supply for Rural Communities in Developing Nations 72**
 - 2.4.1 The Top-Level Problem: Meeting Community Needs 74**
 - 2.4.2 A Lower-Level Problem: Design of a Handpump 77**
 - 2.4.3 Even Lower-Level Design Details: Seals and Bearings 82**
- Problems 85

3 Learning and Problem Solving 88

- 3.1 Introduction 88**
- 3.2 Expertise and The Learning Process 89**
- 3.3 What Do You Know? Levels of Understanding 90**
 - 3.3.1 Knowledge: Recalling Facts from Memory 92**
 - 3.3.2 Comprehension: Understanding Meaning 93**
 - 3.3.3 Application: Using in New Situations 93**
 - 3.3.4 Analysis: Breaking Down into Parts 93**
 - 3.3.5 Synthesis: Constructing a New Integrated Whole 94**

- 3.3.6 Evaluation: Using Judgment to Make Decisions 95
- 3.3.7 Social and Societal Responsibilities of Decision Making 96
- 3.4 Getting Good Results from Your Learning Efforts 96
 - 3.4.1 Get Ready to Learn 97
 - 3.4.2 Building a Good Structure for Knowledge 97
 - 3.4.3 Metacognition: Monitoring Your Own Understanding 101
- 3.5 A Framework for Problem Solving 102
 - 3.5.1 Problem Solving Step 0: I Can 104
 - 3.5.2 Problem Solving Step 1: Define 104
 - 3.5.3 Problem Solving Step 2: Explore 105
 - 3.5.4 Problem Solving Step 3: Plan 106
 - 3.5.5 Problem Solving Step 4: Implement 109
 - 3.5.6 Problem Solving Step 5: Check 109
 - 3.5.7 Problem Solving Step 6: Generalize 111
 - 3.5.8 Problem Solving Step 7: Present the Results 111
- 3.6 How Much CO Does a Typical Passenger Car Produce? 113
 - 3.6.1 Define 113
 - 3.6.2 Explore 114
 - 3.6.3 Plan 115
 - 3.6.4 Do It 115
 - 3.6.5 Check 117
 - 3.6.6 Generalize 117
 - 3.6.7 Present the Results 118
- 3.7 Planning Larger Projects 120
 - 3.7.1 SolderBaat—A Circuit Board Assembly and Test System 121
 - 3.7.2 Task Scheduling 123
 - 3.7.3 Teamwork and Results 126
- 3.8 Heuristics 128
 - 3.8.1 Write It Down 129
 - 3.8.2 Restate in Simpler Terms 129
 - 3.8.3 Draw a Picture 129
 - 3.8.4 Do You Know a Related Problem? 129
 - 3.8.5 Work Backwards/Forwards 130
 - 3.8.6 Work Top-Down/Bottom-Up 131
 - 3.8.7 Divide and Conquer 131
 - 3.8.8 Check for Unnecessary Constraints 133
 - 3.8.9 Discuss 134
 - 3.8.10 Try Solving a Scaled-Down Version of the Problem 134
 - 3.8.11 Try Solving a Simpler but Related Problem 135
 - 3.8.12 Use Models 135
 - 3.8.13 Guess and Check 136
 - 3.8.14 Use an Analogy 137
 - 3.8.15 Change Your Perspective 139
 - 3.8.16 Look at the Big Picture 140
 - 3.8.17 Do the Easy Parts First 140
 - 3.8.18 Plug in Numbers 140
 - 3.8.19 Keep Track of Progress 141
 - 3.8.20 Change the Representation 141
 - 3.8.21 Replan 142
 - 3.8.22 Pay Attention to Hunches 142
 - 3.8.23 Take a Break 142
- Problems 143

Part II MODEL-BASED DESIGN 149

4 Laws of Nature and Theoretical Models 151

- 4.1 Engineering Models 151
- 4.2 Evolution of Theory 154
- 4.3 Models of Motion 156
 - 4.3.1 Aristotle's Physics 156
 - 4.3.2 Galileo and the Scientific Method 157
 - 4.3.3 René Descartes and Conservation of Motion 160
 - 4.3.4 The Royal Society 162
 - 4.3.5 Huygens' Improvements to Descartes' Model 163
 - 4.3.6 Newton's Laws of Motion 167
 - 4.3.7 Leibniz and the "Living Force," Work and Energy 169
- 4.4 Modeling the "Spring of Air" 171
 - 4.4.1 The Horror of the Vacuum 171

- 4.4.2 Boyle's Law 173
- 4.4.3 Hooke's Law 175
- 4.5 The Birth of the Piston Engine 178
 - 4.5.1 Newcomen's Engine 178
 - 4.5.2 James Watt's Improvements to Newcomen's Design 181
- 4.6 The Science of Thermodynamics 183
 - 4.6.1 Sadi Carnot and the Limits of Engine Efficiency 183
 - 4.6.2 James Joule: From Building a Better Brewery to a Theory of Heat and Energy 185
- 4.7 Conservation of Mass 188
 - 4.7.1 Robert Boyle and *The Sceptical Chymist* 188
 - 4.7.2 Antoine Lavoisier 189
- 4.8 Analysis Example: The Internal Combustion Engine 190
 - 4.8.1 Operation of a Four-Stroke Engine 190
 - 4.8.2 Efficiency of the Intake Stroke and Air/Fuel Ratio 191
 - 4.8.3 Efficiency of the Compression Stroke and the Compression Ratio 192
- 4.9 Design Example: The Handpump 195
 - 4.9.1 Problem Definition and Plan of Attack 195
 - 4.9.2 Modeling Forces on the Piston 199
 - 4.9.3 Modeling the Handle Lever Arm 202
 - 4.9.4 Modeling Pump Efficiency 205

5 Data Analysis and Empirical Models 214

- 5.1 Introduction 214
- 5.2 Theory and Data 215
 - 5.2.1 Validating Boyle's Law 215
 - 5.2.2 Exponential Change, Log Plots, and Moore's Law 218
- 5.3 Empirical Models 222
 - 5.3.1 Introduction 222
 - 5.3.2 Running an Experiment 222

- 5.3.3 Interpolation and Fitting a Line to the Data 223
- 5.4 Using Statistics to Quantify Uncertainty 226
 - 5.4.1 Sources of Uncertainty 227
 - 5.4.2 Mean and Standard Deviation: Systematic and Random Error 228
 - 5.4.3 Estimating Probability 230
 - 5.4.4 Frequency of Results and Histograms 233
 - 5.4.5 The Theory of the Bell Curve 234
- 5.5 Trade Studies: Evaluating Tradeoffs Between Design Variables 236
 - 5.5.1 Methodology: Making and Using Maps 238
 - 5.5.2 Problem Definition and Plan of Attack 240
 - 5.5.3 Mapping the Design Space 242
 - 5.5.4 Finding Settings to Satisfy Distance Constraints 245
 - 5.5.5 Minimizing Energy while Launching at a Target 248

6 Modeling Interrelationships in Systems: Lightweight Structures 261

- 6.1 Introduction 261
- 6.2 The Statics Perspective 263
 - 6.2.1 Force as a Vector 263
 - 6.2.2 Addition of Forces 265
 - 6.2.3 Equilibrium of a Point or Particle 269
 - 6.2.4 Equilibrium of Pinned Joints and Bars 270
 - 6.2.5 Loads, Supports, and Reaction Forces 273
 - 6.2.6 Static Analysis of a Complete Truss 275
- 6.3 The Materials Perspective 279
 - 6.3.1 Bars as Springs: Hooke's Law and Young's Modulus 279
 - 6.3.2 Strength of Materials 285
 - 6.3.3 Buckling 289

- 6.4 Putting It All Together 291**
 - 6.4.1 Statics Perspective 291**
 - 6.4.2 Materials Perspective 293**
 - 6.4.3 Statically Determinate and Indeterminate Trusses 294**
- 6.5 Example: A Trade Study of Strength versus Weight in a Truss 296**
 - 6.5.1 Problem Definition and Plan of Attack 296**
 - 6.5.2 Implementation of the Plan 301**
 - 6.5.3 Finding an Acceptable Design 306**
- Problems 307**

7 Modeling Interrelationships in Systems: Digital Electronic Circuits 315

- 7.1 Introduction 315**
- 7.2 Computing Machines 316**
 - 7.2.1 The Logical and Physical Views 316**
 - 7.2.2 History and Background 321**
- 7.3 Digital Circuits from the Symbolic and Logical Perspective 325**
 - 7.3.1 Boolean Logic 326**
 - 7.3.2 Building Computing Machines Out of Switches 330**
 - 7.3.3 Binary Representation of Numbers 332**
 - 7.3.4 Adding Numbers with Switches 335**
- 7.4 Digital Circuits from the Electronics Perspective 337**
 - 7.4.1 Electricity 337**
 - 7.4.2 Electronic Devices 343**
 - 7.4.3 Electrical Circuits 347**
- 7.5 Putting It All Together: Design of an Inverter 353**
 - 7.5.1 Background 353**
 - 7.5.2 Problem Definition and Plan of Attack 354**
 - 7.5.3 Choosing Device Sizes 356**
 - 7.5.4 Calculating Power Consumption 358**
- Problems 360**

8 Modeling Change in Systems 366

- 8.1 Introduction 366**
- 8.2 Predicting the Future: Accumulation of Change 367**
 - 8.2.1 The State of a System 367**
 - 8.2.2 Euler's Method: Predicting Change from One State to the Next 370**
- 8.3 Launching a Softball 373**
 - 8.3.1 Problem Definition and Plan of Attack 374**
 - 8.3.2 Modeling the Softball Trajectory Without Drag 376**
 - 8.3.3 Modeling the Softball Trajectory with Drag 379**
 - 8.3.4 Continuous Versus Discrete Models 384**
- 8.4 Running Out of Gas 385**
 - 8.4.1 Background 386**
 - 8.4.2 Problem Definition and Plan of Attack 395**
 - 8.4.3 Flow Rates and Conservation of Mass 396**
 - 8.4.4 Growth at a Constant Rate: Population and Per-Capita Oil Consumption 398**
 - 8.4.5 Putting It All Together 400**
 - 8.4.6 Will We Really Run Out of Oil by 2040? 406**
- Problems 407**

Part III PROBLEM SOLVING WITH MATLAB 417

9 Getting Started with MATLAB 419

- 9.1 Your First MATLAB Session 419**
 - 9.1.1 Interpreting Simple Arithmetic Expressions 419**
 - 9.1.2 Variables 421**
 - 9.1.3 Scripts 422**
- 9.2 Examples 424**
 - 9.2.1 Determining Velocities After a Collision 424**

- 9.2.2 Mass of CO₂ Produced by a Car 425
- Problems 426

10 Vector Operations in MATLAB 432

- 10.1 Introduction 432
- 10.2 Basic Operations 433
 - 10.2.1 Defining and Accessing Vectors 433
 - 10.2.2 Element-Wise Arithmetic Operations on Vectors 435
 - 10.2.3 Example: Validating Boyle's Law 436
- 10.3 Simple Two-Dimensional Plots and Graphs 438
 - 10.3.1 Plot Basics 438
 - 10.3.2 Adding Titles and Labels 439
 - 10.3.3 Changing Line Styles 440
 - 10.3.4 Multiple Plots on One Set of Axes 440
 - 10.3.5 Multiple Sets of Axes in One Figure 441
 - 10.3.6 Plotting Functions 442
 - 10.3.7 Specialized Plotting 443
 - 10.3.8 Example: Plotting the Results of Boyle's Experiment 444
 - 10.3.9 Example: Moore's Law and Log Plots 446
- 10.4 Statistics 448
 - 10.4.1 The Basics: Minimum, Maximum, Averages, etc. 449
 - 10.4.2 Counting Values in a Range 450
 - 10.4.3 Bin Counts and Histograms 453
 - 10.4.4 Where to Learn More 455
- Problems 455

11 Matrix Operations in MATLAB 463

- 11.1 Basic Operations 463
 - 11.1.1 Defining and Accessing Matrices 463
 - 11.1.2 Element-Wise Arithmetic Operations on Matrices 467

11.2 Parameter Sweeps Over Two Variables 468

- 11.2.1 Creating Tables Using Code meshgrid 468
- 11.2.2 Example: Force on the Piston of a Pump Versus Well Depth and Cylinder Radius 469

11.3 Plotting 3-Dimensional Data 471

- 11.3.1 Mesh and Surface Plots 471
- 11.3.2 Contour Plots 472
- 11.3.3 Side-View Cross-Section Plots 473

11.4 Matrix Arithmetic 474

- 11.4.1 Zero Matrix 474
- 11.4.2 Equality of Matrices 475
- 11.4.3 Matrix Addition 475
- 11.4.4 Multiplication of a Matrix by a Scalar 476
- 11.4.5 Matrix Subtraction 477
- 11.4.6 Matrix Multiplication 477

11.5 Solving Systems of Linear Equations 480

- 11.5.1 Linear Equations in Matrix Form 480
- 11.5.2 The Identity Matrix and the Inverse of a Matrix 481
- 11.5.3 Solving Matrix Equations Using Inversion 483
- 11.5.4 Solving Matrix Equations Using the Backslash Operator 484
- 11.5.5 Example: Analysis of a Truss 484
- 11.5.6 Example: Analysis of Electrical Circuits 487

Problems 492

12 Introduction to Algorithms and Programming in MATLAB 498

12.1 Algorithms, Flow Charts, and Pseudocode 498

- 12.1.1 What Is an Algorithm? 498
- 12.1.2 Describing Simple Sequences of Operations 499
- 12.1.3 Subroutines 501
- 12.1.4 Conditional Branches 502
- 12.1.5 Loops 506

12.2	MATLAB Functions	510
12.2.1	Mathematical Functions Versus MATLAB Functions	510
12.2.2	Functions Calling Functions	513
12.2.3	Watching a Function Call Through the MATLAB Debugger	514
12.3	Conditional Selection Statements	517
12.3.1	Review of Logic Expressions	518
12.3.2	IF/ELSE Statements	519
12.3.3	Stepping Through an IF Statement in the Debugger	520
12.4	Loops or Repetition Statements	522
12.4.1	WHILE Loops	522
12.4.2	FOR Loops	523
12.4.3	Watching a Loop in the Debugger	523
12.4.4	Nested Loops	524
12.4.5	Common Loop Bugs	525
12.5	Examples of Functions, Conditionals, and Loops	526
12.5.1	Subfunctions: The Cake Recipe	526
12.5.2	Vector and Matrix Functions	527
12.6	Accumulation of Change	529

12.6.1	Review: Modeling Population Growth	530
12.6.2	Modeling the Trajectory of a Softball with Drag	532
	Problems	534

Appendix A Problem Solving Process

Appendix B Bloom's Taxonomy: Levels of Understanding

Appendix C Engineering Societies and Professional Organizations

Appendix D Systems of Units

D.1	The SI System	554
D.2	Non-SI Units and Conversion Factors	556

Bibliography

Index