Programming
Second Edition
Contents

Preface xxv

Chapter 0 Notes to the Reader 1

0.1 The structure of this book 2
  0.1.1 General approach 3
  0.1.2 Drills, exercises, etc. 4
  0.1.3 What comes after this book? 5
0.2 A philosophy of teaching and learning 6
  0.2.1 The order of topics 9
  0.2.2 Programming and programming language 10
  0.2.3 Portability 11
0.3 Programming and computer science 12
0.4 Creativity and problem solving 12
0.5 Request for feedback 12
0.6 References 13
0.7 Biographies 13
  Bjarne Stroustrup 14
  Lawrence “Pete” Petersen 15

Chapter 1 Computers, People, and Programming 17

1.1 Introduction 18
1.2 Software 19
1.3 People 21
1.4 Computer science 24
1.5 Computers are everywhere 25
  1.5.1 Screens and no screens 26
  1.5.2 Shipping 26
  1.5.3 Telecommunications 28
  1.5.4 Medicine 30
CONTENTS

1.5.5 Information 31
1.5.6 A vertical view 33
1.5.7 So what? 34
1.6 Ideals for programmers 34

Part I The Basics 41

Chapter 2 Hello, World! 43
2.1 Programs 44
2.2 The classic first program 45
2.3 Compilation 47
2.4 Linking 51
2.5 Programming environments 52

Chapter 3 Objects, Types, and Values 59
3.1 Input 60
3.2 Variables 62
3.3 Input and type 64
3.4 Operations and operators 66
3.5 Assignment and initialization 69
  3.5.1 An example: detect repeated words 71
3.6 Composite assignment operators 73
  3.6.1 An example: find repeated words 73
3.7 Names 74
3.8 Types and objects 77
3.9 Type safety 78
  3.9.1 Safe conversions 79
  3.9.2 Unsafe conversions 80

Chapter 4 Computation 89
4.1 Computation 90
4.2 Objectives and tools 92
4.3 Expressions 94
  4.3.1 Constant expressions 95
  4.3.2 Operators 97
  4.3.3 Conversions 99
4.4 Statements 100
  4.4.1 Selection 102
  4.4.2 Iteration 109
4.5 Functions 113
  4.5.1 Why bother with functions? 115
  4.5.2 Function declarations 117
6.4 Grammars 188
   6.4.1 A detour: English grammar 193
   6.4.2 Writing a grammar 194
6.5 Turning a grammar into code 195
   6.5.1 Implementing grammar rules 196
   6.5.2 Expressions 197
   6.5.3 Terms 200
   6.5.4 Primary expressions 202
6.6 Trying the first version 203
6.7 Trying the second version 208
6.8 Token streams 209
   6.8.1 Implementing Token_stream 211
   6.8.2 Reading tokens 212
   6.8.3 Reading numbers 214
6.9 Program structure 215

Chapter 7 Completing a Program 221
7.1 Introduction 222
7.2 Input and output 222
7.3 Error handling 224
7.4 Negative numbers 229
7.5 Remainder: % 230
7.6 Cleaning up the code 232
   7.6.1 Symbolic constants 232
   7.6.2 Use of functions 234
   7.6.3 Code layout 235
   7.6.4 Commenting 237
7.7 Recovering from errors 239
7.8 Variables 242
   7.8.1 Variables and definitions 242
   7.8.2 Introducing names 247
   7.8.3 Predefined names 250
   7.8.4 Are we there yet? 250

Chapter 8 Technicalities: Functions, etc. 255
8.1 Technicalities 256
8.2 Declarations and definitions 257
   8.2.1 Kinds of declarations 261
   8.2.2 Variable and constant declarations 262
   8.2.3 Default initialization 263
CONTENTS

8.3 Header files 264
8.4 Scope 266
8.5 Function call and return 272
  8.5.1 Declaring arguments and return type 272
  8.5.2 Returning a value 274
  8.5.3 Pass-by-value 275
  8.5.4 Pass-by-const reference 276
  8.5.5 Pass-by-reference 279
  8.5.6 Pass-by-value vs. pass-by-reference 281
  8.5.7 Argument checking and conversion 284
  8.5.8 Function call implementation 285
  8.5.9 constexpr functions 290
8.6 Order of evaluation 291
  8.6.1 Expression evaluation 292
  8.6.2 Global initialization 293
8.7 Namespaces 294
  8.7.1 using declarations and using directives 296

Chapter 9 Technicalities: Classes, etc. 303
  9.1 User-defined types 304
  9.2 Classes and members 305
  9.3 Interface and implementation 306
  9.4 Evolving a class 308
    9.4.1 struct and functions 308
    9.4.2 Member functions and constructors 310
    9.4.3 Keep details private 312
    9.4.4 Defining member functions 314
    9.4.5 Referring to the current object 317
    9.4.6 Reporting errors 317
  9.5 Enumerations 318
    9.5.1 “Plain” enumerations 320
  9.6 Operator overloading 321
  9.7 Class interfaces 323
    9.7.1 Argument types 324
    9.7.2 Copying 326
    9.7.3 Default constructors 327
    9.7.4 const member functions 330
    9.7.5 Members and “helper functions” 332
  9.8 The Date class 334
Part II Input and Output 343

Chapter 10 Input and Output Streams 345
  10.1 Input and output 346
  10.2 The I/O stream model 347
  10.3 Files 349
  10.4 Opening a file 350
  10.5 Reading and writing a file 352
  10.6 I/O error handling 354
  10.7 Reading a single value 358
    10.7.1 Breaking the problem into manageable parts 359
    10.7.2 Separating dialog from function 362
  10.8 User-defined output operators 363
  10.9 User-defined input operators 365
  10.10 A standard input loop 365
  10.11 Reading a structured file 367
    10.11.1 In-memory representation 368
    10.11.2 Reading structured values 370
    10.11.3 Changing representations 374

Chapter 11 Customizing Input and Output 379
  11.1 Regularity and irregularity 380
  11.2 Output formatting 380
    11.2.1 Integer output 381
    11.2.2 Integer input 383
    11.2.3 Floating-point output 384
    11.2.4 Precision 385
    11.2.5 Fields 387
  11.3 File opening and positioning 388
    11.3.1 File open modes 388
    11.3.2 Binary files 390
    11.3.3 Positioning in files 393
  11.4 String streams 394
  11.5 Line-oriented input 395
  11.6 Character classification 396
  11.7 Using nonstandard separators 398
  11.8 And there is so much more 406

Chapter 12 A Display Model 411
  12.1 Why graphics? 412
  12.2 A display model 413
  12.3 A first example 414
CONTENTS

12.4 Using a GUI library 418
12.5 Coordinates 419
12.6 Shapes 420
12.7 Using Shape primitives 421
   12.7.1 Graphics headers and main 421
   12.7.2 An almost blank window 422
   12.7.3 Axis 424
   12.7.4 Graphing a function 426
   12.7.5 Polygons 427
   12.7.6 Rectangles 428
   12.7.7 Fill 431
   12.7.8 Text 431
   12.7.9 Images 433
   12.7.10 And much more 434
12.8 Getting this to run 435
   12.8.1 Source files 437

Chapter 13 Graphics Classes 441
13.1 Overview of graphics classes 442
13.2 Point and Line 444
13.3 Lines 447
13.4 Color 450
13.5 Line_style 452
13.6 Open_polyline 455
13.7 Closed_polyline 456
13.8 Polygon 458
13.9 Rectangle 460
13.10 Managing unnamed objects 465
13.11 Text 467
13.12 Circle 470
13.13 Ellipse 472
13.14 Marked_polyline 474
13.15 Marks 476
13.16 Mark 478
13.17 Images 479

Chapter 14 Graphics Class Design 487
14.1 Design principles 488
   14.1.1 Types 488
   14.1.2 Operations 490
   14.1.3 Naming 491
   14.1.4 Mutability 492
CONTENTS

14.2  **Shape**  493
   14.2.1  An abstract class  495
   14.2.2  Access control  496
   14.2.3  Drawing shapes  500
   14.2.4  Copying and mutability  503

14.3  Base and derived classes  504
   14.3.1  Object layout  506
   14.3.2  Deriving classes and defining virtual functions  507
   14.3.3  Overriding  508
   14.3.4  Access  511
   14.3.5  Pure virtual functions  512

14.4  Benefits of object-oriented programming  513

**Chapter 15  Graphing Functions and Data**  519

15.1  Introduction  520
15.2  Graphing simple functions  520
15.3  **Function**  524
   15.3.1  Default Arguments  525
   15.3.2  More examples  527
   15.3.3  Lambda expressions  528

15.4  **Axis**  529

15.5  Approximation  532
15.6  Graphing data  537
   15.6.1  Reading a file  539
   15.6.2  General layout  541
   15.6.3  Scaling data  542
   15.6.4  Building the graph  543

**Chapter 16  Graphical User Interfaces**  551

16.1  User interface alternatives  552
16.2  The “Next” button  553
16.3  A simple window  554
   16.3.1  A callback function  556
   16.3.2  A wait loop  559
   16.3.3  A lambda expression as a callback  560

16.4  **Button**  and other **Widgets**  561
   16.4.1  Widgets  561
   16.4.2  Buttons  563
   16.4.3  In_box and Out_box  563
   16.4.4  Menus  564

16.5  An example  565
Part III  Data and Algorithms  581

Chapter 17  Vector and Free Store  583
17.1 Introduction  584
17.2 vector basics  586
17.3 Memory, addresses, and pointers  588
  17.3.1 The sizeof operator  590
17.4 Free store and pointers  591
  17.4.1 Free-store allocation  593
  17.4.2 Access through pointers  594
  17.4.3 Ranges  595
  17.4.4 Initialization  596
  17.4.5 The null pointer  598
  17.4.6 Free-store deallocation  598
17.5 Destructors  601
  17.5.1 Generated destructors  603
  17.5.2 Destructors and free store  604
17.6 Access to elements  605
17.7 Pointers to class objects  606
17.8 Messing with types: void* and casts  608
17.9 Pointers and references  610
  17.9.1 Pointer and reference parameters  611
  17.9.2 Pointers, references, and inheritance  612
  17.9.3 An example: lists  613
  17.9.4 List operations  615
  17.9.5 List use  616
17.10 The this pointer  618
  17.10.1 More link use  620

Chapter 18  Vectors and Arrays  627
18.1 Introduction  628
18.2 Initialization  629
18.3 Copying  631
  18.3.1 Copy constructors  633
  18.3.2 Copy assignments  634
  18.3.3 Copy terminology  636
  18.3.4 Moving  637
18.4 Essential operations 640
  18.4.1 Explicit constructors 642
  18.4.2 Debugging constructors and destructors 643
18.5 Access to vector elements 646
  18.5.1 Overloading on const 647
18.6 Arrays 648
  18.6.1 Pointers to array elements 650
  18.6.2 Pointers and arrays 652
  18.6.3 Array initialization 654
  18.6.4 Pointer problems 656
18.7 Examples: palindrome 659
  18.7.1 Palindromes using string 659
  18.7.2 Palindromes using arrays 660
  18.7.3 Palindromes using pointers 661

Chapter 19 Vector, Templates, and Exceptions 667
19.1 The problems 668
19.2 Changing size 671
  19.2.1 Representation 671
  19.2.2 reserve and capacity 673
  19.2.3 resize 674
  19.2.4 push_back 674
  19.2.5 Assignment 675
  19.2.6 Our vector so far 677
19.3 Templates 678
  19.3.1 Types as template parameters 679
  19.3.2 Generic programming 681
  19.3.3 Concepts 683
  19.3.4 Containers and inheritance 686
  19.3.5 Integers as template parameters 687
  19.3.6 Template argument deduction 689
  19.3.7 Generalizing vector 690
19.4 Range checking and exceptions 693
  19.4.1 An aside: design considerations 694
  19.4.2 A confession: macros 696
19.5 Resources and exceptions 697
  19.5.1 Potential resource management problems 698
  19.5.2 Resource acquisition is initialization 700
  19.5.3 Guarantees 701
  19.5.4 unique_ptr 703
  19.5.5 Return by moving 704
  19.5.6 RAII for vector 705
21.7 Copying 789
  21.7.1 Copy 789
  21.7.2 Stream iterators 790
  21.7.3 Using a set to keep order 793
  21.7.4 copy_if 794
21.8 Sorting and searching 794
21.9 Container algorithms 797

Part IV Broadening the View 803

Chapter 22 Ideals and History 805
  22.1 History, ideals, and professionalism 806
     22.1.1 Programming language aims and philosophies 807
     22.1.2 Programming ideals 808
     22.1.3 Styles/paradigms 815
  22.2 Programming language history overview 818
     22.2.1 The earliest languages 819
     22.2.2 The roots of modern languages 821
     22.2.3 The Algol family 826
     22.2.4 Simula 833
     22.2.5 C 836
     22.2.6 C++ 839
     22.2.7 Today 842
     22.2.8 Information sources 844

Chapter 23 Text Manipulation 849
  23.1 Text 850
  23.2 Strings 850
  23.3 I/O streams 855
  23.4 Maps 855
     23.4.1 Implementation details 861
  23.5 A problem 864
  23.6 The idea of regular expressions 866
     23.6.1 Raw string literals 868
  23.7 Searching with regular expressions 869
  23.8 Regular expression syntax 872
     23.8.1 Characters and special characters 872
     23.8.2 Character classes 873
     23.8.3 Repeats 874
     23.8.4 Grouping 876
     23.8.5 Alternation 876
     23.8.6 Character sets and ranges 877
     23.8.7 Regular expression errors 878
CONTENTS

23.9 Matching with regular expressions 880
23.10 References 885

Chapter 24  Numerics 889

24.1 Introduction 890
24.2 Size, precision, and overflow 890
  24.2.1 Numeric limits 894
24.3 Arrays 895
24.4 C-style multidimensional arrays 896
24.5 The Matrix library 897
  24.5.1 Dimensions and access 898
  24.5.2 1D Matrix 901
  24.5.3 2D Matrix 904
  24.5.4 Matrix I/O 907
  24.5.5 3D Matrix 907
24.6 An example: solving linear equations 908
  24.6.1 Classical Gaussian elimination 910
  24.6.2 Pivoting 911
  24.6.3 Testing 912
24.7 Random numbers 914
24.8 The standard mathematical functions 917
24.9 Complex numbers 919
24.10 References 920

Chapter 25  Embedded Systems Programming 925

25.1 Embedded systems 926
25.2 Basic concepts 929
  25.2.1 Predictability 932
  25.2.2 Ideals 932
  25.2.3 Living with failure 933
25.3 Memory management 935
  25.3.1 Free-store problems 936
  25.3.2 Alternatives to the general free store 939
  25.3.3 Pool example 940
  25.3.4 Stack example 942
25.4 Addresses, pointers, and arrays 943
  25.4.1 Unchecked conversions 943
  25.4.2 A problem: dysfunctional interfaces 944
  25.4.3 A solution: an interface class 947
  25.4.4 Inheritance and containers 951
25.5 Bits, bytes, and words 954
  25.5.1 Bits and bit operations 955
  25.5.2 bitset 959
CONTENTS

27.3.5 Conversion of void* 1041
27.3.6 enum 1042
27.3.7 Namespaces 1042
27.4 Free store 1043
27.5 C-style strings 1045
  27.5.1 C-style strings and const 1047
  27.5.2 Byte operations 1048
  27.5.3 An example: strcpy() 1049
  27.5.4 A style issue 1049
27.6 Input/output: stdio 1050
  27.6.1 Output 1050
  27.6.2 Input 1052
  27.6.3 Files 1053
27.7 Constants and macros 1054
27.8 Macros 1055
  27.8.1 Function-like macros 1056
  27.8.2 Syntax macros 1058
  27.8.3 Conditional compilation 1058
27.9 An example: intrusive containers 1059

Part V Appendices 1071

Appendix A Language Summary 1073

  A.1 General 1074
    A.1.1 Terminology 1075
    A.1.2 Program start and termination 1075
    A.1.3 Comments 1076
  A.2 Literals 1077
    A.2.1 Integer literals 1077
    A.2.2 Floating-point-literals 1079
    A.2.3 Boolean literals 1079
    A.2.4 Character literals 1079
    A.2.5 String literals 1080
    A.2.6 The pointer literal 1081
  A.3 Identifiers 1081
    A.3.1 Keywords 1081
  A.4 Scope, storage class, and lifetime 1082
    A.4.1 Scope 1082
    A.4.2 Storage class 1083
    A.4.3 Lifetime 1085
A.5 Expressions 1086
  A.5.1 User-defined operators 1091
  A.5.2 Implicit type conversion 1091
  A.5.3 Constant expressions 1093
  A.5.4 sizeof 1093
  A.5.5 Logical expressions 1094
  A.5.6 new and delete 1094
  A.5.7 Casts 1095
A.6 Statements 1096
A.7 Declarations 1098
  A.7.1 Definitions 1098
A.8 Built-in types 1099
  A.8.1 Pointers 1100
  A.8.2 Arrays 1101
  A.8.3 References 1102
A.9 Functions 1103
  A.9.1 Overload resolution 1104
  A.9.2 Default arguments 1105
  A.9.3 Unspecified arguments 1105
  A.9.4 Linkage specifications 1106
A.10 User-defined types 1106
  A.10.1 Operator overloading 1107
A.11 Enumerations 1107
A.12 Classes 1108
  A.12.1 Member access 1108
  A.12.2 Class member definitions 1112
  A.12.3 Construction, destruction, and copy 1112
  A.12.4 Derived classes 1116
  A.12.5 Bitfields 1120
  A.12.6 Unions 1121
A.13 Templates 1121
  A.13.1 Template arguments 1122
  A.13.2 Template instantiation 1123
  A.13.3 Template member types 1124
A.14 Exceptions 1125
A.15 Namespaces 1127
A.16 Aliases 1128
A.17 Preprocessor directives 1128
  A.17.1 #include 1128
  A.17.2 #define 1129
Appendix B  Standard Library Summary  1131

B.1 Overview  1132
B.1.1 Header files  1133
B.1.2 Namespace std  1136
B.1.3 Description style  1136

B.2 Error handling  1137
B.2.1 Exceptions  1138

B.3 Iterators  1139
B.3.1 Iterator model  1140
B.3.2 Iterator categories  1142

B.4 Containers  1144
B.4.1 Overview  1146
B.4.2 Member types  1147
B.4.3 Constructors, destructors, and assignments  1148
B.4.4 Iterators  1148
B.4.5 Element access  1149
B.4.6 Stack and queue operations  1149
B.4.7 List operations  1150
B.4.8 Size and capacity  1150
B.4.9 Other operations  1151
B.4.10 Associative container operations  1151

B.5 Algorithms  1152
B.5.1 Nonmodifying sequence algorithms  1153
B.5.2 Modifying sequence algorithms  1154
B.5.3 Utility algorithms  1156
B.5.4 Sorting and searching  1157
B.5.5 Set algorithms  1159
B.5.6 Heaps  1160
B.5.7 Permutations  1160
B.5.8 min and max  1161

B.6 STL utilities  1162
B.6.1 Inserters  1162
B.6.2 Function objects  1163
B.6.3 pair and tuple  1165
B.6.4 initializer_list  1166
B.6.5 Resource management pointers  1167

B.7 I/O streams  1168
B.7.1 I/O streams hierarchy  1170
B.7.2 Error handling  1171
B.7.3 Input operations  1172
B.7.4 Output operations 1173
B.7.5 Formatting 1173
B.7.6 Standard manipulators 1173
B.8 String manipulation 1175
B.8.1 Character classification 1175
B.8.2 String 1176
B.8.3 Regular expression matching 1177
B.9 Numerics 1180
B.9.1 Numerical limits 1180
B.9.2 Standard mathematical functions 1181
B.9.3 Complex 1182
B.9.4 valarray 1183
B.9.5 Generalized numerical algorithms 1183
B.9.6 Random numbers 1184
B.10 Time 1185
B.11 C standard library functions 1185
B.11.1 Files 1186
B.11.2 The printf() family 1186
B.11.3 C-style strings 1191
B.11.4 Memory 1192
B.11.5 Date and time 1193
B.10.6 Etc. 1194
B.12 Other libraries 1195

Appendix C Getting Started with Visual Studio 1197
C.1 Getting a program to run 1198
C.2 Installing Visual Studio 1198
C.3 Creating and running a program 1199
C.3.1 Create a new project 1199
C.3.2 Use the std_lib_facilities.h header file 1199
C.3.3 Add a C++ source file to the project 1200
C.3.4 Enter your source code 1200
C.3.5 Build an executable program 1200
C.3.6 Execute the program 1201
C.3.7 Save the program 1201
C.4 Later 1201

Appendix D Installing FLTK 1203
D.1 Introduction 1204
D.2 Downloading FLTK 1204
D.3 Installing FLTK 1205
D.4 Using FLTK in Visual Studio 1205
D.5 Testing if it all worked 1206
Appendix E  GUI Implementation  1207
E.1 Callback implementation  1208
E.2 Widget implementation  1209
E.3 Window implementation  1210
E.4 Vector_ref  1212
E.5 An example: manipulating Widgetidents  1213

Glossary  1217
Bibliography  1223
Index  1227
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Preface

“Damn the torpedoes! Full speed ahead.”

—Admiral Farragut

Programming is the art of expressing solutions to problems so that a computer can execute those solutions. Much of the effort in programming is spent finding and refining solutions. Often, a problem is only fully understood through the process of programming a solution for it.

This book is for someone who has never programmed before but is willing to work hard to learn. It helps you understand the principles and acquire the practical skills of programming using the C++ programming language. My aim is for you to gain sufficient knowledge and experience to perform simple useful programming tasks using the best up-to-date techniques. How long will that take? As part of a first-year university course, you can work through this book in a semester (assuming that you have a workload of four courses of average difficulty). If you work by yourself, don’t expect to spend less time than that (maybe 15 hours a week for 14 weeks).

Three months may seem a long time, but there’s a lot to learn and you’ll be writing your first simple programs after about an hour. Also, all learning is gradual: each chapter introduces new useful concepts and illustrates them with examples inspired by real-world uses. Your ability to express ideas in code — getting a computer to do what you want it to do — gradually and steadily increases as you go along. I never say, “Learn a month’s worth of theory and then see if you can use it.”
Why would you want to program? Our civilization runs on software. Without understanding software you are reduced to believing in “magic” and will be locked out of many of the most interesting, profitable, and socially useful technical fields of work. When I talk about programming, I think of the whole spectrum of computer programs from personal computer applications with GUIs (graphical user interfaces), through engineering calculations and embedded systems control applications (such as digital cameras, cars, and cell phones), to text manipulation applications as found in many humanities and business applications. Like mathematics, programming — when done well — is a valuable intellectual exercise that sharpens our ability to think. However, thanks to feedback from the computer, programming is more concrete than most forms of math, and therefore accessible to more people. It is a way to reach out and change the world — ideally for the better. Finally, programming can be great fun.

Why C++? You can’t learn to program without a programming language, and C++ directly supports the key concepts and techniques used in real-world software. C++ is one of the most widely used programming languages, found in an unsurpassed range of application areas. You find C++ applications everywhere from the bottom of the oceans to the surface of Mars. C++ is precisely and comprehensively defined by a nonproprietary international standard. Quality and/or free implementations are available on every kind of computer. Most of the programming concepts that you will learn using C++ can be used directly in other languages, such as C, C#, Fortran, and Java. Finally, I simply like C++ as a language for writing elegant and efficient code.

This is not the easiest book on beginning programming; it is not meant to be. I just aim for it to be the easiest book from which you can learn the basics of real-world programming. That’s quite an ambitious goal because much modern software relies on techniques considered advanced just a few years ago.

My fundamental assumption is that you want to write programs for the use of others, and to do so responsibly, providing a decent level of system quality; that is, I assume that you want to achieve a level of professionalism. Consequently, I chose the topics for this book to cover what is needed to get started with real-world programming, not just what is easy to teach and learn. If you need a technique to get basic work done right, I describe it, demonstrate concepts and language facilities needed to support the technique, provide exercises for it, and expect you to work on those exercises. If you just want to understand toy programs, you can get along with far less than I present. On the other hand, I won’t waste your time with material of marginal practical importance. If an idea is explained here, it’s because you’ll almost certainly need it.

If your desire is to use the work of others without understanding how things are done and without adding significantly to the code yourself, this book is not for you. If so, please consider whether you would be better served by another book and another language. If that is approximately your view of programming, please
also consider from where you got that view and whether it in fact is adequate for your needs. People often underestimate the complexity of programming as well as its value. I would hate for you to acquire a dislike for programming because of a mismatch between what you need and the part of the software reality I describe. There are many parts of the “information technology” world that do not require knowledge of programming. This book is aimed to serve those who do want to write or understand nontrivial programs.

Because of its structure and practical aims, this book can also be used as a second book on programming for someone who already knows a bit of C++ or for someone who programs in another language and wants to learn C++. If you fit into one of those categories, I refrain from guessing how long it will take you to read this book, but I do encourage you to do many of the exercises. This will help you to counteract the common problem of writing programs in older, familiar styles rather than adopting newer techniques where these are more appropriate. If you have learned C++ in one of the more traditional ways, you’ll find something surprising and useful before you reach Chapter 7. Unless your name is Stroustrup, what I discuss here is not “your father’s C++.”

Programming is learned by writing programs. In this, programming is similar to other endeavors with a practical component. You cannot learn to swim, to play a musical instrument, or to drive a car just from reading a book – you must practice. Nor can you learn to program without reading and writing lots of code. This book focuses on code examples closely tied to explanatory text and diagrams. You need those to understand the ideals, concepts, and principles of programming and to master the language constructs used to express them. That’s essential, but by itself, it will not give you the practical skills of programming. For that, you need to do the exercises and get used to the tools for writing, compiling, and running programs. You need to make your own mistakes and learn to correct them. There is no substitute for writing code. Besides, that’s where the fun is!

On the other hand, there is more to programming – much more – than following a few rules and reading the manual. This book is emphatically not focused on “the syntax of C++.” Understanding the fundamental ideals, principles, and techniques is the essence of a good programmer. Only well-designed code has a chance of becoming part of a correct, reliable, and maintainable system. Also, “the fundamentals” are what last: they will still be essential after today’s languages and tools have evolved or been replaced.

What about computer science, software engineering, information technology, etc.? Is that all programming? Of course not! Programming is one of the fundamental topics that underlie everything in computer-related fields, and it has a natural place in a balanced course of computer science. I provide brief introductions to key concepts and techniques of algorithms, data structures, user interfaces, data processing, and software engineering. However, this book is not a substitute for a thorough and balanced study of those topics.
Code can be beautiful as well as useful. This book is written to help you see that, to understand what it means for code to be beautiful, and to help you to master the principles and acquire the practical skills to create such code. Good luck with programming!

A note to students

Of the many thousands of first-year students we have taught so far using this book at Texas A&M University, about 60% had programmed before and about 40% had never seen a line of code in their lives. Most succeeded, so you can do it, too.

You don't have to read this book as part of a course. The book is widely used for self-study. However, whether you work your way through as part of a course or independently, try to work with others. Programming has an — unfair — reputation as a lonely activity. Most people work better and learn faster when they are part of a group with a common aim. Learning together and discussing problems with friends is not cheating! It is the most efficient — as well as most pleasant — way of making progress. If nothing else, working with friends forces you to articulate your ideas, which is just about the most efficient way of testing your understanding and making sure you remember. You don't actually have to personally discover the answer to every obscure language and programming environment problem. However, please don't cheat yourself by not doing the drills and a fair number of exercises (even if no teacher forces you to do them). Remember: programming is (among other things) a practical skill that you need to practice to master. If you don't write code (do several exercises for each chapter), reading this book will be a pointless theoretical exercise.

Most students — especially thoughtful good students — face times when they wonder whether their hard work is worthwhile. When (not if) this happens to you, take a break, reread this Preface, and look at Chapter 1 (“Computers, People, and Programming”) and Chapter 22 (“Ideals and History”). There, I try to articulate what I find exciting about programming and why I consider it a crucial tool for making a positive contribution to the world. If you wonder about my teaching philosophy and general approach, have a look at Chapter 0 (“Notes to the Reader”).

You might find the weight of this book worrying, but it should reassure you that part of the reason for the heft is that I prefer to repeat an explanation or add an example rather than have you search for the one and only explanation. The other major reason is that the second half of the book is reference material and “additional material” presented for you to explore only if you are interested in more information about a specific area of programming, such as embedded systems programming, text analysis, or numerical computation.

And please don't be too impatient. Learning any major new and valuable skill takes time and is worth it.
A note to teachers

No. This is not a traditional Computer Science 101 course. It is a book about how to construct working software. As such, it leaves out much of what a computer science student is traditionally exposed to (Turing completeness, state machines, discrete math, Chomsky grammars, etc.). Even hardware is ignored on the assumption that students have used computers in various ways since kindergarten. This book does not even try to mention most important CS topics. It is about programming (or more generally about how to develop software), and as such it goes into more detail about fewer topics than many traditional courses. It tries to do just one thing well, and computer science is not a one-course topic. If this book/course is used as part of a computer science, computer engineering, electrical engineering (many of our first students were EE majors), information science, or whatever program, I expect it to be taught alongside other courses as part of a well-rounded introduction.

Please read Chapter 0 (“Notes to the Reader”) for an explanation of my teaching philosophy, general approach, etc. Please try to convey those ideas to your students along the way.

ISO standard C++

C++ is defined by an ISO standard. The first ISO C++ standard was ratified in 1998, so that version of C++ is known as C++98. I wrote the first edition of this book while working on the design of C++11. It was most frustrating not to be able to use the novel features (such as uniform initialization, range-for-loops, move semantics, lambdas, and concepts) to simplify the presentation of principles and techniques. However, the book was designed with C++11 in mind, so it was relatively easy to “drop in” the features in the contexts where they belonged. As of this writing, the current standard is C++11 from 2011, and facilities from the upcoming 2014 ISO standard, C++14, are finding their way into mainstream C++ implementations. The language used in this book is C++11 with a few C++14 features. For example, if your compiler complains about

```cpp
vector<int> v1;
vector<int> v2 {v1};  // C++14-style copy construction
```

use

```cpp
vector<int> v1;
vector<int> v2 = v1;  // C++98-style copy construction
```

instead.
If your compiler does not support C++11, get a new compiler. Good, modern C++ compilers can be downloaded from a variety of suppliers; see www.stroustrup.com/compilers.html. Learning to program using an earlier and less supportive version of the language can be unnecessarily hard.

**Support**

The book’s support website, www.stroustrup.com/Programming, contains a variety of material supporting the teaching and learning of programming using this book. The material is likely to be improved with time, but for starters, you can find:

- Slides for lectures based on the book
- An instructor’s guide
- Header files and implementations of libraries used in the book
- Code for examples in the book
- Solutions to selected exercises
- Potentially useful links
- Errata

Suggestions for improvements are always welcome.

**Acknowledgments**

I’d especially like to thank my late colleague and co-teacher Lawrence “Pete” Petersen for encouraging me to tackle the task of teaching beginners long before I’d otherwise have felt comfortable doing that, and for supplying the practical teaching experience to make the course succeed. Without him, the first version of the course would have been a failure. We worked together on the first versions of the course for which this book was designed and together taught it repeatedly, learning from our experiences, improving the course and the book. My use of “we” in this book initially meant “Pete and me.”

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Thanks to the reviewers that Addison-Wesley found for me. Their comments, mostly based on teaching either C++ or Computer Science 101 at the college level, have been invaluable: Richard Enbody, David Gustafson, Ron McCarty, and K. Narayanaswamy. Also thanks to my editor, Peter Gordon, for many useful comments and (not least) for his patience. I'm very grateful to the production team assembled by Addison-Wesley; they added much to the quality of the book: Linda Begley (proofreader), Kim Arney (compositor), Rob Mauhar (illustrator), Julie Nahil (production editor), and Barbara Wood (copy editor).

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Notes to the Reader

“When the terrain disagrees with the map, trust the terrain.”

—Swiss army proverb

This chapter is a grab bag of information; it aims to give you an idea of what to expect from the rest of the book. Please skim through it and read what you find interesting. A teacher will find most parts immediately useful. If you are reading this book without the benefit of a good teacher, please don’t try to read and understand everything in this chapter; just look at “The structure of this book” and the first part of the “A philosophy of teaching and learning” sections. You may want to return and reread this chapter once you feel comfortable writing and executing small programs.
0.1 The structure of this book

This book consists of four parts and a collection of appendices:

- **Part I, “The Basics,”** presents the fundamental concepts and techniques of programming together with the C++ language and library facilities needed to get started writing code. This includes the type system, arithmetic operations, control structures, error handling, and the design, implementation, and use of functions and user-defined types.

- **Part II, “Input and Output,”** describes how to get numeric and text data from the keyboard and from files, and how to produce corresponding output to the screen and to files. Then, it shows how to present numeric data, text, and geometric shapes as graphical output, and how to get input into a program from a graphical user interface (GUI).

- **Part III, “Data and Algorithms,”** focuses on the C++ standard library’s containers and algorithms framework (the STL, standard template library). It shows how containers (such as `vector`, `list`, and `map`) are implemented (using pointers, arrays, dynamic memory, exceptions, and templates) and used. It also demonstrates the design and use of standard library algorithms (such as `sort`, `find`, and `inner_product`).

- **Part IV, “Broadening the View,”** offers a perspective on programming through a discussion of ideals and history, through examples (such as matrix computation, text manipulation, testing, and embedded systems programming), and through a brief description of the C language.

- **Appendices** provide useful information that doesn’t fit into a tutorial presentation, such as surveys of C++ language and standard library facilities, and descriptions of how to get started with an integrated development environment (IDE) and a graphical user interface (GUI) library.
Unfortunately, the world of programming doesn’t really fall into four cleanly separated parts. Therefore, the “parts” of this book provide only a coarse classification of topics. We consider it a useful classification (obviously, or we wouldn’t have used it), but reality has a way of escaping neat classifications. For example, we need to use input operations far sooner than we can give a thorough explanation of C++ standard I/O streams (input/output streams). Where the set of topics needed to present an idea conflicts with the overall classification, we explain the minimum needed for a good presentation, rather than just referring to the complete explanation elsewhere. Rigid classifications work much better for manuals than for tutorials.

The order of topics is determined by programming techniques, rather than programming language features; see §0.2. For a presentation organized around language features, see Appendix A.

To ease review and to help you if you miss a key point during a first reading where you have yet to discover which kind of information is crucial, we place three kinds of “alert markers” in the margin:

- Blue: concepts and techniques (this paragraph is an example of that)
- Green: advice
- Red: warning

0.1.1 General approach

In this book, we address you directly. That is simpler and clearer than the conventional “professional” indirect form of address, as found in most scientific papers. By “you” we mean “you, the reader,” and by “we” we refer either to “ourselves, the author and teachers,” or to you and us working together through a problem, as we might have done had we been in the same room.

This book is designed to be read chapter by chapter from the beginning to the end. Often, you’ll want to go back to look at something a second or a third time. In fact, that’s the only sensible approach, as you’ll always dash past some details that you don’t yet see the point in. In such cases, you’ll eventually go back again. However, despite the index and the cross-references, this is not a book that you can open to any page and start reading with any expectation of success. Each section and each chapter assume understanding of what came before.

Each chapter is a reasonably self-contained unit, meant to be read in “one sitting” (logically, if not always feasible on a student’s tight schedule). That’s one major criterion for separating the text into chapters. Other criteria include that a chapter is a suitable unit for drills and exercises and that each chapter presents some specific concept, idea, or technique. This plurality of criteria has left a few chapters uncomfortably long, so please don’t take “in one sitting” too literally. In particular, once you have thought about the review questions, done the drill, and
worked on a few exercises, you’ll often find that you have to go back to reread a few sections and that several days have gone by. We have clustered the chapters into “parts” focused on a major topic, such as input/output. These parts make good units of review.

Common praise for a textbook is “It answered all my questions just as I thought of them!” That’s an ideal for minor technical questions, and early readers have observed the phenomenon with this book. However, that cannot be the whole ideal. We raise questions that a novice would probably not think of. We aim to ask and answer questions that you need to consider when writing quality software for the use of others. Learning to ask the right (often hard) questions is an essential part of learning to think as a programmer. Asking only the easy and obvious questions would make you feel good, but it wouldn’t help make you a programmer.

We try to respect your intelligence and to be considerate about your time. In our presentation, we aim for professionalism rather than cuteness, and we’d rather understate a point than hype it. We try not to exaggerate the importance of a programming technique or a language feature, but please don’t underestimate a simple statement like “This is often useful.” If we quietly emphasize that something is important, we mean that you’ll sooner or later waste days if you don’t master it. Our use of humor is more limited than we would have preferred, but experience shows that people’s ideas of what is funny differ dramatically and that a failed attempt at humor can be confusing.

We do not pretend that our ideas or the tools offered are perfect. No tool, library, language, or technique is “the solution” to all of the many challenges facing a programmer. At best, it can help you to develop and express your solution. We try hard to avoid “white lies”; that is, we refrain from oversimplified explanations that are clear and easy to understand, but not true in the context of real languages and real problems. On the other hand, this book is not a reference; for more precise and complete descriptions of C++, see Bjarne Stroustrup, The C++ Programming Language, Fourth Edition (Addison-Wesley, 2013), and the ISO C++ standard.

0.1.2 Drills, exercises, etc.

Programming is not just an intellectual activity, so writing programs is necessary to master programming skills. We provide two levels of programming practice:

- **Drills**: A drill is a very simple exercise devised to develop practical, almost mechanical skills. A drill usually consists of a sequence of modifications of a single program. You should do every drill. A drill is not asking for deep understanding, cleverness, or initiative. We consider the drills part of the basic fabric of the book. If you haven’t done the drills, you have not “done” the book.
0.1 THE STRUCTURE OF THIS BOOK

• Exercises: Some exercises are trivial and others are very hard, but most are intended to leave some scope for initiative and imagination. If you are serious, you’ll do quite a few exercises. At least do enough to know which are difficult for you. Then do a few more of those. That’s how you’ll learn the most. The exercises are meant to be manageable without exceptional cleverness, rather than to be tricky puzzles. However, we hope that we have provided exercises that are hard enough to challenge anybody and enough exercises to exhaust even the best student’s available time. We do not expect you to do them all, but feel free to try.

In addition, we recommend that you (every student) take part in a small project (and more if time allows for it). A project is intended to produce a complete useful program. Ideally, a project is done by a small group of people (e.g., three people) working together for about a month while working through the chapters in Part III. Most people find the projects the most fun and what ties everything together.

Some people like to put the book aside and try some examples before reading to the end of a chapter; others prefer to read ahead to the end before trying to get code to run. To support readers with the former preference, we provide simple suggestions for practical work labeled “Try this” at natural breaks in the text. A Try this is generally in the nature of a drill focused narrowly on the topic that precedes it. If you pass a Try this without trying — maybe because you are not near a computer or you find the text riveting — do return to it when you do the chapter drill; a Try this either complements the chapter drill or is a part of it.

At the end of each chapter you’ll find a set of review questions. They are intended to point you to the key ideas explained in the chapter. One way to look at the review questions is as a complement to the exercises: the exercises focus on the practical aspects of programming, whereas the review questions try to help you articulate the ideas and concepts. In that, they resemble good interview questions.

The “Terms” section at the end of each chapter presents the basic vocabulary of programming and of C++. If you want to understand what people say about programming topics and to articulate your own ideas, you should know what each means.

Learning involves repetition. Our ideal is to make every important point at least twice and to reinforce it with exercises.

0.1.3 What comes after this book?

At the end of this book, will you be an expert at programming and at C++? Of course not! When done well, programming is a subtle, deep, and highly skilled art building on a variety of technical skills. You should no more expect to be an expert at programming in four months than you should expect to be an expert in biology, in math, in a natural language (such as Chinese, English, or Danish), or
at playing the violin in four months — or in half a year, or a year. What you should hope for, and what you can expect if you approach this book seriously, is to have a really good start that allows you to write relatively simple useful programs, to be able to read more complex programs, and to have a good conceptual and practical background for further work.

The best follow-up to this initial course is to work on a real project developing code to be used by someone else. After that, or (even better) in parallel with a real project, read either a professional-level general textbook (such as Stroustrup, *The C++ Programming Language*), a more specialized book relating to the needs of your project (such as Qt for GUI, or ACE for distributed programming), or a textbook focusing on a particular aspect of C++ (such as Koenig and Moo, *Accelerated C++*; Sutter’s *Exceptional C++*; or Gamma et al., *Design Patterns*). For more references, see §0.6 or the Bibliography section at the back of the book.

Eventually, you should learn another programming language. We don’t consider it possible to be a professional in the realm of software — even if you are not primarily a programmer — without knowing more than one language.

### 0.2 A philosophy of teaching and learning

What are we trying to help you learn? And how are we approaching the process of teaching? We try to present the minimal concepts, techniques, and tools for you to do effective practical programs, including

- Program organization
- Debugging and testing
- Class design
- Computation
- Function and algorithm design
- Graphics (two-dimensional only)
- Graphical user interfaces (GUIs)
- Text manipulation
- Regular expression matching
- Files and stream input and output (I/O)
- Memory management
- Scientific/numerical/engineering calculations
- Design and programming ideals
- The C++ standard library
- Software development strategies
- C-language programming techniques
Working our way through these topics, we cover the programming techniques called procedural programming (as with the C programming language), data abstraction, object-oriented programming, and generic programming. The main topic of this book is programming, that is, the ideals, techniques, and tools of expressing ideas in code. The C++ programming language is our main tool, so we describe many of C++’s facilities in some detail. But please remember that C++ is just a tool, rather than the main topic of this book. This is “programming using C++,” not “C++ with a bit of programming theory.”

Each topic we address serves at least two purposes: it presents a technique, concept, or principle and also a practical language or library feature. For example, we use the interface to a two-dimensional graphics system to illustrate the use of classes and inheritance. This allows us to be economical with space (and your time) and also to emphasize that programming is more than simply slinging code together to get a result as quickly as possible. The C++ standard library is a major source of such “double duty” examples — many even do triple duty. For example, we introduce the standard library vector, use it to illustrate widely useful design techniques, and show many of the programming techniques used to implement it. One of our aims is to show you how major library facilities are implemented and how they map to hardware. We insist that craftsmen must understand their tools, not just consider them “magical.”

Some topics will be of greater interest to some programmers than to others. However, we encourage you not to prejudge your needs (how would you know what you’ll need in the future?) and at least look at every chapter. If you read this book as part of a course, your teacher will guide your selection.

We characterize our approach as “depth-first.” It is also “concrete-first” and “concept-based.” First, we quickly (well, relatively quickly, Chapters 1–11) assemble a set of skills needed for writing small practical programs. In doing so, we present a lot of tools and techniques in minimal detail. We focus on simple concrete code examples because people grasp the concrete faster than the abstract. That’s simply the way most humans learn. At this initial stage, you should not expect to understand every little detail. In particular, you’ll find that trying something slightly different from what just worked can have “mysterious” effects. Do try, though! And please do the drills and exercises we provide. Just remember that early on you just don’t have the concepts and skills to accurately estimate what’s simple and what’s complicated; expect surprises and learn from them.

We move fast in this initial phase — we want to get you to the point where you can write interesting programs as fast as possible. Someone will argue, “We must move slowly and carefully; we must walk before we can run!” But have you ever watched a baby learning to walk? Babies really do run by themselves before they learn the finer skills of slow, controlled walking. Similarly, you will dash ahead, occasionally stumbling, to get a feel of programming before slowing down to gain the necessary finer control and understanding. You must run before you can walk!
It is essential that you don’t get stuck in an attempt to learn “everything” about some language detail or technique. For example, you could memorize all of C++’s built-in types and all the rules for their use. Of course you could, and doing so might make you feel knowledgeable. However, it would not make you a programmer. Skipping details will get you “burned” occasionally for lack of knowledge, but it is the fastest way to gain the perspective needed to write good programs. Note that our approach is essentially the one used by children learning their native language and also the most effective approach used to teach foreign languages. We encourage you to seek help from teachers, friends, colleagues, instructors, Mentors, etc. on the inevitable occasions when you are stuck. Be assured that nothing in these early chapters is fundamentally difficult. However, much will be unfamiliar and might therefore feel difficult at first.

Later, we build on the initial skills to broaden your base of knowledge and skills. We use examples and exercises to solidify your understanding, and to provide a conceptual base for programming.

We place a heavy emphasis on ideals and reasons. You need ideals to guide you when you look for practical solutions — to know when a solution is good and principled. You need to understand the reasons behind those ideals to understand why they should be your ideals, why aiming for them will help you and the users of your code. Nobody should be satisfied with “because that’s the way it is” as an explanation. More importantly, an understanding of ideals and reasons allows you to generalize from what you know to new situations and to combine ideas and tools in novel ways to address new problems. Knowing “why” is an essential part of acquiring programming skills. Conversely, just memorizing lots of poorly understood rules and language facilities is limiting, a source of errors, and a massive waste of time. We consider your time precious and try not to waste it.

Many C++ language-technical details are banished to appendices and manuals, where you can look them up when needed. We assume that you have the initiative to search out information when needed. Use the index and the table of contents. Don’t forget the online help facilities of your compiler, and the web. Remember, though, to consider every web resource highly suspect until you have reason to believe better of it. Many an authoritative-looking website is put up by a programming novice or someone with something to sell. Others are simply outdated. We provide a collection of links and information on our support website: www.stroustrup.com/Programming.

Please don’t be too impatient for “realistic” examples. Our ideal example is the shortest and simplest code that directly illustrates a language facility, a concept, or a technique. Most real-world examples are far messier than ours, yet do not consist of more than a combination of what we demonstrate. Successful commercial programs with hundreds of thousands of lines of code are based on techniques that we illustrate in a dozen 50-line programs. The fastest way to understand real-world code is through a good understanding of the fundamentals.
On the other hand, we do not use “cute examples involving cuddly animals” to illustrate our points. We assume that you aim to write real programs to be used by real people, so every example that is not presented as language-technical is taken from a real-world use. Our basic tone is that of professionals addressing (future) professionals.

0.2.1 The order of topics

There are many ways to teach people how to program. Clearly, we don’t subscribe to the popular “the way I learned to program is the best way to learn” theories. To ease learning, we early on present topics that would have been considered advanced only a few years ago. Our ideal is for the topics we present to be driven by problems you meet as you learn to program, to flow smoothly from topic to topic as you increase your understanding and practical skills. The major flow of this book is more like a story than a dictionary or a hierarchical order.

It is impossible to learn all the principles, techniques, and language facilities needed to write a program at once. Consequently, we have to choose a subset of principles, techniques, and features to start with. More generally, a textbook or a course must lead students through a series of subsets. We consider it our responsibility to select topics and to provide emphasis. We can’t just present everything, so we must choose; what we leave out is at least as important as what we leave in — at each stage of the journey.

For contrast, it may be useful for you to see a list of (severely abbreviated) characterizations of approaches that we decided not to take:

- “C first”: This approach to learning C++ is wasteful of students’ time and leads to poor programming practices by forcing students to approach problems with fewer facilities, techniques, and libraries than necessary. C++ provides stronger type checking than C, a standard library with better support for novices, and exceptions for error handling.

- Bottom-up: This approach distracts from learning good and effective programming practices. By forcing students to solve problems with insufficient support from the language and libraries, it promotes poor and wasteful programming practices.

- “If you present something, you must present it fully”: This approach implies a bottom-up approach (by drilling deeper and deeper into every topic touched). It bores novices with technical details they have no interest in and quite likely will not need for years to come. Once you can program, you can look up technical details in a manual. Manuals are good at that, whereas they are awful for initial learning of concepts.

- Top-down: This approach, working from first principles toward details, tends to distract readers from the practical aspects of programming and
force them to concentrate on high-level concepts before they have any chance of appreciating their importance. For example, you simply can’t appreciate proper software development principles before you have learned how easy it is to make a mistake in a program and how hard it can be to correct it.

- “Abstract first”: Focusing on general principles and protecting the student from nasty real-world constraints can lead to a disdain for real-world problems, languages, tools, and hardware constraints. Often, this approach is supported by “teaching languages” that cannot be used later and (deliberately) insulate students from hardware and system concerns.

- “Software engineering principles first”: This approach and the abstract-first approach tend to share the problems of the top-down approach: without concrete examples and practical experience, you simply cannot appreciate the value of abstraction and proper software development practices.

- “Object-oriented from day one”: Object-oriented programming is one of the best ways of organizing code and programming efforts, but it is not the only effective way. In particular, we feel that a grounding in the basics of types and algorithmic code is a prerequisite for appreciation of the design of classes and class hierarchies. We do use user-defined types (what some people would call “objects”) from day one, but we don’t show how to design a class until Chapter 6 and don’t show a class hierarchy until Chapter 12.

- “Just believe in magic”: This approach relies on demonstrations of powerful tools and techniques without introducing the novice to the underlying techniques and facilities. This leaves the student guessing – and usually guessing wrong – about why things are the way they are, what it costs to use them, and where they can be reasonably applied. This can lead to overrigid following of familiar patterns of work and become a barrier to further learning.

Naturally, we do not claim that these other approaches are never useful. In fact, we use several of these for specific subtopics where their strengths can be appreciated. However, as general approaches to learning programming aimed at real-world use, we reject them and apply our alternative: concrete-first and depth-first with an emphasis on concepts and techniques.

0.2.2 Programming and programming language

We teach programming first and treat our chosen programming language as secondary, as a tool. Our general approach can be used with any general-purpose programming language. Our primary aim is to help you learn general concepts,
principles, and techniques. However, those cannot be appreciated in isolation. For example, details of syntax, the kinds of ideas that can be directly expressed, and tool support differ from programming language to programming language. However, many of the fundamental techniques for producing bug-free code, such as writing logically simple code (Chapters 5 and 6), establishing invariants (§9.4.3), and separating interfaces from implementation details (§9.7 and §14.1–2), vary little from programming language to programming language.

Programming and design techniques must be learned using a programming language. Design, code organization, and debugging are not skills you can acquire in the abstract. You need to write code in some programming language and gain practical experience with that. This implies that you must learn the basics of a programming language. We say “the basics” because the days when you could learn all of a major industrial language in a few weeks are gone for good. The parts of C++ we present were chosen as the subset that most directly supports the production of good code. Also, we present C++ features that you can’t avoid encountering either because they are necessary for logical completeness or are common in the C++ community.

0.2.3 Portability

It is common to write C++ to run on a variety of machines. Major C++ applications run on machines we haven’t ever heard of! We consider portability and the use of a variety of machine architectures and operating systems most important. Essentially every example in this book is not only ISO Standard C++, but also portable. Unless specifically stated, the code we present should work on every C++ implementation and has been tested on several machines and operating systems.

The details of how to compile, link, and run a C++ program differ from system to system. It would be tedious to mention the details of every system and every compiler each time we need to refer to an implementation issue. In Appendix C, we give the most basic information about getting started using Visual Studio and Microsoft C++ on a Windows machine.

If you have trouble with one of the popular, but rather elaborate, IDEs (integrated development environments), we suggest you try working from the command line; it’s surprisingly simple. For example, here is the full set of commands needed to compile, link, and execute a simple program consisting of two source files, my_file1.cpp and my_file2.cpp, using the GNU C++ compiler on a Unix or Linux system:

```
c++ -o my_program my_file1.cpp my_file2.cpp
./my_program
```

Yes, that really is all it takes.
0.3 Programming and computer science

Is programming all that there is to computer science? Of course not! The only reason we raise this question is that people have been known to be confused about this. We touch upon major topics from computer science, such as algorithms and data structures, but our aim is to teach programming: the design and implementation of programs. That is both more and less than most accepted notions of computer science:

- More, because programming involves many technical skills that are not usually considered part of any science
- Less, because we do not systematically present the foundation for the parts of computer science we use

The aim of this book is to be part of a course in computer science (if becoming a computer scientist is your aim), to be the foundation for the first of many courses in software construction and maintenance (if your aim is to become a programmer or a software engineer), and in general to be part of a greater whole.

We rely on computer science throughout and we emphasize principles, but we teach programming as a practical skill based on theory and experience, rather than as a science.

0.4 Creativity and problem solving

The primary aim of this book is to help you to express your ideas in code, not to teach you how to get those ideas. Along the way, we give many examples of how we can address a problem, usually through analysis of a problem followed by gradual refinement of a solution. We consider programming itself a form of problem solving: only through complete understanding of a problem and its solution can you express a correct program for it, and only through constructing and testing a program can you be certain that your understanding is complete. Thus, programming is inherently part of an effort to gain understanding. However, we aim to demonstrate this through examples, rather than through “preaching” or presentation of detailed prescriptions for problem solving.

0.5 Request for feedback

We don’t think that the perfect textbook can exist; the needs of individuals differ too much for that. However, we’d like to make this book and its supporting materials as good as we can make them. For that, we need feedback; a good textbook cannot be written in isolation from its readers. Please send us reports on errors, typos, unclear text, missing explanations, etc. We’d also appreciate suggestions
for better exercises, better examples, and topics to add, topics to delete, etc. Constructive comments will help future readers and we’ll post errata on our support website: www.stroustrup.com/Programming.

0.6 References

Along with listing the publications mentioned in this chapter, this section also includes publications you might find helpful.


A more comprehensive list of references can be found in the Bibliography section at the back of the book.

0.7 Biographies

You might reasonably ask, “Who are these guys who want to teach me how to program?” So here is some biographical information. I, Bjarne Stroustrup, wrote this book, and together with Lawrence “Pete” Petersen, I designed and taught the university-level beginner’s (first-year) course that was developed concurrently with the book, using drafts of the book.
Bjarne Stroustrup

I’m the designer and original implementer of the C++ programming language. I have used the language, and many other programming languages, for a wide variety of programming tasks over the last 40 years or so. I just love elegant and efficient code used in challenging applications, such as robot control, graphics, games, text analysis, and networking. I have taught design, programming, and C++ to people of essentially all abilities and interests. I’m a founding member of the ISO standards committee for C++ where I serve as the chair of the working group for language evolution.

This is my first introductory book. My other books, such as The C++ Programming Language and The Design and Evolution of C++, were written for experienced programmers.

I was born into a blue-collar (working-class) family in Århus, Denmark, and got my master’s degree in mathematics with computer science in my hometown university. My Ph.D. in computer science is from Cambridge University, England. I worked for AT&T for about 25 years, first in the famous Computer Science Research Center of Bell Labs — where Unix, C, C++, and so much more was invented — and later in AT&T Labs–Research.

I’m a member of the U.S. National Academy of Engineering, a Fellow of the ACM, and an IEEE Fellow. As the first computer scientist ever, I received the 2005 William Procter Prize for Scientific Achievement from Sigma Xi (the scientific research society). In 2010, I received the University of Aarhus’s oldest and most prestigious honor for contributions to science by a person associated with the university, the Rigmor og Carl Holst-Knudsens Videnskapspris. In 2013, I was made Honorary Doctor of Computer Science from the National Research University, ITMO, St. Petersburg, Russia.

I do have a life outside work. I’m married and have two children, one a medical doctor and one a Post-doctoral Research Fellow. I read a lot (including history, science fiction, crime, and current affairs) and like most kinds of music (including classical, rock, blues, and country). Good food with friends is an essential part of life, and I enjoy visiting interesting places and people, all over the world. To be able to enjoy the good food, I run.

For more information, see my home pages: www.stroustrup.com. In particular, there you can find out how to pronounce my name.
Lawrence “Pete” Petersen

In late 2006, Pete introduced himself as follows: “I am a teacher. For almost 20 years, I have taught programming languages at Texas A&M. I have been selected by students for Teaching Excellence Awards five times and in 1996 received the Distinguished Teaching Award from the Alumni Association for the College of Engineering. I am a Fellow of the Wakonse Program for Teaching Excellence and a Fellow of the Academy for Educator Development.

“As the son of an army officer, I was raised on the move. After completing a degree in philosophy at the University of Washington, I served in the army for 22 years as a Field Artillery Officer and as a Research Analyst for Operational Testing. I taught at the Field Artillery Officers’ Advanced Course at Fort Sill, Oklahoma, from 1971 to 1973. In 1979 I helped organize a Test Officers’ Training Course and taught it as lead instructor at nine different locations across the United States from 1978 to 1981 and from 1985 to 1989.

“In 1991 I formed a small software company that produced management software for university departments until 1999. My interests are in teaching, designing, and programming software that real people can use. I completed master’s degrees in industrial engineering at Georgia Tech and in education curriculum and instruction at Texas A&M. I also completed a master’s program in microcomputers from NTS. My Ph.D. is in information and operations management from Texas A&M.

“My wife, Barbara, and I live in Bryan, Texas. We like to travel, garden, and entertain; and we spend as much time as we can with our sons and their families, and especially with our grandchildren, Angelina, Carlos, Tess, Avery, Nicholas, and Jordan.”

Sadly, Pete died of lung cancer in 2007. Without him, the course would never have succeeded.
Postscript

Most chapters provide a short “postscript” that attempts to give some perspective on the information presented in the chapter. We do that with the realization that the information can be — and often is — daunting and will only be fully comprehended after doing exercises, reading further chapters (which apply the ideas of the chapter), and a later review. Don’t panic! Relax; this is natural and expected. You won’t become an expert in a day, but you can become a reasonably competent programmer as you work your way through the book. On the way, you’ll encounter much information, many examples, and many techniques that lots of programmers have found stimulating and fun.
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This chapter describes how vectors are copied and accessed through subscripting. To do that, we discuss copying in general and consider vector's relation to the lower-level notion of arrays. We present arrays’ relation to pointers and consider the problems arising from their use. We also present the five essential operations that must be considered for every type: construction, default construction, copy construction, copy assignment, and destruction. In addition, a container needs a move constructor and a move assignment.
18.1 Introduction

To get into the air, a plane has to accelerate along the runway until it moves fast enough to “jump” into the air. While the plane is lumbering along the runway, it is little more than a particularly heavy and awkward truck. Once in the air, it soars to become an altogether different, elegant, and efficient vehicle. It is in its true element.

In this chapter, we are in the middle of a “run” to gather enough programming language features and techniques to get away from the constraints and difficulties of plain computer memory. We want to get to the point where we can program using types that provide exactly the properties we want based on logical needs. To “get there” we have to overcome a number of fundamental constraints related to access to the bare machine, such as the following:

- An object in memory is of fixed size.
- An object in memory is in one specific place.
- The computer provides only a few fundamental operations on such objects (such as copying a word, adding the values from two words, etc.).

Basically, those are the constraints on the built-in types and operations of C++ (as inherited through C from hardware; see §22.2.5 and Chapter 27). In Chapter 17, we saw the beginnings of a vector type that controls all access to its elements and provides us with operations that seem “natural” from the point of view of a user, rather than from the point of view of hardware.

This chapter focuses on the notion of copying. This is an important but rather technical point: What do we mean by copying a nontrivial object? To what extent
are the copies independent after a copy operation? What copy operations are there? How do we specify them? And how do they relate to other fundamental operations, such as initialization and cleanup?

Inevitably, we get to discuss how memory is manipulated when we don’t have higher-level types such as vector and string. We examine arrays and pointers, their relationship, their use, and the traps and pitfalls of their use. This is essential information to anyone who gets to work with low-level uses of C++ or C code.

Please note that the details of vector are peculiar to vectors and the C++ ways of building new higher-level types from lower-level ones. However, every “higher-level” type (string, vector, list, map, etc.) in every language is somehow built from the same machine primitives and reflects a variety of resolutions to the fundamental problems described here.

18.2 Initialization

Consider our vector as it was at the end of Chapter 17:

```cpp
class vector {
   int sz;                            // the size
   double* elem;           // a pointer to the elements
public:
   vector(int s)                                                             // constructor
      :sz{s}, elem{new double[s]} {  /* ... */ }  // allocates memory
~vector()                                                                   // destructor
   { delete[] elem; }                                         // deallocates memory
   // . . .
};
```

That’s fine, but what if we want to initialize a vector to a set of values that are not defaults? For example:

```cpp
vector v1 = {1.2, 7.89, 12.34);
```

We can do that, and it is much better than initializing to default values and then assigning the values we really want:

```cpp
vector v2(2);                  // tedious and error-prone
v2[0] = 1.2;
v2[1] = 7.89;
v2[2] = 12.34;
```
Compared to `v1`, the “initialization” of `v2` is tedious and error-prone (we deliberately got the number of elements wrong in that code fragment). Using `push_back()` can save us from mentioning the size:

```cpp
vector v3;               // tedious and repetitive
v2.push_back(1.2);
v2.push_back(7.89);
v2.push_back(12.34);
```

But this is still repetitive, so how do we write a constructor that accepts an initializer list as its argument? A `{ }`-delimited list of elements of type `T` is presented to the programmer as an object of the standard library type `initializer_list<T>`, a list of `Ts`, so we can write

```cpp
class vector {
    int sz;                          // the size
    double* elem;          // a pointer to the elements

public:
    vector(int s)                 // constructor (s is the element count)
        : sz(s), elem{new double[sz]}    // uninitialized memory for elements
    {
        for (int i = 0; i<sz; ++i) elem[i] = 0.0;  // initialize
    }

    vector(initializer_list<double> lst)             // initializer-list constructor
        : sz(lst.size()), elem{new double[sz]}    // uninitialized memory
        { // for elements
            copy( lst.begin(),lst.end(),elem);  // initialize (using std::copy(); §B.5.2)
        }
    // . . .
};
```

We used the standard library `copy` algorithm (§B.5.2). It copies a sequence of elements specified by its first two arguments (here, the beginning and the end of the `initializer_list`) to a sequence of elements starting with its third argument (here, the `vector`'s elements starting at `elem`).

Now we can write

```cpp
vector v1 = {1,2,3};    // three elements 1.0, 2.0, 3.0
vector v2(3);           // three elements each with the (default) value 0.0
```
Note how we use () for an element count and {} for element lists. We need a notation to distinguish them. For example:

```cpp
vector v1 {3};  // one element with the value 3.0
vector v2(3);   // three elements each with the (default) value 0.0
```

This is not very elegant, but it is effective. If there is a choice, the compiler will interpret a value in a {} list as an element value and pass it to the initializer-list constructor as an element of an `initializer_list`.

In most cases — including all cases we will encounter in this book — the = before an {} initializer list is optional, so we can write

```cpp
vector v11 = {1,2,3};   // three elements 1.0, 2.0, 3.0
vector v12 {1,2,3};     // three elements 1.0, 2.0, 3.0
```

The difference is purely one of style.

Note that we pass `initializer_list<double>` by value. That was deliberate and required by the language rules: an `initializer_list` is simply a handle to elements allocated “elsewhere” (see §B.6.4).

## 18.3 Copying

Consider again our incomplete `vector`:

```cpp
class vector {
    int sz;                     // the size
    double* elem;       // a pointer to the elements
public:
    vector(int s) : sz{s}, elem{new double[s]} { /* . . . */ }   // constructor
    ~vector() { delete[] elem; }         // destructor
    // . . .
};
```

Let’s try to copy one of these vectors:

```cpp
void f(int n)
{
    vector v(3);     // define a vector of 3 elements
    v.set(2, 2.2);   // set v[2] to 2.2
}```
vector v2 = v;            // what happens here?
// . . .
}

Ideally, \(v_2\) becomes a copy of \(v\) (that is, = makes copies); that is, \(v_2.size() == v.size()\) and \(v_2[i] == v[i]\) for all \(i\) in the range \([0:v.size()]\). Furthermore, all memory is returned to the free store upon exit from \(f()\). That’s what the standard library \(\text{vector}\) does (of course), but it’s not what happens for our still-far-too-simple \(\text{vector}\). Our task is to improve our \(\text{vector}\) to get it to handle such examples correctly, but first let’s figure out what our current version actually does. Exactly what does it do wrong? How? And why? Once we know that, we can probably fix the problems. More importantly, we have a chance to recognize and avoid similar problems when we see them in other contexts.

The default meaning of copying for a class is “Copy all the data members.” That often makes perfect sense. For example, we copy a \(\text{Point}\) by copying its coordinates. But for a pointer member, just copying the members causes problems. In particular, for the \(\text{vector}\)s in our example, it means that after the copy, we have \(v.sz == v_2.sz\) and \(v.elem == v_2.elem\) so that our \(\text{vector}\)s look like this:

\[
\begin{align*}
\text{v:} & \quad 3 \quad \begin{array}{cccc}
0.0 & 0.0 & 2.2
\end{array} \\
\text{v2:} & \quad 3 \quad \begin{array}{c}
\end{array}
\end{align*}
\]

That is, \(v_2\) doesn’t have a copy of \(v\)’s elements; it shares \(v\)’s elements. We could write

\[
\begin{align*}
v.set(1, 99); & \quad \text{// set } v[1] \text{ to } 99 \\
v2.set(0, 88); & \quad \text{// set } v_2[0] \text{ to } 88 \\
\text{cout} \ll \text{v.get(0)} \ll \text{'}1\text{'} \ll \text{v2.get(1)};
\end{align*}
\]

The result would be the output \(88\ 99\). That wasn’t what we wanted. Had there been no “hidden” connection between \(v\) and \(v_2\), we would have gotten the output \(0\ 0\), because we never wrote to \(v[0]\) or to \(v_2[1]\). You could argue that the behavior we got is “interesting,” “neat!” or “sometimes useful,” but that is not what we intended or what the standard library \(\text{vector}\) provides. Also, what happens when we return from \(f()\) is an unmitigated disaster. Then, the destructors for \(v\) and \(v_2\) are implicitly called; \(v\)’s destructor frees the storage used for the elements using

\[
delete[]\ elem;
\]

and so does \(v_2\)’s destructor. Since \(elem\) points to the same memory location in both \(v\) and \(v_2\), that memory will be freed twice with likely disastrous results (§17.4.6).
18.3.1 Copy constructors

So, what do we do? We’ll do the obvious: provide a copy operation that copies the elements and make sure that this copy operation gets called when we initialize one vector with another.

Initialization of objects of a class is done by a constructor. So, we need a constructor that copies. Unsurprisingly, such a constructor is called a copy constructor. It is defined to take as its argument a reference to the object from which to copy. So, for class vector we need

\[
\text{vector(const vector&);} \\
\]

This constructor will be called when we try to initialize one vector with another. We pass by reference because we (obviously) don’t want to copy the argument of the constructor that defines copying. We pass by const reference because we don’t want to modify our argument (§8.5.6). So we refine vector like this:

```cpp
class vector {
    int sz;
    double* elem;
public:
    vector(const vector&);          // copy constructor: define copy
    // ... 
};
```

The copy constructor sets the number of elements (sz) and allocates memory for the elements (initializing elem) before copying element values from the argument vector:

```cpp
vector::vector(const vector& arg)
    // allocate elements, then initialize them by copying
    :sz(arg.sz), elem(new double[arg.sz])
{
    copy(arg,arg+sz,elem);       // std::copy(); see §B.5.2
}
```

Given this copy constructor, consider again our example:

```
vector v2 = v;
```

This definition will initialize v2 by a call of vector’s copy constructor with v as its argument. Again given a vector with three elements, we now get

```
v: 3 ———— 2.2

v2: 3 ———— 2.2
```
Given that, the destructor can do the right thing. Each set of elements is correctly freed. Obviously, the two vectors are now independent so that we can change the value of elements in v without affecting v2 and vice versa. For example:

\[
\begin{align*}
\textit{v.set(1,99);} & \quad \text{n set v[1] to 99} \\
\textit{v2.set(0,88);} & \quad \text{n set v2[0] to 88} \\
\textit{cout << v.get(0) << ' ' << v2.get(1);}
\end{align*}
\]

This will output 0 0.

Instead of saying

\[
\textit{vector v2 = v;}
\]

we could equally well have said

\[
\textit{vector v2 {v};}
\]

When v (the initializer) and v2 (the variable being initialized) are of the same type and that type has copying conventionally defined, those two notations mean exactly the same thing and you can use whichever notation you like better.

### 18.3.2 Copy assignments

We handle copy construction (initialization), but we can also copy vectors by assignment. As with copy initialization, the default meaning of copy assignment is memberwise copy, so with vector as defined so far, assignment will cause a double deletion (exactly as shown for copy constructors in §18.3.1) plus a memory leak. For example:

\[
\begin{align*}
\textit{void f2(int n)} \\
\textit{\{ } \\
\textit{\quad vector v(3);} & \quad \text{n define a vector} \\
\textit{\quad v.set(2,2.2);} \\
\textit{\quad vector v2(4);} \\
\textit{\quad v2 = v;} & \quad \text{n assignment: what happens here?} \\
\textit{\quad \quad \quad \quad \quad // . . .}
\end{align*}
\]

We would like v2 to be a copy of v (and that’s what the standard library vector does), but since we have said nothing about the meaning of assignment of our vector, the default assignment is used; that is, the assignment is a memberwise copy so that v2’s sz and elem become identical to v’s sz and elem, respectively. We can illustrate that like this:
When we leave `f2()`, we have the same disaster as we had when leaving `f()` in §18.3 before we added the copy constructor: the elements pointed to by both `v` and `v2` are freed twice (using `delete[]`). In addition, we have leaked the memory initially allocated for `v2`'s four elements. We “forgot” to free those. The remedy for this copy assignment is fundamentally the same as for the copy initialization (§18.3.1).

We define an assignment that copies properly:

```cpp
class vector {
  int sz;
  double* elem;
public:
  vector& operator=(const vector&); // copy assignment
  // . . .
};

vector& vector::operator=(const vector& a) // make this vector a copy of a
{
  double* p = new double[a.sz];           // allocate new space
  copy(a.elem, a.elem+a.sz, elem);        // copy elements
  delete[] elem;                          // deallocate old space
  elem = p;                               // now we can reset elem
  sz = a.sz;
  return *this;                           // return a self-reference (see §17.10)
}
```

Assignment is a bit more complicated than construction because we must deal with the old elements. Our basic strategy is to make a copy of the elements from the source `vector`:

```cpp
double* p = new double[a.sz]; // allocate new space
copy(a.elem, a.elem+a.sz, elem); // copy elements
```

Then we free the old elements from the target `vector`:

```cpp
delete[] elem; // deallocate old space
```
Finally, we let \texttt{elem} point to the new elements:

\begin{verbatim}
    elem = p; // now we can reset elem
    sz = a.sz;
\end{verbatim}

We can represent the result graphically like this:

\begin{itemize}
    \item We now have a \texttt{vector} that doesn’t leak memory and doesn’t free \texttt{(delete[])} any memory twice.

    When implementing the assignment, you could consider simplifying the code by freeing the memory for the old elements before creating the copy, but it is usually a very good idea not to throw away information before you know that you can replace it. Also, if you did that, strange things would happen if you assigned a \texttt{vector} to itself:

    \begin{verbatim}
        vector v(10);
        v = v; // self-assignment
    \end{verbatim}

    Please check that our implementation handles that case correctly (if not with optimal efficiency).
\end{itemize}

\textbf{18.3.3 Copy terminology}

Copying is an issue in most programs and in most programming languages. The basic issue is whether you copy a pointer (or reference) or copy the information pointed to (referred to):

- \textit{Shallow copy} copies only a pointer so that the two pointers now refer to the same object. That’s what pointers and references do.

- \textit{Deep copy} copies what a pointer points to so that the two pointers now refer to distinct objects. That’s what \texttt{vectors}, \texttt{strings}, etc. do. We define copy constructors and copy assignments when we want deep copy for objects of our classes.

Here is an example of shallow copy:
int* p = new int{77};
int* q = p; // copy the pointer p
*p = 88; // change the value of the int pointed to by p and q

We can illustrate that like this:

<table>
<thead>
<tr>
<th>p</th>
<th>(copy of p)</th>
</tr>
</thead>
<tbody>
<tr>
<td>88</td>
<td></td>
</tr>
</tbody>
</table>

In contrast, we can do a deep copy:

int* p = new int{77};
int* q = new int{*p}; // allocate a new int, then copy the value pointed to by p
*p = 88; // change the value of the int pointed to by p

We can illustrate that like this:

<table>
<thead>
<tr>
<th>p</th>
<th>q</th>
</tr>
</thead>
<tbody>
<tr>
<td>88</td>
<td>77</td>
</tr>
</tbody>
</table>

Using this terminology, we can say that the problem with our original vector was that it did a shallow copy, rather than copying the elements pointed to by its elem pointer. Our improved vector, like the standard library vector, does a deep copy by allocating new space for the elements and copying their values. Types that provide shallow copy (like pointers and references) are said to have pointer semantics or reference semantics (they copy addresses). Types that provide deep copy (like string and vector) are said to have value semantics (they copy the values pointed to). From a user perspective, types with value semantics behave as if no pointers were involved — just values that can be copied. One way of thinking of types with value semantics is that they “work just like integers” as far as copying is concerned.

### 18.3.4 Moving

If a vector has a lot of elements, it can be expensive to copy. So, we should copy vectors only when we need to. Consider an example:

```cpp
vector fill(istream& is)
{
```
`vector res;`  
`for (double x; is>>x; ) res.push_back(x);`  
`return res;`  
`}
```
```c++
void use()
{
    vector vec = fill(cin);  
    // ... use vec ...  
}
```

Here, we fill the local vector `res` from the input stream and return it to `use()`. Copying `res` out of `fill()` and into `vec` could be expensive. But why copy? We don’t want a copy! We can never use the original (`res`) after the return. In fact, `res` is destroyed as part of the return from `fill()`. So how can we avoid the copy? Consider again how a vector is represented in memory:

![Memory representation of res](image)

We would like to “steal” the representation of `res` to use for `vec`. In other words, we would like `vec` to refer to the elements of `res` without any copy.

After moving `res`’s element pointer and element count to `vec`, `res` holds no elements. We have successfully moved the value from `res` out of `fill()` to `vec`. Now, `res` can be destroyed (simply and efficiently) without any undesirable side effects:

![Memory representation of vec](image)

We have successfully moved 100,000 `doubles` out of `fill()` and into its caller at the cost of four single-word assignments.

How do we express such a move in C++ code? We define move operations to complement the copy operations:

```c++
class vector {
    int sz;
    double* elem;
```
public:
    vector(vector&& a);                     // move constructor
    vector& operator=(vector&&);            // move assignment
    // . . .
};

The funny && notation is called an “rvalue reference.” We use it for defining
move operations. Note that move operations do not take const arguments; that
is, we write (vector&&) and not (const vector&&). Part of the purpose of a move
operation is to modify the source, to make it “empty.” The definitions of move
operations tend to be simple. They tend to be simpler and more efficient than
their copy equivalents. For vector, we get

    vector::vector(vector&& a)
        : sz(a.sz), elem(a.elem)       // copy a’s elem and sz
    {
        a.sz = 0;                       // make a the empty vector
        a.elem = nullptr;
    }

    vector& vector::operator=(vector&& a) // move a to this vector
    {
        delete[] elem;                 // deallocate old space
        elem = a.elem;                 // copy a’s elem and sz
        sz = a.sz;
        a.elem = nullptr;              // make the empty vector
        a.sz = 0;
    return *this;                     // return a self-reference (see §17.10)
    }

By defining a move constructor, we make it easy and cheap to move around large
amounts of information, such as a vector with many elements. Consider again:

    vector fill(istream& is)
    {
        vector res;
        for (double x; is>>x; ) res.push_back(x);
    return res;
    }

The move constructor is implicitly used to implement the return. The compiler
knows that the local value returned (res) is about to go out of scope, so it can
move from it, rather than copying.
The importance of move constructors is that we do not have to deal with pointers or references to get large amounts of information out of a function. Consider this flawed (but conventional) alternative:

```cpp
vector* fill2(istream& is)
{
    vector* res = new vector;
    for (double x; is>>x; ) res->push_back(x);
    return res;
}
```

```cpp
void use2()
{
    vector* vec = fill(cin);
    // ... use vec ...
    delete vec;
}
```

Now we have to remember to delete the `vector`. As described in §17.4.6, deleting objects placed on the free store is not as easy to do consistently and correctly as it might seem.

### 18.4 Essential operations

We have now reached the point where we can discuss how to decide which constructors a class should have, whether it should have a destructor, and whether you need to provide copy and move operations. There are seven essential operations to consider:

- Constructors from one or more arguments
- Default constructor
- Copy constructor (copy object of same type)
- Copy assignment (copy object of same type)
- Move constructor (move object of same type)
- Move assignment (move object of same type)
- Destructor

Usually we need one or more constructors that take arguments needed to initialize an object. For example:
The meaning/use of an initializer is completely up to the constructor. The standard `string`'s constructor uses a character string as an initial value, whereas `Image`'s constructor uses the string as the name of a file to open. Usually we use a constructor to establish an invariant (§9.4.3). If we can’t define a good invariant for a class that its constructors can establish, we probably have a poorly designed class or a plain data structure.

Constructors that take arguments are as varied as the classes they serve. The remaining operations have more regular patterns.

How do we know if a class needs a default constructor? We need a default constructor if we want to be able to make objects of the class without specifying an initializer. The most common example is when we want to put objects of a class into a standard library `vector`. The following works only because we have default values for `int`, `string`, and `vector<int>`:

```cpp
vector<double> vi(10);         // vector of 10 doubles, each initialized to 0.0
vector<string> vs(10);         // vector of 10 strings, each initialized to ""
vector<vector<int>> vvi(10); // vector of 10 vectors, each initialized to vector{}
```

So, having a default constructor is often useful. The question then becomes: “When does it make sense to have a default constructor?” An answer is: “When we can establish the invariant for the class with a meaningful and obvious default value.” For value types, such as `int` and `double`, the obvious value is 0 (for `double`, that becomes 0.0). For `string`, the empty `string`, "", is the obvious choice. For `vector`, the empty `vector` serves well. For every type `T`, `T()` is the default value, if a default exists. For example, `double()` is 0.0, `string()` is "", and `vector<int>()` is the empty `vector` of `ints`.

A class needs a destructor if it acquires resources. A resource is something you “get from somewhere” and that you must give back once you have finished using it. The obvious example is memory that you get from the free store (using `new`) and have to give back to the free store (using `delete` or `delete[]`). Our `vector` acquires memory to hold its elements, so it has to give that memory back; therefore, it needs a destructor. Other resources that you might encounter as your programs increase in ambition and sophistication are files (if you open one, you also have to close it), locks, thread handles, and sockets (for communication with processes and remote computers).
Another sign that a class needs a destructor is simply that it has members that are pointers or references. If a class has a pointer or a reference member, it often needs a destructor and copy operations.

A class that needs a destructor almost always also needs a copy constructor and a copy assignment. The reason is simply that if an object has acquired a resource (and has a pointer member pointing to it), the default meaning of copy (shallow, memberwise copy) is almost certainly wrong. Again, vector is the classic example.

Similarly, a class that needs a destructor almost always also needs a move constructor and a move assignment. The reason is simply that if an object has acquired a resource (and has a pointer member pointing to it), the default meaning of copy (shallow, memberwise copy) is almost certainly wrong and the usual remedy (copy operations that duplicate the complete object state) can be expensive. Again, vector is the classic example.

In addition, a base class for which a derived class may have a destructor needs a virtual destructor (§17.5.2).

### 18.4.1 Explicit constructors

A constructor that takes a single argument defines a conversion from its argument type to its class. This can be most useful. For example:

```cpp
class complex {
public:
    complex(double); // defines double-to-complex conversion
    complex(double, double);
    // . . .
};

complex z1 = 3.14; // OK: convert 3.14 to (3.14,0)
complex z2 = complex(1.2, 3.4);
```

However, implicit conversions should be used sparingly and with caution, because they can cause unexpected and undesirable effects. For example, our vector, as defined so far, has a constructor that takes an int. This implies that it defines a conversion from int to vector. For example:

```cpp
class vector {
    // . . .
    vector(int);
    // . . .
};
```
vector v = 10;  // odd: makes a vector of 10 doubles
v = 20;          // eh! Assigns a new vector of 20 doubles to v
void f(const vector&);
  f(10);          // eh? Calls f with a new vector of 10 doubles

It seems we are getting more than we have bargained for. Fortunately, it is simple to suppress this use of a constructor as an implicit conversion. A constructor-defined *explicit* provides only the usual construction semantics and not the implicit conversions. For example:

class vector {
    // . . .
    explicit vector(int);
    // . . .
};

vector v = 10;  // error: no int-to-vector conversion
v = 20;          // error: no int-to-vector conversion
vector v0(10);  // OK
void f(const vector&);
  f(10);          // error: no int-to-vector<double> conversion
  f(vector(10));  // OK

To avoid surprising conversions, we — and the standard — define vector’s single-argument constructors to be *explicit*. It’s a pity that constructors are not *explicit* by default; if in doubt, make any constructor that can be invoked with a single argument *explicit*.

### 18.4.2 Debugging constructors and destructors

Constructors and destructors are invoked at well-defined and predictable points of a program’s execution. However, we don’t always write *explicit* calls, such as `vector(2)`; rather we do something, such as declaring a `vector`, passing a `vector` as a by-value argument, or creating a `vector` on the free store using `new`. This can cause confusion for people who think in terms of syntax. There is not just a single syntax that triggers a constructor. It is simpler to think of constructors and destructors this way:

- Whenever an object of type `X` is created, one of `X`’s constructors is invoked.
- Whenever an object of type `X` is destroyed, `X`’s destructor is invoked.
A destructor is called whenever an object of its class is destroyed; that happens when names go out of scope, the program terminates, or delete is used on a pointer to an object. A constructor (some appropriate constructor) is invoked whenever an object of its class is created; that happens when a variable is initialized, when an object is created using new (except for built-in types), and whenever an object is copied.

But when does that happen? A good way to get a feel for that is to add print statements to constructors, assignment operations, and destructors and then just try. For example:

```cpp
struct X {
    int val;

    void out(const string& s, int nv)
    {
        cerr << this << "\n" << s << ": " << val << " (" << nv << ")\n"; }

    X() { out("X()",0); val=0; } // default constructor
    X(int v) { val=v; out("X(int)",v); }
    X(const X& x) { val=x.val; out("X(X&) ",x.val); } // copy constructor
    X& operator=(const X& a) // copy assignment
    { out("X::operator=()",a.val); val=a.val; return *this; }
    ~X() { out("~X()",0); } // destructor
};
```

Anything we do with this X will leave a trace that we can study. For example:

```cpp
X glob(2); // a global variable
X copy(X a) { return a; }
X copy2(X a) { X aa = a; return aa; }
X& ref_to(X& a) { return a; }
X* make(int i) { X a(i); return new X(a); }
struct XX { X a; X b; };

int main()
{
    X loc (4); // local variable
    X loc2 (loc); // copy construction
```
loc = X(5);  // copy assignment
loc2 = copy(loc);  // call by value and return
loc2 = copy2(loc);
X loc3 {6};
X& r = ref_to(loc);  // call by reference and return
delete make(7);
delete make(8);
vector<X> v(4);  // default values
XX loc4;
X* p = new X(9);  // an X on the free store
delete p;
X* pp = new X[5];  // an array of Xs on the free store
delete[] pp;
}

Try executing that.

**TRY THIS**

We really mean it: do run this example and make sure you understand the result. If you do, you’ll understand most of what there is to know about construction and destruction of objects.

Depending on the quality of your compiler, you may note some “missing copies” relating to our calls of `copy()` and `copy2()`. We (humans) can see that those functions do nothing: they just copy a value unmodified from input to output. If a compiler is smart enough to notice that, it is allowed to eliminate the calls to the copy constructor. In other words, a compiler is allowed to assume that a copy constructor copies and does nothing but copy. Some compilers are smart enough to eliminate many spurious copies. However, compilers are not guaranteed to be that smart, so if you want portable performance, consider move operations (§18.3.4).

Now consider: Why should we bother with this “silly class X”? It’s a bit like the finger exercises that musicians have to do. After doing them, other things — things that matter — become easier. Also, if you have problems with constructors and destructors, you can insert such print statements in constructors for your real classes to see that they work as intended. For larger programs, this exact kind of tracing becomes tedious, but similar techniques apply. For example, you can determine whether you have a memory leak by seeing if the number of constructions minus the number of destructions equals zero. Forgetting to define copy constructors and copy assignments for classes that allocate memory or hold pointers to objects is a common — and easily avoidable — source of problems.
If your problems get too big to handle by such simple means, you will have learned enough to be able to start using the professional tools for finding such problems; they are often referred to as “leak detectors.” The ideal, of course, is not to leak memory by using techniques that avoid such leaks.

18.5 Access to vector elements

So far (§17.6), we have used set() and get() member functions to access elements. Such uses are verbose and ugly. We want our usual subscript notation: v[i]. The way to get that is to define a member function called operator[]. Here is our first (naive) try:

```cpp
class vector {
    int sz;       // the size
    double* elem; // a pointer to the elements
public:
    // ...
    double operator[](int n) { return elem[n]; }    // return element
};
```

That looks good and especially it looks simple, but unfortunately it is too simple. Letting the subscript operator (operator[]) return a value enables reading but not writing of elements:

```cpp
vector v(10);
double x = v[2];    // fine
```

Here, v[i] is interpreted as a call v.operator[](i), and that call returns the value of v’s element number i. For this overly naive vector, v[3] is a floating-point value, not a floating-point variable.

**TRY THIS**

Make a version of this vector that is complete enough to compile and see what error message your compiler produces for v[3]=x;

Our next try is to let operator[] return a pointer to the appropriate element:

```cpp
class vector {
    int sz;       // the size
    double* elem; // a pointer to the elements
};
```
**18.5 ACCESS TO VECTOR ELEMENTS**

```c++
public:
    //...
    double* operator[](int n) { return &elem[n]; }  // return pointer

Given that definition, we can write

```c++
vector v(10);
for (int i=0; i<v.size(); ++i) {
    // works, but still too ugly
    *v[i] = i;
    cout << *v[i];
}
```

Here, \(v[i]\) is interpreted as a call `v.operator[](i)`, and that call returns a pointer to \(v\)'s element number \(i\). The problem is that we have to write `*` to dereference that pointer to get to the element. That's almost as bad as having to write `set()` and `get()`. Returning a reference from the subscript operator solves this problem:

```c++
class vector {
    //...
    double& operator[](int n) { return elem[n]; }  // return reference

Now we can write

```c++
vector v(10);
for (int i=0; i<v.size(); ++i) {
    // works!
    v[i] = i;  // v[i] returns a reference element i
    cout << v[i];
}
```

We have achieved the conventional notation: \(v[i]\) is interpreted as a call `v.operator[](i)`, and that returns a reference to \(v\)'s element number \(i\).

**18.5.1 Overloading on const**

The `operator[]()` defined so far has a problem: it cannot be invoked for a `const vector`. For example:

```c++
void f(const vector& cv)
{
    double d = cv[1];    // error, but should be fine
    cv[1] = 2.0;         // error (as it should be)
}
```
The reason is that our `vector::operator[](int)()` could potentially change a `vector`. It doesn’t, but the compiler doesn’t know that because we “forgot” to tell it. The solution is to provide a version that is a `const` member function (see §9.7.4). That’s easily done:

```cpp
class vector {
    // . . .
    double& operator[](int n);           // for non-const vectors
    double operator[](int n) const;   // for const vectors
};
```

We obviously couldn’t return a `double&` from the `const` version, so we returned a `double` value. We could equally well have returned a `const double&`, but since a `double` is a small object there would be no point in returning a reference (§8.5.6), so we decided to pass it back by value. We can now write

```cpp
void ff(const vector& cv, vector& v) {
    double d = cv[1];               // fine (uses the const [])
    cv[1] = 2.0;                          // error (uses the const [])
    double d = v[1];                 // fine (uses the non-const [])
    v[1] = 2.0;                            // fine (uses the non-const [])
}
```

Since `vectors` are often passed by `const` reference, this `const` version of `operator[]()` is an essential addition.

## 18.6 Arrays

For a while, we have used `array` to refer to a sequence of objects allocated on the free store. We can also allocate arrays elsewhere as named variables. In fact, they are common

- As global variables (but global variables are most often a bad idea)
- As local variables (but arrays have serious limitations there)
- As function arguments (but an array doesn’t know its own size)
- As class members (but member arrays can be hard to initialize)

Now, you might have detected that we have a not-so-subtle bias in favor of `vectors` over arrays. Use `std::vector` where you have a choice — and you have a choice in most contexts. However, arrays existed long before `vectors` and are roughly equivalent to what is offered in other languages (notably C), so you must know
arrays, and know them well, to be able to cope with older code and with code written by people who don’t appreciate the advantages of vector.

So, what is an array? How do we define an array? How do we use an array? An array is a homogeneous sequence of objects allocated in contiguous memory; that is, all elements of an array have the same type and there are no gaps between the objects of the sequence. The elements of an array are numbered from 0 upward. In a declaration, an array is indicated by “square brackets”:

```c
const int max = 100;
int gai[max];                  // a global array (of 100 ints); “lives forever”

void f(int n)
{
    char lac[20];        // local array; “lives” until the end of scope
    int lai[60];
    double lad[n];    // error: array size not a constant
    // . . .
}
```

Note the limitation: the number of elements of a named array must be known at compile time. If you want the number of elements to be a variable, you must put it on the free store and access it through a pointer. That’s what vector does with its array of elements.

Just like the arrays on the free store, we access named arrays using the subscript and dereference operators ([ ] and *). For example:

```c
void f2()
{
    char lac[20];          // local array; “lives” until the end of scope

    lac[7] = 'a';          // equivalent to lac[0] = 'a'
    *lac = 'b';            // equivalent to lac[0] = 'b'
    lac[−2] = 'b';         // huh?
    lac[200] = 'c';        // huh?
}
```

This function compiles, but we know that “compiles” doesn’t mean “works correctly.” The use of [ ] is obvious, but there is no range checking, so f2() compiles, and the result of writing to lac[−2] and lac[200] is (as for all out-of-range access) usually disastrous. Don’t do it. Arrays do not range check. Again, we are dealing directly with physical memory here; don’t expect “system support.”
But couldn’t the compiler see that \texttt{lac} has just 20 elements so that \texttt{lac[200]} is an error? A compiler could, but as far as we know no production compiler does. The problem is that keeping track of array bounds at compile time is impossible in general, and catching errors in the simplest cases (like the one above) only is not very helpful.

### 18.6.1 Pointers to array elements

A pointer can point to an element of an array. Consider:

```c
double ad[10];
double* p = &ad[5]; // point to ad[5]
```

We now have a pointer \texttt{p} to the \texttt{double} known as \texttt{ad[5]}:

We can subscript and dereference that pointer:

```c
*p = 7;
p[2] = 6;
p[-3] = 9;
```

We get

That is, we can subscript the pointer with both positive and negative numbers. As long as the resulting element is in range, all is well. However, access outside the range of the array pointed into is illegal (as with free-store-allocated arrays; see §17.4.3). Typically, access outside an array is not detected by the compiler and (sooner or later) is disastrous.
Once a pointer points into an array, addition and subscripting can be used to make it point to another element of the array. For example:

\[ p += 2; \]  
\[ \text{move } p \text{ 2 elements to the right} \]

We get

\[ p: \]

\[ \text{ad}: \]

\[ 9 \quad 7 \quad 6 \]

And

\[ p -= 5; \]  
\[ \text{move } p \text{ 5 elements to the left} \]

We get

\[ p: \]

\[ \text{ad}: \]

\[ 9 \quad 7 \quad 6 \]

Using \(+\), \(-\), \(\+=\), and \(-=\) to move pointers around is called \textit{pointer arithmetic}. Obviously, if we do that, we have to take great care to ensure that the result is not a pointer to memory outside the array:

\[ p += 1000; \]  
\[ \text{insane: } p \text{ points into an array with just 10 elements} \]

\[ \text{double } d = *p; \]  
\[ \text{illegal: probably a bad value} \]
\[ \text{(definitely an unpredictable value)} \]

\[ *p = 12.34; \]  
\[ \text{illegal: probably scrambles some unknown data} \]

Unfortunately, not all bad bugs involving pointer arithmetic are that easy to spot. The best policy is usually simply to avoid pointer arithmetic.

The most common use of pointer arithmetic is incrementing a pointer (using \(+\)) to point to the next element and decrementing a pointer (using \(-\)) to point
to the previous element. For example, we could print the value of \texttt{ad}'s elements like this:

\begin{verbatim}
for (double* p = &ad[0]; p<&ad[10]; ++p) cout << *p << \'n\';
\end{verbatim}

Or backward:

\begin{verbatim}
for (double* p = &ad[9]; p>=&ad[0]; --p) cout << *p << \'n\';
\end{verbatim}

This use of pointer arithmetic is not uncommon. However, we find the last (“back-
ward”) example quite easy to get wrong. Why \&ad[9] and not \&ad[10]? Why >=
and not >? These examples could equally well (and equally efficiently) be done
using subscripting. Such examples could be done equally well using subscripting
into a \texttt{vector}, which is more easily range checked.

Note that most real-world uses of pointer arithmetic involve a pointer passed
as a function argument. In that case, the compiler doesn't have a clue how many
elements are in the array pointed into: you are on your own. That is a situation
we prefer to stay away from whenever we can.

Why does C++ have (allow) pointer arithmetic at all? It can be such a bother
and doesn't provide anything new once we have subscripting. For example:

\begin{verbatim}
double* p1 = &ad[0];
double* p2 = p1+7;
double* p3 = &p1[7];
if (p2 != p3) cout << "impossible!\n";
\end{verbatim}

Mainly, the reason is historical. These rules were crafted for C decades ago and
can't be removed without breaking a lot of code. Partly, there can be some con-
venience gained by using pointer arithmetic in some important low-level applica-
tions, such as memory managers.

\textbf{18.6.2 Pointers and arrays}

The name of an array refers to all the elements of the array. Consider:

\begin{verbatim}
char ch[100];
\end{verbatim}

The size of \texttt{ch}, \texttt{sizeof(ch)}, is 100. However, the name of an array turns into (“de-
cays to”) a pointer with the slightest excuse. For example:

\begin{verbatim}
char* p = ch;
\end{verbatim}

Here \texttt{p} is initialized to \&ch[0] and \texttt{sizeof(p)} is something like 4 (not 100).
This can be useful. For example, consider a function `strlen()` that counts the number of characters in a zero-terminated array of characters:

```c
int strlen(const char* p) // similar to the standard library strlen()
{
    int count = 0;
    while (*p) { ++count; ++p; }
    return count;
}
```

We can now call this with `strlen(ch)` as well as `strlen(&ch[0])`. You might point out that this is a very minor notational advantage, and we'd have to agree.

One reason for having array names convert to pointers is to avoid accidentally passing large amounts of data by value. Consider:

```c
int strlen(const char a[]) // similar to the standard library strlen()
{
    int count = 0;
    while (a[count]) { ++count; }
    return count;
}
```

```c
char lots[100000];

void f()
{
    int nchar = strlen(lots); // . . .
}
```

Naively (and quite reasonably), you might expect this call to copy the 100,000 characters specified as the argument to `strlen()`, but that’s not what happens. Instead, the argument declaration `char p[]` is considered equivalent to `char* p`, and the call `strlen(lots)` is considered equivalent to `strlen(&lots[0])`. This saves you from an expensive copy operation, but it should surprise you. Why should it surprise you? Because in every other case, when you pass an object and don’t explicitly declare an argument to be passed by reference (§8.5.3–6), that object is copied.

Note that the pointer you get from treating the name of an array as a pointer to its first element is a value and not a variable, so you cannot assign to it:

```c
char ac[10];
ac = new char [20]; // error: no assignment to array name
&ac[0] = new char [20]; // error: no assignment to pointer value
```
Finally! A problem that the compiler will catch!

As a consequence of this implicit array-name-to-pointer conversion, you can’t even copy arrays using assignment:

```c
int x[100];
int y[100];
// . . .
x = y;            // error
int z[100] = y;  // error
```

This is consistent, but often a bother. If you need to copy an array, you must write some more elaborate code to do so. For example:

```c
for (int i=0; i<100; ++i) x[i] = y[i];   // copy 100 ints
memcpy(x, y, 100*sizeof(int));       // copy 100*sizeof(int) bytes
copy(y, y+100, x);                            // copy 100 ints
```

Note that the C language doesn’t support anything like `vector`, so in C, you must use arrays extensively. This implies that a lot of C++ code uses arrays (§27.1.2). In particular, C-style strings (zero-terminated arrays of characters; see §27.5) are very common.

If we want assignment, we have to use something like the standard library `vector`. The `vector` equivalent to the copying code above is

```c
vector<int> x(100);
vector<int> y(100);
// . . .
x = y;            // copy 100 ints
```

### 18.6.3 Array initialization

An array of `char` can be initialized with a string literal. For example:

```c
char ac[] = "Beorn";
```

Count those characters. There are five, but `ac` becomes an array of six characters because the compiler adds a terminating zero character at the end of a string literal:

```
ac:  'B'|'e'|'o'|'r'|'n'| 0
```
A zero-terminated string is the norm in C and many systems. We call such a zero-terminated array of characters a *C-style string*. All string literals are C-style strings.

For example:

```c
char* pc = "Howdy";  // pc points to an array of 6 chars
```

Graphically:

```
pc: [H o w d y 0]
```

Note that the `char` with the numeric value 0 is not the character '0' or any other letter or digit. The purpose of that terminating zero is to allow functions to find the end of the string. Remember: An array does not know its size. Relying on the terminating zero convention, we can write

```c
int strlen(const char* p)  // similar to the standard library strlen()
{
    int n = 0;
    while (p[n]) ++n;
    return n;
}
```

Actually, we don’t have to define `strlen()` because it is a standard library function defined in the `<string.h>` header (§27.5, §B.11.3). Note that `strlen()` counts the characters, but not the terminating 0; that is, you need \(n+1\) characters to store \(n\) characters in a C-style string.

Only character arrays can be initialized by literal strings, but all arrays can be initialized by a list of values of their element type. For example:

```c
int ai[] = { 1, 2, 3, 4, 5, 6 };  // array of 6 ints
int ai2[100] = {0,1,2,3,4,5,6,7,8,9};  // the last 90 elements are initialized to 0
double ad[100] = { };  // all elements initialized to 0.0
char chars[] = {'a', 'b', 'c'};  // no terminating 0!
```

Note that the number of elements of `ai` is six (not seven) and the number of elements for `chars` is three (not four) – the “add a 0 at the end” rule is for literal character strings only. If an array isn’t given a size, that size is deduced from the initializer list. That’s a rather useful feature. If there are fewer initializer values
than array elements (as in the definitions of \( a_{i2} \) and \( a_d \)), the remaining elements are initialized by the element type’s default value.

### 18.6.4 Pointer problems

Like arrays, pointers are often overused and misused. Often, the problems people get themselves into involve both pointers and arrays, so we’ll summarize the problems here. In particular, all serious problems with pointers involve trying to access something that isn’t an object of the expected type, and many of those problems involve access outside the bounds of an array. Here we will consider

- Access through the null pointer
- Access through an uninitialized pointer
- Access off the end of an array
- Access to a deallocated object
- Access to an object that has gone out of scope

In all cases, the practical problem for the programmer is that the actual access looks perfectly innocent; it is “just” that the pointer hasn’t been given a value that makes the use valid. Worse (in the case of a write through the pointer), the problem may manifest itself only a long time later when some apparently unrelated object has been corrupted. Let’s consider examples:

**Don’t access through the null pointer:**

```c
int* p = nullptr;
*p = 7;            // ouch!
```

Obviously, in real-world programs, this typically occurs when there is some code in between the initialization and the use. In particular, passing \( p \) to a function and receiving it as the result from a function are common examples. We prefer not to pass null pointers around, but if you have to, test for the null pointer before use:

```c
int* p = fct_that_can_return_a_nullptr();

if (p == nullptr) {
    // do something
}
else {
    // use p
    *p = 7;
}
```
and

```cpp
void fct_that_can_receive_a_nullptr(int* p)
{
    if (p == nullptr) {
        // do something
    }
    else {
        // use p
        *p = 7;
    }
}
```

Using references (§17.9.1) and using exceptions to signal errors (§5.6 and §19.5) are the main tools for avoiding null pointers.

*Do initialize your pointers:*

```cpp
int* p;
*p = 9;       // ouch!
```

In particular, don’t forget to initialize pointers that are class members.

*Don’t access nonexistent array elements:*

```cpp
int a[10];
int* p = &a[10];
*p = 11;       // ouch!
a[10] = 12;    // ouch!
```

Be careful with the first and last elements of a loop, and try not to pass arrays around as pointers to their first elements. Instead use *vectors*. If you really must use an array in more than one function (passing it as an argument), then be extra careful and pass its size along.

*Don’t access through a deleted pointer:*

```cpp
int* p = new int(7);
// . . .
delete p;
// . . .
*p = 13;       // ouch!
```

The *delete p* or the code after it may have scribbled all over *p* or used it for something else. Of all of these problems, we consider this one the hardest to
systematically avoid. The most effective defense against this problem is not to have “naked” news that require “naked” deletes: use new and delete in constructors and destructors or use a container, such as Vector_ref (§E.4), to handle deletes.

Don’t return a pointer to a local variable:

\begin{verbatim}
int* f()
{
    int x = 7;
    // . . .
    return &x;
}

// . . .

int* p = f();
// . . .
*p = 15;             // ouch!
\end{verbatim}

The return from f() or the code after it may have scribbled all over *p or used it for something else. The reason for that is that the local variables of a function are allocated (on the stack) upon entry to the function and deallocated again at the exit from the function. In particular, destructors are called for local variables of classes with destructors (§17.5.1). Compilers could catch most problems related to returning pointers to local variables, but few do.

Consider a logically equivalent example:

\begin{verbatim}
vector& ff()
{
    vector x(7);   // 7 elements
    // . . .
    return x;
}       // the vector x is destroyed here

// . . .

vector& p = ff();
// . . .
\end{verbatim}

Quite a few compilers catch this variant of the return problem.

It is common for programmers to underestimate these problems. However, many experienced programmers have been defeated by the innumerable varia-
tions and combinations of these simple array and pointer problems. The solution is not to litter your code with pointers, arrays, `new`, and `delete`. If you do, “being careful” simply isn’t enough in realistically sized programs. Instead, rely on vectors, RAII (“Resource Acquisition Is Initialization”; see §19.5), and other systematic approaches to the management of memory and other resources.

### 18.7 Examples: palindrome

Enough technical examples! Let’s try a little puzzle. A palindrome is a word that is spelled the same from both ends. For example, anna, petep, and malayalam are palindromes, whereas ida and homesick are not. There are two basic ways of determining whether a word is a palindrome:

- Make a copy of the letters in reverse order and compare that copy to the original.
- See if the first letter is the same as the last, then see if the second letter is the same as the second to last, and keep going until you reach the middle.

Here, we’ll take the second approach. There are many ways of expressing this idea in code depending on how we represent the word and how we keep track of how far we have come with the comparison of characters. We’ll write a little program that tests whether words are palindromes in a few different ways just to see how different language features affect the way the code looks and works.

#### 18.7.1 Palindromes using string

First, we try a version using the standard library string with `int` indices to keep track of how far we have come with our comparison:

```cpp
bool is_palindrome(const string& s)
{
    int first = 0;       // index of first letter
    int last = s.length() - 1; // index of last letter
    while (first < last) {
        // we haven’t reached the middle
        if (s[first] != s[last]) return false;
        ++first;            // move forward
        --last;             // move backward
    }
    return true;
}
```

We return `true` if we reach the middle without finding a difference. We suggest that you look at this code to convince yourself that it is correct when there are no
letters in the string, just one letter in the string, an even number of letters in the string, and an odd number of letters in the string. Of course, we should not just rely on logic to see that our code is correct. We should also test. We can exercise \texttt{is\_palindrome()} like this:

\begin{verbatim}
int main()
{
   for (string s; cin >> s; ) {
      cout << s << " is";
      if (!is_palindrome(s)) cout << " not";
      cout << " a palindrome\n";
   }
}
\end{verbatim}

Basically, the reason we are using a \texttt{string} is that "\texttt{strings} are good for dealing with words." It is simple to read a whitespace-separated word into a string, and a \texttt{string} knows its size. Had we wanted to test \texttt{is\_palindrome()} with strings containing whitespace, we could have read using \texttt{getline} (§11.5). That would have shown \texttt{ah ha} and \texttt{as df fd sa} to be palindromes.

18.7.2 Palindromes using arrays

What if we didn’t have \texttt{strings} (or \texttt{vectors}), so that we had to use an array to store the characters? Let’s see:

\begin{verbatim}
bool is_palindrome(const char s[], int n)
   // s points to the first character of an array of n characters
{
   int first = 0;                        // index of first letter
   int last = n - 1;                   // index of last letter
   while (first < last) {               // we haven't reached the middle
      if (s[first] != s[last]) return false;
      ++first;               // move forward
      --last;               // move backward
   }
   return true;
}
\end{verbatim}

To exercise \texttt{is\_palindrome()}, we first have to get characters read into the array. One way to do that safely (i.e., without risk of overflowing the array) is like this:

\begin{verbatim}
istream& read_word(istream&, char* buffer, int max)
   // read at most max- 1 characters from is into buffer
\end{verbatim}
18.7 EXAMPLES: PALINDROME

```cpp
{ 
is.width(max); // read at most max–1 characters in the next >>
is >> buffer; // read whitespace-terminated word,
              // add zero after the last character read into buffer
return is;
}
```

Setting the `istream`'s width appropriately prevents buffer overflow for the next `>>` operation. Unfortunately, it also means that we don’t know if the read terminated by whitespace or by the buffer being full (so that we need to read more characters). Also, who remembers the details of the behavior of `width()` for input? The standard library `string` and `vector` are really better as input buffers because they expand to fit the amount of input. The terminating `0` character is needed because most popular operations on arrays of characters (C-style strings) assume `0` termination. Using `read_word()` we can write

```cpp
int main()
{
    constexpr int max = 128;
    for (char s[max]; read_word(cin,s,max); ) {
        cout << s << " is";
        if (is_palindrome(s,strlen(s))) cout << " not";
        cout << " a palindrome\n";
    }
}
```

The `strlen(s)` call returns the number of characters in the array after the call of `read_word()`, and `cout<<s` outputs the characters in the array up to the terminating `0`.

We consider this “array solution” significantly messier than the “`string` solution,” and it gets much worse if we try to seriously deal with the possibility of long strings. See exercise 10.

18.7.3 Palindromes using pointers

Instead of using indices to identify characters, we could use pointers:

```cpp
bool is_palindrome(const char* first, const char* last)
// first points to the first letter, last to the last letter
{
    while (first < last) { // we haven't reached the middle
        if (*first != *last) return false;
        ++first; // move forward
        --last; // move backward
    }
```

Note that we can actually increment and decrement pointers. Increment makes a pointer point to the next element of an array and decrement makes a pointer point to the previous element. If the array doesn’t have such a next element or previous element, you have a serious uncaught out-of-range error. That’s another problem with pointers.

We call this `is_palindrome()` like this:

```cpp
bool is_palindrome(const char* first, const char* last)
   // first points to the first letter, last to the last letter
{
   if (first<last) {
      if (*first!=*last) return false;
      return is_palindrome(first+1,last-1);
   }
   return true;
}
```

This code becomes obvious when we rephrase the definition of palindrome: a word is a palindrome if the first and the last characters are the same and if the substring you get by removing the first and the last characters is a palindrome.
Drill

In this chapter, we have two drills: one to exercise arrays and one to exercise vectors in roughly the same manner. Do both and compare the effort involved in each.

**Array drill:**

1. Define a global `int` array `ga` of ten `ints` initialized to 1, 2, 4, 8, 16, etc.
2. Define a function `f()` taking an `int` array argument and an `int` argument indicating the number of elements in the array.
3. In `f()`:
   a. Define a local `int` array `la` of ten `ints`.
   b. Copy the values from `ga` into `la`.
   c. Print out the elements of `la`.
   d. Define a pointer `p` to `int` and initialize it with an array allocated on the free store with the same number of elements as the argument array.
   e. Copy the values from the argument array into the free-store array.
   f. Print out the elements of the free-store array.
   g. Deallocate the free-store array.
4. In `main()`:
   a. Call `f()` with `ga` as its argument.
   b. Define an array `aa` with ten elements, and initialize it with the first ten factorial values (1, 2*1, 3*2*1, 4*3*2*1, etc.).
   c. Call `f()` with `aa` as its argument.

**Standard library vector drill:**

1. Define a global `vector<int>` `gv`; initialize it with ten `ints`, 1, 2, 4, 8, 16, etc.
2. Define a function `f()` taking a `vector<int>` argument.
3. In `f()`:
   a. Define a local `vector<int>` `lv` with the same number of elements as the argument `vector`.
   b. Copy the values from `gv` into `lv`.
   c. Print out the elements of `lv`.
   d. Define a local `vector<int>` `lv2`; initialize it to be a copy of the argument `vector`.
   e. Print out the elements of `lv2`.
4. In `main()`:
   a. Call `f()` with `gv` as its argument.
   b. Define a `vector<int>` `vv`, and initialize it with the first ten factorial values (1, 2*1, 3*2*1, 4*3*2*1, etc.).
   c. Call `f()` with `vv` as its argument.
Review

1. What does “Caveat emptor!” mean?
2. What is the default meaning of copying for class objects?
3. When is the default meaning of copying of class objects appropriate?
   When is it inappropriate?
4. What is a copy constructor?
5. What is a copy assignment?
6. What is the difference between copy assignment and copy initialization?
7. What is shallow copy? What is deep copy?
8. How does the copy of a vector compare to its source?
9. What are the five “essential operations” for a class?
10. What is an explicit constructor? Where would you prefer one over the (default) alternative?
11. What operations may be invoked implicitly for a class object?
12. What is an array?
13. How do you copy an array?
14. How do you initialize an array?
15. When should you prefer a pointer argument over a reference argument?
   Why?
16. What is a C-style string?
17. What is a palindrome?

Terms

- array
- array initialization
- copy assignment
- copy constructor
- deep copy
- default constructor
- essential operations
- explicit constructor
- move assignment
- move construction
- palindrome
- shallow copy

Exercises

1. Write a function, `char* strdup(const char*)`, that copies a C-style string into memory it allocates on the free store. Do not use any standard library functions. Do not use subscripting; use the dereference operator `*` instead.
2. Write a function, `char* findx(const char* s, const char* x)`, that finds the first occurrence of the C-style string `x` in `s`. Do not use any standard library functions. Do not use subscripting; use the dereference operator `*` instead.
3. Write a function, `int strcmp(const char* s1, const char* s2)`, that compares C-style strings. Let it return a negative number if `s1` is lexicographically
before \( s_2 \), zero if \( s_1 \) equals \( s_2 \), and a positive number if \( s_1 \) is lexicographically after \( s_2 \). Do not use any standard library functions. Do not use subscripting; use the dereference operator \* instead.

4. Consider what happens if you give \texttt{strdup()}, \texttt{findx()}, and \texttt{strcmp()} an argument that is not a C-style string. Try it! First figure out how to get a \texttt{char*} that doesn’t point to a zero-terminated array of characters and then use it (never do this in real — non-experimental — code; it can create havoc). Try it with free-store-allocated and stack-allocated “fake C-style strings.” If the results still look reasonable, turn off debug mode. Redesign and re-implement those three functions so that they take another argument giving the maximum number of elements allowed in argument strings. Then, test that with correct C-style strings and “bad” strings.

5. Write a function, \texttt{string cat_dot(const string& s1, const string& s2)}, that concatenates two strings with a dot in between. For example, \texttt{cat_dot("Niels", "Bohr")} will return a string containing \texttt{Niels.Bohr}.

6. Modify \texttt{cat_dot()} from the previous exercise to take a string to be used as the separator (rather than dot) as its third argument.

7. Write versions of the \texttt{cat_dot()}s from the previous exercises to take C-style strings as arguments and return a free-store-allocated C-style string as the result. Do not use standard library functions or types in the implementation. Test these functions with several strings. Be sure to free (using \texttt{delete}) all the memory you allocated from free store (using \texttt{new}). Compare the effort involved in this exercise with the effort involved for exercises 5 and 6.

8. Rewrite all the functions in §18.7 to use the approach of making a backward copy of the string and then comparing; for example, take \texttt{"home"}, generate \texttt{"emoh"}, and compare those two strings to see that they are different, so \texttt{home} isn’t a palindrome.

9. Consider the memory layout in §17.4. Write a program that tells the order in which static storage, the stack, and the free store are laid out in memory. In which direction does the stack grow: upward toward higher addresses or downward toward lower addresses? In an array on the free store, are elements with higher indices allocated at higher or lower addresses?

10. Look at the “array solution” to the palindrome problem in §18.7.2. Fix it to deal with long strings by (a) reporting if an input string was too long and (b) allowing an arbitrarily long string. Comment on the complexity of the two versions.

11. Look up (e.g., on the web) \texttt{skip list} and implement that kind of list. This is not an easy exercise.

12. Implement a version of the game “Hunt the Wumpus.” “Hunt the Wumpus” (or just “Wump”) is a simple (non-graphical) computer game originally invented by Gregory Yob. The basic premise is that a rather smelly
monster lives in a dark cave consisting of connected rooms. Your job is to slay the wumpus using bow and arrow. In addition to the wumpus, the cave has two hazards: bottomless pits and giant bats. If you enter a room with a bottomless pit, it’s the end of the game for you. If you enter a room with a bat, the bat picks you up and drops you into another room. If you enter the room with the wumpus or he enters yours, he eats you. When you enter a room you will be told if a hazard is nearby:

“I smell the wumpus”: It’s in an adjoining room.
“I feel a breeze”: One of the adjoining rooms is a bottomless pit.
“I hear a bat”: A giant bat is in an adjoining room.

For your convenience, rooms are numbered. Every room is connected by tunnels to three other rooms. When entering a room, you are told something like “You are in room 12; there are tunnels to rooms 1, 13, and 4; move or shoot?” Possible answers are m13 (“Move to room 13”) and s13–4–3 (“Shoot an arrow through rooms 13, 4, and 3”). The range of an arrow is three rooms. At the start of the game, you have five arrows. The snag about shooting is that it wakes up the wumpus and he moves to a room adjoining the one he was in – that could be your room.

Probably the trickiest part of the exercise is to make the cave by selecting which rooms are connected with which other rooms. You’ll probably want to use a random number generator (e.g., randint() from std_lib_facilities.h) to make different runs of the program use different caves and to move around the bats and the wumpus. Hint: Be sure to have a way to produce a debug output of the state of the cave.

**Postscript**

The standard library vector is built from lower-level memory management facilities, such as pointers and arrays, and its primary role is to help us avoid the complexities of those facilities. Whenever we design a class, we must consider initialization, copying, and destruction.
<. See Less than, 67, 1088

<. See Bitwise logical operations (left shift), 956, 1088

<=. See Less than or equal, 67, 1088

<=. See Bitwise logical operations (shift left and assign), 1090

<. . >. See Template (arguments and parameters), 153, 678–679

=: See
Assignment, 66, 1090
Initialization, 69–73, 1219

==. See Equal, 67, 1088

>. See
Greater than, 67, 1088
Input prompt, 223
Template (argument-list terminator), 679

>=. See Greater than or equal, 67, 1088

>>. See
Bitwise logical operations (right shift), 956, 1088
Input, 61, 365

>>>=. See Bitwise logical operations (shift right and assign), 1090

?. See
Conditional expression, 268, 1089
Regular expression, 867–868, 873, 874–875, 1178

[]. See
Array of (in declaration), 649, 1099
Regular expression (character class), 872, 1178
Subscripting, 594, 649, 1101

\ (backslash). See
Character literal, 1079–1080
Escape character, 1178
Regular expression (escape character), 866–867, 873, 877

^. See
Bitwise logical operations (exclusive or), 956, 1089, 1094
Regular expression (not), 873, 1178

^=. See Bitwise logical operations (xor and assign), 1090

_.. See Underscore, 75, 76, 1081

{. See
Block delimiter, 47, 111
Initialization, 83
List, 83
Regular expression (range), 867, 873–875, 1178

|-. See
Bitwise logical operations (bitwise or), 956, 1089, 1094
Regular expression (or), 867–868, 873, 876, 1178

|. See Bitwise logical operations (or and assign), 1090

||. See
Logical or, 1089, 1094

~. See
Bitwise logical operations (complement), 956, 1087
Destructors, 601–603

0 (zero). See
Null pointer, 598
Prefix, 382, 384
printf() format specifier, 1188–1189

0x. See Prefix, 382, 384

A

a, append file mode, 1186
\a alert, character literal, 1079
abort(), 1194–1195
abs(), absolute value, 917, 1181
complex, 920, 1183
Abstract classes, 495, 1217
class hierarchies, 512
creating, 495, 512, 1118–1119
Shape example, 495–496
Abstract-first approach to programming, 10
Abstraction, 92–93, 1217
level, ideals, 812–813
Access control, 306, 505, 511
base classes, 511
capsulation, 505
members, 492–493
private, 505, 511
private by default, 306–307
private: label, 306
private vs. public, 306–308
protected, 505, 511
protected: label, 511
public, 306, 505, 511
public by default, 307–308. See also struct
public: label, 306
Shape example, 496–499
accumulate(), 759, 770–772, 1183
accumulator, 770
generalizing, 772–774
acos(), arccosine, 917, 1182
INDEX

Action, 47
Activation record, 287. See also Stacks
Ada language, 832–833
Adaptors
bind(), 1164
container, 1144
function objects, 1164
mem_fn(), 1164
not1(), 1164
not2(), 1164
priority_queue, 1144
queue, 1144
stack, 1144
add(), 449–450, 491–492, 615–617
Add (plus) +, 66, 1088
Add and assign +=, 66, 73, 1090
Additive operators, 1088
Address, 588, 1217
unchecked conversions, 943–944
Address of (unary) &, 588, 1087
Ad hoc polymorphism, 682–683
Adjacent_difference(), 770, 1184
Adjacent_find(), 1153
Advance(), 615–617, 739, 1142
Affordability, software, 34
Age distribution example, 538–539
Alert markers, 3
Algol60 language, 827–829
Algol family of languages, 826–829
<algorithm>, 759, 1133
Algorithms, 1217
and containers, 722
header files, 1133–1134
numerical, 1183–1184
passing arguments to. See Function objects
Algorithms, numerical, 770, 1183–1184
Accumulate(), 759, 770–774, 1183
Adjacent_difference(), 770, 1184
Inner_product(), 759, 770, 774–776, 1184
Partial_sum(), 770, 1184
Algorithms, STL, 1152–1153
<algorithm>, 759
Binary_search(), 796
comparing elements, 759
copy(), 759, 789–790
copy_if(), 789
copying elements, 759
count(), 759
count_if(), 759
equal(), 759
equal_range(), 758, 796
find(), 758, 759–763
find_if(), 758, 763–764
heap, 1160
lower_bound(), 796
max(), 1161
merge(), 758
merging sorted sequences, 758
min(), 1161
modifying sequence, 1154–1156
mutating sequence, 1154–1156
nonmodifying sequence, 1153–1154
numerical. See Algorithms, numerical permutations, 1160–1161
search(), 795–796
searching, 1157–1159. See also find_if; find
set, 1159–1160
shuffled(), 1155–1156
sort(), 758, 794–796
sorting, 758, 794–796, 1157–1159
summing elements, 759
testing, 1001–1008
unique_copy(), 758, 789, 792–793
upper_bound(), 796
utility, 1157
value comparisons, 1161–1162
Aliases, 1128, 1217. See also References
Allocating memory. See also Deallocating memory;
Memory
allocator_type, 1147
bad_alloc exception, 1094
C++ and C, 1043–1044
calloc(), 1193
embedded systems, 935–936, 940–942
free store, 593–594
malloc(), 1043–1044, 1193
new, 1094–1095
pools, 940–941
realloc(), 1045
stacks, 942–943
allocator_type, 1147
Almost containers, 751, 1145
alnum, regex character class, 878, 1179
alpha, regex character class, 878, 1179
Alternation
patterns, 194
regular expressions, 876
Ambiguous function call, 1104
Analysis, 35, 176, 179
and, synonym for & , 1037, 1038
and_eq, synonym for &<, 1037, 1038
app mode, 389, 1170
append(), 851, 1177
Append
files, 389, 1186
string +=, 851
Application
collection of programs, 1218
operator (), 766
Approximation, 532–537, 1218
Arccosine, acos(), 917
Arcsine, asin(), 918
Arctangent, atan(), 918
arg(), of complex number, theta, 920, 1183
Argument deduction, 689–690
Argument errors
callee responsibility, 143–145
caller responsibility, 142–143
reasons for, 144–145
Arguments, 272, 1218
formal. See Parameters
functions, 1105–1106
passing. See Passing arguments
program input, 91
source of exceptions, 147–148
templates, 1122–1123
types, class interfaces, 324–326
uninitialized, 1029–1030, 1105–1106
unexpected, 136
Arithmetic if ?, 268. See also Conditional expression ?:
Arithmetic operations. See Numerics
<array>, 1133
Arrays, 648–650, 1218. See also Containers; vector
[] declaration, 649
[] dereferencing, 649
accessing elements, 649, 899–901
assignment, 653–654
associative. See Associative containers
built-in, 747–749
copying, 653–654
C-style strings, 654–655
dereferencing, 649
element numbering, 649
initializing, 596–598, 654–656
multidimensional, 895–897, 1102
palindrome example, 660–661
passing pointers to arrays, 944–951
pointers to elements, 650–652
range checking, 649
subscripting [], 649
terminating zero, 654–655
vector alternative, 947–951
Arrays and pointers, 651–658
debugging, 656–659
array standard library class, 747–749, 1144
asin(), arcsine, 918, 1182
asm(), assembler insert, 1037
Assemblers, 820
Assertions
assert(), 1061
cassert, 1135
debugging, 163
definition, 1218
assign(), 1148
Assignment =, 69–73
arrays, 653–654
assignment and initialization, 69–73
composite assignment operators, 73–74
containers, 1148
Date example, 309–310
enumerators, 318–319
expressions, 1089–1090
string, 851
vector, resizing, 673–677
Assignment operators (composite), 66
%==, 73, 1090
&=, 1090
*==, 73, 1089
+=, 73, 1090, 1141
-=, 73, 1090, 1142
/=, 73, 1090
<<, 1090
>>, 1090
^=, 1090
|, 1090
Assocative arrays. See Associative containers
Associative containers, 776, 1144
e-mail example, 856–860
header files, 776
map, 776
multimap, 776, 860–861
multiset, 776
operations, 1151–1152
set, 776
unordered_map, 776
unordered_multimap, 776
unordered_multiset, 776
unordered_set, 776
Assumptions, testing, 1009–1011
at(), range-checked subscripting, 693–694, 1149
atan(), arctangent, 918, 1182
ate mode, 389, 1170
atof(), string to double, 1192
atoi(), string to int, 1192
atold(), string to long, 1192
AT&T Bell Labs, 838
AT&T Labs, 838
attach() vs. add() example, 491–492
auto, 732–734, 760
Automatic storage, 591–592, 1083. See also Stack storage
Axis example, 424–426, 443, 529–532, 543–546

B
b, binary file mode, 1186
Babbage, Charles, 832
back(), last element, 737, 1149
back_inserter(), 1162
Backus, John, 823
Backus-Naur (BNF) Form, 823, 828
bad_alloc exception, 1094
bad() stream state, 355, 1171
Base-2 number system (binary), 1078–1079
Base-8 number system (octal), 1077–1078
Base-10 logarithms, 918
Base and member initializers, 315, 477, 555
base classes, 493–496, 504–507, 1218
abstract classes, 495, 512–513, 1118–1119
access control, 511
derived classes, 1116–1117
description, 504–506
initialization of, 477, 555, 1113, 1117
interface, 513–514
object layout, 506–507
overriding, 508–511
Shape example, 495–496
virtual function calls, 501, 506–507
vptr, 506
vtbl, 506
Base-e exponentials, 918

basic_string, 852
Basic guarantee, 702
BCPL language, 838
begin() iterator, 1148
string, 851, 1177
vector, 721
Bell Telephone Laboratories (Bell Labs), 836, 838–842, 1022–1023
Bentley, John, 933, 966
Bidirectional iterator, 1142
bidirectional iterators, 752
Big-O notation, complexity, 785
Binary I/O, 390–393
binary mode, 389, 1170
Binary number system, 1078–1079
Binary search, 758, 779, 795–796
binary_search(), 796, 1158
bind() adaptor, 1164
bitand, synonym for &, 1037, 1038
Bitfields, 956–957, 967–969, 1120–1121
bitor, synonym for |, 1038
Bits, 78, 954, 1218
bitfields, 956–957
bool, 955
char, 955
enumerations, 956
integer types, 955
manipulating, 965–967
signed, 961–965
size, 955–956
unsigned, 961–965
bitset, 1133
bitset, 959–961
bitwise logical operations, 960
construction, 959
exceptions, 1138
I/O, 960
Bitwise logical operations, 956–959, 1094
and &, 956–957, 1089, 1094
or |, 956, 1089, 1094
or and assign, |=, 966
and and assign &=, 1090
complement ~, 956
exclusive or ^, 956, 1089, 1094
exclusive or and assign ^=, 1089
left shift <<, 956
left shift and assign <<=, 1089
right shift >>, 956
right shift and assign >>=, 1089
INDEX

blackboard, 36
black-box testing, 992–993
blank, character class, regex, 878, 1179
Block, 111
debugging, 161
delimiter, 47, 111
nesting within functions, 271
try block, 146–147
Block comment /* . . . */, 238
Blue marginal alerts, 3
BNF (Backus-Naur) Form, 823, 828
Body, functions, 114
bool, 63, 66–67, 1099
bits in memory, 78
bit space, 955
C++ and C, 1026, 1038
size, 78
boolalpha, manipulator, 1173
Boolean conversions, 1092
Borland, 831
Bottom-up approach, 9, 811
Bounds error, 149
Branching, testing, 1006–1008. See also Conditional statements
break, case label termination, 106–108
Broadcast functions, 903
bsearch(), 1194–1195
Buffer, 348
flushing, 240–241
iostream, 406
overflow, 661, 792, 1006. See also gets(), scanf()
Bugs, 158, 1218. See also Debugging; Testing
finding the last, 166–167
first documented, 824–825
regression tests, 993
Built-in types, 304, 1099
arrays, 747–749, 1101–1102
bool, 77, 1100
characters, 77, 891, 1100
default constructors, 328
exceptions, 1126
floating-point, 77, 891–895, 961–965, 1100
integers, 77, 891–895, 961–965, 1100
pointers, 588–590, 1100–1101
references, 279–280, 1102–1103
Button example, 443, 561–563
attaching to menus, 571
detecting a click, 557
Byte, 78, 1218
operations, C-style strings, 1048–1049
C
.c suffix, 1029
.cpp suffix, 48, 1200
C# language, 831
C++ language, 839–842. See also Programming:
Programs; Software
coding standards, list of, 983
portability, 11
use for teaching, xxiv, 6–9
C++ and C, 1022–1024
C functions, 1028–1032
C linkage convention, 1033
C missing features, 1025–1027
calling one from the other, 1032–1034
casts, 1040–1041
compatibility, 1024–1025
const, 1054–1055
constants, 1054–1055
container example, 1059–1065
definitions, 1038–1040
enum, 1042
family tree, 1023
free-store, 1043–1045
input/output, 1050–1054
keywords, 1037–1038
layout rules, 1034
macros, 1054–1059
malloc(), 1043–1044
namespaces, 1042–1043
nesting structs, 1037
old-style casts, 1040
opaque types, 1060
performance, 1024
realloc(), 1045
structure tags, 1036–1037
type checking, 1032–1033
void, 1030
void*, 1041–1042
“C first” approach to programming, 9
C language, 836–839. See also C standard library
C++ compatibility, 1022–1024. See also C++ and C
K&R, 838, 1022–1023
linkage convention, 1033
missing features, 1025–1027
C standard library
C-style strings, 1191
header files, 1135
input/output. See C-style I/O (stdio)
memory, 1192–1193
C-style casts, 1040–1041, 1087, 1095
C-style I/O (stdio)
% , conversion specification, 1187
conversion specifications, 1188–1189
file modes, 1186
files, opening and closing, 1186
fprintf(), 1051–1052, 1187
getc(), 1052, 1191
getchar(), 1045, 1052–1053, 1191
gets(), 1052, 1190–1191
output formats, user-defined types, 1189–1190
padding, 1188
printf(), 1050–1051, 1187
scanf(), 1052–1053, 1190
stderr, 1189
stdin, 1189
stdout, 1189
truncation, 1189
C-style strings, 654–655, 1045–1047, 1191
byte operations, 1048–1049
const, 1047–1048
copying, 1046–1047, 1049
executing as a command, system(), 1194
operations, 1191–1192
pointer declaration, 1049–1050
strcat(), concatenate, 1047
strchr(), find character, 1048
strcmp(), compare, 1046
strcpy(), copy, 1047, 1049
from string, c_str(), 350, 851
strlen(), length of, 1046
strncat(), 1047
strncpy(), 1047
strncpy(), 1047
three-way comparison, 1046
C++ and C, 1026, 1038
casting away const, 609
const_cast, 1095
casts. See also Type conversion
casting away const, 609
C-style casts, 1040–1041
dynamic_cast, 932, 1095
lexical_cast example, 855
narrow_cast example, 153
reinterpret_cast, 609
static_cast, 609, 944, 1095
unrelated types, 609
CAT scans, 30
catch, 147, 1038
Catch all exceptions , 152
Catching exceptions, 146–153, 239–241, 1126
cb_next() example, 556–559
<ctype>, 1135, 1175
ceil(), 917, 1181
cerr, 151, 1169, 1189
 cerr, 1135
<cerrno>, 1135
<cstdlib>, 1135
<cmath>, 1135
<chtime>, 1135
Chaining operations, 180–181
Character classes
list of, 1179
in regular expressions, 873–874, 878
Character classification, 397–398, 1175–1176
Character literals, 161, 1079–1080
CHAR_BIT limit macro, 1181
CHAR_MAX limit macro, 1181
CHAR_MIN limit macro, 1181
char type, 63, 66–67, 78
bits, 955
built-in, 1099
properties, 741–742
signed vs. unsigned, 894, 964
cin, 61
C equivalent. See stdin
standard character input, 61, 347, 1169
Circle example, 469–472, 497
to, Ellipse, 474
Circular reference. See Reference (circular)
class, 183, 1036–1037
Class
abstract, 495, 512–513, 1118–1119. See also
Abstract classes
base, 504–506
coding standards, 981
concrete, 495–496, 1218
const member functions, 1110
constructors, 1112–1114, 1119–1120
copying, 1115, 1119
creating objects. See Concrete classes
default constructors, 327–330
defining, 212, 305, 1108, 1218
derived, 504
destructors, 1114–1115, 1119
encapsulation, 505
friend declaration, 1111
generated operations, 1119–1120
grouping related, 512
hierarchies, 512
history of, 834
implementation, 306–308
inheritance, 504–505, 513–514
interface, 513–514
member access. See Access control
definition, 1112
function, 314–316
out-of-class definition, 1112
Token_stream example, 212
Token example, 183–184
Class scope, 267, 1083
Class template
parameterized class, 682–683
parameterized type, 682–683
specialization, 681
type generators, 681
classic_elimination() example, 910–911
Cleaning up code
comments, 237–238
functions, 234–235
layout, 235–236
logical separations, 234–235
revision history, 237–238
scaffolding, 234–235
symbolic constants, 232–234
clear(), 355–358, 1150
<climits>, 1135
<clocale>, 1135
Computers, continued
in daily life, 19–21
information processing, 32
Mars Rover, 33
medicine, 30
pervasiveness of, 19–21
server farms, 31–32
shipping, 26–28
space exploration, 33
telecommunications, 28–29
timekeeping, 26
world total, 19
Computer science, 12, 24–25
Concatenation of strings, 66
+, 68–69, 851, 1176
+=, 68–69, 851, 1176
Concept-based approach to programming, 6
Concrete classes, 495–496, 1218
Concrete-first approach to programming, 6
Concurrency, 932
Conditional compilation, 1058–1059
Conditional expression ?, 268, 1089
Conditional statements. See also Branching, testing
for, 111–113
if, 102–104
switch, 105–109
while, 109–111
Conforming programs, 1075
Confusing variable names, 77
conj(), complex conjugate, 920, 1183
Conjugate, 920
Consistency, ideals, 814–815
Console, as user interface, 552
Console input/output, 552
Console window, displaying, 162
const, 95–97. See also Constant; Static storage,
static const
C++ and G, 1026, 1054–1055
class interfaces, 330–332
C-style strings, 1047–1048
declarations, 262–263
initializing, 262
member functions, 330–332, 1110
overloading on, 647–648
passing arguments by, 276–278, 281–284
type, 1099
* const, immutable pointer, 1099
Constant. See also const, expressions, 1093
const_cast, casting away const, 609, 1095
const_iterator, 1147
constexpr, 96–97, 290–291, 1093, 1104
Constraints, vector range checking, 695
Constructors, 310–312, 1112–1114. See also
Destructors; Initialization
containers, 1148
copy, 633–634, 640–646
Date example, 311
Date example 307, 324–326
debugging, 643–646
default, 327–330, 1119
error handling, 313, 700–702
essential operations, 640–646
exceptions, 700–702
explicit, 642–643
implicit conversions, 642–643
initialization of bases and members, 315, 477, 555
invariant, 313–314, 701–702
move, 637–640
need for default, 641
Token example, 184
Container adaptors, 1144
Containers, 148, 749–751, 1218. See also Arrays;
list, map, associative array; vector
and algorithms, 722
almost containers, 751, 1145
assignments, 1148
associative, 1144, 1151–1152
capacity(), 1150–1151
of characters. See string
comparing, 1151
constructors, 1148
to contiguous storage, 741
copying, 1151
destructors, 1148
element access, 1149
embedded systems, 951–954
header files, 1133–1134
information sources about, 750
iterator categories, 752
iterators, 1148
list operations, 1150
member types, 1147
operations overview, 1146–1147
queue operations, 1149
sequence, 1144
size(), 1150
stack operations, 1149
standard library, 1144–1152
swapping, 1151
templates, 686–687
Contents of * (dereference, indirection), 594
Contiguous storage, 741
Control characters, iscntrl(), 397
Control inversion, GUIs, 569–570
Control variables, 110
Controls. See Widget example
Conversion specifications, printf(), 1188–1189
Conversion. See also Type conversion
c char case, 398
representation, 374–376
unchecked, 943–944
Coordinates. See also Point example
computer screens, 419–420
graphs, 426–427
copy(), 789–790, 1154
Copy assignments, 634–636, 640–646
Copy constructors, 633–634, 640–646
copy_backward(), 1154
copy_if(), 789
copying, 631–637
c arrays, 653–654
class interfaces, 326–327
containers, 1151
C-style strings, 1046–1047, 1049
I/O streams, 790–793
objects, 503–504
sequences, 758, 789–794
c vector, 631–636, 1148
Correctness
definition, 1218
ideals, 92–94, 810
importance of, 929–930
software, 34
cos(), cosine, 527–528, 917, 1181
cosh(), hyperbolic cosine, 1182
Cost, definition, 1219
count(), 758, 1154
count_if(), 758, 1154
cout, 45
C equivalent, See std out
printing error messages, 151. See also cerr
standard output, 347, 1169
Critical systems, coding standards, 982–983<
c stds def>, 1136<
c stdio>, 1135<
c stdlib>, 1135, 1193, 1194
<str f>, 1177<
c string>, 1135, 1175, 1193<ctime>, 1135, 1193
CZ D, 124
CZ Z, 124
Current object, 317. See also this pointer
Cursor, definition, 45<
c wchar>, 1136<
c wctype>, 1136
D
d any decimal digit, regex, 878, 1179
’d’, decimal digit, regex, 873, 1179
’d’, not a decimal digit, regex, 873, 1179
d suffix, 1079
Dahl, Ole-Johan, 833–835
Data. See also Containers; Sequences; list, map,
associative array; vector
abstraction, 816
collections. See Containers
vs. computation, 717–720
generalizing code, 714–716
in memory. See Free store (heap storage)
processing, overview, 712–716
separating from algorithms, 722
storing. See Containers
structure. See Containers; class; struct
traversing. See Iteration; Iterators
uniform access and manipulation, 714–716. See
also STL (Standard Template Library)
Data member, 305, 492–493
Data structure. See Data; struct
Data type. See Type
Date and time, 1193–1194
Date example, See Chapters 6–7
Deallocating memory, 598–600, 1094–1095. See
also delete; delete
Debugging, 52, 158, 1219. See also Errors; Testing
arrays and pointers, 656–659
assertions, 163
block termination, 161
bugs, 158
c character literal termination, 161
commenting code, 159–160
c ompile-time errors, 161
c onsistent code layout, 160
constructors, 643–646
de claring names, 161
displaying the console window, 162
e xpression termination, 161
finding the last bug, 166–167
Debugging, continued
- function size, 160
- GUIs, 575–577
- input data, 166
- invariants, 162–163
- keeping it simple, 160
- logic errors, 154–156
- matching parentheses, 161
- naming conventions, 160
- post-conditions, 165–166
- pre-conditions, 163–165
- process description, 158–159
- reporting errors, 159
- stepping through code, 162
- string literal termination, 161
- systematic approach, 166–167
- test cases, 166, 227
- testing, 1012
- tracing code execution, 162–163
- transient bugs, 595
- using library facilities, 160
- widgets, 576–577

dec manipulator, 382–383, 1174
Decimal digits, isdigit(), 397
Decimal integer literals, 1077
Decimal number system, 381–383, 1077–1078
Deciphering (decryption), example, 969–974
Declaration operators, 1099
  & reference to, 276–279, 1099
  * pointer to, 587, 1099
  [] array of, 649, 1099
  () function of, 113–115, 1099
Declarations, 51, 1098–1099
  C++ and C, 1026
  classes, 306
  collections of, See Header files
  constants, 262–263
  definition, 51, 77, 257, 1098–1099, 1219
  vs. definitions, 259–260
  entities used for, 261
  extern keyword, 259
  forward, 261
  function, 257–258, 1103
  function arguments, 272–273
  function return type, 272–273
  grouping, See Namespaces
  managing, See Header files
  need for, 261
  order of, 215
  parts of, 1098
  subdividing programs, 260–261
  uses for, 1098
  variables, 260, 262–263
Decrementing --, 97
  iterator, 1141–1142
  pointer, 652
Deep copy, 636
Default constructors, 328–329
  alternatives for, 329–330
  for built-in types, 328
  initializing objects, 327
  need for, identifying, 641
  uses for, 328–329
#define, 1129
Definitions, 77, 258–259, 1219. See also
  Declarations
  C++ and C, 1038–1040
  vs. declarations, 259–260
  function, 113–115, 272–273
delete
  C++ and C, 1026, 1037
  deallocating free store, 1094–1095
  destructors, 601–605
  embedded systems, 932, 936–940
  free-store deallocation, 598–600
  in unary expressions, 1087
delete[], 599, 1087, 1094–1095
Delphi language, 831
Dependencies, testing, 1002–1003
Depth-first approach to programming, 6
deque, double ended queue, 1144
<deque>, 1133
Derivation, classes, 505
Derived classes, 505, 1219
  access control, 511
  base classes, 1116–1117
  inheritance, 1116–1117
  multiple inheritance, 1117
  object layout, 506–507
  overview, 504–506, 1116–1117
private bases and members, 511
protected bases and members, 511
public bases and members, 511
specifying, 507–508
virtual functions, 1117–1118
Design, 35, 176, 179, 1219
Design for testing, 1011–1012
Destructors, 601–603, 1114–1115, 1219. See also
   Constructors
   containers, 1148
default, 1119
esential operations, 640–646
exceptions, 700–702
freeing resources, 323, 700–702
and free store, 604–605
generated, 603
RAII, 700–702
virtual, 604–605
where needed, 641–642
Device drivers, 346
Dictionary examples, 123–125, 788
difference_type, 1147
digit, character class, 878, 1179
Digit, word origin, 1077
Dijkstra, Edsger, 827–828, 992
Dimensions, matrices, 898–901
Direct expression of ideas, ideals, 811–812
Dispatch, 504–505
Display model, 413–414
distance(), 1142
Divide /, 66, 1088
Divide and assign /=, 67, 1090
Divide and conquer, 93
Divide-by-zero error, 201–202
divides(), 1164
Domain knowledge, 934
Dot product. See inner_product()
double floating-point type, 63, 66–67, 78, 1099
Doubly-linked lists, 613, 725. See also list
draw() example
   fill color, 500
   line visibility, 500
   Shape, 500–502
draw_lines() example. See also draw() example
   Closed polyline, 458
   Marked polyline, 475–476
   Open polyline, 456
   Polygon, 459
   Rectangle, 465
   Shape, 500–502
duration..., 1016, 1185
duration_cast, 1016, 1185
Dynamic dispatch, 504–505. See also Virtual functions
Dynamic memory, 935–936, 1094. See also Free store (heap storage)
dynamic_cast, type conversion, 1095
   exceptions, 1138
   predictability, 932
E
Efficiency
   ideals, 92–94, 810
   vector range checking, 695
Einstein, Albert, 815
Elements. See also vector
   numbering, 649
   pointers to, 650–652
   variable number of, 649
Ellipse example, 472–474
   vs. Circle, 474
Ellipsis ...
   arguments (unchecked), 1105–1106
   catch all exceptions, 152
else, in if-statements, 102–104
Email example, 855–865
Embedded systems
   coding standards, 975–977, 983
   concurrency, 932
   containers, 951–954
   correctness, 929–930
delete operator, 932
domain knowledge, 934
dynamic_cast, 932
   error handling, 933–935
   examples of, 926–928
   exceptions, 932
   fault tolerance, 930
   fragmentation, 936, 937
   free-store, 936–940
   hard real time, 931
   ideas, 932–933
   maintenance, 929
   memory management, 940–942
new operator, 932
   predictability, 931, 932
   real-time constraints, 931
   real-time response, 928
   reliability, 928
   resource leaks, 931
Embedded systems, continued
resource limitations, 928
soft real time, 931
special concerns, 928–929
Empty
empty(), is container empty? 1150
lists, 729
sequences, 729
statements, 101
Empty statement, 1035–1036
Encapsulation, 505
Enciphering (Encryption), example, 969–974
end()
iterator, 1148
string, 851, 1177
vector, 722
End of file
eof(), 355, 1171
file streams, 366
I/O error, 355
stringstream, 395
End of input, 124
End of line $ (in regular expressions), 873, 1178
Ending programs. See Termination
endl manipulator, 1174
ends manipulator, 1174
English grammar vs. programming grammar, 193–194
enum, 318–321, 1042. See also Enumerations
Enumerations, 318–321, 1107–1108
enum, 318–321, 1042
enumerators, 318–321, 1107–1108
EOF macro, 1053–1054
eof() stream state, 355, 1171
equal(), 759, 1153
Equal ==, 67, 1088
Equality operators, expressions, 1088
equal_range(), 758, 796
equal_to(), 1163
erase()
list, 742–745, 1150
list operations, 615–617
string, 851, 1177
vector, 745–747
errno, error indicator, 918–919, 1182
error() example, 142–143
passing multiple strings, 152
Error diagnostics, templates, 683
Error handling. See also Errors; Exceptions
% for floating-point numbers, 230–231
catching exceptions, 239–241
files fail to open, 389
GUIs, 576
hardware replication, 934
I/O errors. See I/O errors
I/O streams, 1171
mathematical errors, 918–919
modular systems, 934–935
monitoring subsystems, 935
negative numbers, 229–230
positioning in files, 393–394
predictable errors, 933
recovering from errors, 239–241
regular expressions, 878–880
resource leaks, 934
self-checking, 934
STL (Standard Template Library), 1137–1138
testing for errors, 225–229
transient errors, 934
vector resource exceptions, 702
Error messages. See also Reporting errors; error() example; runtime_error
exceptions, printing, 150–151
templates, 683
writing your own, 142
Errors, 1219. See also Debugging; Testing
classifying, 134
compilation-time, 48–50, 134, 136–137
detection ideal, 135
error(), 142–143
estimating results, 157–158
incomplete programs, 136
input format, 64–65
link-time, 134, 139–140
logic, 134, 154–156
poor specifications, 136
recovering from, 239–241. See also Exceptions
sources of, 136
syntax, 137–138
translation units, 139–140
type mismatch, 138–139
undeclared identifier, 258
unexpected arguments, 136
unexpected input, 136
unexpected state, 136
Errors, run-time, 134, 140–142. See also
Exceptions
callee responsibility, 143–145
caller responsibility, 142–143
hardware violations, 141
reasons for, 144–145
reporting, 145–146
Essential operations, 640–646
Estimating development resources, 177
Estimating results, 157–158
Examples
  - age distribution, 538–539
calculator. See Calculator example
  - Date. See Date example
deciphering, 969–974
deleting repeated words, 71–73
dictionary, 123–125, 788
Dow Jones tracking, 782–785
e-mail analysis, 855–865
embedded systems, 926–928
ciphering (encryption), 969–974
exponential function, 527–528
finding largest element, 713–716, 723–724
fruits, 779–782
Gaussian elimination, 910–911
graphics, 414–418, 436
graphing data, 537–539
graphing functions, 527–528
GUI (graphical user interface), 565–569, 573–574, 576–577
Hello, World! 45–46
intrusive containers, 1059–1065
Lines_window, 565–569, 573–574, 576–577
Link, 613–622
list (doubly linked), 613–622
map container, 779–785
Matrix, 908–914
palindromes, 659–662
Pool allocator, 940–941
Punct_stream, 401–405
reading a single value, 359–363
reading a structured file, 367–376
regular expressions, 880–885
school table, 880–885
searching, 864–872
sequences, 723–724
Stack allocator, 942–943
TEA (Tiny Encryption Algorithm), 969–974
text editor, 734–741
vector. See vector example
Widget manipulation, 565–569, 1213–1216
windows, 565–569
word frequency, 777–779
writing a program. See Calculator example
writing files, 352–354
ZIP code detection, 864–872
<exception>, 1135
Exceptions, 146–150, 1125–1126. See also Error handling: Errors
bounds error, 149
C++ and C, 1026
catch, 147, 239–241, 1125–1126
cerr, 151–152
cout, 151–152
destructors, 1126
embedded systems, 932
error messages, printing, 150–151
exception, 152, 1138–1139
failure to catch, 153
GUIs, 576
input, 150–153
narrow_cast example, 153
off-by-one error, 149
out_of_range, 149–150, 152
overview, 146–147
RAII (Resource Acquisition Is Initialization), 1125
range errors, 148–150
re-throwing, 702, 1126
runtime_error, 142, 151, 153
stack unwinding, 1126
standard library exceptions, 1138–1139
terminating a program, 142
throw, 147, 1125
termination, 153
type conversion, 153
uncaught exception, 153
user-defined types, 1126
vector range checking, 693–694
vector resources. See vector
Executable code, 48, 1219
Executing a program, 11, 1200–1201
exit0, terminating a program, 1194–1195
explicit constructor, 642–643, 1038
Expression, 94–95, 1086–1090
coding standards, 980–981
constant expressions, 1093
conversions, 1091–1093
debugging, 161
grouping (, 95, 867, 873, 876
lvalue, 94–95, 1090
magic constants, 96, 143, 232–234, 723
memory management, 1094–1095
mixing types, 99
non-obvious literals, 96
operator precedence, 95
operators, 97–99, 1086–1095
Expression, continued
order of operations, 181
precedence, 1090
preserving values, 1091
promotions, 99, 1091
rvalue, 94–95, 1090
scope resolution, 1086
type conversion, 99–100, 1092
usual arithmetic conversions, 1092
Expression statement, 100
extern, 259, 1033
Extracting text from files, 856–861, 864–865

F

/f suffix, 1079
fail() stream state, 355, 1171
Falling through end of functions, 274
false, 1038
Fault tolerance, 930
fclose(), 1053–1054, 1186
Feature creep, 188, 201, 1219
Feedback, programming, 36
Fields, formatting, 387–388
FILE, 1053–1054
File I/O, 349–350
binary I/O, 391
close(), 352
closing files, 352, 1186
converting representations, 374–376
modes, 1186
open(), 352
opening files. See Opening files
positioning in files, 393–394
reading. See Reading files
writing. See Writing files
Files, 1219. See also File I/O
C++ and C, 1053–1054
opening and closing, C-style I/O, 1186
fill(), 1157
fill_n(), 1157
Fill color example, 462–465, 500
find(), 758–761
associative container operations, 1151
finding links, 615–617
generic use, 761–763
nonmodifying sequence algorithms, 1153
string operations, 851, 1177
find_end(), 1153
find_first_of(), 1153
find_if(), 758, 763–764
Finding. See also Matching; Searching
associative container operations, 1151
elements, 758
links, 615–617
patterns, 864–865, 869–872
strings, 851, 1177
fixed format, 387
fixed manipulator, 385, 1174
<float.h>, 894, 1181
Floating-point, 63, 891, 1219
% remainder (modulo), 201
assigning integers to, 892–893
assigning to integers, 893
conversions, 1092
fixed format, 387
general format, 387
input, 182, 201–202
integral conversions, 1091–1092
literals, 182, 1079
mantissa, 893
output, formatting, 384–385
precision, 386–387
and real numbers, 891
rounding, 386
scientific format, 387
truncation, 893
vector example, 120–123
float type, 1099
floor(), 917, 1181
FLTK (Fast Light Toolkit), 418, 1204
code portability, 418
color, 451, 465–467
current style, obtaining, 500
downloading, 1204
fill, 465
in graphics code, 436
installing, 1205
lines, drawing, 454, 458
outlines, 465
rectangles, drawing, 465
testing, 1206
in Visual Studio, 1205–1206
waiting for user action, 559–560, 569–570
flush manipulator, 1174
Flushing a buffer, 240–241
Fonts for Graphics example, 468–470
fopen(), 1053–1054, 1186
for-statement, 111–113
vs. while, 122
Function call, continued
operator, 766
pass by const reference, 276–278, 281–284
pass by non-const reference, 281–284
pass by reference, 279–284
pass by value, 276, 281–284
recursive, 289
stack growth, 287–290. See also Function activation record
temporary objects, 282
Function-like macros, 1056–1058
Function member
definition, 305–306
same name as class. See Constructors
Function objects, 765–767
operator, 766
abstract view, 766–767
adaptors, 1164
arithmetic operations, 1164
parameterization, 767
predicates, 767–768, 1163
Function parameter (formal argument)
e... ellipsis, unchecked arguments, 1105–1106
pass by const reference, 276–278, 281–284
pass by non-const reference, 281–284
pass by reference, 279–284
pass by value, 276, 281–284
temporary objects, 282
unused, 272
Function template
algorithms, 682–683
argument deduction, 689–690
parameterized functions, 682–683
<functional>, 1133, 1163
Functional cast, 1095
Functional programming, 823
Fused multiply-add, 904
get(), 1172
getc(), 1052, 1191
getchar(), 1053, 1191
gline(), 395–396, 851, 855, 1172
gets(), 1052
C++ alternative >>, 1053
dangerous, 1052
scanf(), 1190
get_token() example, 196
GIF images, 480–482
Global scope, 267, 270, 1082
Global variables
functions modifying, 269
memory for, 591–592
order of initialization, 292–294
Going out of scope, 268–269, 291
good() stream state, 355, 1171
GP. See Generic programming
Grammar example
alternation, patterns, 194
English grammar, 193–194
Expression example, 197–200, 202–203
parsing, 190–193
repetition, patterns, 194
rules vs. tokens, 194
sequencing rules, 195
terminals. See Tokens
writing, 189, 194–195
Graph example. See also Grids, drawing
Axis, 424–426
coordinates, 426–427
drawing, 426–427
points, labeling, 474–476
Graph.h, 421–422
Graphical user interfaces. See GUIs (graphical user interfaces)
Graphics, 412. See also Graphics example; Color example; Shape example
displaying, 479–482
display model, 413–414
drawing on screen, 423–424
encoding, 480
filling shapes, 431
formats, 480
geometric shapes, 427
GIF, 480–482
graphics libraries, 481–482
graphs, 426–427
images from files, 433–434
importance of, 412–413
JPEG, 480–482

G
Gadgets. See Embedded systems
Garbage collection, 600, 938–939
Gaussian elimination, 910–911
gcount(), 1172
general format, 387
general manipulator, 385
generate(), 1157
generate_no(), 1157
Generic code, 491
Generic programming, 682–683, 816, 1219
Geometric shapes, 427
line style, 431
loading from files, 433–434
screen coordinates, 419–420
selecting a sub-picture from, 480
user interface. See GUIs (graphical user interfaces)

Graphics example
  Graph.h, 421–422
  GUI system, giving control to, 423
  header files, 421–422
  main(), 421–422
  Point.h, 444
  points, 426–427
  Simple_window.h, 444
  wait_for_button(), 423
  Window.h, 444

Graphics example, design principles
  access control. See Access control
  attach() vs. add(), 491–492
  class diagram, 505
  class size, 489–490
  common style, 490–491
  data modification access, 492–493
  generic code, 491
  inheritance, interface, 513–514
  inheritances, implementation, 513–514
  mutability, 492–493
  naming, 491–492
  object-oriented programming, benefits of, 513–514
  operations, 490–491
  private data members, 492–493
  protected data, 492–493
  public data, 492–493
  types, 488–490
  width/height, specifying, 490

Graphics example, GUI classes, 442–444. See also
  Graphics example, interfaces
  Button, 443
  In_box, 443
  Menu, 443
  Out_box, 443
  Simple_window, 422–424, 443
  Widget, 561–563, 1209–1210
  Window, 443, 1210–1212

Graphics example, interfaces, 442–443. See also
  Graphics example, GUI classes
  Axis, 424–426, 443, 529–532
  Circle, 469–472, 497
  Closed_polyline, 456–458
  Color, 450
  Ellipse, 472–474
  Function, 443, 524–528
  Image, 443, 479–482
  Line, 445–448
  Line_style, 452–455
  Lines, 448–450, 497
  Mark, 478–479
  Marked_polyline, 474–476
  Marks, 476–477, 497
  Open_polyline, 455–456, 497
  Point, 426–427, 445
  Polygon, 427–428, 458–460, 497
  Rectangle, 428–431, 460–465, 497
  Text, 431–433, 467–470

Graphing data example, 538–546
Graphing functions example, 520–524, 532–537

Graph_lib namespace, 421–422

greater(), 1163
Greater than >, 67, 1088
Greater than or equal >=, 1088

greater_equal(), 1163
Green marginal alerts, 3

Grids, drawing, 448–449, 452–455
Grouping regular expressions, 867, 873, 876
Guarantees, 701–702

Guidelines. See Ideals

GUIs (graphical user interfaces), 552–553. See also
  Graphics example, GUI classes
  callback functions, 556–559
  callback implementation, 1208–1209
  cb_next() example, 556–559
  common problems, 575–577
  control inversion, 569–570
  controls. See Widget example
  coordinates, computer screens, 419–420
  debugging, 575–577
  error handling, 576
  exceptions, 576
  FLTK (Fast Light Toolkit), 418
  layers of code, 557
  next() example, 558–559
  pixels, 419–420
  portability, 418
  standard library, 418–419
  toolkit, 418
  vector_ref example, 1212–1213
  vector of references, simulating, 1212–1213
**GUIs (graphical user interfaces), continued**
- Wait loops, 559–560
  - `wait_for_button()` example, 559–560
- Waiting for user action, 559–560, 569–570
- **Widget** example, 561–569, 1209–1210, 1213–1216
- **Window** example, 565–569, 1210–1212
- GUI system, giving control to, 423

**H**
- `.h` file suffix, 46
- Half open sequences, 119, 721
- Hard real-time, 931, 981–982
- Hardware replication, error handling, 934
- Hardware violations, 141
- Hashed container. See unordered_map
- Hash function, 785–786
- Hashing, 785
- Hash tables, 785
- Hash values, 785
- Header files, 46, 1219
  - C standard library, 1135–1136
  - declarations, managing, 264
  - definitions, managing, 264
  - graphics example, 421–422
  - including in source files, 264–266, 1129
  - multiple inclusion, 1059
  - standard library, 1133–1134
- Headers. See Header files
- Heap algorithm, 1160
- Heap memory, 592, 935–936, 1084, 1160. See also
  - Free store (heap storage)
- Hejlsberg, Anders, 831
- “Hello, World!” program, 45–47
- Helper functions
  - `==` equality, 333
  - `!=` inequality, 333
  - class interfaces, 332–334
  - Date example, 309–310, 332–333
  - namespaces, 333
  - validity checking date values, 310
- **hex** manipulator, 382–383, 1174
- Hexadecimal digits, 397
- Hexadecimal number system, 381–383, 1077–1078
- Hiding information, 1220
- Hopper, Grace Murray, 824–825
- Hyperbolic cosine, **cosh()**, 918
- Hyperbolic sine, **sinh()**, 918, 1182
- Hyperbolic tangent, **tanh()**, 917

**I**
- I/O errors
  - bad() stream state, 355
  - clear(), 355–358
  - end of file, 355
  - eof() stream state, 355
  - error handling, 1171
  - fail() stream state, 355
  - good() stream state, 355
  - **ios_base**, 357
  - recovering from, 355–358
  - stream states, 355
  - unexpected errors, 355
  - unget(), 355–358
- I/O streams, 1168–1169
  - >> input operator, 855
  - << output operator, 855
  - **cerr**, standard error output stream, 151–152, 1169, 1189
  - **cin** standard input, 347
  - class hierarchy, 855, 1170–1171
  - **cout** standard output, 347
  - error handling, 1171
  - formatting, 1172–1173
  - **fstream**, 388–390, 393, 1170
  - get(), 855
  - getline(), 855
  - header files, 1134
  - **ifstream**, 388–390, 1170
  - input operations, 1172
  - input streams, 347–349
  - iostream library, 347–349, 1168–1169
  - **istream**, 347–349, 1169–1170
  - **istringstream**, 1170
  - **ofstream**, 388–390, 1170
  - input operations, 1172
  - input streams, 347–349
  - iostream library, 347–349, 1168–1169
  - **ofstream**, 347–349, 1168–1169
  - **ostringstream**, 388–390, 1170
  - output operations, 1173
  - output streams, 347–349
  - standard manipulators, 382, 1173–1174
  - standard streams, 1169
  - states, 1171
  - stream behavior, changing, 382
  - stream buffers, **streambufs**, 1169
  - stream modes, 1170
  - string, 855
stringstream, 395, 1170
throwing exceptions, 1171
unformatted input, 1172
IBM, 823
Ichbiah, Jean, 832
IDE (interactive development environment), 52
Ideals
abstraction level, 812–813
bottom-up approach, 811
class interfaces, 323
code structure, 810–811
coding standards, 976–977
consistency, 814–815
correct approaches, 811
correctness, 810
definition, 1219
direct expression of ideas, 811–812
efficiency, 810
embedded systems, 932–933
importance of, 8
KISS, 815
maintainability, 810
minimalism, 814–815
modularity, 813–814
overview, 808–809
performance, 810
software, 34–37
on-time delivery, 810
top-down approach, 811
Identifiers, 1081. See also Names
reserved, 75–76. See also Keywords
if-statements, 102–104
ifndef, 1058–1059
endif, 1058–1059
ifstream type, 350–352
imag(), imaginary part, 920, 1183
Image example, 443, 479–482
Images. See Graphics
Imaginary part, 920
Immutable values, class interfaces, 330–332
Implementation, 1219
class, 306–308
inheritance, 513–514
programs, 36
Implementation-defined feature, 1075
Implicit conversions, 642–643
in mode, 389, 1170
in_box example, 443, 563–564
In-class member definition, 1112
#include, 46, 264–266, 1128–1129
Include guard, 1059
includes(), 1159
Including headers, 1129. See also #include
Incrementing ++, 66, 721
iterators, 721, 750, 1140–1141
pointers, 651–652
variables, 73–74, 97–98
Indenting nested code, 271
Inequality != (not equal), 67, 1088, 1101
complex, 919, 1183
containers, 1151
helper function, 333
iterators, 721, 1141
string, 67, 851, 1176
Infinite loop, 1219
Infinite recursion, 198, 1220
Information hiding, 1220
Information processing, 32
Inheritance
class diagram, 505
definition, 504
derived classes, 1116–1117
embedded systems, 951–954
history of, 834
implementation, 513–514
interface, 513–514
multiple, 1117
pointers vs. references, 612–613
templates, 686–687
Initialization, 69–73, 1220
{} initialization notation, 83
arrays, 596–598, 654–656
constants, 262, 329–330, 1099
constructors, 310–312
Date example, 309–312
default, 263, 327, 1085
invariants, 313–314, 701–702
menus, 571
pointers, 596–598, 657
pointer targets, 596–598
Token example, 184
initializer_list, 630
inline, 1037
Inline
functions, 1026
member functions, 316
inner_product(), 759. See also Dot product
description, 774–775
generalizing, 775–776
**index**

inner_product(), continued
- matrices, 904
- multiplying sequences, 1184
- standard library, 759, 770

inplace_merge(), 1158

Input, 60–62. See also Input >>; I/O streams
- binary I/O, 390–393
- C++ and C, 1052–1053
- calculator example, 179, 182, 185, 201–202, 206–208
- case sensitivity, 64
- cin, standard input stream, 61
dividing functions logically, 359–362
files. See File I/O
format errors, 64–65
individual characters, 396–398
integers, 383–384
istringstream, 394
line-oriented input, 395–396
newline character \n, 61–62, 64
potential problems, 358–363
prompting for, 61, 179
separating dialog from function, 362–363
a series of values, 356–358
a single value, 358–363
source of exceptions, 150–153

istringstream, 394
line-oriented input, 395–396
newline character \n, 61–62, 64
potential problems, 358–363
prompting for, 61, 179
separating dialog from function, 362–363
a series of values, 356–358
a single value, 358–363
source of exceptions, 150–153

istringstream, 394
line-oriented input, 395–396
newline character \n, 61–62, 64
potential problems, 358–363
prompting for, 61, 179
separating dialog from function, 362–363
a series of values, 356–358
a single value, 358–363
source of exceptions, 150–153

stringstream, 395
tab character \t, 64
terminating, 61–62
type sensitivity, 64–65
whitespace, 64

Input >>, 61
case sensitivity, 64
complex, 920, 1183
formatted input, 1172
multiple values per statement, 65
strings, 851, 1177
text input, 851, 855
user-defined, 365
whitespace, ignoring, 64

Input devices, 346–347
Input iterators, 752, 1142
Input loops, 365–367

Input/output, 347–349. See also Input; Output buffering, 348, 406
C++ and C. See stdio
computation overview, 91
device drivers, 346
erors. See I/O errors
files. See File I/O
formatting. See Manipulators; printf()
Invariants, 313–314, 1220. See also Post-conditions; Pre-conditions assertions, 163
Lambda expression, 560–561
Largest integer, finding, 917
Laws of optimization, 931
Layers of code, GUIs, 557
Layout rules, 979, 1034
Leaks, memory, 598–600, 601–605, 937
Leap year, 309
left manipulator, 1174
Legal programs, 1075
length(), 851, 1176
Length of strings, finding, 851, 1046, 1176
less(), 1163
Less than, <, 1088
Less than or equal, <=, 67, 1088
less_equal(), 1163
Letters, identifying, 247, 397
lexical_cast, 855
Lexicographical comparison
  <= comparison, 1176
  < comparison, 1176
  >= comparison, 1176
  > comparison, 1176
  < comparison, 851
C-style strings, 1046
  lexicographical_compare(), 1162
Libraries, 51, 1220. See also Standard library
  role in debugging, 160
  uses for, 177
Lifetime, objects, 1085–1086, 1220
Limit macros, 1181
<limits>, 894, 1135, 1180
Limits, 894–895
<limits.h>, 894, 1181
Linear equations example, 908–914
  back_substitution(), 910–911
  classic_elimination(), 910–911
Gaussian elimination, 910–911
  pivoting, 911–912
  testing, 912–914
Line comment //, 45
Line example, 445–447
to, Lines, 448
Line-oriented input, 395–396
Lines example, 448–450, 497
to, Line, 448
Lines (graphic), drawing. See also Graphics;
  draw_lines()
on graphs, 529–532
  line styles, 452–455
  multiple lines, 448–450
  single lines, 443–447
styles, 431, 454
  visibility, 500
Lines (of text), identifying, 736–737
line_style example, 452–455
lines_window example, 565–569, 573–574, 576–577
Link example, 613–622
Link-time errors. See Errors, link-time
Linkage convention, C, 1033
Linkage specifications, 1106
Linked lists, 725. See also Lists
Linkers, 51, 1220
Linking programs, 51
Links, 613–615, 620–622, 725
Lint, consistency checking program, 836
Lisp language, 825–826
list, 727, 1146–1151
  () initialization notation, 83
  add(), 615–617
  advance(), 615–617
  back(), 737
  erase(), 615–617, 742–745
  find(), 615–617
  insert(), 615–617, 742–745
  operations, 615–617
  properties, 741–742
  referencing last element, 737
  sequence containers, 1144
  subscripting, 727
<list>, 1133
Lists
  containers, 1150
  doubly linked, 613, 725
  empty, 729
  erasing elements, 742–745
  examples, 613–615, 734–741
  finding links, 615–617
  getting the nth element, 615–617
  inserting elements, 613–615, 742–745
  iteration, 727–729, 737–741
  link manipulation, 615–617
  links, examples, 613–615, 620–622, 726
  operations, 726–727
  removing elements, 615–617
  singly linked, 612–613, 725
this pointer, 618–620
Literals, 62, 1077, 1220
  character, 161, 1079–1080
  decimal integer, 1077
  in expressions, 96
  F suffix, 1079
  floating-point, 1079
hexadecimal integer, 1077
integer, 1077
</u> suffix, 1077
magic constants, 96, 143, 232–234, 723
non-obvious, 96
null pointer, 8, 1081
number systems, 1077–1079
octal integer, 1077
special characters, 1079–1080
string, 161, 1080
termination, debugging, 161
for types, 63
</u>/</u> suffix, 1077
unsigned, 1077
Local (automatic) objects, lifetime, 1085
Local classes, nesting, 270
Local functions, nesting, 270
Local scope, 267, 1083
Local variables, array pointers, 658
Locale, 406
</locale>, 1135
log(), 918, 1182
log10(), 918, 1182
Logic errors. See Errors, logic
Logical and &&, 1089, 1094
Logical operations, 1094
Logical or ||, 1089, 1094
</logical_and(), 1163
</logical_not(), 1163
</logical_or(), 1163
Logs, graphing, 528
</long integer, 955, 1099
Look-ahead problem, 204–209
Loop, 110–111, 112, 1220
examples, parser, 200
infinite, 198, 1219
testing, 1005–1006
variable, 110–111, 112
Lovelace, Augusta Ada, 832
</lower, 878, 1179
</lower_bound(), 796, 1152, 1158
Lower case. See Case (of characters)
Lucent Bell Labs, 838
Lvalue, 94–95, 1090
Machine code. See Executable code
Macros, 1055–1056
conditional compilation, 1058–1059
</define, 1056–1058, 1129
function-like, 1056–1058
</define, 1058–1059
</find, 1059
</include, 1058, 1128–1129
include guard, 1059
naming conventions, 1055
syntax, 1058
uses for, 1056
Macro substitution, 1129
Maddock, John, 865
Magic constants, 96, 143, 232–234, 723
Magical approach to programming, 10
</main(), 46–47
arguments to, 1076
global objects, 1076
return values, 47, 1075–1076
starting a program, 1075–1076
Maintainability, software, 35, 810
Maintenance, 929
</make_heap(), 1160
</make_pair(), 782, 1165–1166
</make_unique(), 1167
</make_vec(), 702
malloc(), 1043–1044, 1193
Manipulators, 382, 1173–1174
complete list of, 1173–1174
dec, 1174
diff, 1174
fixed, 1174
hex, 1174
</noskipws, 1174
</oct, 1174
resetiosflags(), 1174
</scientific, 1174
setiosflags(), 1174
</setprecision(), 1174
</skipws, 1174
Mantissa, 893
</map, associative array, 776–782. See also set;
</unordered_map
</[], subscripting, 777, 1151
balanced trees, 780–782
binary search trees, 779
case sensitivity, No_case example, 795
counting words example, 777–779
Dow Jones example, 782–785
email example, 855–872
</erase(), 781, 1150
finding elements in, 776–777, 781,
    1151–1152
fruits example, 779–782
map, associative array, continued
    insert(), 782, 1150
    iterators, 1144
    key storage, 776
make_pair(), 782
No_case example, 782, 795
Node example, 779–782
red-black trees, 779
set, 788
standard library, 1146–1152
tree structure, 779–782
without values. See set
<map>, 776, 1133
mapped_type, 1147
Marginal alerts, 3
Mark example, 478–479
Marked polyline example, 474–476
Marks example, 476–477, 497
Mars Rover, 33
Matching. See also Finding; Searching
    regular expressions, regex, 1177–1179
text patterns. See Regular expressions
Math functions, 528, 1181–1182
Mathematics. See Numerics
Mathematical functions, standard
    abs(), absolute value, 917
    acos(), arccosine, 917
    asin(), arcsine, 918
    atan(), arctangent, 918
    ceil(), 917
    ccmath>, 918, 1135
    ccomplex>, 919–920
    cos(), cosine, 917
    cosh(), hyperbolic cosine, 918
    errno, error indicator, 918–919
    error handling, 918–919
    exp(), natural exponent, 918
    floor(), 917
    log(), natural logarithm, 918
    log10, base-10 logarithm, 918
    sin(), sine, 917
    sinh(), hyperbolic sine, 918
    sqrt(), square root, 917
    tan(), tangent, 917
    tanh(), hyperbolic tangent, 917
Matrices, 899–901, 905–906
Matrix library example, 899–901, 905
    [], subscripting (C style), 897, 899
    (), subscripting (Fortran style), 899
    accessing array elements, 899–901
    apply(), 903
    broadcast functions, 903
clear_row, 906
columns, 900–901, 906
dimensions, 898–901
dot product, 904
fused multiply-add, 904
initializing, 906
inner_product, 904
input/output, 907
linear equations example, 910–914
multidimensional matrices, 898–908
rows, 900–901, 906
scale_and_add(), 904
slice(), 901–902, 905
start_row, 906
subscripting, 899–901, 905
swap_columns(), 906
swap_rows(), 906
max(), 1161
max_element(), 1162
max_size(), 1151
McCarthy, John, 825–826
McIlroy, Doug, 837, 1032
Medicine, computer use, 30
Member, 305–307. See also Class
    allocated at same address, 1121
    class, nesting, 270
    in-class definition, 1112
    definition, 1108
    definitions, 1112
    out-of-class definition, 1112
Member access. See also Access control
    . (dot), 1109
    :: scope resolution, 315, 1109
    notation, 184
    operators, 608
    this pointer, 1110
    by unqualified name, 1110
Member function. See also Class members;
    Constructors; Destructors; Date example
calls, 120
nesting, 270
Token example, 184
Member initializer list, 184
Member selection, expressions, 1087
Member types
    containers, 1147
templates, 1124
memchr(), 1193
memset(), 1193
memcpy(), 1192
mem_fn() adaptor, 1164
memmove(), 1192
Memory, 588–590
addresses, 588
allocating. See Allocating memory
automatic storage, 591–592
bad_alloc exception, 1094
for code, 591–592
C standard library functions, 1192–1193
deallocating, 598–600
embedded systems, 940–942
exhausting, 1094
freeing. See Deallocating memory
free store, 592–594
for function calls, 591–592
for global variables, 591–592
heap. See Free store (heap storage)
layout, 591–592
object layout, 506–507
object size, getting, 590–591
pointers to, 588–590
sizeof, 590–591
stack storage, 591–592
static storage, 591–592
text storage, 591–592
<memory>, 1134
memset(), 1193
Menu example, 443, 564–565, 570–575
merge(), 758, 1158
Messages to the user, 564
min(), 1161
min_element(), 1162
Minimalism, ideals, 814–815
minus(), 1164
Missing copies, 645
MT, 825–826, 838
Modifying sequence algorithms, 1154–1156
Modularity, ideals, 813–814
Modular systems, error handling, 934–935
Modulo (remainder) %, 66. See also Remainder
modulo(), 1164
Monitoring subsystems, error handling, 935
move(), 502, 562
Move assignments, 637–640
Move backward +=, 1101
Move forward +=, 1101
Move constructors, 637–640
Moving, 637–640
Multi-paradigm programming languages, 818
Multidimensional matrices, 898–908
multimap, 776, 860–861, 1144
<multimap>, 776
Multiplicative operators, expressions, 1088
multiplies(), 1164
Multiply *, 66, 1088
Multiply and assign *=, 67
multiset, 776, 1144
<multiset>, 776
Mutability, 492–493, 1220
class interfaces, 332–334
and copying, 503–504
mutable, 1037
Mutating sequence algorithms, 1154–1156
\n newline, character literal, 61–62, 64, 1079
Named character classes, in regular expressions, 877–878
Names, 74–77
_ (underscore), 75, 76
capital letters, 76–77
case sensitivity, 75
confusing, 77
conditions, 74–75
declarations, 257–258
descriptive, 76
function, 47
length, 76
overloaded, 140, 508–509, 1104–1105
reserved, 75–76. See also Keywords
namespace, 271, 1037
Namespaces, 294, 1127. See also Scope
:: scope resolution, 295–296
C++ and C, 1042–1043
fully qualified names, 295–297
helper functions, 333
objects, lifetime, 1085
scope, 267, 1082
std, 296–297
for the STL, 1136
using declarations, 296–297
using directives, 296–297, 1127
variables, order of initialization, 292–294
Naming conventions, 74–77
coding standards, 979–980
functions, 491–492
macros, 1055
Naming conventions, continued
role in debugging, 160
scope, 269
narrow_cast example, 153
Narrowing conversions, 80–83
Narrowing errors, 153
Natural language differences, 406
Natural logarhythms, 918
Naur, Peter, 827–828
 negate(), 1164
Negative numbers, 229–230
Nested blocks, 271
Non-algorithms, testing, 1001–1008
Non-error, 139
Non-intrusive containers, 1059
Non-modifying sequence algorithm, 1153–1154
Non-narrowing initialization, 83
Nonstandard separators, 398–405
 norm(), 919, 1183
Norwegian Computing Center, 833–835
noshowbase, 383, 1173
noshowpoint, 1173
noshowpos, 1173
noshwps, 1174
not, synonym for ! 1037, 1038
Not ! 1087
 not0() adaptor, 1164
 not2() adaptor, 1164
 Not-conforming constructs, 1075
Not equal != (inequality), 67, 1088, 1101
 not_eq, synonym for !=, 1038
 not_equal_to(), 1163
 not_equal_to(), 1163
 nth_element(), 1158
Null pointer, 598, 656–657, 1081
nullptr, 598
Number example, 189
Number systems
base-2, binary, 1078–1079
base-8, octal, 381–384, 1077–1078
base-10, decimal, 381–384, 1077–1078
base-16, hexadecimal, 381–384, 1077–1078
<numeric>, 1135, 1183
Numerical algorithms. See Algorithms, numerical
Numerics, 890–891
absolute values, 917
arithmetic function objects, 1164
arrays. See Matrix library example
<cmath>, 918
columns, 895–896
 complex, 919–920, 1182–1183
<complex>, 919–920
floating-point rounding errors, 892–893
header files, 1134
integer and floating-point, 892–893
integer overflow, 891–893
largest integer, finding, 917
limit macros, 1181
limits, 894
mantissa, 893
mathematical functions, 917–918
 Matrix library example, 897–908
multi-dimensional array, 895–897
numeric_limits, 1180
numerical algorithms, 1183–1184
overflow, 891–895
precision, 891–895
random numbers, 914–917
real numbers, 891. See also Floating-point
results, plausibility checking, 891
rounding errors, 891
rows, 895–896
size, 891–895
sizeof(), 892
smallest integer, finding, 917
standard mathematical functions, 917–918, 1181–1182
truncation, 893
valarray, 1183
whole numbers. See Integers
Nygaard, Kristen, 833–835
.O.obj file suffix, 48
Object, 60, 1220
aliases. See References
behavior like a function. See Function object
constructing, 184
copying, 1115, 1119
current (this), 317
Date example, 334–338
initializing, 327–330. See also Constructors
layout in memory, 308–309, 506–507
lifetime, 1085–1086
named. See Variables
Shape example, 495
sizeof(), 590–591
state, 2, 305
type, 77–78
value. See Values
Object code, 48, 1220. See also Executable code
Object-oriented programming, 1220
"from day one," 10
vs. generic programming, 682
for graphics, benefits of, 513–514
history of, 816, 834
oct manipulator, 382–383, 1174
Octal number system, 381–383, 1077–1078
Off-by-one error, 149
ofstream, 351–352
Old-style casts, 1040
One-dimensional (1D) matrices, 901–904
On-time delivery, ideals, 810
\000 octal, character literal, 1080
OOP. See Object-oriented programming
Opaque types, 1060
open(), 352, 1170
Open modes, 389–390
Open shapes, 455–456
Opening files, 350–352. See also File I/O
binary files, 390–393
binary mode, 389
C-style I/O, 1186
failure to open, 389
file streams, 350–352
nonexistent files, 389
open modes, 389–390
testing after opening, 352
Open polyline example, 455–456, 497
Operations, 66–69, 305, 1220
chaining, 180–181
goals, 1060
graphics classes, 490–491
Operator, 1038
Operator overloading, 321
C++ standard operators, 322–323
restrictions, 322
user-defined operators, 322
uses for, 321–323
Operator, 97–99
not, 1087
! not, 1087
!= not-equal (inequality), 1088
& (unary) address of, 588, 1087
& (binary) bitwise and, 956, 1089, 1094
&& logical and, 1089, 1094
&= and and assign, 1090
% remainder (modulo), 1088
%= remainder (modulo) and assign, 1090
* (binary) multiply, 1088
* (unary) object contents, pointing to, 1087
*= multiply and assign, 1089
+ add (plus), 1088
++ increment, 1087
+= add and assign, 1090
– subtract (minus), 65, 1088
–= decrement, 66, 1087, 1141
-> (arrow) member access, 608, 1087
. (dot) member access, 1086–1087
/ divide, 1088
/= divide and assign, 1090
:: scope resolution, 1086
< less than, 1088
<< shift left, 1088. See also ostream
<= shift left and assign, 1090
< less than or equal, 1088
= assign, 1089
== equal, 1088
> greater than, 1088
Operator, continued

\[\geq\]: greater than or equal, 1088
\[\gg\]: shift right, 1088. See also \texttt{istream}
\[\gg\gg\]: shift right and assign, 1090
\texttt{t}: conditional expression (arithmetic if), 1089

\[\[\]: subscript, 1086
\[\wedge\]: bitwise exclusive or, 1089, 1094
\[\wedge=\]: xor and assign, 1090
\[\|\]: bitwise or, 1089, 1094
\[|=\]: or and assign, 1090
\|\|: logical or, 1089, 1094
\sim: complement, 1087

additive operators, 1088
\texttt{const\_cast}, 1086, 1095
\texttt{delete}, 1087, 1094–1095
\texttt{delete\[]}, 1087, 1094–1095
dereference. See Contents of
\texttt{dynamic\_cast}, 1086, 1095
expressions, 1086–1095
\texttt{new}, 1087, 1094–1095
\texttt{reinterpret\_cast}, 1086, 1095
\texttt{sizeof}, 1087, 1094
\texttt{static\_cast}, 1086, 1095
\texttt{throw}, 1090
\texttt{typeid}, 1086

Optimization, laws of, 931
or, synonym for |. 1038
Order of evaluation, 291–292
or\_eq, synonym for |=, 1038
\texttt{ostream}, 347–349, 1168–1169
\[\,<\], text output, 851, 855
\[\,<\]: user-defined, 363–365
binary I/O, 390–393
connecting to output device, 1170
file I/O, \texttt{fstream}, 349–354, 1170
\texttt{stringstreams}, 395
using together with stdio, 1050
\texttt{<ostream>}, 1134, 1168–1169, 1173
\texttt{ostream\_iterator} type, 790–793
\texttt{ostringstream}, 394–395
\texttt{out} mode, 389, 1170
Out-of-class member definition, 1112
Out-of-range conditions, 595–596
\texttt{Out\_box} example, 443, 563–564
\texttt{out\_of\_range}, 149–150, 152
Output, 1220. See also Input/output; I/O streams
devices, 346–347
to file. See File I/O, writing files
floating point values, 384–385
format specifier \%, 1187
formatting. See Input/output, formatting
integers, 381–383
iterator, 752, 1142
operations, 1173
streams. See I/O streams
to string. See \texttt{stringstream}
testing, 1001
Output \[\,<\], 47, 67, 1173
\texttt{complex}, 920, 1183
\texttt{string}, 851
text output, 851, 855
user-defined, 363–365
Overflow, 891–895, 1220
Overloading, 1104–1105, 1221
alternative to, 526
C++ and C, 1026
on const, 647–648
linkage, 140
operators. See Operator overloading
and overriding, 508–511
resolution, 1104–1105
Override, 508–511, 1221

P

Padding, C-style I/O, 1188
\texttt{pair}, 1165–1166
reading sequence elements, 1152–1153
searching, 1158
sorting, 1158
Palindromes, example, 659–660
Paradigm, 815–818, 1221
Parameterization, function objects, 767
Parameterized type, 682–683
Parameters, 1221
functions, 47, 115
list, 115
naming, 273
omitting, 273
templates, 679–681, 687–689
Parametric polymorphism, 682–683
Parsers, 190, 195
\texttt{Expression} example, 190, 197–200, 202–203
functions required, 196
grammar rules, 194–195
rules \texttt{vs}. tokens, 194
Parsing
expressions, 190–193
grammar, English, 193–194
INDEX

grammar, programming, 190–193
tokens, 190–193
partial_sort(), 1157
partial_sort_copy(), 1158
partial_sum(), 770, 1184
partition(), 1158
Pascal language, 829–831

Passing arguments
by const reference, 276–278, 281–284
copies of, 276
modified arguments, 278
by non-const reference, 281–284
by reference, 279–284
temporary objects, 282
unmodified arguments, 277
by value, 276, 281–284

Patterns. See Regular expressions

Performance
C++ and C, 1024
ideals, 810
testing, 1012–1014
timing, 1015–1016
Permutations, 1160–1161
Petersen, Lawrence, 15

Pictures. See Graphics
Pivoting, 911–912
Pixels, 419–420

Point example, 445–447
pointer, 1147

Pointers, 594. See also Arrays; Iterators; Memory
* contents of, 594
* pointer to (in declarations), 587, 1099
[] subscripting, 594
arithmetic, 651–652
array. See Pointers and arrays
casting. See Type conversion to class objects, 606–608
conversion. See Type conversion to current object, this, 618–620
debugging, 656–659
declaration, C-style strings, 1049–1050
decrementing, 651–652
definition, 587–588, 1221
deleted, 657–658
explicit type conversion. See Type conversion to functions, 1034–1036
incrementing, 651–652
initializing, 596–598, 657
eq. iterators, 1140

literal (0), 1081
to local variables, 658
moving around, 651
to nonexistent elements, 657–658
null, 0, 598, 656–657, 1081
NULL macro, 1190
vs. objects pointed to, 593–594
out-of-range conditions, 595–596
palindromes, example, 661–662
ranges, 595–596
reading and writing through, 594–596
semantics, 637
size, getting, 590–591
subscripting [], 594
this, 676–677
unknown, 608–610
void*, 608–610

Pointers and arrays
converting array names to, 653–654
pointers to array elements, 650–652

Pointers and inheritance
polymorphism, 951–954
a problem, 944–948
a solution, 947–951
user-defined interface class, 947–951
vector alternative, 947–951

Pointers and references
differences, 610–611
inheritance, 612–613
list example, 613–622
parameters, 611–612
this pointer, 618–620
polart(), 920, 1183
Polar coordinates, 920, 1183

Polygon example, 427–428, 458–460, 497
vs. Closed_polyline, 458
invariants, 460

Polyline example
closed, 456–458
marked, 474–476
open, 455–456
vs. rectangles, 429–431

Polymorphism
ad hoc, 682–683
embedded systems, 951–954
parametric, 682–683
run-time, 504–505
templates, 682–683
Pools, embedded systems, 940–941
Pop-up menus, 572
pop_back(), 1149
pop_front(), 1149
pop_heap(), 1160
Portability, 11
C++, 1075
FLTK, 418, 1204
Positioning in files, 393–394
Post-conditions, 165–166, 1001–1002, 1221. See also Invariants
Post-decrement --, 1086, 1101
Post-increment ++, 1086, 1101
Postfix expressions, 1086
Pre-conditions, 163–165, 1001–1002, 1221. See also Invariants
Pre-decrement --, 1087, 1101
Pre-increment ++, 1087, 1101
Precedence, in expressions, 1090
Precision, numeric, 386–387, 891–895
Predicates, 763
on class members, 767–768
function objects, 1163
passing. See Function objects searching, 763–764
Predictability, 931
error handling, 933–934
features to avoid, 932
memory allocation, 936, 940
Preprocessing, 265
Preprocessor directives
#define, macro substitution, 1129
#include, 1058–1059
#undef, 1059
#ifndef, 1059
#include, including headers, 1129
Preprocessor, 1128
coding standards, 978–979
prev_permutation(), 1161
Princeton University, 838
print, character class, 878, 1179
Printable characters, identifying, 397
printf family
%, conversion specification, 1187
conversion specifications, 1188–1189
gets(), 1052, 1190–1191
output formats, user-defined types, 1189–1190
padding, 1188
printf(), 1050–1051, 1187
scanf(), 1052–1053, 1190
stdin, 1189
stdout, 1189

synchronizing with I/O streams, 1050–1051
truncation, 1189
Printing
error messages, 150–151
variable values, 246

priority_queue container adaptor, 1144
Private, 312
base classes, 511
implementation details, 210, 306–308, 312–313
members, 492–493, 505, 511
private: label, 306, 1037
Problem analysis, 175
development stages, 176
estimating resources, 177
problem statement, 176–177
prototyping, 178
strategy, 176–178
Problem statement, 176–177
Procedural programming languages, 815–816
Programmers. See also Programming
communication skills, 22
computation ideals, 92–94
skills requirements, 22–23
stereotypes of, 21–22
worldwide numbers of, 843
Programming, xxiii, 1221. See also Computation;
Software
abstract-first approach, 10
analysis stage, 35
bottom-up approach, 9
c C first approach, 9
concept-based approach, 6
concrete-first approach, 6
depth-first approach, 6
design stage, 35
environments, 52
feedback, 36
genetic, 1219
implementation, 36
magical approach, 10
object-oriented, 10, 1220
programming stage, 36
software engineering principles first approach, 10
stages of, 35–36
testing stage, 36
top-down approach, 9–10
writing a program. See Calculator example
Programming languages, 818–819, 821, 843
Ada, 832–833
Algol60, 827–829
Algot family, 826–829
assemblers, 820
auto codes, 820
BCPL, 838–839
C, 836–839
C#, 831
C++, 839–842
COBOL, 823–825
Common Lisp, 825
Delphi, 831
Fortran, 821–823
Lisp, 825–826
Pascal, 829–831
Scheme, 825
Simula, 833–835
Turbo Pascal, 831
Programming philosophy, 807, 1221. See also
Programming languages
Programming ideals
abstraction level, 812–813
aims, 807–809
bottom-up approach, 811
code structure, 810–811
consistency, 814–815
correct approaches, 811
correctness, 810
data abstraction, 816
desirable properties, 807–808
direct expression of ideas, 811–812
efficiency, 810
generic programming, 816
KISS, 815
maintainability, 810
minimalism, 814–815
modularity, 813–814
multi-paradigm, 818
object-oriented programming, 815–818
overview, 808–809
paradigms, 815–818
performance, 810
philosophies, 807–809
procedural, 815–816
styles, 815–818
on-time delivery, 810
top-down approach, 811
Programming, history, 818–819. See also Programming languages
BNF (Backus-Naur) Form, 823, 828
classes, 834
CODASYL committee, 824
early languages, 819–821
first documented bug, 824–825
first modern stored program, 819–821
first programming book, 820
functional programming, 823
function calls, 820
inheritance, 834
K&R, 838
lint, 836
object-oriented design, 834
STL (Standard Template Library), 841
virtual functions, 834
Programs, 44, 1221. See also Computation; Software
audiences for, 46
compiling, See Compilers
computing values. See Expression
conforming, 1075
experimental. See Prototyping
flow, tracing, 72
implementation defined, 1075
legal, 1075
linking, 51
not-conforming constructs, 1075
run. See Command line; Visual Studio, 52
starting execution, 46–47, 1075–1076
stored on a computer, 109
subdividing, 177–178
terminating, 208–209, 1075–1076
text of. See Source code
translation units, 51
troubleshooting. See Debugging
unspecified constructs, 1075
valid, 1075
writing, example. See Calculator example
writing your first, 45–47
Program organization. See also Programming ideals
abstraction, 92–93
divide and conquer, 93
Projects, Visual Studio, 1199–1200
Promotions, 99, 1091
Prompting for input, 61
>, input prompt, 223
calculator example, 179
sample code, 223–224
Proofs, testing, 992
protected, 492–493, 505, 511, 1037
Prototyping, 178
Pseudo code, 179, 1221
Public, 396, 1037
base class, 508
interface, 210, 496–499

Public, continued
member, 306
public by default, struct, 307–308
public: label, 306
punct, punctuation character class, 878, 1179
Punct_stream example, 401–405
Pure virtual functions, 495, 1221
push_back()
growing a vector, 119–120
queue operations, 1149
resizing vector, 674–675
stack operations, 1149
string operations, 1177
push_front(), 1149
push_heap(), 1160
put(), 1173
putback() naming convention, 211
putting tokens back, 206–207
return value, disabling, 211–212
putc(), 1191
putchar(), 1191
Putting back input, 206–208
Q
qsort(), 1194–1195
<queue>, 1134
queue container adaptor, 1144
Queue operations, 1149
R
\v carriage return, character literal, 1079
r, reading file mode, 1186
r+, reading and writing file mode, 1186
RAII (Resource Acquisition Is Initialization)
definition, 1221
exceptions, 700–701, 1125
testing, 1004–1005
for vector, 705–707
<random>, 1134
Random numbers, 914–917
Random-access iterators, 752, 1142
Range
definition, 1221
efficiency, 695
efficiency, 695
errors, 148–150
pointers, 595–596
regular expressions, 877–878
Range checking
at(), 693–694
[], 650–652, 693–696
arrays, 650–652
compatibility, 695
constraints, 695
design considerations, 694–696
efficiency, 695
exceptions, 693–694
macros, 696–697
optional checking, 695–696
overview, 693–694
pointer, 650–652
vector, 693–696
range-for, 119
rbegin(), 1148
Re-throwing exceptions, 702, 1126
read(), unformatted input, 1172
Readability
expressions, 95
indenting nested code, 271
nested code, 271
Reading
dividing functions logically, 359–362
files. See Reading files
with iterators, 1140–1141
numbers, 214–215
potential problems, 358–363
separating dialog from function, 362–363
a series of values, 356–358
a single value, 358–363
into strings, 851
tokens, 185
Reading files
binary I/O, 391
converting representations, 374–376
to end of file, 366
element, 352–354
ifstream type, 350–352
istream type, 350–352
input loops, 365–367
istream type, 349–354, 391
in-memory representation, 368–370
ostream type, 391
process steps, 350
structured files, 367–376
structured values, 370–374
symbolic representations, 374–376
terminator character, specifying, 366
real), 920, 1183
Real numbers, 891
Real part, 920
Real-time constraints, 931
Real-time response, 928
realloc(), 1045, 1193
Recovering from errors, 239–241, 355–358. See also Error handling; Exceptions
Rectangle example, 428–431, 460–465, 497
Recursion
definition, 1221
infinite, 198, 1220
looping, 200
Recursive function calls, 289
Red-black trees, 779. See also Associative containers; map, associative array
Red margin alerts, 3
Reference semantics, 637
References, 1221. See also Aliases
& in declarations, 276–279
to arguments, 277–278
circular. See Circular reference
to last vector element, back(), 737
to pointers. See Pointers and references
<regex>, 1134, 1175
regex. See Regular expressions
regex_error exception, 1138
regex_match(), 1177
to regex_search(), 883
regex_search(), 1177
to regex_match(), 883
regex pattern matching, 866–868
$ end of line, 873, 1178
() grouping, 867, 873, 876
* zero or more occurrences, 868, 873–874
[] character class, 873
\ escape character, 866–867, 873
\ as literal, 877
* negation, 873
* start of line, 873
() count, 867, 873–875
| alternative (or), 867–868, 873, 876
+ one or more occurrences, 873, 874–875
. wildcard, 873
? optional occurrence, 867–868, 873, 874–875
alternation, 876
character classes. See regex character classes
character sets, 877–878
definition, 870
grouping, 876
matches, 870
pattern matching, 872–873
ranges, 877–878
regex operators, 873, 1177–1179
regex_match(), 1177
regex_search(), 1177
repeating patterns, 874–876
searching with, 869–872, 880
smatch, 870
sub-patterns, 867, 870
regex character classes, 877–878
alnum, 878
alpha, 878
blank, 878
cntrl, 878
d, 878
\d, 873
\D, 873
digit, 878
graph, 878
\l, 873
\L, 874
lower, 878
print, 878
punct, 878
regex_match() vs. regex_search(), 883
s, 878
\s, 873
\S, 874
space, 878
\u, 873
\U, 874
upper, 878
w, 878
\w, 873
\W, 873
xdigit, 878
Regression tests, 993
Regular expressions, 866–868, 872, 1221. See also regex pattern matching
character classes, 873–874
error handling, 878–880
grouping, 867, 873, 876
uses for, 865
ZIP code example, 880–885
Regularity, 380
reinterpret_cast, 609–610, 1095
casting unrelated types, 609
hardware access, 944
Relational operators, 1088
Reliability, software, 34, 928
Remainder and assign %=, 1090
Remainder % (modulo), 66, 1088
correspondence to * and /, 68
floating-point, 201, 230–231
integer and floating-point, 66
remove(), 1155
remove_copy(), 1155
remove_copy_if(), 1155
rend(), 1148
Repeated words examples, 71–74
Repeating patterns, 194
Repetition, 1178. See also Iteration; regex
replace(), 1155
replace_copy(), 1155
reservation, 1151
Reporting errors
Date example, 317–318
debugging, 159
error(), 142–143
run-time, 145–146
syntax errors, 137–138
Representation, 305, 671–673
Requirements, 1221. See also Invariants; Post-conditions; Pre-conditions
for functions, 153
reserve(), 673–674, 691, 747, 1151
Reserved names, 75–76. See also Keywords
resetiosflags() manipulator, 1174
reset(), 674, 1151
Resource, 1221
leaks, 931, 934
limitations, 928
management. See Resource management
testing, 1001–1002
vector example, 697–698
Resource Acquisition Is Initialization (RAII), 1221
exceptions, 700–701, 1125
testing, 1004–1005
for vector, 705–707
Resource management, 697–702. See also vector
example
basic guarantee, 702
error handling, 702
guarantees, 701–702
make_vec(), 702
no-throw guarantee, 702
problems, 698–700
RAII, 700–701, 705–707
resources, examples, 697–698
strong guarantee, 702
testing, 1004–1005
Results, 91. See also Return values
return and move, 704–705
return statement, 272–273
Return types, functions, 47, 272–273
Return values, 113–115
functions, 1103
no return value, void, 212
omitting, 115
returning, 272–273
reverse(), 1155
reverse_copy(), 1155
reverse_iterator, 1147
Revision history, 237–238
Rho, 920
Richards, Martin, 838
right manipulator, 1174
Ritchie, Dennis, 836, 837, 842, 1022–1023, 1032
Robot-assisted surgery, 30
rotate(), 1155
rotate_copy(), 1155
Rounding, 386, 1221. See also Truncation
errors, 891
floating-point values, 386
Rows, matrices, 900–901, 906
Rules, for programming. See Ideals
Rules, grammatical, 194–195
Run-time dispatch, 504–505. See also Virtual
functions
Run-time errors. See Errors, run-time
Run-time polymorphism, 504–505
runtime_error, 142, 151, 153
rvalue reference, 639
Rvalues, 94–95, 1090
S
s, character class, 878, 1179
\s, “not space,” regex, 874
\s, “space,” regex, 873
Safe conversions, 79–80
Safety, type. See Type, safety
Scaffolding, cleaning up, 234–235
scale_and_add() example, 904
scale_and_multiply() example, 912
Scaling data, 542–543
INDEX

scanf(), 1052, 1190
Scenarios. See Use cases
Scheme language, 825
scientific format, 387
scientific manipulator, 385, 1174
Scope, 266–267, 1082–1083, 1221
class, 267, 1082
enumerators, 320–321
global, 267, 270, 1082
going out of, 268–269
kinds of, 267
local, 267, 1083
namespace, 267, 271, 1082
resolution ::, 295–296, 1086
statement, 267, 1083
Scope and nesting
blocks within functions, 271
classes within classes, 270
classes within functions, 270
functions within classes, 270
functions within functions, 271
indenting nested code, 271
local classes, 270
local functions, 270
member classes, 270
member functions, 270
nested blocks, 271
nested classes, 270
nested functions, 270
Scope and object lifetime, 1085–1086
free-store objects, 1085
local (automatic) objects, 1085
namespace objects, 1085
static class members, 1085
temporary objects, 1085
Scope and storage class, 1083–1084
automatic storage, 1083–1084
free store (heap), 1084
static storage, 1084
Screens. See also GUIs (graphical user interfaces)
data graph layout, 541–542
drawing on, 423–424
labeling, 425
search(), 795–796, 1153
Searching. See also Finding; Matching; find_if();
find() algorithms for, 1157–1159
binary searches, 779, 795–796
in C, 1194–1195
for characters, 740
(key, value) pairs, by key. See Associative containers
for links, 615–617
map elements. See unordered_map
predicates, 763
with regular expressions, 869–872, 880–885, 1177–1179
search_n(), 1153
Self reference. See this pointer
Self assignment, 676–677
Self-checking, error handling, 934
Separators, nonstandard, 398–405
Sequence containers, 1144
Sequences, 720, 1221
algorithms. See Algorithms, STL
differences between adjacent elements, 770
empty, 729
element, 723–724
half open, 721
Sequencing rules, 195
Server farms, 31–32
set, 776, 787–789
iterators, 1144
vs. map, 788
subscripting, 788
set(), 605–606
<set>, 776, 1134
Set algorithms, 1159–1160
set_difference(), 1160
set_intersection(), 1159
set_symmetric_difference(), 1160
set_union(), 1159
setbase() manipulator, 1174
setfill() manipulator, 1174
setiosflags() manipulator, 1174
setprecision() manipulator, 386–387, 1174
setw() manipulator, 1174
Shallow copies, 636
Shape example, 493–494
abstract classes, 495–496
access control, 496–499
attaching to Window, 545–546
as base class, 445, 495–496
close(), 504
copying objects, 503–504
draw(), 500–502
draw_lines(), 500–502
fill color, 500
implementation inheritance, 513–514
interface inheritance, 513–514
Shape example, continued
line visibility, 500
move(), 502
mutability, 503–504
number_of_points(), 449
object layout, 506–507
object-oriented programming, 513–514
point(), 449
slicing shapes, 504
virtual function calls, 501, 506–507
Shift operators, 1088
Shipping, computer use, 26–28
short, 955, 1099
Shorthand notation, regular expressions, 1179
showbase, manipulator, 383, 1173
showpoint, manipulator, 1173
showpos, manipulator, 1173
Shuffle algorithm, 1155–1156
Signed and unsigned integers, 961–965
Signed type, 1099
Simple_window, 422–424, 443
Simplicity ideal, 92–94
Simula language, 833–835
sin(), sine, 917, 1182
Singly-linked lists, 613, 725
sinh(), hyperbolic sine, 918, 1182
Size
bit strings, 955–956
containers, 1150–1151
getting, sizeof(), 590–591
of numbers, 891–895
vectors, getting, 119–120
size()
container capacity, 1150
number of elements, 120, 851
string length, 851, 1176
vectors, 120, 122–123
sizeof(), 590–591, 1094
object size, 1087
value size, 892
size_type, 730, 1147
skipws, 1174
slice(), 901–902, 905
Slicing
matrices, 901–902, 905
objects, 504
Smallest integer, finding, 917
smatch, 870
Soft real-time, 931
Software, 19, 1222. See also Programming; Programs
affordability, 34
correctness, 34
ideals, 34–37
maintainability, 35
reliability, 34
troubleshooting. See Debugging
useful design, 34
uses for, 19–33
Software layers, GUIs, 557
sort(), 758, 794–796, 1157
sort_heap(), 1160
Sorting
algorithms for, 1157–1159
in C, qsort(), 1194
sort(), 758, 794–796, 1157
Source code
definition, 48, 1222
entering, 1200
Source files, 48, 1222
adding to projects, 1200
space, 878, 1179
Space exploration, computer use, 33
Special characters, 1079–1080
regular expressions, 1178
Specialization, 681, 1123
Specifications
definition, 1221
source of errors, 136
Speed of light, 96
sprintf(), 1187
sqrt(), square root, 917, 1181
Square of abs(), norm, 919
sstream, 1134
stable_partition(), 1158
stable_sort(), 1157
stack, 1134
stack container adaptor, 1144
Stack of activation records, 287
Stack storage, 591–592
Stacks
canceller operations, 1149
embedded systems, 935–936, 940, 942–943
growth, 287–290
unwinding, 1126
Stages of programming, 35–36
Standard
conformance, 836, 974, 1075
ISO, 1075, 1222
manipulators. See Manipulators
mathematical functions, 917–918

Standard library. See also C standard library; STL
(Standard Template Library) algorithms. See Algorithms
complex. See complex
containers. See Containers
C-style I/O. See printf() family
C-style strings. See C-style strings
date and time, 1193–1194
function objects. See Function objects
I/O streams. See Input; Input/output;
Output
iterators. See Iterators
mathematical functions. See Mathematical
functions (standard) numerical algorithms. See Algorithms,
numerical; Numerics
string. See string
time, 1015–1016, 1193
valarray. See valarray
Standard library header files, 1133–1136
algorithms, 1133–1134
containers, 1133–1134
C standard libraries, 1135–1136
I/O streams, 1134
iterators, 1133–1134
numerics, 1134–1135
string manipulation, 1134
utility and language support, 1135
Standard library I/O streams, 1168–1169. See also
I/O streams
Standard library string manipulation
character classification, 1175–1176
containers. See map, associative array; set;
unordered_map; vector
input/output. See I/O streams
regular expressions. See regex
string manipulation. See string
Stanford University, 826
Starting programs, 1075–1076. See also main()
State, 90–91, 1222
I/O stream, 1171
of objects, 305
source of errors, 136
testing, 1001
validity checking, 313
valid state, 313
Statement scope, 267, 1083

Statements, 47
grammar, 1096–1097
named sequence of. See Function
terminator ; (semicolon), 50, 100
Static storage, 591–592, 1084
class members, lifetime, 1085
embedded systems, 935–936, 944
static, 1084
static const, 326. See also const
static local variables, order of initialization, 294
std namespace, 296–297, 1136
stderr, 1189
<stdio.h>, 1135
stdin, 1050, 1189. See also stdio
stdio, standard C I/O, 1050, 1190–1191
EOF macro, 1053–1054
errno, error indicator, 918–919
fclose(), 1053–1054
FILE, 1053–1054
fopen(), 1053–1054
getchar(), 1052–1053, 1191
gets(), 1052, 1190–1191
input, 1052–1053
output, 1050–1051
printf(), 1050–1051, 1188–1191
scanf(), 1052, 1190
stderr, cerr equivalent, 1189
stdin, cin equivalent, 1050, 1189
stdout, 1050, 1189. See also stdio
stdout, cout equivalent, 1050, 1189
<stdio.h> header file, 1199–1200
stdout, 1050, 1189. See also stdio
Stepanov, Alexander, 720, 722, 841
Stepping through code, 162
Stereotypes of programmers, 21–22
STL (Standard Template Library), 717, 1149–
1168 (large range, not sure this is correct). See
also C standard library; Standard library
algorithms. See STL algorithms
containers. See STL containers
function objects. See STL function objects
history of, 841
ideals, 717–720
iterators. See STL iterators
namespace, std, 1136
STL algorithms, 1152–1162
See Algorithms, STL.
alternatives to, 1195
built-in arrays, 747–749
STL algorithms, continued
computation vs. data, 717–720
heap, 1160
\texttt{max()}, 1161
\texttt{min()}, 1161
modifying sequence, 1154–1156
mutating sequence, 1154–1156
nonmodifying sequence, 1153–1154
permutations, 1160–1161
searching, 1157–1159
set, 1159–1160
shuffle, 1155–1156
sorting, 1157–1159
utility, 1157
value comparisons, 1161–1162
STL containers, 749–751, 1144–1152
almost, 751, 1145
assignments, 1148
associative, 1144, 1151–1152
capacity, 1150–1151
comparing, 1151
constructors, 1148
corner adaptors, 1144
copying, 1151
destructors, 1148
element access, 1149
information sources about, 750
iterator categories for, 752, 1143–1145,
1148
list operations, 1150
member types, 1147
operations overview, 1146–1147
queue operations, 1149
sequence, 1144
size, 1150–1151
stack operations, 1149
swapping, 1151
STL function objects, 1163
adaptors, 1164
arithmetic operations, 1164
inserters, 1162–1163
predicates, 767–768, 1163
STL iterators, 1139–1140
basic operations, 721
categories, 1142–1143
definition, 721, 1139
description, 721–722
empty lists, 729
example, 737–741
operations, 1141–1142
\texttt{vs.} pointers, 1140
sequence of elements, 1140–1141
Storage class, 1083–1084
automatic storage, 1083–1084
free store (heap), 1084
static storage, 1084
Storing data. See Containers
\texttt{str()}, string extractor, 395
\texttt{strcat()}, 1047, 1191
\texttt{strchr()}, 1048, 1192
\texttt{strcmp()}, 1047, 1192
\texttt{strcpy()}, 1047, 1049, 1192
Stream
buffers, 1169
iterators, 790–793
modes, 1170
states, 355
types, 1170
\texttt{streambuf}, 406, 1169
\texttt{<streambuf>}, 1134
\texttt{<string>}, 1134, 1172
\texttt{string}, 66, 851, 1222. See also Text
\texttt{[]} subscripting, 851
+ concatenation, 68–69, 851, 1176
+= append, 851
\texttt{<} lexicographical comparison, 851
\texttt{==} equal, 851
\texttt{=} assign, 851
\texttt{>>} input, 851
\texttt{<<} output, 851
almost container, 1145
\texttt{append()}, 851
\texttt{basic\_string}, 852
C++ to C-style conversion, 851
\texttt{c\_str()}, C++ to C-style conversion, 851
\texttt{erase()}, removing characters, 851
exceptions, 1138
\texttt{find()}, 851
\texttt{from\_string()}, 853–854
\texttt{getline()}, 851
input terminator (whitespace), 65
\texttt{insert()}, adding characters, 851
\texttt{length()}, number of characters, 851
\texttt{lexical\_cast} example, 855
literals, debugging, 161
operations, 851, 1176–1177
operators, 66–67, 68
palindromes, example, 659–660
INDEX

pattern matching. See Regular expressions
properties, 741–742
size, 78
size(), number of characters, 851
standard library, 852
stringstream, 852–854
string to value conversion, 853–854
subscripting [], 851
to_string() example, 852–854
values to string conversion, 852
vs. vector, 745
whitespace, 854
String literal, 62, 1080
stringstream, 395, 852–854, 1170
strlen(), 1046, 1191
strncat(), 1047, 1192
strncmp(), 1047, 1192
strncpy(), 1047, 1192
Strong guarantee, 702
Stroustrup, Bjarne
advisor, 820
Bell Labs colleagues, 836–839, 1023
biography, 13–14
education on invariants, 828
inventor of C++, 839–842
Kristen Nygaard, 834
strpbrk(), 1192
strrchr(), 1192
strstr(), 1192
strconv(), 1192
system(), 1194
system_clock, 1016, 1185
System, definition, 1222
System tests, 1009–1011
T
\t tab character, 109, 1079
tan(), tangent, 917, 1182
tanh(), hyperbolic tangent, 917, 1182
TEA (Tiny Encryption Algorithm), 820, 969–974
Technical University of Copenhagen, 828
Template, 1038
Template, 678–679, 1121–1122, 1222
arguments, 1122–1123
class, 681–683. See also Class template
compiling, 684
containers, 686–687
error diagnostics, 683
function, 682–690. See also Function template
generic programming, 682–683
inheritance, 686–687
instantiation, 681, 1123–1124
integer parameters, 687–689
member types, 1124
parameters, 679–681, 687–689
parametric polymorphism, 682–683
specialization, 1123
typename, 1124
type parameters, 679–681
weaknesses, 683
Template-style casts, 1040
Temporary objects, 282, 1085
Terminals, in grammars. See Tokens
Termination
abort() a program, 1194
on exceptions, 142
exit() a program, 1194
input, 61–62, 179
normal program termination, 1075–1076
for string input, 65
zero, for C-style strings, 654–655
Terminator character, specifying, 366
Testing, 992–993, 1222. See also Debugging
algorithms, 1001–1008
for bad input, 103
black box, 992–993
branching, 1006–1008
bug reports, retention period, 993
calculator example, 225
code coverage, 1008
debugging, 1012
dependencies, 1002–1003
designing for, 1011–1012
faulty assumptions, 1009–1011
files, after opening, 352
FLTK, 1206
inputs, 1001
loops, 1005–1006
non-algorithms, 1001–1008
outputs, 1001
performance, 1012–1014
pre- and post-conditions, 1001–1002
proofs, 992
RAIL, 1004–1005
regression tests, 993
resource management, 1004–1005
resources, 1001–1002
stage of programming, 36
state, 1001
system tests, 1009–1011
test cases, definition, 166
test harness, 997–999
timing, 1015–1016
white box, 992–993
Testing units
formal specification, 994–995
random sequences, 999–1001
strategy for, 995–997
systematic testing, 994–995
test harness, 997–999
Text
caracter strings. See C-style strings; string
e-mail example, 856–861, 864–865
extracting text from files, 855–861, 864–865
finding patterns, 864–865, 869–872
in graphics. See Text
implementation details, 861–864
input/output, GUIs, 563–564
maps. See map
storage, 591–592
substrings, 863
vector example, 123–125
words frequency example, 777–779
Text example, 431–433, 467–470
Text editor example, 737–741
Theta, 920
this pointer, 618–620, 676–677
Thompson, Ken, 836–838
Three-way comparison, 1046
Throwing exceptions, 147, 1125
I/O stream, 1171
re-throwing, 702
standard library, 1138–1139
throw, 147, 1090, 1125–1126
vector, 697–698
Time
date and time, 1193–1194
measuring, 1015–1016
Timekeeping, computer use, 26
time_point, 1016
time_t, 1193
Tiny Encryption Algorithm (TEA), 820, 969–974

Token example, 183–184
Token_stream example, 206–214
tolower(), 398, 1176
Top-down approach, 9–10, 811
toupper(), 398, 1176
Tracing code execution, 162–163
Trade-off, definition, 1222

transform(), 1154
Transient errors, handling, 934
Translation units, 51, 139–140
Transparency, 451, 463

Tree structure, map container, 779–782
true, 1037, 1038
trunc mode, 389, 1170
Truncation, 82, 1222
C-style I/O, 1189
exceptions, 153
floating-point numbers, 893
try–catch, 146–153, 693–694, 1037
Turbo Pascal language, 831
Two-dimensional matrices, 904–906
Two’s complement, 961
Type, 60, 77, 1222
aliases, 730
built-in. See Built-in types
checking, C++ and C, 1032–1033
generators, 681
graphics classes, 488–490
mismatch errors, 138–139
mixing in expressions, 99

naming. See Namespaces
objects, 77–78
operations, 305
organizing. See Namespaces
parameterized, 682–683. See also Template
as parameters. See Template
pointers. See Pointer
promotion, 99
representation of object, 308–309, 506–507

safety, 78–79, 82
subtype, 1222
supertype, 1222
truncation, 82
user-defined. See UDTs (user-defined types)
uses for, 304

values, 77
variables. See Variables

Type conversion
casting, 609–610
const_cast, casting away const, 609–610
exceptions, 153
explicit, 609
in expressions, 99–100
function arguments, 284–285
implicit, 642–643
int to pointer, 590
operators, 1095
pointers, 590, 609–610
reinterpret_cast, 609
safety, 79–83
static_cast, 609
string to value, 853–854
truncation, 82
value to string, 852

Type conversion, implicit, 642–643
bool, 1092
compiler warnings, 1091
floating-point and integral, 1091–1092
integral promotion, 1091
pointer and reference, 1092
preserving values, 1091
promotions, 1091
user-defined, 1091
usual arithmetic, 1092

Type safety, 78–79
implicit conversions, 80–83
narrowing conversions, 80–83
pointers, 596–598, 656–659
range error, 148–150, 595–596
safe conversions, 79–80
unsafe conversions, 80–83

typedef, 730
typedef, 1037, 1087, 1138
<typeinfo>, 1135
typename, 1037, 1124

u

u/U suffix, 1077
U, “not uppercase,” regex, 874
u, “uppercase character,” regex, 873, 1179
UDTs (user-defined types). See Class;
Enumerations

Unary expressions, 1087
“Uncaught exception” error, 153
Unchecked conversions, 943–944
“Undeclared identifier” error, 258
Undefined order of evaluation, 263
unget(), 355–358
ungetc(), 1191
Uninitialized variables, 327–330, 1222
uninitialized_copy(), 1157
uninitialized_fill(), 1157
union, 1121
unique(), 1155
unique_copy(), 758, 789, 792–793, 1155
unique_ptr, 703–704
Unit tests
formal specification, 994–995
random sequences, 999–1001
strategy for, 995–997
systematic testing, 994–995
test harness, 997–999
Universal and uniform initialization, 83
Unnamed objects, 465–467
unordered_map, 776, 1134
unordered_map, 776. See also map, associative array
finding elements, 785–787
hashing, 785
hash tables, 785
hash values, 785
iterators, 1144
unordered_multimap, 776, 1144
unordered_multiset, 776, 1144
unordered_set, 776, 1134
Unsafe conversions, 80–83
unsetf(), 384
Unsigned and signed, 961–965
unsigned type, 1099
Unspecified constructs, 1075
upper, character class, 878, 1179
upper_bound, 796, 1152, 1158
Upper case. See Case (of characters)
uppercase, 1174
U.S. Department of Defense, 832
U.S. Navy, 824
Use cases, 179, 1222
User-defined conversions, 1091
User-defined operators, 1091
User-defined types (UDTs), 304. See also Class; Enumerations
exceptions, 1126
operator overloading, 1107
operators, 1107
standard library types, 304
User interfaces
console input/output, 552
graphical, & GUIs (graphical user interfaces)
web browser, 552–553
using declarations, 296–297
using directives, 296–297, 1127
Usual arithmetic conversions, 1092
Utilities, STL
function objects, 1163–1164
inserters, 1162–1163
make_pair(), 1165–1166
pair, 1165–1166
<utility>, 1134, 1165–1166
Utility algorithms, 1157
Utility and language support, header files, 1135
V
vertical tab, character literal, 1079
valarray, 1145, 1183
<valarray>, 1135
Valid pointer, 598
Valid programs, 1075
Valid state, 313
Validity checking, 313
constructors, 313
enumerations, 320
invariants, 313
rules for, 313
Value semantics, 637
value_comp(), 1152
Values, 77–78, 1222
symbolic constants for. See Enumerations and variables, 62, 73–74, 243
value_type, 1147
Variables, 62–63, 1083
++ increment, 73–74
= assignment, 69–73
changing values, 73–74
composite assignment operators, 73–74
constructing, 291–292
declarations, 260, 262–263
going out of scope, 291
incrementing ++, 73–74
initialization, 69–73
input, 60
naming, 74–77
type of, 66–67
uninitialized, class interfaces, 327–330
value of, 73–74

**<vector>**, 1134

**vector** example, 584–587, 629–636, 668–679

[] subscripting, 646, 693–697
= assignment, 675–677
. (dot) access, 607–608
allocators, 691
changing size, 668–679
at(), checked subscripting, 694
copying, 631–636
destructor, 601–605
element type as parameter, 679–681
erase() (removing elements), 745–747
exceptions, 693–694, 705–707
explicit constructors, 642–643
inheritance, 686–687
insert() (adding elements), 745–747
overloading on const, 647–648
push_back(), 674–675, 692
representation, 671–673
reserve(), 673, 691, 704–705
resize(), 674, 692
subscripting, 594, 607–608, 646–647

**vector** of references, simulating, 1212–1213

**Vector_ref** example, 444, 1212–1213

**vector_size()**, 119

**virtual**, 1037

Virtual destructors, 604–605. *See also* Destructors

Virtual functions, 501, 506–507
declaring, 508
definition, 501, 1222
history of, 834
object layout, 506–507
overriding, 508–511
pure, 512–513

**Shape** example, 501, 506–507

**vptr**, 506–507

**vtable**, virtual function table, 506

**W**

w, writing file mode, 878, 1179, 1186
w+, writing and reading file mode, 1186
\W, “not word character,” *regex*, 874, 1179
\w, “word character,” *regex*, 873, 1179
wait(), 559–560, 569–570
Wait loops, 559–560
wait_for_button() example, 559–560
Waiting for user action, 559–560, 569–570

**wchar_t**, 1038
Web browser, as user interface, 552–553
Wheeler, David, 109, 820, 954, 969
while-statements, 109–111
vs. for, 122
White-box testing, 992–993
Whitespace
formatting, 397, 398–405
identifying, 397
Whitespace in input, 64

string, 854

*Widget* example, 561–563

*Button*, 422–424, 553–561
control inversion, 569–570
debugging, 576–577

*hide*, 562

implementation, 1209–1210

*In_box*, 563–564

line drawing example, 565–569

*Menu*, 564–565, 570–575

*move*, 562

*Out_box*, 563–564

*put_on_top*, 1211

*show*, 562

technical example, 1213–12116
text input/output, 563–564

visibility, 562

*Wild cards, regular expressions*, 1178

*Wilkes, Maurice*, 820

*Window* example, 420, 443
canvas, 420

creating, 422–424, 554–556
disappearing, 576
drawing area, 420

implementation, 1210–1212

line drawing example, 565–569

*put_on_top*, 1211

*Window.h* example, 421–422

*Wirth, Niklaus*, 830–831

*Word frequency, example*, 777

*Words (of memory)*, 1222

*write*, unformatted output, 1173

*Writing files*, 350. *See also File I/O*

appending to, 389

binary I/O, 391
element, 352–354

*fstream* type, 350–352

*ofstream* type, 351–352

*ostream* type, 349–354, 391

*ws* manipulator, 1174

*X*

*xdigit*, 878, 1179

\xhhh, hexadecimal character literal, 1080

*xor*, synonym for *, 1038

*xor_eq*, synonym for *=*, 1038

*Z*

zero-terminated array, 1045. *See also C-style strings*

ZIP code example, 880–885