

Bestseller Since 1986

Completely Rewritten for the New C++11 Standard



Fifth Edition

C++ Primer

Stanley B. Lippman
Josée Lajoie
Barbara Moo

FREE SAMPLE CHAPTER



SHARE WITH OTHERS

C++ Primer
Fifth Edition

This page intentionally left blank

C++ Primer
Fifth Edition

Stanley B. Lippman
Josée Lajoie
Barbara E. Moo

◆◆ Addison-Wesley

Upper Saddle River, NJ • Boston • Indianapolis • San Francisco
New York • Toronto • Montreal • London • Munich • Paris • Madrid
Capetown • Sidney • Tokyo • Singapore • Mexico City

Many of the designations used by manufacturers and sellers to distinguish their products are claimed as trademarks. Where those designations appear in this book, and the publisher was aware of a trademark claim, the designations have been printed with initial capital letters or in all capitals.

The authors and publisher have taken care in the preparation of this book, but make no expressed or implied warranty of any kind and assume no responsibility for errors or omissions. No liability is assumed for incidental or consequential damages in connection with or arising out of the use of the information or programs contained herein.

The publisher offers excellent discounts on this book when ordered in quantity for bulk purchases or special sales, which may include electronic versions and/or custom covers and content particular to your business, training goals, marketing focus, and branding interests. For more information, please contact:

U. S. Corporate and Government Sales
(800) 382-3419
corpsales@pearsontechgroup.com

For sales outside the U. S., please contact:

International Sales
international@pearsoned.com

Visit us on the Web: informit.com/aw

Library of Congress Cataloging-in-Publication Data

Lippman, Stanley B.

C++ primer / Stanley B. Lippman, Josée Lajoie, Barbara E. Moo. – 5th ed.

p. cm.

Includes index.

ISBN 0-321-71411-3 (pbk. : alk. paper) 1. C++ (Computer program language) I. Lajoie, Josée. II. Moo, Barbara E. III. Title.

QA76.73.C153L57697 2013

005.13'3–dc23

2012020184

Copyright © 2013 Objectwrite Inc., Josée Lajoie and Barbara E. Moo

All rights reserved. Printed in the United States of America. This publication is protected by copyright, and permission must be obtained from the publisher prior to any prohibited reproduction, storage in a retrieval system, or transmission in any form or by any means, electronic, mechanical, photocopying, recording, or likewise. To obtain permission to use material from this work, please submit a written request to Pearson Education, Inc., Permissions Department, One Lake Street, Upper Saddle River, New Jersey 07458, or you may fax your request to (201) 236-3290.

C++ Primer, Fifth Edition, features an enhanced, layflat binding, which allows the book to stay open more easily when placed on a flat surface. This special binding method—notable by a small space inside the spine—also increases durability.

ISBN-13: 978-0-321-71411-4

ISBN-10: 0-321-71411-3

Text printed in the United States on recycled paper at Courier in Westford, Massachusetts.

Sixth printing, May 2015

*To Beth,
who makes this,
and all things,
possible.*

*To Daniel and Anna,
who contain
virtually
all possibilities.*
—SBL

*To Mark and Mom,
for their
unconditional love and support.*
—JL

*To Andy,
who taught me
to program
and so much more.*
—BEM

This page intentionally left blank

Contents

Preface	xxiii
Chapter 1 Getting Started	1
1.1 Writing a Simple C++ Program	2
1.1.1 Compiling and Executing Our Program	3
1.2 A First Look at Input/Output	5
1.3 A Word about Comments	9
1.4 Flow of Control	11
1.4.1 The while Statement	11
1.4.2 The for Statement	13
1.4.3 Reading an Unknown Number of Inputs	14
1.4.4 The if Statement	17
1.5 Introducing Classes	19
1.5.1 The Sales_item Class	20
1.5.2 A First Look at Member Functions	23
1.6 The Bookstore Program	24
Chapter Summary	26
Defined Terms	26
Part I The Basics	29
Chapter 2 Variables and Basic Types	31
2.1 Primitive Built-in Types	32
2.1.1 Arithmetic Types	32
2.1.2 Type Conversions	35
2.1.3 Literals	38
2.2 Variables	41
2.2.1 Variable Definitions	41
2.2.2 Variable Declarations and Definitions	44
2.2.3 Identifiers	46
2.2.4 Scope of a Name	48
2.3 Compound Types	50
2.3.1 References	50
2.3.2 Pointers	52

2.3.3	Understanding Compound Type Declarations	57
2.4	<code>const</code> Qualifier	59
2.4.1	References to <code>const</code>	61
2.4.2	Pointers and <code>const</code>	62
2.4.3	Top-Level <code>const</code>	63
2.4.4	<code>constexpr</code> and Constant Expressions	65
2.5	Dealing with Types	67
2.5.1	Type Aliases	67
2.5.2	The <code>auto</code> Type Specifier	68
2.5.3	The <code>decltype</code> Type Specifier	70
2.6	Defining Our Own Data Structures	72
2.6.1	Defining the <code>Sales_data</code> Type	72
2.6.2	Using the <code>Sales_data</code> Class	74
2.6.3	Writing Our Own Header Files	76
	Chapter Summary	78
	Defined Terms	78
Chapter 3 Strings, Vectors, and Arrays		81
3.1	Namespace using Declarations	82
3.2	Library <code>string</code> Type	84
3.2.1	Defining and Initializing <code>strings</code>	84
3.2.2	Operations on <code>strings</code>	85
3.2.3	Dealing with the Characters in a <code>string</code>	90
3.3	Library <code>vector</code> Type	96
3.3.1	Defining and Initializing <code>vectors</code>	97
3.3.2	Adding Elements to a <code>vector</code>	100
3.3.3	Other <code>vector</code> Operations	102
3.4	Introducing Iterators	106
3.4.1	Using Iterators	106
3.4.2	Iterator Arithmetic	111
3.5	Arrays	113
3.5.1	Defining and Initializing Built-in Arrays	113
3.5.2	Accessing the Elements of an Array	116
3.5.3	Pointers and Arrays	117
3.5.4	C-Style Character Strings	122
3.5.5	Interfacing to Older Code	124
3.6	Multidimensional Arrays	125
	Chapter Summary	131
	Defined Terms	131
Chapter 4 Expressions		133
4.1	Fundamentals	134
4.1.1	Basic Concepts	134
4.1.2	Precedence and Associativity	136
4.1.3	Order of Evaluation	137
4.2	Arithmetic Operators	139
4.3	Logical and Relational Operators	141

4.4	Assignment Operators	144
4.5	Increment and Decrement Operators	147
4.6	The Member Access Operators	150
4.7	The Conditional Operator	151
4.8	The Bitwise Operators	152
4.9	The sizeof Operator	156
4.10	Comma Operator	157
4.11	Type Conversions	159
4.11.1	The Arithmetic Conversions	159
4.11.2	Other Implicit Conversions	161
4.11.3	Explicit Conversions	162
4.12	Operator Precedence Table	166
	Chapter Summary	168
	Defined Terms	168
Chapter 5	Statements	171
5.1	Simple Statements	172
5.2	Statement Scope	174
5.3	Conditional Statements	174
5.3.1	The if Statement	175
5.3.2	The switch Statement	178
5.4	Iterative Statements	183
5.4.1	The while Statement	183
5.4.2	Traditional for Statement	185
5.4.3	Range for Statement	187
5.4.4	The do while Statement	189
5.5	Jump Statements	190
5.5.1	The break Statement	190
5.5.2	The continue Statement	191
5.5.3	The goto Statement	192
5.6	try Blocks and Exception Handling	193
5.6.1	A throw Expression	193
5.6.2	The try Block	194
5.6.3	Standard Exceptions	197
	Chapter Summary	199
	Defined Terms	199
Chapter 6	Functions	201
6.1	Function Basics	202
6.1.1	Local Objects	204
6.1.2	Function Declarations	206
6.1.3	Separate Compilation	207
6.2	Argument Passing	208
6.2.1	Passing Arguments by Value	209
6.2.2	Passing Arguments by Reference	210
6.2.3	const Parameters and Arguments	212
6.2.4	Array Parameters	214

6.2.5	main: Handling Command-Line Options	218
6.2.6	Functions with Varying Parameters	220
6.3	Return Types and the <code>return</code> Statement	222
6.3.1	Functions with No Return Value	223
6.3.2	Functions That Return a Value	223
6.3.3	Returning a Pointer to an Array	228
6.4	Overloaded Functions	230
6.4.1	Overloading and Scope	234
6.5	Features for Specialized Uses	236
6.5.1	Default Arguments	236
6.5.2	Inline and <code>constexpr</code> Functions	238
6.5.3	Aids for Debugging	240
6.6	Function Matching	242
6.6.1	Argument Type Conversions	245
6.7	Pointers to Functions	247
	Chapter Summary	251
	Defined Terms	251
Chapter 7	Classes	253
7.1	Defining Abstract Data Types	254
7.1.1	Designing the <code>Sales_data</code> Class	254
7.1.2	Defining the Revised <code>Sales_data</code> Class	256
7.1.3	Defining Nonmember Class-Related Functions	260
7.1.4	Constructors	262
7.1.5	Copy, Assignment, and Destruction	267
7.2	Access Control and Encapsulation	268
7.2.1	Friends	269
7.3	Additional Class Features	271
7.3.1	Class Members Revisited	271
7.3.2	Functions That Return <code>*this</code>	275
7.3.3	Class Types	277
7.3.4	Friendship Revisited	279
7.4	Class Scope	282
7.4.1	Name Lookup and Class Scope	283
7.5	Constructors Revisited	288
7.5.1	Constructor Initializer List	288
7.5.2	Delegating Constructors	291
7.5.3	The Role of the Default Constructor	293
7.5.4	Implicit Class-Type Conversions	294
7.5.5	Aggregate Classes	298
7.5.6	Literal Classes	299
7.6	<code>static</code> Class Members	300
	Chapter Summary	305
	Defined Terms	305

Part II	The C++ Library	307
Chapter 8	The IO Library	309
8.1	The IO Classes	310
8.1.1	No Copy or Assign for IO Objects	311
8.1.2	Condition States	312
8.1.3	Managing the Output Buffer	314
8.2	File Input and Output	316
8.2.1	Using File Stream Objects	317
8.2.2	File Modes	319
8.3	string Streams	321
8.3.1	Using an <code>istringstream</code>	321
8.3.2	Using <code>ostringstreams</code>	323
	Chapter Summary	324
	Defined Terms	324
Chapter 9	Sequential Containers	325
9.1	Overview of the Sequential Containers	326
9.2	Container Library Overview	328
9.2.1	Iterators	331
9.2.2	Container Type Members	332
9.2.3	<code>begin</code> and <code>end</code> Members	333
9.2.4	Defining and Initializing a Container	334
9.2.5	Assignment and <code>swap</code>	337
9.2.6	Container Size Operations	340
9.2.7	Relational Operators	340
9.3	Sequential Container Operations	341
9.3.1	Adding Elements to a Sequential Container	341
9.3.2	Accessing Elements	346
9.3.3	Erasing Elements	348
9.3.4	Specialized <code>forward_list</code> Operations	350
9.3.5	Resizing a Container	352
9.3.6	Container Operations May Invalidate Iterators	353
9.4	How a <code>vector</code> Grows	355
9.5	Additional <code>string</code> Operations	360
9.5.1	Other Ways to Construct <code>strings</code>	360
9.5.2	Other Ways to Change a <code>string</code>	361
9.5.3	<code>string</code> Search Operations	364
9.5.4	The <code>compare</code> Functions	366
9.5.5	Numeric Conversions	367
9.6	Container Adaptors	368
	Chapter Summary	372
	Defined Terms	372

Chapter 10 Generic Algorithms	375
10.1 Overview	376
10.2 A First Look at the Algorithms	378
10.2.1 Read-Only Algorithms	379
10.2.2 Algorithms That Write Container Elements	380
10.2.3 Algorithms That Reorder Container Elements	383
10.3 Customizing Operations	385
10.3.1 Passing a Function to an Algorithm	386
10.3.2 Lambda Expressions	387
10.3.3 Lambda Captures and Returns	392
10.3.4 Binding Arguments	397
10.4 Revisiting Iterators	401
10.4.1 Insert Iterators	401
10.4.2 <code>iostream</code> Iterators	403
10.4.3 Reverse Iterators	407
10.5 Structure of Generic Algorithms	410
10.5.1 The Five Iterator Categories	410
10.5.2 Algorithm Parameter Patterns	412
10.5.3 Algorithm Naming Conventions	413
10.6 Container-Specific Algorithms	415
Chapter Summary	417
Defined Terms	417
Chapter 11 Associative Containers	419
11.1 Using an Associative Container	420
11.2 Overview of the Associative Containers	423
11.2.1 Defining an Associative Container	423
11.2.2 Requirements on Key Type	424
11.2.3 The <code>pair</code> Type	426
11.3 Operations on Associative Containers	428
11.3.1 Associative Container Iterators	429
11.3.2 Adding Elements	431
11.3.3 Erasing Elements	434
11.3.4 Subscripting a <code>map</code>	435
11.3.5 Accessing Elements	436
11.3.6 A Word Transformation Map	440
11.4 The Unordered Containers	443
Chapter Summary	447
Defined Terms	447
Chapter 12 Dynamic Memory	449
12.1 Dynamic Memory and Smart Pointers	450
12.1.1 The <code>shared_ptr</code> Class	450
12.1.2 Managing Memory Directly	458
12.1.3 Using <code>shared_ptrs</code> with <code>new</code>	464
12.1.4 Smart Pointers and Exceptions	467
12.1.5 <code>unique_ptr</code>	470

- 12.1.6 `weak_ptr` 473
- 12.2 Dynamic Arrays 476
 - 12.2.1 `new` and Arrays 477
 - 12.2.2 The `allocator` Class 481
- 12.3 Using the Library: A Text-Query Program 484
 - 12.3.1 Design of the Query Program 485
 - 12.3.2 Defining the Query Program Classes 487
- Chapter Summary 491
- Defined Terms 491

Part III Tools for Class Authors 493

Chapter 13 Copy Control 495

- 13.1 Copy, Assign, and Destroy 496
 - 13.1.1 The Copy Constructor 496
 - 13.1.2 The Copy-Assignment Operator 500
 - 13.1.3 The Destructor 501
 - 13.1.4 The Rule of Three/Five 503
 - 13.1.5 Using `= default` 506
 - 13.1.6 Preventing Copies 507
- 13.2 Copy Control and Resource Management 510
 - 13.2.1 Classes That Act Like Values 511
 - 13.2.2 Defining Classes That Act Like Pointers 513
- 13.3 Swap 516
- 13.4 A Copy-Control Example 519
- 13.5 Classes That Manage Dynamic Memory 524
- 13.6 Moving Objects 531
 - 13.6.1 Rvalue References 532
 - 13.6.2 Move Constructor and Move Assignment 534
 - 13.6.3 Rvalue References and Member Functions 544
- Chapter Summary 549
- Defined Terms 549

Chapter 14 Overloaded Operations and Conversions 551

- 14.1 Basic Concepts 552
- 14.2 Input and Output Operators 556
 - 14.2.1 Overloading the Output Operator `<<` 557
 - 14.2.2 Overloading the Input Operator `>>` 558
- 14.3 Arithmetic and Relational Operators 560
 - 14.3.1 Equality Operators 561
 - 14.3.2 Relational Operators 562
- 14.4 Assignment Operators 563
- 14.5 Subscript Operator 564
- 14.6 Increment and Decrement Operators 566
- 14.7 Member Access Operators 569
- 14.8 Function-Call Operator 571

14.8.1	Lambdas Are Function Objects	572
14.8.2	Library-Defined Function Objects	574
14.8.3	Callable Objects and <code>function</code>	576
14.9	Overloading, Conversions, and Operators	579
14.9.1	Conversion Operators	580
14.9.2	Avoiding Ambiguous Conversions	583
14.9.3	Function Matching and Overloaded Operators	587
	Chapter Summary	590
	Defined Terms	590
Chapter 15	Object-Oriented Programming	591
15.1	OOP: An Overview	592
15.2	Defining Base and Derived Classes	594
15.2.1	Defining a Base Class	594
15.2.2	Defining a Derived Class	596
15.2.3	Conversions and Inheritance	601
15.3	Virtual Functions	603
15.4	Abstract Base Classes	608
15.5	Access Control and Inheritance	611
15.6	Class Scope under Inheritance	617
15.7	Constructors and Copy Control	622
15.7.1	Virtual Destructors	622
15.7.2	Synthesized Copy Control and Inheritance	623
15.7.3	Derived-Class Copy-Control Members	625
15.7.4	Inherited Constructors	628
15.8	Containers and Inheritance	630
15.8.1	Writing a Basket Class	631
15.9	Text Queries Revisited	634
15.9.1	An Object-Oriented Solution	636
15.9.2	The <code>query_base</code> and <code>query</code> Classes	639
15.9.3	The Derived Classes	642
15.9.4	The <code>eval</code> Functions	645
	Chapter Summary	649
	Defined Terms	649
Chapter 16	Templates and Generic Programming	651
16.1	Defining a Template	652
16.1.1	Function Templates	652
16.1.2	Class Templates	658
16.1.3	Template Parameters	668
16.1.4	Member Templates	672
16.1.5	Controlling Instantiations	675
16.1.6	Efficiency and Flexibility	676
16.2	Template Argument Deduction	678
16.2.1	Conversions and Template Type Parameters	679
16.2.2	Function-Template Explicit Arguments	681
16.2.3	Trailing Return Types and Type Transformation	683

- 16.2.4 Function Pointers and Argument Deduction 686
- 16.2.5 Template Argument Deduction and References 687
- 16.2.6 Understanding `std::move` 690
- 16.2.7 Forwarding 692
- 16.3 Overloading and Templates 694
- 16.4 Variadic Templates 699
 - 16.4.1 Writing a Variadic Function Template 701
 - 16.4.2 Pack Expansion 702
 - 16.4.3 Forwarding Parameter Packs 704
- 16.5 Template Specializations 706
- Chapter Summary 713
- Defined Terms 713

Part IV Advanced Topics 715

Chapter 17 Specialized Library Facilities 717

- 17.1 The tuple Type 718
 - 17.1.1 Defining and Initializing tuples 718
 - 17.1.2 Using a tuple to Return Multiple Values 721
- 17.2 The bitset Type 723
 - 17.2.1 Defining and Initializing bitsets 723
 - 17.2.2 Operations on bitsets 725
- 17.3 Regular Expressions 728
 - 17.3.1 Using the Regular Expression Library 729
 - 17.3.2 The Match and Regex Iterator Types 734
 - 17.3.3 Using Subexpressions 738
 - 17.3.4 Using `regex_replace` 741
- 17.4 Random Numbers 745
 - 17.4.1 Random-Number Engines and Distribution 745
 - 17.4.2 Other Kinds of Distributions 749
- 17.5 The IO Library Revisited 752
 - 17.5.1 Formatted Input and Output 753
 - 17.5.2 Unformatted Input/Output Operations 761
 - 17.5.3 Random Access to a Stream 763
- Chapter Summary 769
- Defined Terms 769

Chapter 18 Tools for Large Programs 771

- 18.1 Exception Handling 772
 - 18.1.1 Throwing an Exception 772
 - 18.1.2 Catching an Exception 775
 - 18.1.3 Function `try` Blocks and Constructors 777
 - 18.1.4 The `noexcept` Exception Specification 779
 - 18.1.5 Exception Class Hierarchies 782
- 18.2 Namespaces 785
 - 18.2.1 Namespace Definitions 785

18.2.2	Using Namespace Members	792
18.2.3	Classes, Namespaces, and Scope	796
18.2.4	Overloading and Namespaces	800
18.3	Multiple and Virtual Inheritance	802
18.3.1	Multiple Inheritance	803
18.3.2	Conversions and Multiple Base Classes	805
18.3.3	Class Scope under Multiple Inheritance	807
18.3.4	Virtual Inheritance	810
18.3.5	Constructors and Virtual Inheritance	813
	Chapter Summary	816
	Defined Terms	816
Chapter 19 Specialized Tools and Techniques		819
19.1	Controlling Memory Allocation	820
19.1.1	Overloading new and delete	820
19.1.2	Placement new Expressions	823
19.2	Run-Time Type Identification	825
19.2.1	The dynamic_cast Operator	825
19.2.2	The typeid Operator	826
19.2.3	Using RTTI	828
19.2.4	The type_info Class	831
19.3	Enumerations	832
19.4	Pointer to Class Member	835
19.4.1	Pointers to Data Members	836
19.4.2	Pointers to Member Functions	838
19.4.3	Using Member Functions as Callable Objects	841
19.5	Nested Classes	843
19.6	union: A Space-Saving Class	847
19.7	Local Classes	852
19.8	Inherently Nonportable Features	854
19.8.1	Bit-fields	854
19.8.2	volatile Qualifier	856
19.8.3	Linkage Directives: extern "C"	857
	Chapter Summary	862
	Defined Terms	862
Appendix A The Library		865
A.1	Library Names and Headers	866
A.2	A Brief Tour of the Algorithms	870
A.2.1	Algorithms to Find an Object	871
A.2.2	Other Read-Only Algorithms	872
A.2.3	Binary Search Algorithms	873
A.2.4	Algorithms That Write Container Elements	873
A.2.5	Partitioning and Sorting Algorithms	875
A.2.6	General Reordering Operations	877
A.2.7	Permutation Algorithms	879
A.2.8	Set Algorithms for Sorted Sequences	880

- A.2.9 Minimum and Maximum Values 880
- A.2.10 Numeric Algorithms 881
- A.3 Random Numbers 882
 - A.3.1 Random Number Distributions 883
 - A.3.2 Random Number Engines 884

Index **887**

This page intentionally left blank

New Features in C++11

2.1.1	long long Type	33
2.2.1	List Initialization	43
2.3.2	nullptr Literal	54
2.4.4	constexpr Variables	66
2.5.1	Type Alias Declarations	68
2.5.2	The auto Type Specifier	68
2.5.3	The decltype Type Specifier	70
2.6.1	In-Class Initializers	73
3.2.2	Using auto or decltype for Type Abbreviation	88
3.2.3	Range for Statement	91
3.3	Defining a vector of vectors	97
3.3.1	List Initialization for vectors	98
3.4.1	Container cbegin and cend Functions	109
3.5.3	Library begin and end Functions	118
3.6	Using auto or decltype to Simplify Declarations	129
4.2	Rounding Rules for Division	141
4.4	Assignment from a Braced List of Values	145
4.9	sizeof Applied to a Class Member	157
5.4.3	Range for Statement	187
6.2.6	Library initializer_list Class	220
6.3.2	List Initializing a Return Value	226
6.3.3	Declaring a Trailing Return Type	229
6.3.3	Using decltype to Simplify Return Type Declarations	230
6.5.2	constexpr Functions	239
7.1.4	Using = default to Generate a Default Constructor	265
7.3.1	In-class Initializers for Members of Class Type	274
7.5.2	Delegating Constructors	291
7.5.6	constexpr Constructors	299
8.2.1	Using strings for File Names	317
9.1	The array and forward_list Containers	327
9.2.3	Container cbegin and cend Functions	334
9.2.4	List Initialization for Containers	336
9.2.5	Container Nonmember swap Functions	339
9.3.1	Return Type for Container insert Members	344
9.3.1	Container emplace Members	345

9.4	<code>shrink_to_fit</code>	357
9.5.5	Numeric Conversion Functions for <code>strings</code>	367
10.3.2	Lambda Expressions	388
10.3.3	Trailing Return Type in Lambda Expressions	396
10.3.4	The Library <code>bind</code> Function	397
11.2.1	List Initialization of an Associative Container	423
11.2.3	List Initializing <code>pair</code> Return Type	427
11.3.2	List Initialization of a <code>pair</code>	431
11.4	The Unordered Containers	443
12.1	Smart Pointers	450
12.1.1	The <code>shared_ptr</code> Class	450
12.1.2	List Initialization of Dynamically Allocated Objects	459
12.1.2	<code>auto</code> and Dynamic Allocation	459
12.1.5	The <code>unique_ptr</code> Class	470
12.1.6	The <code>weak_ptr</code> Class	473
12.2.1	Range <code>for</code> Doesn't Apply to Dynamically Allocated Arrays	477
12.2.1	List Initialization of Dynamically Allocated Arrays	478
12.2.1	<code>auto</code> Can't Be Used to Allocate an Array	478
12.2.2	<code>allocator::construct</code> Can Use any Constructor	482
13.1.5	Using <code>= default</code> for Copy-Control Members	506
13.1.6	Using <code>= delete</code> to Prevent Copying Class Objects	507
13.5	Moving Instead of Copying Class Objects	529
13.6.1	Rvalue References	532
13.6.1	The Library <code>move</code> Function	533
13.6.2	Move Constructor and Move Assignment	534
13.6.2	Move Constructors Usually Should Be <code>noexcept</code>	535
13.6.2	Move Iterators	543
13.6.3	Reference Qualified Member Functions	546
14.8.3	The <code>function</code> Class Template	577
14.9.1	<code>explicit</code> Conversion Operators	582
15.2.2	<code>override</code> Specifier for Virtual Functions	596
15.2.2	Preventing Inheritance by Defining a Class as <code>final</code>	600
15.3	<code>override</code> and <code>final</code> Specifiers for Virtual Functions	606
15.7.2	Deleted Copy Control and Inheritance	624
15.7.4	Inherited Constructors	628
16.1.2	Declaring a Template Type Parameter as a Friend	666
16.1.2	Template Type Aliases	666
16.1.3	Default Template Arguments for Template Functions	670
16.1.5	Explicit Control of Instantiation	675
16.2.3	Template Functions and Trailing Return Types	684
16.2.5	Reference Collapsing Rules	688
16.2.6	<code>static_cast</code> from an Lvalue to an Rvalue	691
16.2.7	The Library <code>forward</code> Function	694
16.4	Variadic Templates	699
16.4	The <code>sizeof... Operator</code>	700
16.4.3	Variadic Templates and Forwarding	704

17.1	The Library <code>tuple</code> Class Template	718
17.2.2	New <code>bitset</code> Operations	726
17.3	The Regular Expression Library	728
17.4	The Random Number Library	745
17.5.1	Floating-Point Format Control	757
18.1.4	The <code>noexcept</code> Exception Specifier	779
18.1.4	The <code>noexcept</code> Operator	780
18.2.1	Inline Namespaces	790
18.3.1	Inherited Constructors and Multiple Inheritance	804
19.3	Scoped enums	832
19.3	Specifying the Type Used to Hold an enum	834
19.3	Forward Declarations for enums	834
19.4.3	The Library <code>mem_fn</code> Class Template	843
19.6	Union Members of Class Types	848

This page intentionally left blank

Preface

Countless programmers have learned C++ from previous editions of *C++ Primer*. During that time, C++ has matured greatly: Its focus, and that of its programming community, has widened from looking mostly at *machine* efficiency to devoting more attention to *programmer* efficiency.

In 2011, the C++ standards committee issued a major revision to the ISO C++ standard. This revised standard is latest step in C++'s evolution and continues the emphasis on programmer efficiency. The primary goals of the new standard are to

- Make the language more uniform and easier to teach and to learn
- Make the standard libraries easier, safer, and more efficient to use
- Make it easier to write efficient abstractions and libraries

In this edition, we have completely revised the *C++ Primer* to use the latest standard. You can get an idea of how extensively the new standard has affected C++ by reviewing the New Features Table of Contents, which lists the sections that cover new material and appears on page xxi.

Some additions in the new standard, such as `auto` for type inference, are pervasive. These facilities make the code in this edition easier to read and to understand. Programs (and programmers!) can ignore type details, which makes it easier to concentrate on what the program is intended to do. Other new features, such as smart pointers and move-enabled containers, let us write more sophisticated classes without having to contend with the intricacies of resource management. As a result, we can start to teach how to write your own classes much earlier in the book than we did in the Fourth Edition. We—and you—no longer have to worry about many of the details that stood in our way under the previous standard.

We've marked those parts of the text that cover features defined by the new standard, with a marginal icon. We hope that readers who are already familiar with the core of C++ will find these alerts useful in deciding where to focus their attention. We also expect that these icons will help explain error messages from compilers that might not yet support every new feature. Although nearly all of the examples in this book have been compiled under the current release of the GNU compiler, we realize some readers will not yet have access to completely updated compilers. Even though numerous capabilities have been added by the latest standard, the core language remains unchanged and forms the bulk of the material that we cover. Readers can use these icons to note which capabilities may not yet be available in their compiler.



Why Read This Book?

Modern C++ can be thought of as comprising three parts:

- The low-level language, much of which is inherited from C
- More advanced language features that allow us to define our own types and to organize large-scale programs and systems
- The standard library, which uses these advanced features to provide useful data structures and algorithms

Most texts present C++ in the order in which it evolved. They teach the C subset of C++ first, and present the more abstract features of C++ as advanced topics at the end of the book. There are two problems with this approach: Readers can get bogged down in the details inherent in low-level programming and give up in frustration. Those who do press on learn bad habits that they must unlearn later.

We take the opposite approach: Right from the start, we use the features that let programmers ignore the details inherent in low-level programming. For example, we introduce and use the library `string` and `vector` types along with the built-in arithmetic and array types. Programs that use these library types are easier to write, easier to understand, and much less error-prone.

Too often, the library is taught as an “advanced” topic. Instead of using the library, many books use low-level programming techniques based on pointers to character arrays and dynamic memory management. Getting programs that use these low-level techniques to work correctly is much harder than writing the corresponding C++ code using the library.

Throughout C++ *Primer*, we emphasize good style: We want to help you, the reader, develop good habits immediately and avoid needing to unlearn bad habits as you gain more sophisticated knowledge. We highlight particularly tricky matters and warn about common misconceptions and pitfalls.

We also explain the rationale behind the rules—explaining the why not just the what. We believe that by understanding why things work as they do, readers can more quickly cement their grasp of the language.

Although you do not need to know C in order to understand this book, we assume you know enough about programming to write, compile, and run a program in at least one modern block-structured language. In particular, we assume you have used variables, written and called functions, and used a compiler.

Changes to the Fifth Edition

New to this edition of C++ *Primer* are icons in the margins to help guide the reader. C++ is a large language that offers capabilities tailored to particular kinds of programming problems. Some of these capabilities are of great import for large project teams but might not be necessary for smaller efforts. As a result, not every programmer needs to know every detail of every feature. We’ve added these marginal icons to help the reader know which parts can be learned later and which topics are more essential.



We’ve marked sections that cover the fundamentals of the language with an image of a person studying a book. The topics covered in sections marked this

way form the core part of the language. Everyone should read and understand these sections.

We've also indicated those sections that cover advanced or special-purpose topics. These sections can be skipped or skimmed on a first reading. We've marked such sections with a stack of books to indicate that you can safely put down the book at that point. It is probably a good idea to skim such sections so you know that the capability exists. However, there is no reason to spend time studying these topics until you actually need to use the feature in your own programs.



To help readers guide their attention further, we've noted particularly tricky concepts with a magnifying-glass icon. We hope that readers will take the time to understand thoroughly the material presented in the sections so marked. In at least some of these sections, the import of the topic may not be readily apparent; but we think you'll find that these sections cover topics that turn out to be essential to understanding the language.



Another aid to reading this book, is our extensive use of cross-references. We hope these references will make it easier for readers to dip into the middle of the book, yet easily jump back to the earlier material on which later examples rely.

What remains unchanged is that *C++ Primer* is a clear, correct, and thorough tutorial guide to C++. We teach the language by presenting a series of increasingly sophisticated examples, which explain language features and show how to make the best use of C++.

Structure of This Book

We start by covering the basics of the language and the library together in Parts I and II. These parts cover enough material to let you, the reader, write significant programs. Most C++ programmers need to know essentially everything covered in this portion of the book.

In addition to teaching the basics of C++, the material in Parts I and II serves another important purpose: By using the abstract facilities defined by the library, you will become more comfortable with using high-level programming techniques. The library facilities are themselves abstract data types that are usually written in C++. The library can be defined using the same class-construction features that are available to any C++ programmer. Our experience in teaching C++ is that by first using well-designed abstract types, readers find it easier to understand how to build their own types.

Only after a thorough grounding in using the library—and writing the kinds of abstract programs that the library allows—do we move on to those C++ features that will enable you to write your own abstractions. Parts III and IV focus on writing abstractions in the form of classes. Part III covers the fundamentals; Part IV covers more specialized facilities.

In Part III, we cover issues of copy control, along with other techniques to make classes that are as easy to use as the built-in types. Classes are the foundation for object-oriented and generic programming, which we also cover in Part III. *C++ Primer* concludes with Part IV, which covers features that are of most use in structuring large, complicated systems. We also summarize the library algorithms in Appendix A.

Aids to the Reader

Each chapter concludes with a summary, followed by a glossary of defined terms, which together recap the chapter's most important points. Readers should use these sections as a personal checklist: If you do not understand a term, restudy the corresponding part of the chapter.

We've also incorporated a number of other learning aids in the body of the text:

- Important terms are indicated in **bold**; important terms that we assume are already familiar to the reader are indicated in *bold italics*. Each term appears in the chapter's Defined Terms section.
- Throughout the book, we highlight parts of the text to call attention to important aspects of the language, warn about common pitfalls, suggest good programming practices, and provide general usage tips.
- To make it easier to follow the relationships among features and concepts, we provide extensive forward and backward cross-references.
- We provide sidebar discussions on important concepts and for topics that new C++ programmers often find most difficult.
- Learning any programming language requires writing programs. To that end, the Primer provides extensive examples throughout the text. Source code for the extended examples is available on the Web at the following URL:

<http://www.informit.com/title/0321714113>

A Note about Compilers

As of this writing (July, 2012), compiler vendors are hard at work updating their compilers to match the latest ISO standard. The compiler we use most frequently is the GNU compiler, version 4.7.0. There are only a few features used in this book that this compiler does not yet implement: inheriting constructors, reference qualifiers for member functions, and the regular-expression library.

Acknowledgments

In preparing this edition we are very grateful for the help of several current and former members of the standardization committee: Dave Abrahams, Andy Koenig, Stephan T. Lavavej, Jason Merrill, John Spicer, and Herb Sutter. They provided invaluable assistance to us in understanding some of the more subtle parts of the new standard. We'd also like to thank the many folks who worked on updating the GNU compiler making the standard a reality.

As in previous editions of *C++ Primer*, we'd like to extend our thanks to Bjarne Stroustrup for his tireless work on C++ and for his friendship to the authors during most of that time. We'd also like to thank Alex Stepanov for his original insights that led to the containers and algorithms at the core of the standard library. Finally, our thanks go to all the C++ Standards committee members for their hard work in clarifying, refining, and improving C++ over many years.

We extend our deep-felt thanks to our reviewers, whose helpful comments led us to make improvements great and small throughout the book: Marshall Clow, Jon Kalb, Nevin Liber, Dr. C. L. Tondo, Daveed Vandevoorde, and Steve Vinoski.

This book was typeset using \LaTeX and the many packages that accompany the \LaTeX distribution. Our well-justified thanks go to the members of the \LaTeX community, who have made available such powerful typesetting tools.

Finally, we thank the fine folks at Addison-Wesley who have shepherded this edition through the publishing process: Peter Gordon, our editor, who provided the impetus for us to revise *C++ Primer* once again; Kim Boedigheimer, who keeps us all on schedule; Barbara Wood, who found lots of editing errors for us during the copy-edit phase, and Elizabeth Ryan, who was again a delight to work with as she guided us through the design and production process.

This page intentionally left blank

C H A P T E R 12

D Y N A M I C M E M O R Y

CONTENTS

Section 12.1 Dynamic Memory and Smart Pointers . . .	450
Section 12.2 Dynamic Arrays	476
Section 12.3 Using the Library: A Text-Query Program	484
Chapter Summary	491
Defined Terms	491

The programs we've written so far have used objects that have well-defined lifetimes. Global objects are allocated at program start-up and destroyed when the program ends. Local, automatic objects are created and destroyed when the block in which they are defined is entered and exited. Local `static` objects are allocated before their first use and are destroyed when the program ends.

In addition to supporting automatic and `static` objects, C++ lets us allocate objects dynamically. Dynamically allocated objects have a lifetime that is independent of where they are created; they exist until they are explicitly freed.

Properly freeing dynamic objects turns out to be a surprisingly rich source of bugs. To make using dynamic objects safer, the library defines two smart pointer types that manage dynamically allocated objects. Smart pointers ensure that the objects to which they point are automatically freed when it is appropriate to do so.

Our programs have used only static or stack memory. Static memory is used for local `static` objects (§ 6.1.1, p. 205), for class `static` data members (§ 7.6, p. 300), and for variables defined outside any function. Stack memory is used for nonstatic objects defined inside functions. Objects allocated in static or stack memory are automatically created and destroyed by the compiler. Stack objects exist only while the block in which they are defined is executing; `static` objects are allocated before they are used, and they are destroyed when the program ends.

In addition to static or stack memory, every program also has a pool of memory that it can use. This memory is referred to as the **free store** or **heap**. Programs use the heap for objects that they **dynamically allocate**—that is, for objects that the program allocates at run time. The program controls the lifetime of dynamic objects; our code must explicitly destroy such objects when they are no longer needed.



Although necessary at times, dynamic memory is notoriously tricky to manage correctly.

12.1 Dynamic Memory and Smart Pointers

In C++, dynamic memory is managed through a pair of operators: `new`, which allocates, and optionally initializes, an object in dynamic memory and returns a pointer to that object; and `delete`, which takes a pointer to a dynamic object, destroys that object, and frees the associated memory.

Dynamic memory is problematic because it is surprisingly hard to ensure that we free memory at the right time. Either we forget to free the memory—in which case we have a memory leak—or we free the memory when there are still pointers referring to that memory—in which case we have a pointer that refers to memory that is no longer valid.

C++
11

To make using dynamic memory easier (and safer), the new library provides two **smart pointer** types that manage dynamic objects. A smart pointer acts like a regular pointer with the important exception that it automatically deletes the object to which it points. The new library defines two kinds of smart pointers that differ in how they manage their underlying pointers: `shared_ptr`, which allows multiple pointers to refer to the same object, and `unique_ptr`, which “owns” the object to which it points. The library also defines a companion class named `weak_ptr` that is a weak reference to an object managed by a `shared_ptr`. All three are defined in the memory header.



12.1.1 The `shared_ptr` Class

Like vectors, smart pointers are templates (§ 3.3, p. 96). Therefore, when we create a smart pointer, we must supply additional information—in this case, the type to which the pointer can point. As with `vector`, we supply that type inside angle brackets that follow the name of the kind of smart pointer we are defining:

```
shared_ptr<string> p1;    // shared_ptr that can point at a string
```

```
shared_ptr<list<int>> p2; // shared_ptr that can point at a list of ints
```

A default initialized smart pointer holds a null pointer (§ 2.3.2, p. 53). In § 12.1.3 (p. 464), we'll cover additional ways to initialize a smart pointer.

We use a smart pointer in ways that are similar to using a pointer. Dereferencing a smart pointer returns the object to which the pointer points. When we use a smart pointer in a condition, the effect is to test whether the pointer is null:

```
// if p1 is not null, check whether it's the empty string
if (p1 && p1->empty())
    *p1 = "hi"; // if so, dereference p1 to assign a new value to that string
```

Table 12.1 (overleaf) lists operations common to `shared_ptr` and `unique_ptr`. Those that are particular to `shared_ptr` are listed in Table 12.2 (p. 453).

The `make_shared` Function

The safest way to allocate and use dynamic memory is to call a library function named `make_shared`. This function allocates and initializes an object in dynamic memory and returns a `shared_ptr` that points to that object. Like the smart pointers, `make_shared` is defined in the memory header.

When we call `make_shared`, we must specify the type of object we want to create. We do so in the same way as we use a template class, by following the function name with a type enclosed in angle brackets:

```
// shared_ptr that points to an int with value 42
shared_ptr<int> p3 = make_shared<int>(42);
// p4 points to a string with value 999999999
shared_ptr<string> p4 = make_shared<string>(10, '9');
// p5 points to an int that is value initialized (§ 3.3.1 (p. 98)) to 0
shared_ptr<int> p5 = make_shared<int>();
```

Like the sequential-container `emplace` members (§ 9.3.1, p. 345), `make_shared` uses its arguments to construct an object of the given type. For example, a call to `make_shared<string>` must pass argument(s) that match one of the `string` constructors. Calls to `make_shared<int>` can pass any value we can use to initialize an `int`. And so on. If we do not pass any arguments, then the object is value initialized (§ 3.3.1, p. 98).

Of course, ordinarily we use `auto` (§ 2.5.2, p. 68) to make it easier to define an object to hold the result of `make_shared`:

```
// p6 points to a dynamically allocated, empty vector<string>
auto p6 = make_shared<vector<string>>();
```

Copying and Assigning `shared_ptr`s

When we copy or assign a `shared_ptr`, each `shared_ptr` keeps track of how many other `shared_ptr`s point to the same object:

```
auto p = make_shared<int>(42); // object to which p points has one user
auto q(p); // p and q point to the same object
// object to which p and q point has two users
```


Table 12.1: Operations Common to `shared_ptr` and `unique_ptr`

<code>shared_ptr<T> sp</code>	Null smart pointer that can point to objects of type T.
<code>unique_ptr<T> up</code>	
<code>p</code>	Use <code>p</code> as a condition; <code>true</code> if <code>p</code> points to an object.
<code>*p</code>	Dereference <code>p</code> to get the object to which <code>p</code> points.
<code>p->mem</code>	Synonym for <code>(*p).mem</code> .
<code>p.get()</code>	Returns the pointer in <code>p</code> . Use with caution; the object to which the returned pointer points will disappear when the smart pointer deletes it.
<code>swap(p, q)</code>	Swaps the pointers in <code>p</code> and <code>q</code> .
<code>p.swap(q)</code>	

We can think of a `shared_ptr` as if it has an associated counter, usually referred to as a **reference count**. Whenever we copy a `shared_ptr`, the count is incremented. For example, the counter associated with a `shared_ptr` is incremented when we use it to initialize another `shared_ptr`, when we use it as the right-hand operand of an assignment, or when we pass it to (§ 6.2.1, p. 209) or return it from a function by value (§ 6.3.2, p. 224). The counter is decremented when we assign a new value to the `shared_ptr` and when the `shared_ptr` itself is destroyed, such as when a local `shared_ptr` goes out of scope (§ 6.1.1, p. 204).

Once a `shared_ptr`'s counter goes to zero, the `shared_ptr` automatically frees the object that it manages:

```
auto r = make_shared<int>(42); // int to which r points has one user
r = q; // assign to r, making it point to a different address
      // increase the use count for the object to which q points
      // reduce the use count of the object to which r had pointed
      // the object r had pointed to has no users; that object is automatically freed
```

Here we allocate an `int` and store a pointer to that `int` in `r`. Next, we assign a new value to `r`. In this case, `r` is the only `shared_ptr` pointing to the one we previously allocated. That `int` is automatically freed as part of assigning `q` to `r`.



It is up to the implementation whether to use a counter or another data structure to keep track of how many pointers share state. The key point is that the class keeps track of how many `shared_ptr`s point to the same object and automatically frees that object when appropriate.

`shared_ptr`s Automatically Destroy Their Objects ...

When the last `shared_ptr` pointing to an object is destroyed, the `shared_ptr` class automatically destroys the object to which that `shared_ptr` points. It does so through another special member function known as a **destructor**. Analogous to its constructors, each class has a destructor. Just as a constructor controls initialization, the destructor controls what happens when objects of that class type are destroyed.

Table 12.2: Operations Specific to `shared_ptr`

<code>make_shared<T>(args)</code>	Returns a <code>shared_ptr</code> pointing to a dynamically allocated object of type <code>T</code> . Uses <code>args</code> to initialize that object.
<code>shared_ptr<T> p(q)</code>	<code>p</code> is a copy of the <code>shared_ptr</code> <code>q</code> ; increments the count in <code>q</code> . The pointer in <code>q</code> must be convertible to <code>T*</code> (§ 4.11.2, p. 161).
<code>p = q</code>	<code>p</code> and <code>q</code> are <code>shared_ptr</code> s holding pointers that can be converted to one another. Decrements <code>p</code> 's reference count and increments <code>q</code> 's count; deletes <code>p</code> 's existing memory if <code>p</code> 's count goes to 0.
<code>p.unique()</code>	Returns <code>true</code> if <code>p.use_count()</code> is one; <code>false</code> otherwise.
<code>p.use_count()</code>	Returns the number of objects sharing with <code>p</code> ; may be a slow operation, intended primarily for debugging purposes.

Destructors generally free the resources that an object has allocated. For example, the `string` constructors (and other `string` members) allocate memory to hold the characters that compose the `string`. The `string` destructor frees that memory. Similarly, several `vector` operations allocate memory to hold the elements in the `vector`. The destructor for `vector` destroys those elements and frees the memory used for the elements.

The destructor for `shared_ptr` decrements the reference count of the object to which that `shared_ptr` points. If the count goes to zero, the `shared_ptr` destructor destroys the object to which the `shared_ptr` points and frees the memory used by that object.

... and Automatically Free the Associated Memory

The fact that the `shared_ptr` class automatically frees dynamic objects when they are no longer needed makes it fairly easy to use dynamic memory. For example, we might have a function that returns a `shared_ptr` to a dynamically allocated object of a type named `Foo` that can be initialized by an argument of type `T`:

```
// factory returns a shared_ptr pointing to a dynamically allocated object
shared_ptr<Foo> factory(T arg)
{
    // process arg as appropriate
    // shared_ptr will take care of deleting this memory
    return make_shared<Foo>(arg);
}
```

Because `factory` returns a `shared_ptr`, we can be sure that the object allocated by `factory` will be freed when appropriate. For example, the following function stores the `shared_ptr` returned by `factory` in a local variable:

```
void use_factory(T arg)
{
    shared_ptr<Foo> p = factory(arg);
    // use p
} // p goes out of scope; the memory to which p points is automatically freed
```

Because `p` is local to `use_factory`, it is destroyed when `use_factory` ends (§ 6.1.1, p. 204). When `p` is destroyed, its reference count is decremented and checked. In this case, `p` is the only object referring to the memory returned by `factory`. Because `p` is about to go away, the object to which `p` points will be destroyed and the memory in which that object resides will be freed.

The memory will not be freed if there is any other `shared_ptr` pointing to it:

```
shared_ptr<Foo> use_factory(T arg)
{
    shared_ptr<Foo> p = factory(arg);
    // use p
    return p; // reference count is incremented when we return p
} // p goes out of scope; the memory to which p points is not freed
```

In this version, the return statement in `use_factory` returns a copy of `p` to its caller (§ 6.3.2, p. 224). Copying a `shared_ptr` adds to the reference count of that object. Now when `p` is destroyed, there will be another user for the memory to which `p` points. The `shared_ptr` class ensures that so long as there are any `shared_ptr`s attached to that memory, the memory itself will not be freed.

Because memory is not freed until the last `shared_ptr` goes away, it can be important to be sure that `shared_ptr`s don't stay around after they are no longer needed. The program will execute correctly but may waste memory if you neglect to destroy `shared_ptr`s that the program does not need. One way that `shared_ptr`s might stay around after you need them is if you put `shared_ptr`s in a container and subsequently reorder the container so that you don't need all the elements. You should be sure to erase `shared_ptr` elements once you no longer need those elements.



If you put `shared_ptr`s in a container, and you subsequently need to use some, but not all, of the elements, remember to erase the elements you no longer need.

Classes with Resources That Have Dynamic Lifetime

Programs tend to use dynamic memory for one of three purposes:

1. They don't know how many objects they'll need
2. They don't know the precise type of the objects they need
3. They want to share data between several objects

The container classes are an example of classes that use dynamic memory for the first purpose and we'll see examples of the second in Chapter 15. In this section, we'll define a class that uses dynamic memory in order to let several objects share the same underlying data.

So far, the classes we've used allocate resources that exist only as long as the corresponding objects. For example, each `vector` "owns" its own elements. When we copy a `vector`, the elements in the original `vector` and in the copy are separate from one another:

```
vector<string> v1; // empty vector
{ // new scope
    vector<string> v2 = {"a", "an", "the"};
    v1 = v2; // copies the elements from v2 into v1
} // v2 is destroyed, which destroys the elements in v2
// v1 has three elements, which are copies of the ones originally in v2
```

The elements allocated by a `vector` exist only while the `vector` itself exists. When a `vector` is destroyed, the elements in the `vector` are also destroyed.

Some classes allocate resources with a lifetime that is independent of the original object. As an example, assume we want to define a class named `Blob` that will hold a collection of elements. Unlike the containers, we want `Blob` objects that are copies of one another to share the same elements. That is, when we copy a `Blob`, the original and the copy should refer to the same underlying elements.

In general, when two objects share the same underlying data, we can't unilaterally destroy the data when an object of that type goes away:

```
Blob<string> b1; // empty Blob
{ // new scope
    Blob<string> b2 = {"a", "an", "the"};
    b1 = b2; // b1 and b2 share the same elements
} // b2 is destroyed, but the elements in b2 must not be destroyed
// b1 points to the elements originally created in b2
```

In this example, `b1` and `b2` share the same elements. When `b2` goes out of scope, those elements must stay around, because `b1` is still using them.



One common reason to use dynamic memory is to allow multiple objects to share the same state.

Defining the `StrBlob` Class

Ultimately, we'll implement our `Blob` class as a template, but we won't learn how to do so until § 16.1.2 (p. 658). For now, we'll define a version of our class that can manage strings. As a result, we'll name this version of our class `StrBlob`.

The easiest way to implement a new collection type is to use one of the library containers to manage the elements. That way, we can let the library type manage the storage for the elements themselves. In this case, we'll use a `vector` to hold our elements.

However, we can't store the `vector` directly in a `Blob` object. Members of an object are destroyed when the object itself is destroyed. For example, assume that `b1` and `b2` are two `Blobs` that share the same `vector`. If that `vector` were stored in one of those `Blobs`—say, `b2`—then that `vector`, and therefore its elements, would no longer exist once `b2` goes out of scope. To ensure that the elements continue to exist, we'll store the `vector` in dynamic memory.

To implement the sharing we want, we'll give each `StrBlob` a `shared_ptr` to a dynamically allocated `vector`. That `shared_ptr` member will keep track of how many `StrBlobs` share the same `vector` and will delete the `vector` when the last `StrBlob` using that `vector` is destroyed.

We still need to decide what operations our class will provide. For now, we'll implement a small subset of the vector operations. We'll also change the operations that access elements (e.g., `front` and `back`): In our class, these operations will throw an exception if a user attempts to access an element that doesn't exist.

Our class will have a default constructor and a constructor that has a parameter of type `initializer_list<string>` (§ 6.2.6, p. 220). This constructor will take a braced list of initializers.

```
class StrBlob {
public:
    typedef std::vector<std::string>::size_type size_type;
    StrBlob();
    StrBlob(std::initializer_list<std::string> il);
    size_type size() const { return data->size(); }
    bool empty() const { return data->empty(); }
    // add and remove elements
    void push_back(const std::string &t) { data->push_back(t); }
    void pop_back();
    // element access
    std::string& front();
    std::string& back();
private:
    std::shared_ptr<std::vector<std::string>> data;
    // throws msg if data[i] isn't valid
    void check(size_type i, const std::string &msg) const;
};
```

Inside the class we implemented the `size`, `empty`, and `push_back` members. These members forward their work through the `data` pointer to the underlying vector. For example, `size()` on a `StrBlob` calls `data->size()`, and so on.

StrBlob Constructors

Each constructor uses its constructor initializer list (§ 7.1.4, p. 265) to initialize its data member to point to a dynamically allocated vector. The default constructor allocates an empty vector:

```
StrBlob::StrBlob(): data(make_shared<vector<string>>()) { }
StrBlob::StrBlob(initializer_list<string> il):
    data(make_shared<vector<string>>(il)) { }
```

The constructor that takes an `initializer_list` passes its parameter to the corresponding vector constructor (§ 2.2.1, p. 43). That constructor initializes the vector's elements by copying the values in the list.

Element Access Members

The `pop_back`, `front`, and `back` operations access members in the vector. These operations must check that an element exists before attempting to access that element. Because several members need to do the same checking, we've given

our class a private utility function named `check` that verifies that a given index is in range. In addition to an index, `check` takes a `string` argument that it will pass to the exception handler. The `string` describes what went wrong:

```
void StrBlob::check(size_type i, const string &msg) const
{
    if (i >= data->size())
        throw out_of_range(msg);
}
```

The `pop_back` and `element` access members first call `check`. If `check` succeeds, these members forward their work to the underlying vector operation:

```
string& StrBlob::front()
{
    // if the vector is empty, check will throw
    check(0, "front on empty StrBlob");
    return data->front();
}
string& StrBlob::back()
{
    check(0, "back on empty StrBlob");
    return data->back();
}
void StrBlob::pop_back()
{
    check(0, "pop_back on empty StrBlob");
    data->pop_back();
}
```

The `front` and `back` members should be overloaded on `const` (§ 7.3.2, p. 276). Defining those versions is left as an exercise.

Copying, Assigning, and Destroying `StrBlobs`

Like our `Sales_data` class, `StrBlob` uses the default versions of the operations that copy, assign, and destroy objects of its type (§ 7.1.5, p. 267). By default, these operations copy, assign, and destroy the data members of the class. Our `StrBlob` has only one data member, which is a `shared_ptr`. Therefore, when we copy, assign, or destroy a `StrBlob`, its `shared_ptr` member will be copied, assigned, or destroyed.

As we've seen, copying a `shared_ptr` increments its reference count; assigning one `shared_ptr` to another increments the count of the right-hand operand and decrements the count in the left-hand operand; and destroying a `shared_ptr` decrements the count. If the count in a `shared_ptr` goes to zero, the object to which that `shared_ptr` points is automatically destroyed. Thus, the vector allocated by the `StrBlob` constructors will be automatically destroyed when the last `StrBlob` pointing to that vector is destroyed.

EXERCISES SECTION 12.1.1

Exercise 12.1: How many elements do `b1` and `b2` have at the end of this code?

```
StrBlob b1;
{
    StrBlob b2 = {"a", "an", "the"};
    b1 = b2;
    b2.push_back("about");
}
```

Exercise 12.2: Write your own version of the `StrBlob` class including the `const` versions of `front` and `back`.

Exercise 12.3: Does this class need `const` versions of `push_back` and `pop_back`? If so, add them. If not, why aren't they needed?

Exercise 12.4: In our `check` function we didn't check whether `i` was greater than zero. Why is it okay to omit that check?

Exercise 12.5: We did not make the constructor that takes an `initializer_list` explicit (§ 7.5.4, p. 296). Discuss the pros and cons of this design choice.

12.1.2 Managing Memory Directly

The language itself defines two operators that allocate and free dynamic memory. The `new` operator allocates memory, and `delete` frees memory allocated by `new`.

For reasons that will become clear as we describe how these operators work, using these operators to manage memory is considerably more error-prone than using a smart pointer. Moreover, classes that do manage their own memory—unlike those that use smart pointers—cannot rely on the default definitions for the members that copy, assign, and destroy class objects (§ 7.1.4, p. 264). As a result, programs that use smart pointers are likely to be easier to write and debug.



Until you have read Chapter 13, your classes should allocate dynamic memory *only* if they use smart pointers to manage that memory.

Using `new` to Dynamically Allocate and Initialize Objects

Objects allocated on the free store are unnamed, so `new` offers no way to name the objects that it allocates. Instead, `new` returns a pointer to the object it allocates:

```
int *pi = new int;           // pi points to a dynamically allocated,
                             // unnamed, uninitialized int
```

This `new` expression constructs an object of type `int` on the free store and returns a pointer to that object.

By default, dynamically allocated objects are default initialized (§ 2.2.1, p. 43), which means that objects of built-in or compound type have undefined value; objects of class type are initialized by their default constructor:

```
string *ps = new string; // initialized to empty string
int *pi = new int;      // pi points to an uninitialized int
```

We can initialize a dynamically allocated object using direct initialization (§ 3.2.1, p. 84). We can use traditional construction (using parentheses), and under the new standard, we can also use list initialization (with curly braces):

C++
11

```
int *pi = new int(1024); // object to which pi points has value 1024
string *ps = new string(10, '9'); // *ps is "9999999999"
// vector with ten elements with values from 0 to 9
vector<int> *pv = new vector<int>{0,1,2,3,4,5,6,7,8,9};
```

We can also value initialize (§ 3.3.1, p. 98) a dynamically allocated object by following the type name with a pair of empty parentheses:

```
string *ps1 = new string; // default initialized to the empty string
string *ps = new string(); // value initialized to the empty string
int *pi1 = new int;      // default initialized; *pi1 is undefined
int *pi2 = new int();    // value initialized to 0; *pi2 is 0
```

For class types (such as `string`) that define their own constructors (§ 7.1.4, p. 262), requesting value initialization is of no consequence; regardless of form, the object is initialized by the default constructor. In the case of built-in types the difference is significant; a value-initialized object of built-in type has a well-defined value but a default-initialized object does not. Similarly, members of built-in type in classes that rely on the synthesized default constructor will also be uninitialized if those members are not initialized in the class body (§ 7.1.4, p. 263).



For the same reasons as we usually initialize variables, it is also a good idea to initialize dynamically allocated objects.

When we provide an initializer inside parentheses, we can use `auto` (§ 2.5.2, p. 68) to deduce the type of the object we want to allocate from that initializer. However, because the compiler uses the initializer's type to deduce the type to allocate, we can use `auto` only with a single initializer inside parentheses:

C++
11

```
auto p1 = new auto(obj); // p points to an object of the type of obj
// that object is initialized from obj
auto p2 = new auto{a,b,c}; // error: must use parentheses for the initializer
```

The type of `p1` is a pointer to the `auto`-deduced type of `obj`. If `obj` is an `int`, then `p1` is `int*`; if `obj` is a `string`, then `p1` is a `string*`; and so on. The newly allocated object is initialized from the value of `obj`.

Dynamically Allocated `const` Objects

It is legal to use `new` to allocate `const` objects:

```
// allocate and initialize a const int
const int *pci = new const int(1024);
// allocate a default-initialized const empty string
const string *pcs = new const string;
```


Like any other `const`, a dynamically allocated `const` object must be initialized. A `const` dynamic object of a class type that defines a default constructor (§ 7.1.4, p. 263) may be initialized implicitly. Objects of other types must be explicitly initialized. Because the allocated object is `const`, the pointer returned by `new` is a pointer to `const` (§ 2.4.2, p. 62).

Memory Exhaustion

Although modern machines tend to have huge memory capacity, it is always possible that the free store will be exhausted. Once a program has used all of its available memory, `new` expressions will fail. By default, if `new` is unable to allocate the requested storage, it throws an exception of type `bad_alloc` (§ 5.6, p. 193). We can prevent `new` from throwing an exception by using a different form of `new`:

```
// if allocation fails, new returns a null pointer
int *p1 = new int; // if allocation fails, new throws std::bad_alloc
int *p2 = new (nothrow) int; // if allocation fails, new returns a null pointer
```

For reasons we'll explain in § 19.1.2 (p. 824) this form of `new` is referred to as **placement new**. A placement `new` expression lets us pass additional arguments to `new`. In this case, we pass an object named `nothrow` that is defined by the library. When we pass `nothrow` to `new`, we tell `new` that it must not throw an exception. If this form of `new` is unable to allocate the requested storage, it will return a null pointer. Both `bad_alloc` and `nothrow` are defined in the `new` header.

Freeing Dynamic Memory

In order to prevent memory exhaustion, we must return dynamically allocated memory to the system once we are finished using it. We return memory through a **delete expression**. A `delete` expression takes a pointer to the object we want to free:

```
delete p; // p must point to a dynamically allocated object or be null
```

Like `new`, a `delete` expression performs two actions: It destroys the object to which its given pointer points, and it frees the corresponding memory.

Pointer Values and delete

The pointer we pass to `delete` must either point to dynamically allocated memory or be a null pointer (§ 2.3.2, p. 53). Deleting a pointer to memory that was not allocated by `new`, or deleting the same pointer value more than once, is undefined:

```
int i, *pi1 = &i, *pi2 = nullptr;
double *pd = new double(33), *pd2 = pd;
delete i; // error: i is not a pointer
delete pi1; // undefined: pi1 refers to a local
delete pd; // ok
delete pd2; // undefined: the memory pointed to by pd2 was already freed
delete pi2; // ok: it is always ok to delete a null pointer
```

The compiler will generate an error for the `delete` of `i` because it knows that `i` is not a pointer. The errors associated with executing `delete` on `pi1` and `pd2` are more insidious: In general, compilers cannot tell whether a pointer points to a statically or dynamically allocated object. Similarly, the compiler cannot tell whether memory addressed by a pointer has already been freed. Most compilers will accept these `delete` expressions, even though they are in error.

Although the value of a `const` object cannot be modified, the object itself can be destroyed. As with any other dynamic object, a `const` dynamic object is freed by executing `delete` on a pointer that points to that object:

```
const int *pci = new const int(1024);
delete pci; // ok: deletes a const object
```

Dynamically Allocated Objects Exist until They Are Freed

As we saw in § 12.1.1 (p. 452), memory that is managed through a `shared_ptr` is automatically deleted when the last `shared_ptr` is destroyed. The same is not true for memory we manage using built-in pointers. A dynamic object managed through a built-in pointer exists until it is explicitly deleted.

Functions that return pointers (rather than smart pointers) to dynamic memory put a burden on their callers—the caller must remember to delete the memory:

```
// factory returns a pointer to a dynamically allocated object
Foo* factory(T arg)
{
    // process arg as appropriate
    return new Foo(arg); // caller is responsible for deleting this memory
}
```

Like our earlier `factory` function (§ 12.1.1, p. 453), this version of `factory` allocates an object but does not delete it. Callers of `factory` are responsible for freeing this memory when they no longer need the allocated object. Unfortunately, all too often the caller forgets to do so:

```
void use_factory(T arg)
{
    Foo *p = factory(arg);
    // use p but do not delete it
} // p goes out of scope, but the memory to which p points is not freed!
```

Here, our `use_factory` function calls `factory`, which allocates a new object of type `Foo`. When `use_factory` returns, the local variable `p` is destroyed. That variable is a built-in pointer, not a smart pointer.

Unlike class types, nothing happens when objects of built-in type are destroyed. In particular, when a pointer goes out of scope, nothing happens to the object to which the pointer points. If that pointer points to dynamic memory, that memory is not automatically freed.



WARNING

Dynamic memory managed through built-in pointers (rather than smart pointers) exists until it is explicitly freed.

In this example, `p` was the only pointer to the memory allocated by `factory`. Once `use_factory` returns, the program has no way to free that memory. Depending on the logic of our overall program, we should fix this bug by remembering to free the memory inside `use_factory`:

```
void use_factory(T arg)
{
    Foo *p = factory(arg);
    // use p
    delete p; // remember to free the memory now that we no longer need it
}
```

or, if other code in our system needs to use the object allocated by `use_factory`, we should change that function to return a pointer to the memory it allocated:

```
Foo* use_factory(T arg)
{
    Foo *p = factory(arg);
    // use p
    return p; // caller must delete the memory
}
```

CAUTION: MANAGING DYNAMIC MEMORY IS ERROR-PRONE

There are three common problems with using `new` and `delete` to manage dynamic memory:

1. Forgetting to `delete` memory. Neglecting to delete dynamic memory is known as a “memory leak,” because the memory is never returned to the free store. Testing for memory leaks is difficult because they usually cannot be detected until the application is run for a long enough time to actually exhaust memory.
2. Using an object after it has been deleted. This error can sometimes be detected by making the pointer null after the delete.
3. Deleting the same memory twice. This error can happen when two pointers address the same dynamically allocated object. If `delete` is applied to one of the pointers, then the object’s memory is returned to the free store. If we subsequently `delete` the second pointer, then the free store may be corrupted.

These kinds of errors are considerably easier to make than they are to find and fix.



You can avoid *all* of these problems by using smart pointers exclusively. The smart pointer will take care of deleting the memory *only* when there are no remaining smart pointers pointing to that memory.

Resetting the Value of a Pointer after a `delete` ...

When we `delete` a pointer, that pointer becomes invalid. Although the pointer is invalid, on many machines the pointer continues to hold the address of the (freed) dynamic memory. After the `delete`, the pointer becomes what is referred to as a

dangling pointer. A dangling pointer is one that refers to memory that once held an object but no longer does so.

Dangling pointers have all the problems of uninitialized pointers (§ 2.3.2, p. 54). We can avoid the problems with dangling pointers by deleting the memory associated with a pointer just before the pointer itself goes out of scope. That way there is no chance to use the pointer after the memory associated with the pointer is freed. If we need to keep the pointer around, we can assign `nullptr` to the pointer after we use `delete`. Doing so makes it clear that the pointer points to no object.

... Provides Only Limited Protection

A fundamental problem with dynamic memory is that there can be several pointers that point to the same memory. Resetting the pointer we use to `delete` that memory lets us check that particular pointer but has no effect on any of the other pointers that still point at the (freed) memory. For example:

```
int *p(new int(42)); // p points to dynamic memory
auto q = p;         // p and q point to the same memory
delete p;           // invalidates both p and q
p = nullptr;       // indicates that p is no longer bound to an object
```

Here both `p` and `q` point at the same dynamically allocated object. We `delete` that memory and set `p` to `nullptr`, indicating that the pointer no longer points to an object. However, resetting `p` has no effect on `q`, which became invalid when we deleted the memory to which `p` (and `q`!) pointed. In real systems, finding all the pointers that point to the same memory is surprisingly difficult.

EXERCISES SECTION 12.1.2

Exercise 12.6: Write a function that returns a dynamically allocated vector of ints. Pass that vector to another function that reads the standard input to give values to the elements. Pass the vector to another function to print the values that were read. Remember to `delete` the vector at the appropriate time.

Exercise 12.7: Redo the previous exercise, this time using `shared_ptr`.

Exercise 12.8: Explain what if anything is wrong with the following function.

```
bool b() {
    int* p = new int;
    // ...
    return p;
}
```

Exercise 12.9: Explain what happens in the following code:

```
int *q = new int(42), *r = new int(100);
r = q;
auto q2 = make_shared<int>(42), r2 = make_shared<int>(100);
r2 = q2;
```

12.1.3 Using `shared_ptr`s with `new`

As we've seen, if we do not initialize a smart pointer, it is initialized as a null pointer. As described in Table 12.3, we can also initialize a smart pointer from a pointer returned by `new`:

```
shared_ptr<double> p1; // shared_ptr that can point at a double
shared_ptr<int> p2(new int(42)); // p2 points to an int with value 42
```

The smart pointer constructors that take pointers are `explicit` (§ 7.5.4, p. 296). Hence, we cannot implicitly convert a built-in pointer to a smart pointer; we must use the direct form of initialization (§ 3.2.1, p. 84) to initialize a smart pointer:

```
shared_ptr<int> p1 = new int(1024); // error: must use direct initialization
shared_ptr<int> p2(new int(1024)); // ok: uses direct initialization
```

The initialization of `p1` implicitly asks the compiler to create a `shared_ptr` from the `int*` returned by `new`. Because we can't implicitly convert a pointer to a smart pointer, this initialization is an error. For the same reason, a function that returns a `shared_ptr` cannot implicitly convert a plain pointer in its return statement:

```
shared_ptr<int> clone(int p) {
    return new int(p); // error: implicit conversion to shared_ptr<int>
}
```

We must explicitly bind a `shared_ptr` to the pointer we want to return:

```
shared_ptr<int> clone(int p) {
    // ok: explicitly create a shared_ptr<int> from int*
    return shared_ptr<int>(new int(p));
}
```

By default, a pointer used to initialize a smart pointer must point to dynamic memory because, by default, smart pointers use `delete` to free the associated object. We can bind smart pointers to pointers to other kinds of resources. However, to do so, we must supply our own operation to use in place of `delete`. We'll see how to supply our own deletion code in § 12.1.4 (p. 468).



Don't Mix Ordinary Pointers and Smart Pointers ...

A `shared_ptr` can coordinate destruction only with other `shared_ptr`s that are copies of itself. Indeed, this fact is one of the reasons we recommend using `make_shared` rather than `new`. That way, we bind a `shared_ptr` to the object at the same time that we allocate it. There is no way to inadvertently bind the same memory to more than one independently created `shared_ptr`.

Consider the following function that operates on a `shared_ptr`:

```
// ptr is created and initialized when process is called
void process(shared_ptr<int> ptr)
{
    // use ptr
} // ptr goes out of scope and is destroyed
```

Table 12.3: Other Ways to Define and Change `shared_ptr`s

<code>shared_ptr<T> p(q)</code>	<code>p</code> manages the object to which the built-in pointer <code>q</code> points; <code>q</code> must point to memory allocated by <code>new</code> and must be convertible to <code>T*</code> .
<code>shared_ptr<T> p(u)</code>	<code>p</code> assumes ownership from the <code>unique_ptr</code> <code>u</code> ; makes <code>u</code> null.
<code>shared_ptr<T> p(q, d)</code>	<code>p</code> assumes ownership for the object to which the built-in pointer <code>q</code> points. <code>q</code> must be convertible to <code>T*</code> (§ 4.11.2, p. 161). <code>p</code> will use the callable object <code>d</code> (§ 10.3.2, p. 388) in place of <code>delete</code> to free <code>q</code> .
<code>shared_ptr<T> p(p2, d)</code>	<code>p</code> is a copy of the <code>shared_ptr</code> <code>p2</code> as described in Table 12.2 except that <code>p</code> uses the callable object <code>d</code> in place of <code>delete</code> .
<code>p.reset()</code>	If <code>p</code> is the only <code>shared_ptr</code> pointing at its object, <code>reset</code> frees <code>p</code> 's existing object. If the optional built-in pointer <code>q</code> is passed, makes <code>p</code> point to <code>q</code> , otherwise makes <code>p</code> null. If <code>d</code> is supplied, will call <code>d</code> to free <code>q</code> otherwise uses <code>delete</code> to free <code>q</code> .
<code>p.reset(q)</code>	
<code>p.reset(q, d)</code>	

The parameter to `process` is passed by value, so the argument to `process` is copied into `ptr`. Copying a `shared_ptr` increments its reference count. Thus, inside `process` the count is at least 2. When `process` completes, the reference count of `ptr` is decremented but cannot go to zero. Therefore, when the local variable `ptr` is destroyed, the memory to which `ptr` points will not be deleted.

The right way to use this function is to pass it a `shared_ptr`:

```
shared_ptr<int> p(new int(42)); // reference count is 1
process(p); // copying p increments its count; in process the reference count is 2
int i = *p; // ok: reference count is 1
```

Although we cannot pass a built-in pointer to `process`, we can pass `process` a (temporary) `shared_ptr` that we explicitly construct from a built-in pointer. However, doing so is likely to be an error:

```
int *x(new int(1024)); // dangerous: x is a plain pointer, not a smart pointer
process(x); // error: cannot convert int* to shared_ptr<int>
process(shared_ptr<int>(x)); // legal, but the memory will be deleted!
int j = *x; // undefined: x is a dangling pointer!
```

In this call, we passed a temporary `shared_ptr` to `process`. That temporary is destroyed when the expression in which the call appears finishes. Destroying the temporary decrements the reference count, which goes to zero. The memory to which the temporary points is freed when the temporary is destroyed.

But `x` continues to point to that (freed) memory; `x` is now a dangling pointer. Attempting to use the value of `x` is undefined.

When we bind a `shared_ptr` to a plain pointer, we give responsibility for that memory to that `shared_ptr`. Once we give `shared_ptr` responsibility for a pointer, we should no longer use a built-in pointer to access the memory to which the `shared_ptr` now points.



It is dangerous to use a built-in pointer to access an object owned by a smart pointer, because we may not know when that object is destroyed.



...and Don't Use `get` to Initialize or Assign Another Smart Pointer

The smart pointer types define a function named `get` (described in Table 12.1 (p. 452)) that returns a built-in pointer to the object that the smart pointer is managing. This function is intended for cases when we need to pass a built-in pointer to code that can't use a smart pointer. The code that uses the return from `get` must not delete that pointer.

Although the compiler will not complain, it is an error to bind another smart pointer to the pointer returned by `get`:

```
shared_ptr<int> p(new int(42)); // reference count is 1
int *q = p.get(); // ok: but don't use q in any way that might delete its pointer
{ // new block
    // undefined: two independent shared_ptrs point to the same memory
    auto local = shared_ptr<int>(q);
} // block ends, local is destroyed; the memory to which p and q points is freed
int foo = *p; // undefined; the memory to which p points was freed
```

Here, `p`, `q`, and `local` all point to the same memory. Because `p` and `local` were created independently from one another, each has a reference count of 1. When the inner block ends, `local` is destroyed. Because `local`'s reference count is 1, the memory to which it points will be freed. That makes `p` and `q` into a dangling pointers; what happens when we attempt to use `p` or `q` is undefined. Moreover, when `p` is destroyed, the pointer to that memory will be deleted a second time.



Use `get` only to pass access to the pointer to code that you know will not delete the pointer. In particular, never use `get` to initialize or assign to another smart pointer.

Other `shared_ptr` Operations

The `shared_ptr` class gives us a few other operations, which are listed in Table 12.2 (p. 453) and Table 12.3 (on the previous page). We can use `reset` to assign a new pointer to a `shared_ptr`:

```
p = new int(1024); // error: cannot assign a pointer to a shared_ptr
p.reset(new int(1024)); // ok: p points to a new object
```

Like assignment, `reset` updates the reference counts and, if appropriate, deletes the object to which `p` points. The `reset` member is often used together with `unique` to control changes to the object shared among several `shared_ptr`s. Before changing the underlying object, we check whether we're the only user. If not, we make a new copy before making the change:

```
if (!p.unique())
    p.reset(new string(*p)); // we aren't alone; allocate a new copy
*p += newVal; // now that we know we're the only pointer, okay to change this object
```

EXERCISES SECTION 12.1.3

Exercise 12.10: Explain whether the following call to the `process` function defined on page 464 is correct. If not, how would you correct the call?

```
shared_ptr<int> p(new int(42));
process(shared_ptr<int>(p));
```

Exercise 12.11: What would happen if we called `process` as follows?

```
process(shared_ptr<int>(p.get()));
```

Exercise 12.12: Using the declarations of `p` and `sp` explain each of the following calls to `process`. If the call is legal, explain what it does. If the call is illegal, explain why:

```
auto p = new int();
auto sp = make_shared<int>();
(a) process(sp);
(b) process(new int());
(c) process(p);
(d) process(shared_ptr<int>(p));
```

Exercise 12.13: What happens if we execute the following code?

```
auto sp = make_shared<int>();
auto p = sp.get();
delete p;
```

12.1.4 Smart Pointers and Exceptions



In § 5.6.2 (p. 196) we noted that programs that use exception handling to continue processing after an exception occurs need to ensure that resources are properly freed if an exception occurs. One easy way to make sure resources are freed is to use smart pointers.

When we use a smart pointer, the smart pointer class ensures that memory is freed when it is no longer needed even if the block is exited prematurely:

```
void f()
{
    shared_ptr<int> sp(new int(42)); // allocate a new object
    // code that throws an exception that is not caught inside f
} // shared_ptr freed automatically when the function ends
```

When a function is exited, whether through normal processing or due to an exception, all the local objects are destroyed. In this case, `sp` is a `shared_ptr`, so destroying `sp` checks its reference count. Here, `sp` is the only pointer to the memory it manages; that memory will be freed as part of destroying `sp`.

In contrast, memory that we manage directly is not automatically freed when an exception occurs. If we use built-in pointers to manage memory and an exception occurs after a `new` but before the corresponding `delete`, then that memory won't be freed:


```

void f()
{
    int *ip = new int(42);    // dynamically allocate a new object
    // code that throws an exception that is not caught inside f
    delete ip;              // free the memory before exiting
}

```

If an exception happens between the `new` and the `delete`, and is not caught inside `f`, then this memory can never be freed. There is no pointer to this memory outside the function `f`. Thus, there is no way to free this memory.



Smart Pointers and Dumb Classes

Many C++ classes, including all the library classes, define destructors (§ 12.1.1, p. 452) that take care of cleaning up the resources used by that object. However, not all classes are so well behaved. In particular, classes that are designed to be used by both C and C++ generally require the user to specifically free any resources that are used.

Classes that allocate resources—and that do not define destructors to free those resources—can be subject to the same kind of errors that arise when we use dynamic memory. It is easy to forget to release the resource. Similarly, if an exception happens between when the resource is allocated and when it is freed, the program will leak that resource.

We can often use the same kinds of techniques we use to manage dynamic memory to manage classes that do not have well-behaved destructors. For example, imagine we're using a network library that is used by both C and C++. Programs that use this library might contain code such as

```

struct destination; // represents what we are connecting to
struct connection; // information needed to use the connection

connection connect(destination*); // open the connection
void disconnect(connection);      // close the given connection
void f(destination &d /* other parameters */)
{
    // get a connection; must remember to close it when done
    connection c = connect(&d);
    // use the connection
    // if we forget to call disconnect before exiting f, there will be no way to close c
}

```

If `connection` had a destructor, that destructor would automatically close the connection when `f` completes. However, `connection` does not have a destructor. This problem is nearly identical to our previous program that used a `shared_ptr` to avoid memory leaks. It turns out that we can also use a `shared_ptr` to ensure that the `connection` is properly closed.



Using Our Own Deletion Code

By default, `shared_ptr`s assume that they point to dynamic memory. Hence, by default, when a `shared_ptr` is destroyed, it executes `delete` on the pointer it

holds. To use a `shared_ptr` to manage a connection, we must first define a function to use in place of `delete`. It must be possible to call this **deleter** function with the pointer stored inside the `shared_ptr`. In this case, our deleter must take a single argument of type `connection*`:

```
void end_connection(connection *p) { disconnect(*p); }
```

When we create a `shared_ptr`, we can pass an optional argument that points to a deleter function (§ 6.7, p. 247):

```
void f(destination &d /* other parameters */)
{
    connection c = connect(&d);
    shared_ptr<connection> p(&c, end_connection);
    // use the connection
    // when f exits, even if by an exception, the connection will be properly closed
}
```

When `p` is destroyed, it won't execute `delete` on its stored pointer. Instead, `p` will call `end_connection` on that pointer. In turn, `end_connection` will call `disconnect`, thus ensuring that the connection is closed. If `f` exits normally, then `p` will be destroyed as part of the return. Moreover, `p` will also be destroyed, and the connection will be closed, if an exception occurs.

CAUTION: SMART POINTER PITFALLS

Smart pointers can provide safety and convenience for handling dynamically allocated memory only when they are used properly. To use smart pointers correctly, we must adhere to a set of conventions:

- Don't use the same built-in pointer value to initialize (or reset) more than one smart pointer.
- Don't delete the pointer returned from `get()`.
- Don't use `get()` to initialize or reset another smart pointer.
- If you use a pointer returned by `get()`, remember that the pointer will become invalid when the last corresponding smart pointer goes away.
- If you use a smart pointer to manage a resource other than memory allocated by `new`, remember to pass a deleter (§ 12.1.4, p. 468, and § 12.1.5, p. 471).

EXERCISES SECTION 12.1.4

Exercise 12.14: Write your own version of a function that uses a `shared_ptr` to manage a connection.

Exercise 12.15: Rewrite the first exercise to use a lambda (§ 10.3.2, p. 388) in place of the `end_connection` function.

12.1.5 `unique_ptr`

C++
11

A `unique_ptr` “owns” the object to which it points. Unlike `shared_ptr`, only one `unique_ptr` at a time can point to a given object. The object to which a `unique_ptr` points is destroyed when the `unique_ptr` is destroyed. Table 12.4 lists the operations specific to `unique_ptr`s. The operations common to both were covered in Table 12.1 (p. 452).

Unlike `shared_ptr`, there is no library function comparable to `make_shared` that returns a `unique_ptr`. Instead, when we define a `unique_ptr`, we bind it to a pointer returned by `new`. As with `shared_ptr`s, we must use the direct form of initialization:

```
unique_ptr<double> p1; // unique_ptr that can point at a double
unique_ptr<int> p2(new int(42)); // p2 points to int with value 42
```

Because a `unique_ptr` owns the object to which it points, `unique_ptr` does not support ordinary copy or assignment:

```
unique_ptr<string> p1(new string("Stegosaurus"));
unique_ptr<string> p2(p1); // error: no copy for unique_ptr
unique_ptr<string> p3;
p3 = p2; // error: no assign for unique_ptr
```

Table 12.4: `unique_ptr` Operations (See Also Table 12.1 (p. 452))

<code>unique_ptr<T> u1</code>	Null <code>unique_ptr</code> s that can point to objects of type T. <code>u1</code> will
<code>unique_ptr<T, D> u2</code>	use <code>delete</code> to free its pointer; <code>u2</code> will use a callable object of type D to free its pointer.
<code>unique_ptr<T, D> u(d)</code>	Null <code>unique_ptr</code> that point to objects of type T that uses <code>d</code> , which must be an object of type D in place of <code>delete</code> .
<code>u = nullptr</code>	Deletes the object to which <code>u</code> points; makes <code>u</code> null.
<code>u.release()</code>	Relinquishes control of the pointer <code>u</code> had held; returns the pointer <code>u</code> had held and makes <code>u</code> null.
<code>u.reset()</code>	Deletes the object to which <code>u</code> points;
<code>u.reset(q)</code>	If the built-in pointer <code>q</code> is supplied, makes <code>u</code> point to that object.
<code>u.reset(nullptr)</code>	Otherwise makes <code>u</code> null.

Although we can’t copy or assign a `unique_ptr`, we can transfer ownership from one (nonconst) `unique_ptr` to another by calling `release` or `reset`:

```
// transfers ownership from p1 (which points to the string Stegosaurus) to p2
unique_ptr<string> p2(p1.release()); // release makes p1 null
unique_ptr<string> p3(new string("Trex"));
// transfers ownership from p3 to p2
p2.reset(p3.release()); // reset deletes the memory to which p2 had pointed
```

The `release` member returns the pointer currently stored in the `unique_ptr` and makes that `unique_ptr` null. Thus, `p2` is initialized from the pointer value that had been stored in `p1` and `p1` becomes null.

The `reset` member takes an optional pointer and repositions the `unique_ptr` to point to the given pointer. If the `unique_ptr` is not null, then the object to which the `unique_ptr` had pointed is deleted. The call to `reset` on `p2`, therefore, frees the memory used by the `string` initialized from "Stegosaurus", transfers `p3`'s pointer to `p2`, and makes `p3` null.

Calling `release` breaks the connection between a `unique_ptr` and the object it had been managing. Often the pointer returned by `release` is used to initialize or assign another smart pointer. In that case, responsibility for managing the memory is simply transferred from one smart pointer to another. However, if we do not use another smart pointer to hold the pointer returned from `release`, our program takes over responsibility for freeing that resource:

```
p2.release(); // WRONG: p2 won't free the memory and we've lost the pointer
auto p = p2.release(); // ok, but we must remember to delete(p)
```

Passing and Returning `unique_ptr`s

There is one exception to the rule that we cannot copy a `unique_ptr`: We can copy or assign a `unique_ptr` that is about to be destroyed. The most common example is when we return a `unique_ptr` from a function:

```
unique_ptr<int> clone(int p) {
    // ok: explicitly create a unique_ptr<int> from int*
    return unique_ptr<int>(new int(p));
}
```

Alternatively, we can also return a copy of a local object:

```
unique_ptr<int> clone(int p) {
    unique_ptr<int> ret(new int(p));
    // ...
    return ret;
}
```

In both cases, the compiler knows that the object being returned is about to be destroyed. In such cases, the compiler does a special kind of "copy" which we'll discuss in § 13.6.2 (p. 534).

BACKWARD COMPATIBILITY: `auto_ptr`

Earlier versions of the library included a class named `auto_ptr` that had some, but not all, of the properties of `unique_ptr`. In particular, it was not possible to store an `auto_ptr` in a container, nor could we return one from a function.

Although `auto_ptr` is still part of the standard library, programs should use `unique_ptr` instead.

Passing a Deleter to `unique_ptr`

Like `shared_ptr`, by default, `unique_ptr` uses `delete` to free the object to which a `unique_ptr` points. As with `shared_ptr`, we can override the default

deleter in a `unique_ptr` (§ 12.1.4, p. 468). However, for reasons we'll describe in § 16.1.6 (p. 676), the way `unique_ptr` manages its deleter is different from the way `shared_ptr` does.

Overriding the deleter in a `unique_ptr` affects the `unique_ptr` type as well as how we construct (or reset) objects of that type. Similar to overriding the comparison operation of an associative container (§ 11.2.2, p. 425), we must supply the deleter type inside the angle brackets along with the type to which the `unique_ptr` can point. We supply a callable object of the specified type when we create or reset an object of this type:

```
// p points to an object of type objT and uses an object of type delT to free that object
// it will call an object named fcn of type delT
unique_ptr<objT, delT> p (new objT, fcn);
```

As a somewhat more concrete example, we'll rewrite our connection program to use a `unique_ptr` in place of a `shared_ptr` as follows:

```
void f(destination &d /* other needed parameters */)
{
    connection c = connect(&d); // open the connection
    // when p is destroyed, the connection will be closed
    unique_ptr<connection, decltype(end_connection)*>
        p(&c, end_connection);
    // use the connection
    // when f exits, even if by an exception, the connection will be properly closed
}
```

Here we use `decltype` (§ 2.5.3, p. 70) to specify the function pointer type. Because `decltype(end_connection)` returns a function type, we must remember to add a `*` to indicate that we're using a pointer to that type (§ 6.7, p. 250).

EXERCISES SECTION 12.1.5

Exercise 12.16: Compilers don't always give easy-to-understand error messages if we attempt to copy or assign a `unique_ptr`. Write a program that contains these errors to see how your compiler diagnoses them.

Exercise 12.17: Which of the following `unique_ptr` declarations are illegal or likely to result in subsequent program error? Explain what the problem is with each one.

```
int ix = 1024, *pi = &ix, *pi2 = new int(2048);
typedef unique_ptr<int> IntP;
(a) IntP p0(ix);                (b) IntP p1(pi);
(c) IntP p2(pi2);              (d) IntP p3(&ix);
(e) IntP p4(new int(2048));     (f) IntP p5(p2.get());
```

Exercise 12.18: Why doesn't `shared_ptr` have a `release` member?

12.1.6 weak_ptr


**C++
11**

A `weak_ptr` (Table 12.5) is a smart pointer that does not control the lifetime of the object to which it points. Instead, a `weak_ptr` points to an object that is managed by a `shared_ptr`. Binding a `weak_ptr` to a `shared_ptr` does not change the reference count of that `shared_ptr`. Once the last `shared_ptr` pointing to the object goes away, the object itself will be deleted. That object will be deleted even if there are `weak_ptr`s pointing to it—hence the name `weak_ptr`, which captures the idea that a `weak_ptr` shares its object “weakly.”

When we create a `weak_ptr`, we initialize it from a `shared_ptr`:

```
auto p = make_shared<int>(42);
weak_ptr<int> wp(p); // wp weakly shares with p; use count in p is unchanged
```

Here both `wp` and `p` point to the same object. Because the sharing is weak, creating `wp` doesn’t change the reference count of `p`; it is possible that the object to which `wp` points might be deleted.

Because the object might no longer exist, we cannot use a `weak_ptr` to access its object directly. To access that object, we must call `lock`. The `lock` function checks whether the object to which the `weak_ptr` points still exists. If so, `lock` returns a `shared_ptr` to the shared object. As with any other `shared_ptr`, we are guaranteed that the underlying object to which that `shared_ptr` points continues to exist at least as long as that `shared_ptr` exists. For example:

```
if (shared_ptr<int> np = wp.lock()) { // true if np is not null
    // inside the if, np shares its object with p
}
```

Here we enter the body of the `if` only if the call to `lock` succeeds. Inside the `if`, it is safe to use `np` to access that object.

Table 12.5: weak_ptr

<code>weak_ptr<T> w</code>	Null <code>weak_ptr</code> that can point at objects of type <code>T</code> .
<code>weak_ptr<T> w(sp)</code>	<code>weak_ptr</code> that points to the same object as the <code>shared_ptr</code> <code>sp</code> . <code>T</code> must be convertible to the type to which <code>sp</code> points.
<code>w = p</code>	<code>p</code> can be a <code>shared_ptr</code> or a <code>weak_ptr</code> . After the assignment <code>w</code> shares ownership with <code>p</code> .
<code>w.reset()</code>	Makes <code>w</code> null.
<code>w.use_count()</code>	The number of <code>shared_ptr</code> s that share ownership with <code>w</code> .
<code>w.expired()</code>	Returns <code>true</code> if <code>w.use_count()</code> is zero, <code>false</code> otherwise.
<code>w.lock()</code>	If <code>expired</code> is <code>true</code> , returns a null <code>shared_ptr</code> ; otherwise returns a <code>shared_ptr</code> to the object to which <code>w</code> points.

Checked Pointer Class

As an illustration of when a `weak_ptr` is useful, we’ll define a companion pointer class for our `StrBlob` class. Our pointer class, which we’ll name `StrBlobPtr`,

will store a `weak_ptr` to the data member of the `StrBlob` from which it was initialized. By using a `weak_ptr`, we don't affect the lifetime of the vector to which a given `StrBlob` points. However, we can prevent the user from attempting to access a vector that no longer exists.

`StrBlobPtr` will have two data members: `wptr`, which is either null or points to a vector in a `StrBlob`; and `curr`, which is the index of the element that this object currently denotes. Like its companion `StrBlob` class, our pointer class has a check member to verify that it is safe to dereference the `StrBlobPtr`:

```
// StrBlobPtr throws an exception on attempts to access a nonexistent element
class StrBlobPtr {
public:
    StrBlobPtr(): curr(0) { }
    StrBlobPtr(StrBlob &a, size_t sz = 0):
        wptr(a.data), curr(sz) { }
    std::string& deref() const;
    StrBlobPtr& incr();           // prefix version
private:
    // check returns a shared_ptr to the vector if the check succeeds
    std::shared_ptr<std::vector<std::string>>
        check(std::size_t, const std::string&) const;
    // store a weak_ptr, which means the underlying vector might be destroyed
    std::weak_ptr<std::vector<std::string>> wptr;
    std::size_t curr;           // current position within the array
};
```

The default constructor generates a null `StrBlobPtr`. Its constructor initializer list (§ 7.1.4, p. 265) explicitly initializes `curr` to zero and implicitly initializes `wptr` as a null `weak_ptr`. The second constructor takes a reference to `StrBlob` and an optional index value. This constructor initializes `wptr` to point to the vector in the `shared_ptr` of the given `StrBlob` object and initializes `curr` to the value of `sz`. We use a default argument (§ 6.5.1, p. 236) to initialize `curr` to denote the first element by default. As we'll see, the `sz` parameter will be used by the end member of `StrBlob`.

It is worth noting that we cannot bind a `StrBlobPtr` to a `const StrBlob` object. This restriction follows from the fact that the constructor takes a reference to a nonconst object of type `StrBlob`.

The check member of `StrBlobPtr` differs from the one in `StrBlob` because it must check whether the vector to which it points is still around:

```
std::shared_ptr<std::vector<std::string>>
StrBlobPtr::check(std::size_t i, const std::string &msg) const
{
    auto ret = wptr.lock();    // is the vector still around?
    if (!ret)
        throw std::runtime_error("unbound StrBlobPtr");
    if (i >= ret->size())
        throw std::out_of_range(msg);
    return ret; // otherwise, return a shared_ptr to the vector
}
```

Because a `weak_ptr` does not participate in the reference count of its corresponding `shared_ptr`, the vector to which this `StrBlobPtr` points might have been deleted. If the vector is gone, `lock` will return a null pointer. In this case, any reference to the vector will fail, so we throw an exception. Otherwise, `check` verifies its given index. If that value is okay, `check` returns the `shared_ptr` it obtained from `lock`.

Pointer Operations

We'll learn how to define our own operators in Chapter 14. For now, we've defined functions named `deref` and `incr` to dereference and increment the `StrBlobPtr`, respectively. The `deref` member calls `check` to verify that it is safe to use the vector and that `curr` is in range:

```
std::string& StrBlobPtr::deref() const
{
    auto p = check(curr, "dereference past end");
    return (*p)[curr]; // (*p) is the vector to which this object points
}
```

If `check` succeeds, `p` is a `shared_ptr` to the vector to which this `StrBlobPtr` points. The expression `(*p)[curr]` dereferences that `shared_ptr` to get the vector and uses the subscript operator to fetch and return the element at `curr`.

The `incr` member also calls `check`:

```
// prefix: return a reference to the incremented object
StrBlobPtr& StrBlobPtr::incr()
{
    // if curr already points past the end of the container, can't increment it
    check(curr, "increment past end of StrBlobPtr");
    ++curr; // advance the current state
    return *this;
}
```

We'll also give our `StrBlob` class `begin` and `end` operations. These members will return `StrBlobPtr`s pointing to the first or one past the last element in the `StrBlob` itself. In addition, because `StrBlobPtr` accesses the data member of `StrBlob`, we must also make `StrBlobPtr` a friend of `StrBlob` (§ 7.3.4, p. 279):

```
class StrBlob {
    friend class StrBlobPtr;
    // other members as in § 12.1.1 (p. 456)
    StrBlobPtr begin(); // return StrBlobPtr to the first element
    StrBlobPtr end(); // and one past the last element
};
// these members can't be defined until StrStrBlob and StrStrBlobPtr are defined
StrBlobPtr StrBlob::begin() { return StrBlobPtr(*this); }
StrBlobPtr StrBlob::end()
    { return StrBlobPtr(*this, data->size()); }
```


EXERCISES SECTION 12.1.6

Exercise 12.19: Define your own version of `StrBlobPtr` and update your `StrBlob` class with the appropriate friend declaration and `begin` and `end` members.

Exercise 12.20: Write a program that reads an input file a line at a time into a `StrBlob` and uses a `StrBlobPtr` to print each element in that `StrBlob`.

Exercise 12.21: We could have written `StrBlobPtr`'s `deref` member as follows:

```
std::string& deref() const
{ return (*check(curr, "dereference past end"))[curr]; }
```

Which version do you think is better and why?

Exercise 12.22: What changes would need to be made to `StrBlobPtr` to create a class that can be used with a `const StrBlob`? Define a class named `ConstStrBlobPtr` that can point to a `const StrBlob`.



12.2 Dynamic Arrays

The `new` and `delete` operators allocate objects one at a time. Some applications, need the ability to allocate storage for many objects at once. For example, `vectors` and `strings` store their elements in contiguous memory and must allocate several elements at once whenever the container has to be reallocated (§ 9.4, p. 355).

To support such usage, the language and library provide two ways to allocate an array of objects at once. The language defines a second kind of `new` expression that allocates and initializes an array of objects. The library includes a template class named `allocator` that lets us separate allocation from initialization. For reasons we'll explain in § 12.2.2 (p. 481), using an `allocator` generally provides better performance and more flexible memory management.

Many, perhaps even most, applications have no direct need for dynamic arrays. When an application needs a varying number of objects, it is almost always easier, faster, and safer to do as we did with `StrBlob`: use a `vector` (or other library container). For reasons we'll explain in § 13.6 (p. 531), the advantages of using a library container are even more pronounced under the new standard. Libraries that support the new standard tend to be dramatically faster than previous releases.



Most applications should use a library container rather than dynamically allocated arrays. Using a container is easier, less likely to contain memory-management bugs, *and* is likely to give better performance.

As we've seen, classes that use the containers can use the default versions of the operations for copy, assignment, and destruction (§ 7.1.5, p. 267). Classes that allocate dynamic arrays must define their own versions of these operations to manage the associated memory when objects are copied, assigned, and destroyed.



WARNING

Do not allocate dynamic arrays in code inside classes until you have read Chapter 13.

12.2.1 new and Arrays



We ask `new` to allocate an array of objects by specifying the number of objects to allocate in a pair of square brackets after a type name. In this case, `new` allocates the requested number of objects and (assuming the allocation succeeds) returns a pointer to the first one:

```
// call get_size to determine how many ints to allocate
int *pia = new int[get_size()]; // pia points to the first of these ints
```

The size inside the brackets must have integral type but need not be a constant.

We can also allocate an array by using a type alias (§ 2.5.1, p. 67) to represent an array type. In this case, we omit the brackets:

```
typedef int arrT[42]; // arrT names the type array of 42 ints
int *p = new arrT; // allocates an array of 42 ints; p points to the first one
```

Here, `new` allocates an array of `ints` and returns a pointer to the first one. Even though there are no brackets in our code, the compiler executes this expression using `new []`. That is, the compiler executes this expression as if we had written

```
int *p = new int[42];
```

Allocating an Array Yields a Pointer to the Element Type

Although it is common to refer to memory allocated by `new T[]` as a “dynamic array,” this usage is somewhat misleading. When we use `new` to allocate an array, we do not get an object with an array type. Instead, we get a pointer to the element type of the array. Even if we use a type alias to define an array type, `new` does not allocate an object of array type. In this case, the fact that we’re allocating an array is not even visible; there is no `[num]`. Even so, `new` returns a pointer to the element type.

Because the allocated memory does not have an array type, we cannot call `begin` or `end` (§ 3.5.3, p. 118) on a dynamic array. These functions use the array dimension (which is part of an array’s type) to return pointers to the first and one past the last elements, respectively. For the same reasons, we also cannot use a range `for` to process the elements in a (so-called) dynamic array.

C++
11



It is important to remember that what we call a dynamic array does not have an array type.

Initializing an Array of Dynamically Allocated Objects

By default, objects allocated by `new`—whether allocated as a single object or in an array—are default initialized. We can value initialize (§ 3.3.1, p. 98) the elements in an array by following the size with an empty pair of parentheses.

```
int *pia = new int[10]; // block of ten uninitialized ints
int *pia2 = new int[10](); // block of ten ints value initialized to 0
string *psa = new string[10]; // block of ten empty strings
string *psa2 = new string[10](); // block of ten empty strings
```

C++
11

Under the new standard, we can also provide a braced list of element initializers:

```
// block of ten ints each initialized from the corresponding initializer
int *pia3 = new int[10]{0,1,2,3,4,5,6,7,8,9};
// block of ten strings; the first four are initialized from the given initializers
// remaining elements are value initialized
string *psa3 = new string[10]{"a", "an", "the", string(3,'x')};
```

As when we list initialize an object of built-in array type (§ 3.5.1, p. 114), the initializers are used to initialize the first elements in the array. If there are fewer initializers than elements, the remaining elements are value initialized. If there are more initializers than the given size, then the new expression fails and no storage is allocated. In this case, new throws an exception of type `bad_array_new_length`. Like `bad_alloc`, this type is defined in the new header.

Although we can use empty parentheses to value initialize the elements of an array, we cannot supply an element initializer inside the parentheses. The fact that we cannot supply an initial value inside the parentheses means that we cannot use `auto` to allocate an array (§ 12.1.2, p. 459).

C++
11

It Is Legal to Dynamically Allocate an Empty Array

We can use an arbitrary expression to determine the number of objects to allocate:

```
size_t n = get_size(); // get_size returns the number of elements needed
int* p = new int[n]; // allocate an array to hold the elements
for (int* q = p; q != p + n; ++q)
    /* process the array */ ;
```

An interesting question arises: What happens if `get_size` returns 0? The answer is that our code works fine. Calling `new[n]` with `n` equal to 0 is legal even though we cannot create an array variable of size 0:

```
char arr[0]; // error: cannot define a zero-length array
char *cp = new char[0]; // ok: but cp can't be dereferenced
```

When we use `new` to allocate an array of size zero, `new` returns a valid, nonzero pointer. That pointer is guaranteed to be distinct from any other pointer returned by `new`. This pointer acts as the off-the-end pointer (§ 3.5.3, p. 119) for a zero-element array. We can use this pointer in ways that we use an off-the-end iterator. The pointer can be compared as in the loop above. We can add zero to (or subtract zero from) such a pointer and can subtract the pointer from itself, yielding zero. The pointer cannot be dereferenced—after all, it points to no element.

In our hypothetical loop, if `get_size` returns 0, then `n` is also 0. The call to `new` will allocate zero objects. The condition in the `for` will fail (`p` is equal to `q + n` because `n` is 0). Thus, the loop body is not executed.

Freeing Dynamic Arrays

To free a dynamic array, we use a special form of `delete` that includes an empty pair of square brackets:

```
delete p;      // p must point to a dynamically allocated object or be null
delete [] pa; // pa must point to a dynamically allocated array or be null
```

The second statement destroys the elements in the array to which `pa` points and frees the corresponding memory. Elements in an array are destroyed in reverse order. That is, the last element is destroyed first, then the second to last, and so on.

When we `delete` a pointer to an array, the empty bracket pair is essential: It indicates to the compiler that the pointer addresses the first element of an array of objects. If we omit the brackets when we `delete` a pointer to an array (or provide them when we `delete` a pointer to an object), the behavior is undefined.

Recall that when we use a type alias that defines an array type, we can allocate an array without using `[]` with `new`. Even so, we must use brackets when we `delete` a pointer to that array:

```
typedef int arrT[42]; // arrT names the type array of 42 ints
int *p = new arrT;   // allocates an array of 42 ints; p points to the first one
delete [] p;         // brackets are necessary because we allocated an array
```

Despite appearances, `p` points to the first element of an array of objects, not to a single object of type `arrT`. Thus, we must use `[]` when we `delete p`.



The compiler is unlikely to warn us if we forget the brackets when we `delete` a pointer to an array or if we use them when we `delete` a pointer to an object. Instead, our program is apt to misbehave without warning during execution.

Smart Pointers and Dynamic Arrays

The library provides a version of `unique_ptr` that can manage arrays allocated by `new`. To use a `unique_ptr` to manage a dynamic array, we must include a pair of empty brackets after the object type:

```
// up points to an array of ten uninitialized ints
unique_ptr<int []> up(new int[10]);
up.reset(); // automatically uses delete [] to destroy its pointer
```

The brackets in the type specifier (`<int []>`) say that `up` points not to an `int` but to an array of `ints`. Because `up` points to an array, when `up` destroys the pointer it manages, it will automatically use `delete []`.

`unique_ptr`s that point to arrays provide slightly different operations than those we used in § 12.1.5 (p. 470). These operations are described in Table 12.6 (overleaf). When a `unique_ptr` points to an array, we cannot use the dot and arrow member access operators. After all, the `unique_ptr` points to an array, not an object so these operators would be meaningless. On the other hand, when a `unique_ptr` points to an array, we can use the subscript operator to access the elements in the array:

```
for (size_t i = 0; i != 10; ++i)
    up[i] = i; // assign a new value to each of the elements
```

Table 12.6: `unique_ptr`s to Arrays

Member access operators (dot and arrow) are not supported for `unique_ptr`s to arrays. Other `unique_ptr` operations unchanged.

<code>unique_ptr<T[]> u</code>	<code>u</code> can point to a dynamically allocated array of type <code>T</code> .
<code>unique_ptr<T[]> u(p)</code>	<code>u</code> points to the dynamically allocated array to which the built-in pointer <code>p</code> points. <code>p</code> must be convertible to <code>T*</code> (§ 4.11.2, p. 161).
<code>u[i]</code>	Returns the object at position <code>i</code> in the array that <code>u</code> owns. <code>u</code> must point to an array.

Unlike `unique_ptr`, `shared_ptr`s provide no direct support for managing a dynamic array. If we want to use a `shared_ptr` to manage a dynamic array, we must provide our own deleter:

```
// to use a shared_ptr we must supply a deleter
shared_ptr<int> sp(new int[10], [](int *p) { delete[] p; });
sp.reset(); // uses the lambda we supplied that uses delete[] to free the array
```

Here we pass a lambda (§ 10.3.2, p. 388) that uses `delete[]` as the deleter.

Had we neglected to supply a deleter, this code would be undefined. By default, `shared_ptr` uses `delete` to destroy the object to which it points. If that object is a dynamic array, using `delete` has the same kinds of problems that arise if we forget to use `[]` when we delete a pointer to a dynamic array (§ 12.2.1, p. 479).

The fact that `shared_ptr` does not directly support managing arrays affects how we access the elements in the array:

```
// shared_ptr doesn't have subscript operator and doesn't support pointer arithmetic
for (size_t i = 0; i != 10; ++i)
    *(sp.get() + i) = i; // use get to get a built-in pointer
```

There is no subscript operator for `shared_ptr`s, and the smart pointer types do not support pointer arithmetic. As a result, to access the elements in the array, we must use `get` to obtain a built-in pointer, which we can then use in normal ways.

EXERCISES SECTION 12.2.1

Exercise 12.23: Write a program to concatenate two string literals, putting the result in a dynamically allocated array of `char`. Write a program to concatenate two library strings that have the same value as the literals used in the first program.

Exercise 12.24: Write a program that reads a string from the standard input into a dynamically allocated character array. Describe how your program handles varying size inputs. Test your program by giving it a string of data that is longer than the array size you've allocated.

Exercise 12.25: Given the following new expression, how would you delete `pa`?

```
int *pa = new int[10];
```

12.2.2 The allocator Class



An aspect of new that limits its flexibility is that new combines allocating memory with constructing object(s) in that memory. Similarly, delete combines destruction with deallocation. Combining initialization with allocation is usually what we want when we allocate a single object. In that case, we almost certainly know the value the object should have.

When we allocate a block of memory, we often plan to construct objects in that memory as needed. In this case, we'd like to decouple memory allocation from object construction. Decoupling construction from allocation means that we can allocate memory in large chunks and pay the overhead of constructing the objects only when we actually need to create them.

In general, coupling allocation and construction can be wasteful. For example:

```
string *const p = new string[n]; // construct n empty strings
string s;
string *q = p; // q points to the first string
while (cin >> s && q != p + n)
    *q++ = s; // assign a new value to *q
const size_t size = q - p; // remember how many strings we read
// use the array
delete[] p; // p points to an array; must remember to use delete []
```

This new expression allocates and initializes *n* strings. However, we might not need *n* strings; a smaller number might suffice. As a result, we may have created objects that are never used. Moreover, for those objects we do use, we immediately assign new values over the previously initialized strings. The elements that are used are written twice: first when the elements are default initialized, and subsequently when we assign to them.

More importantly, classes that do not have default constructors cannot be dynamically allocated as an array.

The allocator Class

The library `allocator` class, which is defined in the memory header, lets us separate allocation from construction. It provides type-aware allocation of raw, unconstructed, memory. Table 12.7 (overleaf) outlines the operations that `allocator` supports. In this section, we'll describe the `allocator` operations. In § 13.5 (p. 524), we'll see an example of how this class is typically used.

Like `vector`, `allocator` is a template (§ 3.3, p. 96). To define an `allocator` we must specify the type of objects that a particular `allocator` can allocate. When an `allocator` object allocates memory, it allocates memory that is appropriately sized and aligned to hold objects of the given type:

```
allocator<string> alloc; // object that can allocate strings
auto const p = alloc.allocate(n); // allocate n unconstructed strings
```

This call to `allocate` allocates memory for *n* strings.

Table 12.7: Standard `allocator` Class and Customized Algorithms

<code>allocator<T> a</code>	Defines an <code>allocator</code> object named <code>a</code> that can allocate memory for objects of type <code>T</code> .
<code>a.allocate(n)</code>	Allocates raw, unconstructed memory to hold <code>n</code> objects of type <code>T</code> .
<code>a.deallocate(p, n)</code>	Deallocates memory that held <code>n</code> objects of type <code>T</code> starting at the address in the <code>T*</code> pointer <code>p</code> ; <code>p</code> must be a pointer previously returned by <code>allocate</code> , and <code>n</code> must be the size requested when <code>p</code> was created. The user must run <code>destroy</code> on any objects that were constructed in this memory before calling <code>deallocate</code> .
<code>a.construct(p, args)</code>	<code>p</code> must be a pointer to type <code>T</code> that points to raw memory; <code>args</code> are passed to a constructor for type <code>T</code> , which is used to construct an object in the memory pointed to by <code>p</code> .
<code>a.destroy(p)</code>	Runs the destructor (§ 12.1.1, p. 452) on the object pointed to by the <code>T*</code> pointer <code>p</code> .

allocators Allocate Unconstructed Memory

The memory an `allocator` allocates is *unconstructed*. We use this memory by constructing objects in that memory. In the new library the `construct` member takes a pointer and zero or more additional arguments; it constructs an element at the given location. The additional arguments are used to initialize the object being constructed. Like the arguments to `make_shared` (§ 12.1.1, p. 451), these additional arguments must be valid initializers for an object of the type being constructed. In particular, if the , object is a class type, these arguments must match a constructor for that class:

C++
11

```
auto q = p; // q will point to one past the last constructed element
alloc.construct(q++); // *q is the empty string
alloc.construct(q++, 10, 'c'); // *q is ccccccccc
alloc.construct(q++, "hi"); // *q is hi!
```

In earlier versions of the library, `construct` took only two arguments: the pointer at which to construct an object and a value of the element type. As a result, we could only copy an element into unconstructed space, we could not use any other constructor for the element type.

It is an error to use raw memory in which an object has not been constructed:

```
cout << *p << endl; // ok: uses the string output operator
cout << *q << endl; // disaster: q points to unconstructed memory!
```



WARNING

We must construct objects in order to use memory returned by `allocate`. Using unconstructed memory in other ways is undefined.

When we're finished using the objects, we must destroy the elements we constructed, which we do by calling `destroy` on each constructed element. The `destroy` function takes a pointer and runs the destructor (§ 12.1.1, p. 452) on the pointed-to object:

```
while (q != p)
    alloc.destroy(--q);           // free the strings we actually allocated
```

At the beginning of our loop, `q` points one past the last constructed element. We decrement `q` before calling `destroy`. Thus, on the first call to `destroy`, `q` points to the last constructed element. We `destroy` the first element in the last iteration, after which `q` will equal `p` and the loop ends.



WARNING

We may `destroy` only elements that are actually constructed.

Once the elements have been destroyed, we can either reuse the memory to hold other strings or return the memory to the system. We free the memory by calling `deallocate`:

```
alloc.deallocate(p, n);
```

The pointer we pass to `deallocate` cannot be null; it must point to memory allocated by `allocate`. Moreover, the size argument passed to `deallocate` must be the same size as used in the call to `allocate` that obtained the memory to which the pointer points.

Algorithms to Copy and Fill Uninitialized Memory

As a companion to the `allocator` class, the library also defines two algorithms that can construct objects in uninitialized memory. These functions, described in Table 12.8, are defined in the `memory` header.

Table 12.8: allocator Algorithms

These functions construct elements in the destination, rather than assigning to them.

```
uninitialized_copy(b, e, b2)
```

Copies elements from the input range denoted by iterators `b` and `e` into unconstructed, raw memory denoted by the iterator `b2`. The memory denoted by `b2` must be large enough to hold a copy of the elements in the input range.

```
uninitialized_copy_n(b, n, b2)
```

Copies `n` elements starting from the one denoted by the iterator `b` into raw memory starting at `b2`.

```
uninitialized_fill(b, e, t)
```

Constructs objects in the range of raw memory denoted by iterators `b` and `e` as a copy of `t`.

```
uninitialized_fill_n(b, n, t)
```

Constructs an unsigned number `n` objects starting at `b`. `b` must denote unconstructed, raw memory large enough to hold the given number of objects.

As an example, assume we have a `vector` of `ints` that we want to copy into dynamic memory. We'll allocate memory for twice as many `ints` as are in the `vector`. We'll construct the first half of the newly allocated memory by copying elements from the original `vector`. We'll construct elements in the second half by filling them with a given value:


```

// allocate twice as many elements as vi holds
auto p = alloc.allocate(vi.size() * 2);
// construct elements starting at p as copies of elements in vi
auto q = uninitialized_copy(vi.begin(), vi.end(), p);
// initialize the remaining elements to 42
uninitialized_fill_n(q, vi.size(), 42);

```

Like the copy algorithm (§ 10.2.2, p. 382), `uninitialized_copy` takes three iterators. The first two denote an input sequence and the third denotes the destination into which those elements will be copied. The destination iterator passed to `uninitialized_copy` must denote unconstructed memory. Unlike `copy`, `uninitialized_copy` constructs elements in its destination.

Like `copy`, `uninitialized_copy` returns its (incremented) destination iterator. Thus, a call to `uninitialized_copy` returns a pointer positioned one element past the last constructed element. In this example, we store that pointer in `q`, which we pass to `uninitialized_fill_n`. This function, like `fill_n` (§ 10.2.2, p. 380), takes a pointer to a destination, a count, and a value. It will construct the given number of objects from the given value at locations starting at the given destination.

EXERCISES SECTION 12.2.2

Exercise 12.26: Rewrite the program on page 481 using an allocator.



12.3 Using the Library: A Text-Query Program

To conclude our discussion of the library, we'll implement a simple text-query program. Our program will let a user search a given file for words that might occur in it. The result of a query will be the number of times the word occurs and a list of lines on which that word appears. If a word occurs more than once on the same line, we'll display that line only once. Lines will be displayed in ascending order—that is, line 7 should be displayed before line 9, and so on.

For example, we might read the file that contains the input for this chapter and look for the word `element`. The first few lines of the output would be

```

element occurs 112 times
(line 36) A set element contains only a key;
(line 158) operator creates a new element
(line 160) Regardless of whether the element
(line 168) When we fetch an element from a map, we
(line 214) If the element is not found, find returns

```

followed by the remaining 100 or so lines in which the word `element` occurs.

12.3.1 Design of the Query Program



A good way to start the design of a program is to list the program's operations. Knowing what operations we need can help us see what data structures we'll need. Starting from requirements, the tasks our program must do include the following:

- When it reads the input, the program must remember the line(s) in which each word appears. Hence, the program will need to read the input a line at a time and break up the lines from the input file into its separate words
- When it generates output,
 - The program must be able to fetch the line numbers associated with a given word
 - The line numbers must appear in ascending order with no duplicates
 - The program must be able to print the text appearing in the input file at a given line number.

These requirements can be met quite neatly by using various library facilities:

- We'll use a `vector<string>` to store a copy of the entire input file. Each line in the input file will be an element in this `vector`. When we want to print a line, we can fetch the line using its line number as the index.
- We'll use an `istringstream` (§ 8.3, p. 321) to break each line into words.
- We'll use a `set` to hold the line numbers on which each word in the input appears. Using a `set` guarantees that each line will appear only once and that the line numbers will be stored in ascending order.
- We'll use a `map` to associate each word with the `set` of line numbers on which the word appears. Using a `map` will let us fetch the `set` for any given word.

For reasons we'll explain shortly, our solution will also use `shared_ptrs`.

Data Structures

Although we could write our program using `vector`, `set`, and `map` directly, it will be more useful if we define a more abstract solution. We'll start by designing a class to hold the input file in a way that makes querying the file easy. This class, which we'll name `TextQuery`, will hold a `vector` and a `map`. The `vector` will hold the text of the input file; the `map` will associate each word in that file to the `set` of line numbers on which that word appears. This class will have a constructor that reads a given input file and an operation to perform the queries.

The work of the query operation is pretty simple: It will look inside its `map` to see whether the given word is present. The hard part in designing this function is deciding what the query function should return. Once we know that a word was found, we need to know how often it occurred, the line numbers on which it occurred, and the corresponding text for each of those line numbers.

The easiest way to return all those data is to define a second class, which we'll name `QueryResult`, to hold the results of a query. This class will have a `print` function to print the results in a `QueryResult`.

Sharing Data between Classes

Our `QueryResult` class is intended to represent the results of a query. Those results include the set of line numbers associated with the given word and the corresponding lines of text from the input file. These data are stored in objects of type `TextQuery`.

Because the data that a `QueryResult` needs are stored in a `TextQuery` object, we have to decide how to access them. We could copy the set of line numbers, but that might be an expensive operation. Moreover, we certainly wouldn't want to copy the vector, because that would entail copying the entire file in order to print (what will usually be) a small subset of the file.

We could avoid making copies by returning iterators (or pointers) into the `TextQuery` object. However, this approach opens up a pitfall: What happens if the `TextQuery` object is destroyed before a corresponding `QueryResult`? In that case, the `QueryResult` would refer to data in an object that no longer exists.

This last observation about synchronizing the lifetime of a `QueryResult` with the `TextQuery` object whose results it represents suggests a solution to our design problem. Given that these two classes conceptually "share" data, we'll use `shared_ptr` (§ 12.1.1, p. 450) to reflect that sharing in our data structures.

Using the `TextQuery` Class

When we design a class, it can be helpful to write programs using the class before actually implementing the members. That way, we can see whether the class has the operations we need. For example, the following program uses our proposed `TextQuery` and `QueryResult` classes. This function takes an `ifstream` that points to the file we want to process, and interacts with a user, printing the results for the given words:

```
void runQueries(ifstream &infile)
{
    // infile is an ifstream that is the file we want to query
    TextQuery tq(infile); // store the file and build the query map
    // iterate with the user: prompt for a word to find and print results
    while (true) {
        cout << "enter word to look for, or q to quit: ";
        string s;
        // stop if we hit end-of-file on the input or if a 'q' is entered
        if (!(cin >> s) || s == "q") break;
        // run the query and print the results
        print(cout, tq.query(s)) << endl;
    }
}
```

We start by initializing a `TextQuery` object named `tq` from a given `ifstream`. The `TextQuery` constructor reads that file into its vector and builds the map that associates the words in the input with the line numbers on which they appear.

The `while` loop iterates (indefinitely) with the user asking for a word to query and printing the related results. The loop condition tests the literal `true` (§ 2.1.3, p. 41), so it always succeeds. We exit the loop through the `break` (§ 5.5.1, p. 190)

after the first `if`. That `if` checks that the read succeeded. If so, it also checks whether the user entered a `q` to quit. Once we have a word to look for, we ask `tq` to find that word and then call `print` to print the results of the search.

EXERCISES SECTION 12.3.1

Exercise 12.27: The `TextQuery` and `QueryResult` classes use only capabilities that we have already covered. Without looking ahead, write your own versions of these classes.

Exercise 12.28: Write a program to implement text queries without defining classes to manage the data. Your program should take a file and interact with a user to query for words in that file. Use `vector`, `map`, and `set` containers to hold the data for the file and to generate the results for the queries.

Exercise 12.29: We could have written the loop to manage the interaction with the user as a `do while` (§ 5.4.4, p. 189) loop. Rewrite the loop to use a `do while`. Explain which version you prefer and why.

12.3.2 Defining the Query Program Classes



We'll start by defining our `TextQuery` class. The user will create objects of this class by supplying an `istream` from which to read the input file. This class also provides the `query` operation that will take a `string` and return a `QueryResult` representing the lines on which that `string` appears.

The data members of the class have to take into account the intended sharing with `QueryResult` objects. The `QueryResult` class will share the `vector` representing the input file and the `sets` that hold the line numbers associated with each word in the input. Hence, our class has two data members: a `shared_ptr` to a dynamically allocated `vector` that holds the input file, and a `map` from `string` to `shared_ptr<set>`. The `map` associates each word in the file with a dynamically allocated `set` that holds the line numbers on which that word appears.

To make our code a bit easier to read, we'll also define a type member (§ 7.3.1, p. 271) to refer to line numbers, which are indices into a `vector` of `strings`:

```
class QueryResult; // declaration needed for return type in the query function
class TextQuery {
public:
    using line_no = std::vector<std::string>::size_type;
    TextQuery(std::ifstream&);
    QueryResult query(const std::string&) const;
private:
    std::shared_ptr<std::vector<std::string>> file; // input file
    // map of each word to the set of the lines in which that word appears
    std::map<std::string,
            std::shared_ptr<std::set<line_no>>> wm;
};
```

The hardest part about this class is untangling the class names. As usual, for code that will go in a header file, we use `std::` when we use a library name (§ 3.1, p. 83). In this case, the repeated use of `std::` makes the code a bit hard to read at first. For example,

```
std::map<std::string, std::shared_ptr<std::set<line_no>>> wm;
```

is easier to understand when rewritten as

```
map<string, shared_ptr<set<line_no>>> wm;
```

The TextQuery Constructor

The `TextQuery` constructor takes an `ifstream`, which it reads a line at a time:

```
// read the input file and build the map of lines to line numbers
TextQuery::TextQuery(ifstream &is): file(new vector<string>)
{
    string text;
    while (getline(is, text)) {           // for each line in the file
        file->push_back(text);           // remember this line of text
        int n = file->size() - 1;        // the current line number
        istringstream line(text);        // separate the line into words
        string word;
        while (line >> word) {           // for each word in that line
            // if word isn't already in wm, subscripting adds a new entry
            auto &lines = wm[word];      // lines is a shared_ptr
            if (!lines) // that pointer is null the first time we see word
                lines.reset(new set<line_no>); // allocate a new set
            lines->insert(n);             // insert this line number
        }
    }
}
```

The constructor initializer allocates a new vector to hold the text from the input file. We use `getline` to read the file a line at a time and push each line onto the vector. Because `file` is a `shared_ptr`, we use the `->` operator to dereference `file` to fetch the `push_back` member of the vector to which `file` points.

Next we use an `istringstream` (§ 8.3, p. 321) to process each word in the line we just read. The inner `while` uses the `istringstream` input operator to read each word from the current line into `word`. Inside the `while`, we use the `map` subscript operator to fetch the `shared_ptr<set>` associated with `word` and bind `lines` to that pointer. Note that `lines` is a reference, so changes made to `lines` will be made to the element in `wm`.

If `word` wasn't in the `map`, the subscript operator adds `word` to `wm` (§ 11.3.4, p. 435). The element associated with `word` is value initialized, which means that `lines` will be a null pointer if the subscript operator added `word` to `wm`. If `lines` is null, we allocate a new `set` and call `reset` to update the `shared_ptr` to which `lines` refers to point to this newly allocated `set`.

Regardless of whether we created a new `set`, we call `insert` to add the current line number. Because `lines` is a reference, the call to `insert` adds an element

to the set in `wm`. If a given word occurs more than once in the same line, the call to `insert` does nothing.

The `QueryResult` Class

The `QueryResult` class has three data members: a `string` that is the word whose results it represents; a `shared_ptr` to the `vector` containing the input file; and a `shared_ptr` to the set of line numbers on which this word appears. Its only member function is a constructor that initializes these three members:

```
class QueryResult {
friend std::ostream& print(std::ostream&, const QueryResult&);
public:
    QueryResult(std::string s,
                std::shared_ptr<std::set<line_no>> p,
                std::shared_ptr<std::vector<std::string>> f):
        sought(s), lines(p), file(f) { }
private:
    std::string sought; // word this query represents
    std::shared_ptr<std::set<line_no>> lines; // lines it's on
    std::shared_ptr<std::vector<std::string>> file; // input file
};
```

The constructor's only job is to store its arguments in the corresponding data members, which it does in the constructor initializer list (§ 7.1.4, p. 265).

The `query` Function

The `query` function takes a `string`, which it uses to locate the corresponding set of line numbers in the map. If the `string` is found, the `query` function constructs a `QueryResult` from the given `string`, the `TextQuery` `file` member, and the set that was fetched from `wm`.

The only question is: What should we return if the given `string` is not found? In this case, there is no set to return. We'll solve this problem by defining a local static object that is a `shared_ptr` to an empty set of line numbers. When the word is not found, we'll return a copy of this `shared_ptr`:

```
QueryResult
TextQuery::query(const string &sought) const
{
    // we'll return a pointer to this set if we don't find sought
    static shared_ptr<set<line_no>> nodata(new set<line_no>);
    // use find and not a subscript to avoid adding words to wm!
    auto loc = wm.find(sought);
    if (loc == wm.end())
        return QueryResult(sought, nodata, file); // not found
    else
        return QueryResult(sought, loc->second, file);
}
```

Printing the Results

The print function prints its given QueryResult object on its given stream:

```
ostream &print(ostream & os, const QueryResult &qr)
{
    // if the word was found, print the count and all occurrences
    os << qr.sought << " occurs " << qr.lines->size() << " "
      << make_plural(qr.lines->size(), "time", "s") << endl;
    // print each line in which the word appeared
    for (auto num : *qr.lines) // for every element in the set
        // don't confound the user with text lines starting at 0
        os << "\t(line " << num + 1 << ") "
          << *(qr.file->begin() + num) << endl;
    return os;
}
```

We use the size of the set to which the `qr.lines` points to report how many matches were found. Because that set is in a `shared_ptr`, we have to remember to dereference lines. We call `make_plural` (§ 6.3.2, p. 224) to print `time` or `times`, depending on whether that size is equal to 1.

In the `for` we iterate through the set to which `lines` points. The body of the `for` prints the line number, adjusted to use human-friendly counting. The numbers in the set are indices of elements in the vector, which are numbered from zero. However, most users think of the first line as line number 1, so we systematically add 1 to the line numbers to convert to this more common notation.

We use the line number to fetch a line from the vector to which `file` points. Recall that when we add a number to an iterator, we get the element that many elements further into the vector (§ 3.4.2, p. 111). Thus, `file->begin() + num` is the `num`th element after the start of the vector to which `file` points.

Note that this function correctly handles the case that the word is not found. In this case, the set will be empty. The first output statement will note that the word occurred 0 times. Because `*res.lines` is empty, the `for` loop won't be executed.

EXERCISES SECTION 12.3.2

Exercise 12.30: Define your own versions of the `TextQuery` and `QueryResult` classes and execute the `runQueries` function from § 12.3.1 (p. 486).

Exercise 12.31: What difference(s) would it make if we used a vector instead of a set to hold the line numbers? Which approach is better? Why?

Exercise 12.32: Rewrite the `TextQuery` and `QueryResult` classes to use a `StrBlob` instead of a `vector<string>` to hold the input file.

Exercise 12.33: In Chapter 15 we'll extend our query system and will need some additional members in the `QueryResult` class. Add members named `begin` and `end` that return iterators into the set of line numbers returned by a given query, and a member named `get_file` that returns a `shared_ptr` to the file in the `QueryResult` object.

CHAPTER SUMMARY

In C++, memory is allocated through `new` expressions and freed through `delete` expressions. The library also defines an `allocator` class for allocating blocks of dynamic memory.

Programs that allocate dynamic memory are responsible for freeing the memory they allocate. Properly freeing dynamic memory is a rich source of bugs: Either the memory is never freed, or it is freed while there are still pointers referring to the memory. The new library defines smart pointers—`shared_ptr`, `unique_ptr`, and `weak_ptr`—that make managing dynamic memory much safer. A smart pointer automatically frees the memory once there are no other users of that memory. When possible, modern C++ programs ought to use smart pointers.

DEFINED TERMS

allocator Library class that allocates unconstructed memory.

dangling pointer A pointer that refers to memory that once had an object but no longer does. Program errors due to dangling pointers are notoriously difficult to debug.

delete Frees memory allocated by `new`. `delete p` frees the object and `delete [] p` frees the array to which `p` points. `p` may be null or point to memory allocated by `new`.

deleter Function passed to a smart pointer to use in place of `delete` when destroying the object to which the pointer is bound.

destructor Special member function that cleans up an object when the object goes out of scope or is deleted.

dynamically allocated Object that is allocated on the free store. Objects allocated on the free store exist until they are explicitly deleted or the program terminates.

free store Memory pool available to a program to hold dynamically allocated objects.

heap Synonym for free store.

new Allocates memory from the free store. `new T` allocates and constructs an object of type `T` and returns a pointer to that object; if `T` is an array type, `new` returns a pointer to the first element in the array. Similarly,

`new [n] T` allocates n objects of type `T` and returns a pointer to the first element in the array. By default, the allocated object is default initialized. We may also provide optional initializers.

placement new Form of `new` that takes additional arguments passed in parentheses following the keyword `new`; for example, `new (nothrow) int` tells `new` that it should not throw an exception.

reference count Counter that tracks how many users share a common object. Used by smart pointers to know when it is safe to delete memory to which the pointers point.

shared_ptr Smart pointer that provides shared ownership: The object is deleted when the last `shared_ptr` pointing to that object is destroyed.

smart pointer Library type that acts like a pointer but can be checked to see whether it is safe to use. The type takes care of deleting memory when appropriate.

unique_ptr Smart pointer that provides single ownership: The object is deleted when the `unique_ptr` pointing to that object is destroyed. `unique_ptr`s cannot be directly copied or assigned.

weak_ptr Smart pointer that points to an object managed by a `shared_ptr`. The `shared_ptr` does not count `weak_ptr`s when deciding whether to delete its object.

This page intentionally left blank

This page intentionally left blank

Index

Bold face numbers refer to the page on which the term was first defined. Numbers in *italic* refer to the “Defined Terms” section in which the term is defined.

What’s new in C++11

- = default, 265, 506
- = delete, 507
- allocator, construct forwards to any constructor, 482
- array container, 327
- auto, 68
 - for type abbreviation, 88, 129
 - not with dynamic array, 478
 - with dynamic object, 459
- begin function, 118
- bind function, 397
- bitset enhancements, 726
- constexpr
 - constructor, 299
 - function, 239
 - variable, 66
- container
 - cbegin and cend, 109, 334
 - emplace members, 345
 - insert return type, 344
 - nonmember swap, 339
 - of container, 97, 329
 - shrink_to_fit, 357
- decltype, 70
 - function return type, 250
- delegating constructor, 291
- deleted copy-control, 624
- division rounding, 141
- end function, 118
- enumeration
 - controlling representation, 834
 - forward declaration, 834
 - scoped, 832
- explicit conversion operator, 582
- explicit instantiation, 675
- final class, 600
- format control for floating-point, 757
- forward function, 694
- forward_list container, 327
- function interface to callable objects, 577
- in-class initializer, 73, 274
- inherited constructor, 628, 804
- initializer_list, 220
- inline namespace, 790
- lambda expression, 388
- list initialization
 - = (assignment), 145
 - container, 336, 423
 - dynamic array, 478
 - dynamic object, 459
 - pair, 431
 - return value, 226, 427
 - variable, 43
 - vector, 98
- long long, 33
- mem_fn function, 843
- move function, 533
- move avoids copies, 529
- move constructor, 534
- move iterator, 543
- move-enabled this pointer, 546
- noexcept
 - exception specification, 535, 779
 - operator, 780
- nullptr, 54
- random-number library, 745
- range for statement, 91, 187
 - not with dynamic array, 477
- regular expression-library, 728
- rvalue reference, 532
 - cast from lvalue, 691
 - reference collapsing, 688
- sizeof data member, 157
- sizeof... operator, 700

- smart pointer, 450
 - shared_ptr, 450
 - unique_ptr, 470
 - weak_ptr, 473
- string
 - numeric conversions, 367
 - parameter with IO types, 317
- template
 - function template default template
 - argument, 670
 - type alias, 666
 - type parameter as friend, 666
 - variadic, 699
 - variadics and forwarding, 704
- trailing return type, 229
 - in function template, 684
 - in lambda expression, 396
- tuple, 718
- type alias declaration, 68
- union member of class type, 848
- unordered containers, 443
- virtual function
 - final, 606
 - override, 596, 606

Symbols

- ... (ellipsis parameter), 222
- /* */ (block comment), 9, 26
- // (single-line comment), 9, 26
- = default, 265, 306
 - copy-control members, 506
 - default constructor, 265
- = delete, 507
 - copy control, 507–508
 - default constructor, 507
 - function matching, 508
 - move operations, 538
- __DATE__, 242
- __FILE__, 242
- __LINE__, 242
- __TIME__, 242
- __cplusplus, 860
- \0 (null character), 39
- \Xnm (hexadecimal escape sequence), 39
- \n (newline character), 39
- \t (tab character), 39
- \nmn (octal escape sequence), 39
- { } (curly brace), 2, 26
- #include, 6, 28
 - standard header, 6
 - user-defined header, 21
- #define, 77, 80
- #endif, 77, 80
- #ifdef, 77, 80
- #ifndef, 77, 80
- ~classname, see destructor
- ; (semicolon), 3
 - class definition, 73
 - null statement, 172
- ++ (increment), 12, 28, 147–149, 170
 - iterator, 107, 132
 - overloaded operator, 566–568
 - pointer, 118
 - precedence and associativity, 148
 - reverse iterator, 407
 - StrBlobPtr, 566
- (decrement), 13, 28, 147–149, 170
 - iterator, 107
 - overloaded operator, 566–568
 - pointer, 118
 - precedence and associativity, 148
 - reverse iterator, 407, 408
 - StrBlobPtr, 566
- * (dereference), 53, 80, 448
 - iterator, 107
 - map iterators, 429
 - overloaded operator, 569
 - pointer, 53
 - precedence and associativity, 148
 - smart pointer, 451
 - StrBlobPtr, 569
- & (address-of), 52, 80
 - overloaded operator, 554
- > (arrow operator), 110, 132, 150
 - overloaded operator, 569
 - StrBlobPtr, 569
- . (dot), 23, 28, 150
- >* (pointer to member arrow), 837
- .* (pointer to member dot), 837
- [] (subscript), 93
 - array, 116, 132
 - array, 347
 - bitset, 727
 - deque, 347
 - does not add elements, 104
 - map, and unordered_map, 435, 448
 - adds element, 435
 - multidimensional array, 127
 - out-of-range index, 93
 - overloaded operator, 564
 - pointer, 121

- string, **93**, 132, 347
- StrVec, 565
- subscript range, 95
- vector, **103**, 132, 347
- () (call operator), **23**, 28, **202**, 252
 - absInt, 571
 - const member function, 573
 - execution flow, 203
 - overloaded operator, 571
 - PrintString, 571
 - ShorterString, 573
 - SizeComp, 573
- :: (scope operator), **8**, 28, 82
 - base-class member, 607
 - class type member, 88, 282
 - container, type members, 333
 - global namespace, **789**, 818
 - member function, definition, 259
 - overrides name lookup, 286
- = (assignment), **12**, 28, 144–147
 - see also* copy assignment
 - see also* move assignment
 - associativity, 145
 - base from derived, 603
 - container, **89**, 103, 337
 - conversion, 145, 159
 - derived class, 626
 - in condition, 146
 - initializer_list, 563
 - list initialization, 145
 - low precedence, 146
 - multiple inheritance, 805
 - overloaded operator, 500, 563
 - pointer, 55
 - to signed, 35
 - to unsigned, 35
 - vs. == (equality), 146
 - vs. initialization, 42
- += (compound assignment), **12**, 28, 147
 - bitwise operators, 155
 - iterator, 111
 - overloaded operator, 555, 560
 - Sales_data, 564
 - exception version, 784
 - string, 89
- + (addition), **6**, 140
 - iterator, 111
 - pointer, 119
 - Sales_data, 560
 - exception version, 784
 - Sales_item, 22
 - SmallInt, 588
 - string, 89
- (subtraction), **140**
 - iterator, 111
 - pointer, 119
- * (multiplication), **140**
- / (division), **140**
 - rounding, 141
- % (modulus), **141**
 - grading program, 176
- == (equality), **18**, 28
 - arithmetic conversion, 144
 - container, **88**, 102, 340, 341
 - iterator, 106, 107
 - overloaded operator, 561, 562
 - pointer, 55, 120
 - Sales_data, 561
 - string, 88
 - tuple, 720
 - unordered container key_type, 443
 - used in algorithms, 377, 385, 413
 - vs. = (assignment), 146
- != (inequality), 28
 - arithmetic conversion, 144
 - container, **88**, 102, 340, 341
 - iterator, 106, 107
 - overloaded operator, 562
 - pointer, 55, 120
 - Sales_data, 561
 - string, 88
 - tuple, 720
- < (less-than), 28, **143**
 - container, **88**, 340
 - ordered container key_type, 425
 - overloaded operator, 562
 - strict weak ordering, 562
 - string, 88
 - tuple, 720
 - used in algorithms, 378, 385, 413
- <= (less-than-or-equal), **12**, 28, **143**
 - container, **88**, 340
 - string, **88**
- > (greater-than), 28, **143**
 - container, **88**, 340
 - string, **88**
- >= (greater-than-or-equal), 28, **143**
 - container, **88**, 340
 - string, **88**
- >> (input operator), **8**, 28
 - as condition, 15, 86, 312
 - chained-input, 8

- istream, **8**
 - istream_iterator, 403
 - overloaded operator, 558–559
 - precedence and associativity, 155
 - Sales_data, 558
 - Sales_item, 21
 - string, 85, 132
 - << (output operator), 7, 28
 - bitset, 727
 - chained output, 7
 - ostream, 7
 - ostream_iterator, 405
 - overloaded operator, 557–558
 - precedence and associativity, 155
 - Query, 641
 - Sales_data, 557
 - Sales_item, 21
 - string, 85, 132
 - >> (right-shift), **153**, 170
 - << (left-shift), **153**, 170
 - && (logical AND), **94**, 132, 142, 169
 - order of evaluation, 138
 - overloaded operator, 554
 - short-circuit evaluation, 142
 - || (logical OR), **142**
 - order of evaluation, 138
 - overloaded operator, 554
 - short-circuit evaluation, 142
 - & (bitwise AND), **154**, 169
 - Query, 638, 644
 - ! (logical NOT), **87**, 132, 143, 170
 - || (logical OR), 132, 170
 - | (bitwise OR), **154**, 170
 - Query, 638, 644
 - ^ (bitwise XOR), **154**, 170
 - ~ (bitwise NOT), **154**, 170
 - Query, 638, 643
 - , (comma operator), **157**, 169
 - order of evaluation, 138
 - overloaded operator, 554
 - ? : (conditional operator), **151**, 169
 - order of evaluation, 138
 - precedence and associativity, 151
 - + (unary plus), **140**
 - (unary minus), **140**
 - L'c' (wchar_t literal), 38
 - ddd.dddL or ddd.dddl (long double literal), 41
 - numEnum or *numenum* (double literal), 39
 - numF or *numf* (float literal), 41
 - numL or *numl* (long literal), 41
 - numLL or *numll* (long long literal), 41
 - numU or *numu* (unsigned literal), 41
 - class member: *constant expression*, see bit-field
- ## A
- absInt, 571
 - () (call operator), 571
 - abstract base class, **610**, 649
 - BinaryQuery, 643
 - Disc_quote, 610
 - Query_base, 636
 - abstract data type, **254**, 305
 - access control, 611–616
 - class derivation list, 596
 - default inheritance access, 616
 - default member access, 268
 - derived class, 613
 - derived-to-base conversion, 613
 - design, 614
 - inherited members, 612
 - local class, 853
 - nested class, 844
 - private, 268
 - protected, 595, 611
 - public, 268
 - using declaration, 615
 - access specifier, **268**, 305
 - accessible, **611**, 649
 - derived-to-base conversion, 613
 - Account, 301
 - accumulate, 379, 882
 - bookstore program, 406
 - Action, 839
 - adaptor, 372
 - back_inserter, 402
 - container, **368**, 368–371
 - front_inserter, 402
 - inserter, 402
 - make_move_iterator, 543
 - add, Sales_data, 261
 - add_item, Basket, 633
 - add_to_Folder, Message, 522
 - address, **33**, 78
 - adjacent_difference, 882
 - adjacent_find, 871
 - advice
 - always initialize a pointer, 54
 - avoid casts, 165

- avoid undefined behavior, 36
- choosing a built-in type, 34
- define small utility functions, 277
- define variables near first use, 48
- don't create unnecessary regex objects, 733
- forwarding parameter pattern, 706
- keep lambda captures simple, 394
- managing iterators, 331, 354
- prefix vs. postfix operators, 148
- rule of five, 541
- use move sparingly, 544
- use constructor initializer lists, 289
- when to use overloading, 233
- writing compound expressions, 139
- aggregate class, 298, 305
 - initialization, 298
- algorithm header, 376
- algorithms, 376, 418
 - see also* Appendix A
 - architecture
 - _copy versions, 383, 414
 - _if versions, 414
 - naming convention, 413–414
 - operate on iterators not containers, 378
 - overloading pattern, 414
 - parameter pattern, 412–413
 - read-only, 379–380
 - reorder elements, 383–385, 414
 - write elements, 380–383
 - associative container and, 430
 - bind as argument, 397
 - can't change container size, 385
 - element type requirements, 377
 - function object arguments, 572
 - istream_iterator, 404
 - iterator category, 410–412
 - iterator range, 376
 - lambda as argument, 391, 396
 - library function object, 575
 - ostream_iterator, 404
 - sort comparison, requires strict weak ordering, 425
 - supplying comparison operation, 386, 413
 - function, 386
 - lambda, 389, 390
 - two input ranges, 413
 - type independence, 377
 - use element's == (equality), 385, 413
 - use element's < (less-than), 385, 413
 - accumulate, 379
 - bookstore program, 406
 - copy, 382
 - count, 378
 - equal_range, 722
 - equal, 380
 - fill_n, 381
 - fill, 380
 - find_if, 388, 397, 414
 - find, 376
 - for_each, 391
 - replace_copy, 383
 - replace, 383
 - set_intersection, 647
 - sort, 384
 - stable_sort, 387
 - transform, 396
 - unique, 384
- alias declaration
 - namespace, 792, 817
 - template type, 666
 - type, 68
- all_of, 871
- alloc_n_copy, StrVec, 527
- allocate, allocator, 481
- allocator, 481, 481–483, 491, 524–531
 - allocate, 481, 527
 - compared to operator new, 823
 - construct, 482
 - forwards to constructor, 527
 - deallocate, 483, 528
 - compared to operator delete, 823
 - destroy, 482, 528
- alternative operator name, 46
- alternative_sum, program, 682
- ambiguous
 - conversion, 583–589
 - multiple inheritance, 806
 - function call, 234, 245, 251
 - multiple inheritance, 808
 - overloaded operator, 588
- AndQuery, 637
 - class definition, 644
 - eval function, 646
- anonymous union, 848, 862
- any, bitset, 726
- any_of, 871
- app (file mode), 319
- append, string, 362

- argc, 219
- argument, **23**, 26, **202**, 251
 - array, 214–219
 - buffer overflow, 215
 - to pointer conversion, 214
 - C-style string, 216
 - conversion, function matching, 234
 - default, **236**
 - forwarding, 704
 - initializes parameter, 203
 - iterator, 216
 - low-level const, 213
 - main function, 218
 - multidimensional array, 218
 - nonreference parameter, 209
 - pass by reference, **210**, 252
 - pass by value, **209**, 252
 - uses copy constructor, 498
 - uses move constructor, 539, 541
 - passing, 208–212
 - pointer, 214
 - reference parameter, 210, 214
 - reference to const, 211
 - top-level const, 212
- argument list, **202**
- argument-dependent lookup, 797
 - move and forward, 798
- argv, 219
- arithmetic
 - conversion, 35, **159**, 168
 - in equality and relational operators, 144
 - integral promotion, **160**, 169
 - signed to unsigned, 34
 - to bool, 162
 - operators, 139
 - compound assignment (e.g., +=), 147
 - function object, 574
 - overloaded, 560
 - type, **32**, 78
 - machine-dependent, 32
- arithmetic (addition and subtraction)
 - iterators, **111**, 131
 - pointers, **119**, 132
- array, 113–130
 - [] (subscript), **116**, 132
 - argument and parameter, 214–219
 - argument conversion, 214
 - auto returns pointer, 117
 - begin function, 118
 - compound type, 113
 - conversion to pointer, 117, 161
 - function arguments, 214
 - template argument deduction, 679
 - decltype returns array type, 118
 - definition, 113
 - dimension, constant expression, 113
 - dynamically allocated, **476**, 476–484
 - allocator, 481
 - can't use begin and end, 477
 - can't use range for statement, 477
 - delete [], 478
 - empty array, 478
 - new [], 477
 - shared_ptr, 480
 - unique_ptr, 479
 - elements and destructor, 502
 - end function, 118
 - initialization, 114
 - initializer of vector, 125
 - multidimensional, 125–130
 - no copy or assign, 114
 - of char initialization, 114
 - parameter
 - buffer overflow, 215
 - converted to pointer, 215
 - function template, 654
 - pointer to, 218
 - reference to, 217
 - return type, 204
 - trailing, 229
 - type alias, 229
 - decltype, 230
 - sizeof, 157
 - subscript range, 116
 - subscript type, 116
 - understanding complicated declarations, 115
- array
 - see also* container
 - see also* sequential container
 - [] (subscript), 347
 - = (assignment), 337
 - assign, 338
 - copy initialization, 337
 - default initialization, 336
 - definition, 336
 - header, 329
 - initialization, 334–337
 - list initialization, 337
 - overview, 327
 - random-access iterator, 412

- swap, 339
- assert preprocessor macro, 241, 251
- assign
 - array, 338
 - invalidates iterator, 338
 - sequential container, 338
 - string, 362
- assignment, vs. initialization, 42, 288
- assignment operators, 144–147
- associative array, *see* map
- associative container, 420, 447
 - and library algorithms, 430
 - initialization, 423, 424
 - key_type requirements, 425, 445
 - members
 - begin, 430
 - count, 437, 438
 - emplace, 432
 - end, 430
 - equal_range, 439
 - erase, 434
 - find, 437, 438
 - insert, 432
 - key_type, 428, 447
 - mapped_type, 428, 448
 - value_type, 428, 448
 - override default comparison, 425
 - override default hash, 446
 - overview, 423
- associativity, 134, 136–137, 168
 - = (assignment), 145
 - ? : (conditional operator), 151
 - dot and dereference, 150
 - increment and dereference, 148
 - IO operator, 155
 - overloaded operator, 553
- at
 - deque, 348
 - map, 435
 - string, 348
 - unordered_map, 435
 - vector, 348
- ate (file mode), 319
- auto, 68, 78
 - cbegin, 109, 379
 - cend, 109, 379
 - for type abbreviation, 88, 129
 - of array, 117
 - of reference, 69
 - pointer to function, 249
 - with new, 459

- auto_ptr deprecated, 471
- automatic object, 205, 251
 - see also* local variable
 - see also* parameter and destructor, 502
- avg_price, Sales_data, 259

B

- back
 - queue, 371
 - sequential container, 346
 - StrBlob, 457
- back_inserter, 382, 402, 417
 - requires push_back, 382, 402
- bad, 313
- bad_alloc, 197, 460
- bad_cast, 197, 826
- bad_typeid, 828
- badbit, 312
- base, reverse iterator, 409
- base class, 592, 649
 - see also* virtual function
 - abstract, 610, 649
 - base-to-derived conversion, not automatic, 602
 - can be a derived class, 600
 - definition, 594
 - derived-to-base conversion, 597
 - accessibility, 613
 - key concepts, 604
 - multiple inheritance, 805
 - final, 600
 - friendship not inherited, 614
 - initialized or assigned from derived, 603
 - member hidden by derived, 619
 - member new and delete, 822
 - multiple, *see* multiple inheritance
 - must be complete type, 600
 - protected member, 611
 - scope, 617
 - inheritance, 617–621
 - multiple inheritance, 807
 - virtual function, 620
 - static members, 599
 - user of, 614
 - virtual, *see* virtual base class
 - virtual destructor, 622
- Basket, 631
 - add_item, 633

- total, 632
- Bear, 803
 - virtual base class, 812
- before_begin, forward_list, 351
- begin
 - associative container, 430
 - container, **106**, 131, 333, 372
 - function, **118**, 131
 - not with dynamic array, 477
 - multidimensional array, 129
 - StrBlob, 475
 - StrVec, 526
- bernoulli_distribution, 752
- best match, **234**, 251
 - see also* function matching
- bidirectional iterator, **412**, 417
- biggies program, 391
- binary (file mode), 319
- binary operators, **134**, 168
 - overloaded operator, 552
- binary predicate, **386**, 417
- binary_function deprecated, 579
- binary_search, 873
- BinaryQuery, 637
 - abstract base class, 643
- bind, **397**, 417
 - check_size, 398
 - generates callable object, 397
 - from pointer to member, 843
 - placeholders, 399
 - reference parameter, 400
- bind1st deprecated, 401
- bind2nd deprecated, 401
- binops desk calculator, 577
- bit-field, **854**, 862
 - access to, 855
 - constant expression, 854
- bitset, **723**, 723–728, 769
 - [] (subscript), 727
 - << (output operator), 727
 - any, 726
 - count, 727
 - flip, 727
 - grading program, 728
 - header, 723
 - initialization, 723–725
 - from string, 724
 - from unsigned, 723
 - none, 726
 - reset, 727
 - set, 727
 - test, 727
 - to_ulong, 727
- bitwise, bitset, operators, 725
- bitwise operators, 152–156
 - += (compound assignment), 155
 - compound assignment (e.g., +=), 147
 - grading program, 154
 - operand requirements, 152
- Blob
 - class template, 659
 - constructor, 662
 - initializer_list, 662
 - iterator parameters, 673
 - instantiation, 660
 - member functions, 661–662
- block, **2**, 12, 26, **173**, 199
 - function, 204
 - scope, **48**, 80, 173
 - try, **193**, 194, 200, 818
- block (/ * */), comment, **9**, 26
- book from author program, 438–440
- bookstore program
 - Sales_data, 255
 - using algorithms, 406
 - Sales_item, 24
- bool, **32**
 - conversion, 35
 - literal, 41
 - in condition, 143
- boolalpha, manipulator, 754
- brace, curly, **2**, 26
- braced list, *see* list initialization
- break statement, **190**, 199
 - in switch, 179–181
- bucket management, unordered container, 444
- buffer, **7**, 26
 - flushing, 314
- buffer overflow, **105**, 116, 131
 - array parameter, 215
 - C-style string, 123
- buildMap program, 442
- built-in type, **2**, 26, 32–34
 - default initialization, 43
- Bulk_quote
 - class definition, 596
 - constructor, 598, 610
 - derived from Disc_quote, 610
 - design, 592
 - synthesized copy control, 623
- byte, **33**, 78

C

- . C file, 4
- . cc file, 4
- . cpp file, 4
- . cp file, 4
- C library header, 91
- C-style cast, 164
- C-style string, 114, **122**, 122–123, 131
 - buffer overflow, 123
 - initialization, 122
 - parameter, 216
 - string, 124
- c_str, 124
- call by reference, 208, 210, 251
- call by value, **209**, 251
 - uses copy constructor, 498
 - uses move constructor, 539
- call signature, **576**, 590
- callable object, **388**, 417, 571–572
 - absInt, 571
 - bind, 397
 - call signature, 576
 - function and function pointers, 388
 - function objects, 572
 - pointer to member
 - and bind, 843
 - and function, 842
 - and mem_fn, 843
 - not callable, 842
 - PrintString, 571
 - ShorterString, 573
 - SizeComp, 573
 - with function, 576–579
 - with algorithms, 390
- candidate function, **243**, 251
 - see also* function matching
 - function template, 695
 - namespace, 800
 - overloaded operator, 587
- capacity
 - string, 356
 - StrVec, 526
 - vector, 356
- capture list, *see* lambda expression
- case label, **179**, 179–182, 199
 - default, **181**
 - constant expression, 179
- case sensitive, string, 365
- cassert header, 241
- cast, *see also* named cast, 168
 - checked, *see* dynamic_cast
 - old-style, 164
 - to rvalue reference, 691
- catch, **193**, 195, 199, **775**, 816
 - catch(...), **777**, 816
 - exception declaration, 195, 200, 775, 816
 - exception object, 775
 - matching, 776
 - ordering of, 776
 - runtime_error, 195
- catch all (catch(...)), **777**, 816
- caution
 - ambiguous conversion operator, 581
 - conversions to unsigned, 37
 - dynamic memory pitfalls, 462
 - exception safety, 196
 - IO buffers, 315
 - overflow, 140
 - overloaded operator misuse, 555
 - overloaded operators and conversion operators, 586
 - smart pointer, pitfalls, 469
 - uninitialized variables, 45
 - using directives cause pollution, 795
- cbegin
 - auto, 109, 379
 - decltype, 109, 379
 - container, **109**, 333, 334, 372
- cctype
 - functions, 91–93
 - header, 91
- ccend
 - auto, 109, 379
 - decltype, 109, 379
 - container, **109**, 333, 334, 372
- cerr, 6, 26
- chained input, 8
- chained output, 7
- char, 32
 - signed, 34
 - unsigned, 34
 - array initialization, 114
 - literal, 39
 - representation, 34
- char16_t, 33
- char32_t, 33
- character
 - newline (\n), 39
 - nonprintable, **39**, 79
 - null (\0), 39

- tab (\t), 39
- character string literal, *see* string literal
- check
 - StrBlob, 457
 - StrBlobPtr, 474
- check_size, 398
 - bind, 398
- checked cast, *see* dynamic_cast
- children's story program, 383–391
- chk_n_alloc, StrVec, 526
- cin, 6, 26
 - tied to cout, 315
- cl, 5
- class, 19, 26, 72, 305
 - see also* constructor
 - see also* destructor
 - see also* member function
 - see also* static member
 - access specifier, 268
 - default, 268
 - private, 268, 306
 - public, 268, 306
 - aggregate, 298, 305
 - assignment operator
 - see* copy assignment
 - see* move assignment
 - base, *see* base class, 649
 - data member, 73, 78
 - const vs. mutable, 274
 - const, initialization, 289
 - in-class initializer, 274
 - initialization, 263, 274
 - must be complete type, 279
 - mutable, 274, 306
 - order of destruction, 502
 - order of initialization, 289
 - pointer, not deleted, 503
 - reference, initialization, 289
 - sizeof, 157
 - declaration, 278, 305
 - default inheritance specifier, 616
 - definition, 72, 256–267
 - ends with semicolon, 73
 - derived, *see* derived class, 649
 - exception, 193, 200
 - final specifier, 600
 - forward declaration, 279, 306
 - friend, 269, 280
 - class, 280
 - function, 269
 - member function, 280
 - overloaded function, 281
 - scope, 270, 281
 - template class or function, 664
 - implementation, 254
 - interface, 254
 - literal, 299
 - local, *see* local class
 - member, 73, 78
 - member access, 282
 - member new and delete, 822
 - member: *constant expression*, *see* bit-field
 - multiple base classes, *see* multiple inheritance
 - name lookup, 284
 - nested, *see* nested class
 - pointer to member, *see* pointer to member
 - preventing copies, 507
 - scope, 73, 282, 282–287, 305
 - synthesized, copy control, 267, 497, 500, 503, 537
 - template member, *see* member template
 - type member, 271
 - :: (scope operator), 282
 - user of, 255
 - valuelike, 512
 - without move constructor, 540
- class
 - compared to typename, 654
 - default access specifier, 268
 - default inheritance specifier, 616
 - template parameter, 654
- class derivation list, 596
 - access control, 612
 - default access specifier, 616
 - direct base class, 600
 - indirect base class, 600
 - multiple inheritance, 803
 - virtual base class, 812
- class template, 96, 131, 658, 659, 658–667, 713
 - see also* template parameter
 - see also* instantiation
 - Blob, 659
 - declaration, 669
 - default template argument, 671
 - definition, 659
 - error detection, 657
 - explicit instantiation, 675, 675–676

- explicit template argument, 660
- friend, 664
 - all instantiations, 665
 - declaration dependencies, 665
 - same instantiation, 664
 - specific instantiation, 665
- instantiation, 660
- member function
 - defined outside class body, 661
 - instantiation, 663
- member template, *see* member template
- specialization, 707, 709–712, 714
 - hash<key_type>, 709, 788
 - member, 711
 - namespace, 788
 - partial, 711, 714
- static member, 667
 - accessed through an instantiation, 667
 - definition, 667
- template argument, 660
- template parameter, used in definition, 660
- type parameter as friend, 666
- type-dependent code, 658
- class type, 19, 26
 - conversion, 162, 305, 590
 - ambiguities, 587
 - conversion operator, 579
 - converting constructor, 294
 - impact on function matching, 584
 - overloaded function, 586
 - with standard conversion, 581
 - default initialization, 44
 - initialization, 73, 84, 262
 - union member of, 848
 - variable vs. function declaration, 294
- clear
 - sequential container, 350
 - stream, 313
- clog, 6, 26
- close, file stream, 318
- cmath, 733
- cmath header, 751, 757
- collapsing rule, reference, 688
- combine, Sales_data, 259
- comma (,) operator, 157
- comment, 9, 26
 - block (`/* */`), 9, 26
 - single-line (`//`), 9, 26
- compare
 - default template argument, 670
 - function template, 652
 - default template argument, 670
 - explicit template argument, 683
 - specialization, 706
 - string literal version, 654
 - template argument deduction, 680
 - string, 366
- compareIsbn
 - and associative container, 426
 - Sales_data, 387
- compilation
 - common errors, 16
 - compiler options, 207
 - conditional, 240
 - declaration vs. definition, 44
 - mixing C and C++, 860
 - needed when class changes, 270
 - templates, 656
 - error detection, 657
 - explicit instantiation, 675–676
- compiler
 - extension, 114, 131
 - GNU, 5
 - Microsoft, 5
 - options for separate compilation, 207
- composition vs. inheritance, 637
- compound assignment (e.g., +=)
 - arithmetic operators, 147
 - bitwise operators, 147
- compound expression, *see* expression
- compound statement, 173, 199
- compound type, 50, 50–58, 78
 - array, 113
 - declaration style, 57
 - understanding complicated declarations, 115
- concatenation
 - string, 89
 - string literal, 39
- condition, 12, 26
 - = (assignment) in, 146
 - conversion, 159
 - do while statement, 189
 - for statement, 13, 185
 - if statement, 18, 175
 - in IO expression, 156
 - logical operators, 141
 - smart pointer as, 451
 - stream type as, 15, 162, 312

- while statement, 12, 183
- condition state, IO classes, **312**, 324
- conditional compilation, 240
- conditional operator (? :), 151
- connection, 468
- console window, 6
- const, **59**, 78
 - and typedef, 68
 - conversion, 162
 - template argument deduction, 679
 - dynamically allocated
 - destruction, 461
 - initialization, 460
 - initialization, 59
 - class type object, 262
 - low-level const, **64**
 - argument and parameter, 213
 - conversion from, 163
 - conversion to, 162
 - overloaded function, 232
 - template argument deduction, 693
 - member function, **258**, 305
 - () (call operator), 573
 - not constructors, 262
 - overloaded function, 276
 - reference return, 276
 - parameter, 212
 - function matching, 246
 - overloaded function, 232
 - pointer, **63**, 78
 - pointer to, **62**, 79
 - conversion from nonconst, 162
 - initialization from nonconst, 62
 - overloaded parameter, 232
 - reference, *see* reference to const
 - top-level const, **64**
 - and auto, 69
 - argument and parameter, 212
 - decltype, 71
 - parameter, 232
 - template argument deduction, 679
 - variable, 59
 - declared in header files, 76
 - extern, 60
 - local to file, 60
- const_cast, 163, **163**
- const_iterator, container, **108**, 332
- const_reference, container, 333
- const_reverse_iterator, container, 332, 407
- constant expression, **65**, 78
 - array dimension, 113
 - bit-field, 854
 - case label, 179
 - enumerator, 833
 - integral, **65**
 - nontype template parameter, 655
 - sizeof, 156
 - static data member, 303
- constexpr, **66**, 78
 - constructor, **299**
 - declared in header files, 76
 - function, **239**, 251
 - nonconstant return value, 239
 - function template, 655
 - pointer, 67
 - variable, 66
- construct
 - allocator, 482
 - forwards to constructor, 527
- constructor, **262**, **264**, 262–266, 305
 - see also* default constructor
 - see also* copy constructor
 - see also* move constructor
 - calls to virtual function, 627
 - constexpr, **299**
 - converting, 294, 305
 - function matching, 585
 - Sales_data, 295
 - with standard conversion, 580
 - default argument, 290
 - delegating, **291**, 306
 - derived class, 598
 - initializes direct base class, 610
 - initializes virtual base, 813
 - explicit, **296**, 306
 - function try block, 778, 817
 - inherited, 628
 - initializer list, **265**, 288–292, 305
 - class member initialization, 274
 - compared to assignment, 288
 - derived class, 598
 - function try block, 778, 817
 - sometimes required, 288
 - virtual base class, 814
 - initializer_list parameter, 662
 - not const, 262
 - order of initialization, 289
 - derived class object, 598, 623
 - multiple inheritance, 804
 - virtual base classes, 814
 - overloaded, 262

- StrBlob, 456
- StrBlobPtr, 474
- TextQuery, 488
- Blob, 662
 - initializer_list, 662
 - iterator parameters, 673
- Bulk_quote, 598, 610
- Disc_quote, 609
- Sales_data, 264–266
- container, **96**, 131, **326**, 372
 - see also* sequential container
 - see also* associative container
 - adaptor, **368**, 368–371
 - equality and relational operators, 370
 - initialization, 369
 - requirements on container, 369
 - and inheritance, 630
 - as element type, 97, 329
 - associative, **420**, 447
 - copy initialization, 334
 - element type constraints, 329, 341
 - elements and destructor, 502
 - elements are copies, 342
 - initialization from iterator range, 335
 - list initialization, 336
 - members
 - see also* iterator
 - = (assignment), 337
 - == (equality), 341
 - != (inequality), 341
 - begin, **106**, 333, 372
 - cbegin, **109**, 333, 334, 372
 - cend, **109**, 333, 334, 372
 - const_iterator, **108**, 332
 - const_reference, 333
 - const_reverse_iterator, 332, 407
 - crbegin, 333
 - crend, 333
 - difference_type, 131, 332
 - empty, **87**, 102, 131, 340
 - end, **106**, 131, 333, 373
 - equality and relational operators, **88**, 102, 340
 - iterator, **108**, 332
 - rbegin, 333, 407
 - reference, 333
 - relational operators, 341
 - rend, 333, 407
 - reverse_iterator, 332, 407
 - size, **88**, 102, 132, 340
 - size_type, **88**, 102, 132, 332
 - swap, 339
 - move operations, 529
 - moved-from object is valid but unspecified, 537
 - nonmember swap, 339
 - of container, 97, 329
 - overview, 328
 - sequential, **326**, 373
 - type members, :: (scope operator), 333
- continue statement, **191**, 199
- control, flow of, 11, **172**, 200
- conversion, 78, **159**, 168
 - = (assignment), 145, 159
 - ambiguous, 583–589
 - argument, 203
 - arithmetic, 35, **159**, 168
 - array to pointer, 117
 - argument, 214
 - exception object, 774
 - multidimensional array, 128
 - template argument deduction, 679
 - base-to-derived, not automatic, 602
- bool, 35
- class type, 162, 294, 305, 590
 - ambiguities, 587
 - conversion operator, 579
 - function matching, 584, 586
 - with standard conversion, 581
- condition, 159
- derived-to-base, **597**, 649
 - accessibility, 613
 - key concepts, 604
 - shared_ptr, 630
- floating-point, 35
- function to pointer, 248
 - exception object, 774
 - template argument deduction, 679
- integral promotion, **160**, 169
- istream, 162
- multiple inheritance, 805
 - ambiguous, 806
- narrowing, 43
- operand, 159
- pointer to bool, 162
- rank, 245
- return value, 223
- Sales_data, 295
- signed type, 160

- signed to unsigned, 34
- to const, 162
 - from pointer to nonconst, 62
 - from reference to nonconst, 61
 - template argument deduction, 679
- unscoped enumeration to integer, 834
- unsigned, 36
- virtual base class, 812
- conversion operator, **580**, 580–587, 590
 - design, 581
 - explicit, **582**, 590
 - bool, 583
 - function matching, 585, 586
 - SmallInt, 580
 - used implicitly, 580
 - with standard conversion, 580
- converting constructor, **294**, 305
 - function matching, 585
 - with standard conversion, 580
- _copy algorithms, 383, 414
- copy, 382, 874
- copy and swap assignment, **518**
 - move assignment, 540
 - self-assignment, 519
- copy assignment, 500–501, 549
 - = default, 506
 - = delete, 507
 - base from derived, 603
 - copy and swap, 518, 549
 - derived class, 626
 - HasPtr
 - reference counted, 516
 - valuelike, 512
 - memberwise, 500
 - Message, 523
 - preventing copies, 507
 - private, 509
 - reference count, 514
 - rule of three/five, **505**
 - virtual destructor exception, 622
 - self-assignment, 512
 - StrVec, 528
 - synthesized, **500**, 550
 - deleted function, 508, 624
 - derived class, 623
 - multiple inheritance, 805
 - union with class type member, 852
 - valuelike class, 512
- copy constructor, **496**, 496–499, 549
 - = default, 506
 - = delete, 507
- base from derived, 603
- derived class, 626
- HasPtr
 - reference counted, 515
 - valuelike, 512
- memberwise, 497
- Message, 522
- parameter, 496
- preventing copies, 507
- private, 509
- reference count, 514
- rule of three/five, **505**
 - virtual destructor exception, 622
- StrVec, 528
- synthesized, **497**, 550
 - deleted function, 508, 624
 - derived class, 623
 - multiple inheritance, 805
- union with class type member, 851
- used for copy-initialization, 498
- copy control, 267, **496**, 549
 - = delete, 507–508
 - inheritance, 623–629
 - memberwise, 267, 550
 - copy assignment, 500
 - copy constructor, 497
 - move assignment, 538
 - move constructor, 538
 - multiple inheritance, 805
 - synthesized, 267
 - as deleted function, 508
 - as deleted in derived class, 624
 - move operations as deleted function, 538
 - unions, 849
 - virtual base class, synthesized, 815
- copy initialization, **84**, 131, **497**, 497–499, 549
 - array, 337
 - container, 334
 - container elements, 342
 - explicit constructor, 498
 - invalid for arrays, 114
 - move vs. copy, 539
 - parameter and return value, 498
 - uses copy constructor, 497
 - uses move constructor, 541
- copy_backward, 875
- copy_if, 874
- copy_n, 874
- copyUnion, Token, 851

- count
 - algorithm, 378, 871
 - associative container, 437, 438
 - bitset, 727
 - count_calls, program, 206
 - count_if, 871
 - cout, 6, 26
 - tied to cin, 315
 - cplusplus_primer, namespace, 787
 - crbegin, container, 333
 - cref, binds reference parameter, 400, 417
 - cregex_iterator, 733, 769
 - crend, container, 333
 - cstdlib header, 116, 120
 - cstdlibio header, 762
 - cstdliblib header, 54, 227, 778, 823
 - cstring
 - functions, 122–123
 - header, 122
 - csub_match, 733, 769
 - ctime header, 749
 - curly brace, 2, 26
- D**
- dangling else, 177, 199
 - dangling pointer, 225, 463, 491
 - undefined behavior, 463
 - data abstraction, 254, 306
 - data hiding, 270
 - data member, *see* class data member
 - data structure, 19, 26
 - deallocate, allocator, 483, 528
 - debug_rep program
 - additional nontemplate versions, 698
 - general template version, 695
 - nontemplate version, 697
 - pointer template version, 696
 - DebugDelete, member template, 673
 - dec, manipulator, 754
 - decimal, literal, 38
 - declaration, 45, 78
 - class, 278, 305
 - class template, 669
 - class type, variable, 294
 - compound type, 57
 - dependencies
 - member function as friend, 281
 - overloaded templates, 698
 - template friends, 665
 - template instantiation, 657
 - template specializations, 708
 - variadic templates, 702
 - derived class, 600
 - explicit instantiation, 675
 - friend, 269
 - function template, 669
 - instantiation, 713
 - member template, 673
 - template, 669
 - template specialization, 708
 - type alias, 68
 - using, 82, 132
 - access control, 615
 - overloaded inherited functions, 621
 - variable, 45
 - const, 60
 - declarator, 50, 79
 - decltype, 70, 79
 - array return type, 230
 - cbegin, 109, 379
 - cend, 109, 379
 - depends on form, 71
 - for type abbreviation, 88, 106, 129
 - of array, 118
 - of function, 250
 - pointer to function, 249
 - top-level const, 71
 - yields lvalue, 71, 135
 - decrement operators, 147–149
 - default argument, 236, 251
 - adding default arguments, 237
 - and header file, 238
 - constructor, 290
 - default constructor, 291
 - function call, 236
 - function matching, 243
 - initializer, 238
 - static member, 304
 - virtual function, 607
 - default case label, 181, 199
 - default constructor, 263, 306
 - = default, 265
 - = delete, 507
 - default argument, 291
 - Sales_data, 262
 - StrVec, 526
 - synthesized, 263, 306
 - deleted function, 508, 624
 - derived class, 623
 - Token, 850
 - used implicitly

- default initialization, 293
 - value initialization, 293
- default initialization, **43**
 - array, 336
 - built-in type, 43
 - class type, 44
 - string, 44, 84
 - uses default constructor, 293
 - vector, 97
- default template argument, **670**
 - class template, 671
 - compare, 670
 - function template, 670
 - template<>, 671
- default_random_engine, 745, 769
- defaultfloat manipulator, 757
- definition, 79
 - array, 113
 - associative container, 423
 - base class, 594
 - class, 72, 256–267
 - class template, 659
 - member function, 661
 - static member, 667
 - class template partial specialization, 711
 - derived class, 596
 - dynamically allocated object, 459
 - explicit instantiation, **675**
 - function, 577
 - in `if` condition, 175
 - in `while` condition, 183
 - instantiation, 713
 - member function, 256–260
 - multidimensional array, 126
 - namespace, 785
 - can be discontinuous, 786
 - member, 788
 - overloaded operator, 500, 552
 - pair, 426
 - pointer, 52
 - pointer to function, 247
 - pointer to member, 836
 - reference, 51
 - sequential container, 334
 - shared_ptr, 450
 - static member, 302
 - string, 84
 - template specialization, 706–712
 - unique_ptr, 470, 472
 - variable, 41, 45
 - const, 60
 - variable after case label, 182
 - vector, 97
 - weak_ptr, 473
- delegating constructor, **291, 306**
- delete, **460, 460–463, 491**
 - const object, 461
 - execution flow, 820
 - memory leak, 462
 - null pointer, 461
 - pointer, 460
 - runs destructor, 502
- delete [], dynamically allocated array, 478
- deleted function, **507, 549**
- deleter, **469, 491**
 - shared_ptr, 469, 480, 491
 - unique_ptr, 472, 491
- deprecated, **401**
 - auto_ptr, 471
 - binary_function, 579
 - bind1st, 401
 - bind2nd, 401
 - generalized exception specification, 780
 - ptr_fun, 401
 - unary_function, 579
- deque, 372
 - see also* container, container member
 - see also* sequential container
 - [] (subscript), 347
 - at, 348
 - header, 329
 - initialization, 334–337
 - list initialization, 336
 - overview, 327
 - push_back, invalidates iterator, 354
 - push_front, invalidates iterator, 354
 - random-access iterator, 412
 - value initialization, 336
- deref, StrBlobPtr, 475
- derived class, **592, 649**
 - see also* virtual function
 - :: (scope operator) to access base-class member, 607
 - = (assignment), 626
 - access control, 613
 - as base class, 600
 - assigned or copied to base object, 603
 - base-to-derived conversion, not automatic, 602

- constructor, 598
 - initializer list, 598
 - initializes direct base class, 610
 - initializes virtual base, 813
- copy assignment, 626
- copy constructor, 626
- declaration, 600
- default derivation specifier, 616
- definition, 596
- derivation list, **596**, 649
 - access control, 612
- derived object
 - contains base part, 597
 - multiple inheritance, 803
- derived-to-base conversion, 597
 - accessibility, 613
 - key concepts, 604
 - multiple inheritance, 805
- destructor, 627
- direct base class, **600**, 649
- `final`, 600
- friendship not inherited, 615
- indirect base class, **600**, 650
- is user of base class, 614
- member new and delete, 822
- move assignment, 626
- move constructor, 626
- multiple inheritance, 803
- name lookup, 617
- order of destruction, 627
 - multiple inheritance, 805
- order of initialization, 598, 623
 - multiple inheritance, 804
 - virtual base classes, 814
- scope, 617
 - hidden base members, 619
 - inheritance, 617–621
 - multiple inheritance, 807
 - name lookup, 618
 - virtual function, 620
- `static` members, 599
- synthesized
 - copy control members, 623
 - deleted copy control members, 624
- using declaration
 - access control, 615
 - overloaded inherited functions, 621
- virtual function, 596
- derived-to-base conversion, **597**, 649
 - accessible, 613
 - key concepts, 604
 - multiple inheritance, 805
 - not base-to-derived, 602
 - `shared_ptr`, 630
- design
 - access control, 614
 - `Bulk_quote`, 592
 - conversion operator, 581
 - `Disc_quote`, 608
 - equality and relational operators, 562
 - generic programs, 655
 - inheritance, 637
 - Message class, 520
 - namespace, 786
 - overloaded operator, 554–556
 - Query classes, 636–639
 - Quote, 592
 - reference count, 514
 - `StrVec`, 525
- destination sequence, 381, 413
- `destroy`, `allocator`, 482, 528
- destructor, **452**, 491, **501**, 501–503, 549
 - = default, 506
 - called during exception handling, 773
 - calls to virtual function, 627
 - container elements, 502
 - derived class, 627
 - doesn't delete pointer members, 503
 - explicit call to, 824
 - `HasPtr`
 - reference counted, 515
 - valuelike, 512
 - local variables, 502
 - Message, 522
 - not deleted function, 508
 - not private, 509
 - order of destruction, 502
 - derived class, 627
 - multiple inheritance, 805
 - virtual base classes, 815
 - reference count, 514
 - rule of three/five, **505**
 - virtual destructor, exception, 622
 - run by `delete`, 502
 - `shared_ptr`, 453
 - should not throw exception, 774
 - `StrVec`, 528
 - synthesized, **503**, 550
 - deleted function, 508, 624
 - derived class, 623
 - multiple inheritance, 805
 - Token, 850

- valuelike class, 512
 - virtual function, 622
 - virtual in base class, 622
- development environment, integrated, 3
- `difference_type`, **112**
 - `vector`, **112**
 - container, 131, 332
 - string, **112**
- direct base class, **600**
- direct initialization, **84**, 131
 - emplace members use, 345
- `Disc_quote`
 - abstract base class, 610
 - class definition, 609
 - constructor, 609
 - design, 608
- discriminant, **849**, 862
 - Token, 850
- distribution types
 - `bernoulli_distribution`, 752
 - default template argument, 750
 - `normal_distribution`, 751
 - random-number library, **745**
 - `uniform_int_distribution`, 746
 - `uniform_real_distribution`, 750
- `divides<T>`, 575
- division rounding, 141
- do while statement, **189**, 200
- `domain_error`, 197
- double, 33
 - literal (`numEnum` or `numenum`), 38
 - output format, 755
 - output notation, 757
- dynamic binding, 593, 650
 - requirements for, 603
 - static vs. dynamic type, 605
- dynamic type, **601**, 650
- `dynamic_cast`, **163**, 825, **825**, 862
 - `bad_cast`, 826
 - to pointer, 825
 - to reference, 826
- dynamically allocated, **450**, 491
 - array, **476**, 476–484
 - allocator, 481
 - can't use `begin` and `end`, 477
 - can't use `range` for statement, 477
 - `delete []`, 478
 - empty array, 478
 - `new []`, 477
 - returns pointer to an element, 477
 - `shared_ptr`, 480

- `unique_ptr`, 479
- `delete` runs destructor, 502
- lifetime, 450
- new runs constructor, 458
- object, 458–463
 - const object, 460
 - `delete`, 460
 - factory program, 461
 - initialization, 459
 - `make_shared`, 451
 - new, 458
 - shared objects, 455, 486
 - `shared_ptr`, 464
 - `unique_ptr`, 470

E

- echo command, 4
- ECMAScript, 730, 739
 - regular expression library, 730
- edit-compile-debug, **16**, 26
 - errors at link time, 657
- element type constraints, container, 329, 341
- `elimDups` program, 383–391
- ellipsis, parameter, 222
- else, *see* if statement
- emplace
 - associative container, 432
 - `priority_queue`, 371
 - queue, 371
 - sequential container, **345**
 - stack, 371
- `emplace_back`
 - sequential container, **345**
 - `StrVec`, 704
- `emplace_front`, sequential container, **345**
- empty
 - container, **87**, 102, 131, 340
 - `priority_queue`, 371
 - queue, 371
 - stack, 371
- encapsulation, **254**, 306
 - benefits of, 270
- end
 - associative container, 430
 - container, **106**, 131, 333, 373
 - function, **118**, 131
 - multidimensional array, 129
 - `StrBlob`, 475
 - `StrVec`, 526

- end-of-file, **15**, 26, 762
 - character, 15
- Endangered, 803
- endl, **7**
 - manipulator, 314
- ends, manipulator, 315
- engine, random-number library, **745**, 770
 - default_random_engine, 745
 - max, min, 747
 - retain state, 747
 - seed, 748, 770
- enum, unscoped enumeration, 832
- enum class, scoped enumeration, 832
- enumeration, **832**, 863
 - as union discriminant, 850
 - function matching, 835
 - scoped, 832, 864
 - unscoped, 832, 864
 - conversion to integer, 834
 - unnamed, 832
- enumerator, **832**, 863
 - constant expression, 833
 - conversion to integer, 834
- eof, 313
- eofbit, 312
- equal, 380, 872
- equal virtual function, 829
- equal_range
 - algorithm, 722, 873
 - associative container, 439
- equal_to<T>, 575
- equality operators, 141
 - arithmetic conversion, 144
 - container adaptor, 370
 - container member, 340
 - iterator, 106
 - overloaded operator, 561
 - pointer, 120
 - Sales_data, 561
 - string, 88
 - vector, 102
- erase
 - associative container, 434
 - changes container size, 385
 - invalidates iterator, 349
 - sequential container, 349
 - string, 362
- error, standard, **6**
- error_type, 732
- error_msg program, 221
- ERRORLEVEL, 4
- escape sequence, **39**, 79
 - hexadecimal (`\Xnnn`), 39
 - octal (`\nnn`), **39**
- eval function
 - AndQuery, 646
 - NotQuery, 647
 - OrQuery, 645
- exception
 - class, **193**, 200
 - class hierarchy, 783
 - deriving from, 782
 - Sales_data, 783
 - header, 197
 - initialization, 197
 - what, 195, 782
- exception handling, 193–198, **772**, 817
 - see also* throw
 - see also* catch
 - exception declaration, 195, 775, 816
 - and inheritance, 775
 - must be complete type, 775
 - exception in destructor, 773
 - exception object, **774**, 817
 - finding a catch, 776
 - function try block, **778**, 817
 - handler, *see* catch
 - local variables destroyed, 773
 - noexcept specification, 535, **779**, 817
 - nonthrowing function, **779**, 818
 - safe resource allocation, 467
 - stack unwinding, **773**, 818
 - terminate function, **196**, 200
 - try block, 194, **773**
 - uncaught exception, 773
 - unhandled exception, 196
 - exception object, **774**, 817
 - catch, 775
 - conversion to pointer, 774
 - initializes catch parameter, 775
 - pointer to local object, 774
 - rethrow, 777
- exception safety, 196, 200
 - smart pointers, 467
- exception specification
 - argument, 780
 - generalized, deprecated, 780
 - noexcept, **779**
 - nonthrowing, **779**
 - pointer to function, 779, 781
 - throw(), 780
 - violation, 779

- virtual function, 781
- executable file, 5, 251
- execution flow
 - () (call operator), 203
 - delete, 820
 - for statement, 186
 - new, 820
 - switch statement, 180
 - throw, 196, 773
- EXIT_FAILURE, 227
- EXIT_SUCCESS, 227
- expansion
 - forward, 705
 - parameter pack, 702, 702–704, 714
 - function parameter pack, 703
 - template parameter pack, 703
 - pattern, 702
- explicit
 - constructor, 296, 306
 - copy initialization, 498
 - conversion operator, 582, 590
 - conversion to bool, 583
- explicit call to
 - destructor, 824
 - overloaded operator, 553
 - postfix operators, 568
- explicit instantiation, 675, 713
- explicit template argument, 660, 713
 - class template, 660
 - forward, 694
 - function template, 682
 - function pointer, 686
 - template argument deduction, 682
- exporting C++ to C, 860
- expression, 7, 27, 134, 168
 - callable, *see* callable object
 - constant, 65, 78
 - lambda, *see* lambda expression
 - operand conversion, 159
 - order of evaluation, 137
 - parenthesized, 136
 - precedence and associativity, 136–137
 - regular, *see* regular expression
- expression statement, 172, 200
- extension, compiler, 114, 131
- extern
 - and const variables, 60
 - explicit instantiation, 675
 - variable declaration, 45
- extern 'C', *see* linkage directive

F

- fact program, 202
- factorial program, 227
- factory program
 - new, 461
 - shared_ptr, 453
- fail, 313
- failbit, 312
- failure, new, 460
- file, source, 4
- file extension, program, 730
 - version 2, 738
- file marker, stream, 765
- file mode, 319, 324
- file redirection, 22
- file static, 792, 817
- file stream, *see* fstream
- fill, 380, 874
- fill_n, 381, 874
- final specifier, 600
 - class, 600
 - virtual function, 607
- find
 - algorithm, 376, 871
 - associative container, 437, 438
 - string, 364
- find last word program, 408
- find_char program, 211
- find_first_of, 872
- find_first_not_of, string, 365
- find_first_of, 872
 - string, 365
- find_if, 388, 397, 414, 871
- find_if_not, 871
- find_if_not_of, 871
- find_last_not_of, string, 366
- find_last_of, string, 366
- findBook, program, 721
- fixed manipulator, 757
- flip
 - bitset, 727
 - program, 694
- flip1, program, 692
- flip2, program, 693
- float, 33
 - literal (*numF* or *numf*), 41
- floating-point, 32
 - conversion, 35
 - literal, 38
 - output format, 755

- output notation, 757
- flow of control, 11, **172**, 200
- flush, manipulator, 315
- Folder, *see* Message
- for statement, **13**, **27**, **185**, 185–187, 200
 - condition, 13
 - execution flow, 186
 - for header, 185
 - range, **91**, **187**, 187–189, 200
 - can't add elements, 101, 188
 - multidimensional array, 128
- for_each, 391, 872
- format state, stream, 753
- formatted IO, **761**, 769
- forward, **694**
 - argument-dependent lookup, 798
 - explicit template argument, 694
 - pack expansion, 705
 - passes argument type unchanged, 694, 705
 - usage pattern, 706
- forward declaration, class, **279**, 306
- forward iterator, **411**, 417
- forward_list
 - see also* container
 - see also* sequential container
 - before_begin, 351
 - forward iterator, 411
 - header, 329
 - initialization, 334–337
 - list initialization, 336
 - merge, 415
 - overview, 327
 - remove, 415
 - remove_if, 415
 - reverse, 415
 - splice_after, 416
 - unique, 415
 - value initialization, 336
- forwarding, 692–694
 - passes argument type unchanged, 694
 - preserving type information, 692
 - rvalue reference parameters, 693, 705
 - typical implementation, 706
 - variadic template, 704
- free, StrVec, 528
- free library function, **823**, 863
- free store, **450**, 491
- friend, **269**, 306
 - class, 280
 - class template type parameter, 666
 - declaration, **269**
 - declaration dependencies
 - member function as friend, 281
 - template friends, 665
 - function, 269
 - inheritance, 614
 - member function, 280, 281
 - overloaded function, 281
 - scope, 270, 281
 - namespace, 799
 - template as, 664
- front
 - queue, 371
 - sequential container, 346
 - StrBlob, 457
- front_inserter, **402**, 417
 - compared to inserter, 402
 - requires push_front, 402
- fstream, 316–320
 - close, 318
 - file marker, 765
 - file mode, **319**
 - header, 310, 316
 - initialization, 317
 - off_type, 766
 - open, 318
 - pos_type, 766
 - random access, 765
 - random IO program, 766
 - seek and tell, 763–768
- function, **2**, **27**, **202**, 251
 - see also* return type
 - see also* return value
 - block, 204
 - body, **2**, **27**, **202**, 251
 - callable object, 388
 - candidate, 251
 - candidate function, **243**
 - constexpr, **239**, 251
 - nonconstant return value, 239
 - declaration, 206
 - declaration and header file, 207
 - decltype returns function type, 250
 - default argument, **236**, 251
 - adding default arguments, 237
 - and header file, 238
 - initializer, 238
 - deleted, **507**, 549
 - function matching, 508
 - exception specification
 - noexcept, 779

- throw(), 780
 - friend, 269
 - function to pointer conversion, 248
 - inline, **238**, 252
 - and header, 240
 - linkage directive, 859
 - member, *see* member function
 - name, 2, 27
 - nonthrowing, **779**, 818
 - overloaded
 - compared to redeclaration, 231
 - friend declaration, 281
 - scope, 234
 - parameter, *see* parameter
 - parameter list, 2, 27, **202**, 204
 - prototype, **207**, 251
 - recursive, **227**
 - variadic template, 701
 - scope, 204
 - viable, 252
 - viable function, **243**
 - virtual, *see* virtual function
- function, **577**, 576–579, 590
- and pointer to member, 842
 - definition, 577
 - desk calculator, 577
- function call
- ambiguous, **234**, 245, 251
 - default argument, 236
 - execution flow, 203
 - overhead, 238
 - through pointer to function, 248
 - through pointer to member, 839
 - to overloaded operator, 553
 - to overloaded postfix operator, 568
- function matching, **233**, 251
- = delete, 508
 - argument, conversion, 234
 - candidate function, **243**
 - overloaded operator, 587
 - const arguments, 246
 - conversion, class type, 583–587
 - conversion operator, 585, 586
 - conversion rank, 245
 - class type conversions, 586
 - default argument, 243
 - enumeration, 835
 - function template, 694–699
 - specialization, 708
 - integral promotions, 246
 - member function, 273
 - multiple parameters, 244
 - namespace, 800
 - overloaded operator, 587–589
 - prefers more specialized function, 695
 - rvalue reference, 539
 - variadic template, 702
 - viable function, **243**
- function object, **571**, 590
 - argument to algorithms, 572
 - arithmetic operators, 574
 - is callable object, 571
- function parameter, *see* parameter
- function parameter pack, **700**
 - expansion, 703
 - pattern, 704
- function pointer, 247–250
 - callable object, 388
 - definition, 247
 - exception specification, 779, 781
 - function template instantiation, 686
 - overloaded function, 248
 - parameter, 249
 - return type, 204, 249
 - using decltype, 250
 - template argument deduction, 686
 - type alias declaration, 249
 - typedef, 249
- function table, 577, **577**, 590, 840
- function template, **652**, 713
 - see also* template parameter
 - see also* template argument deduction
 - see also* instantiation
 - argument conversion, 680
 - array function parameters, 654
 - candidate function, 695
 - compare, 652
 - string literal version, 654
 - constexpr, 655
 - declaration, 669
 - default template argument, 670
 - error detection, 657
 - explicit instantiation, **675**, 675–676
 - explicit template argument, **682**
 - compare, 683
 - function matching, 694–699
 - inline function, 655
 - nontype parameter, 654
 - overloaded function, 694–699
 - parameter pack, 713
 - specialization, 707, 714
 - compare, 706

- function matching, 708
- is an instantiation, 708
- namespace, 788
- scope, 708
- trailing return type, 684
- type-dependent code, 658
- function try block, 778, 817
- functional header, 397, 399, 400, 575, 577, 843

G

- g++, 5
- gcount, *istream*, 763
- generate, 874
- generate_n, 874
- generic algorithms, *see* algorithms
- generic programming, 108
 - type-independent code, 655
- get
 - istream*, 761
 - multi-byte version, *istream*, 762
 - returns int, *istream*, 762, 764
- get<n>, 719, 770
- getline, 87, 131
 - istream*, 762
 - istringstream*, 321
 - TextQuery* constructor, 488
- global function
 - operator delete, 863
 - operator new, 863
- global namespace, 789, 817
 - :: (scope operator), 789, 818
- global scope, 48, 80
- global variable, lifetime, 204
- GNU compiler, 5
- good, 313
- goto statement, 192, 200
- grade clusters program, 103
- greater<T>, 575
- greater_equal<T>, 575

H

- .h file header, 19
- handler, *see* catch
- has-a relationship, 637
- hash<key_type>, 445, 447
 - override, 446
 - specialization, 709, 788
 - compatible with == (equality), 710

- hash function, 443, 447
- HasPtr*
 - reference counted, 514–516
 - copy assignment, 516
 - destructor, 515
 - valuelike, 512
 - copy assignment, 512
 - move assignment, 540
 - move constructor, 540
 - swap, 516
- header, 6, 27
 - iostream*, 27
 - C library, 91
 - const and *constexpr*, 76
 - default argument, 238
 - function declaration, 207
 - .h file, 19
 - #include, 6, 21
 - inline function, 240
 - inline member function definition, 273
 - namespace members, 786
 - standard, 6
 - table of library names, 866
 - template definition, 656
 - template specialization, 708
 - user-defined, 21, 76–77, 207, 240
 - using declaration, 83
 - Sales_data.h*, 76
 - Sales_item.h*, 19
 - algorithm, 376
 - array, 329
 - bitset, 723
 - cassert, 241
 - cctype, 91
 - cmath, 751, 757
 - cstddef, 116, 120
 - cstdio, 762
 - cstdlib, 54, 227, 778, 823
 - cstring, 122
 - ctime, 749
 - deque, 329
 - exception, 197
 - forward_list, 329
 - fstream*, 310, 316
 - functional, 397, 399, 400, 575, 577, 843
 - initializer_list, 220
 - iomanip*, 756
 - iostream*, 6, 310
 - iterator, 119, 382, 401

- list, 329
 - map, 420
 - memory, 450, 451, 481, 483
 - new, 197, 460, 478, 821
 - numeric, 376, 881
 - queue, 371
 - random, 745
 - regex, 728
 - set, 420
 - sstream, 310, 321
 - stack, 370
 - stdexcept, 194, 197
 - string, 74, 76, 84
 - tuple, 718
 - type_info, 197
 - type_traits, 684
 - typeid, 826, 827, 831
 - unordered_map, 420
 - unordered_set, 420
 - utility, 426, 530, 533, 694
 - vector, 96, 329
 - header guard, 77, 79
 - preprocessor, 77
 - heap, 450, 491
 - hex, manipulator, 754
 - hexadecimal
 - escape sequence (`\Xnnn`), 39
 - literal (`0Xnum` or `0xnum`), 38
 - hexfloat manipulator, 757
 - high-order bits, 723, 770
- ## I
- i before e, program, 729
 - version 2, 734
 - IDE, 3
 - identifier, 46, 79
 - reserved, 46
 - `_if` algorithms, 414
 - `if` statement, 17, 27, 175, 175–178, 200
 - compared to `switch`, 178
 - condition, 18, 175
 - dangling `else`, 177
 - `else` branch, 18, 175, 200
 - `ifstream`, 311, 316–320, 324
 - see also* `istream`
 - close, 318
 - file marker, 765
 - file mode, 319
 - initialization, 317
 - `off_type`, 766
 - open, 318
 - `pos_type`, 766
 - random access, 765
 - random IO program, 766
 - seek and tell, 763–768
 - ignore, `istream`, 763
 - implementation, 254, 254, 306
 - `in` (file mode), 319
 - in scope, 49, 79
 - in-class initializer, 73, 73, 79, 263, 265, 274
 - `#include`
 - standard header, 6, 21
 - user-defined header, 21
 - `includes`, 880
 - incomplete type, 279, 306
 - can't be base class, 600
 - not in exception declaration, 775
 - restrictions on use, 279
 - `incr`, `StrBlobPtr`, 475
 - increment operators, 147–149
 - indentation, 19, 177
 - index, 94, 131
 - see also* [] (subscript)
 - indirect base class, 600, 650
 - inferred return type, lambda expression, 396
 - inheritance, 650
 - and container, 630
 - conversions, 604
 - copy control, 623–629
 - friend, 614
 - hierarchy, 592, 600
 - interface class, 637
 - IO classes, 311, 324
 - name collisions, 618
 - `private`, 612, 650
 - `protected`, 612, 650
 - `public`, 612, 650
 - vs. composition, 637
 - inherited, constructor, 628
 - initialization
 - aggregate class, 298
 - array, 114
 - associative container, 423, 424
 - `bitset`, 723–725
 - C-style string, 122
 - class type objects, 73, 262
 - `const`
 - static data member, 302
 - class type object, 262
 - data member, 289

- object, 59
 - copy, **84**, 131, **497**, 497–499, 549
 - default, **43**, 293
 - direct, **84**, 131
 - dynamically allocated object, 459
 - exception, 197
 - istream_iterator, 405
 - list, *see* list initialization
 - lvalue reference, 532
 - multidimensional array, 126
 - new [], 477
 - ostream_iterator, 405
 - pair, 426
 - parameter, 203, 208
 - pointer, 52–54
 - to const, 62
 - queue, 369
 - reference, 51
 - data member, 289
 - to const, 61
 - return value, 224
 - rvalue reference, 532
 - sequential container, 334–337
 - shared_ptr, 464
 - stack, 369
 - string, 84–85, 360–361
 - string streams, 321
 - tuple, 718
 - unique_ptr, 470
 - value, **98**, 132, 293
 - variable, 42, 43, 79
 - vector, 97–101
 - vs. assignment, 42, 288
 - weak_ptr, 473
- initializer_list, **220**, 220–222, 252
 - = (assignment), 563
 - constructor, 662
 - header, 220
- inline function, **238**, 252
 - and header, 240
 - function template, 655
 - member function, 257, 273
 - and header, 273
- inline namespace, **790**, 817
- inner scope, **48**, 79
- inner_product, 882
- inplace_merge, 875
- input, standard, **6**
- input iterator, **411**, 418
- insert
 - associative container, 432
 - multiple key container, 433
 - sequential container, 343
 - string, 362
- insert iterator, **382**, **401**, **402**, 418
 - back_inserter, 402
 - front_inserter, 402
 - inserter, 402
- inserter, 402, 418
 - compared to front_inserter, 402
- instantiation, **96**, 131, **653**, 656, 713
 - Blob, 660
 - class template, 660
 - member function, 663
 - declaration, 713
 - definition, 713
 - error detection, 657
 - explicit, 675–676
 - function template from function pointer, 686
 - member template, 674
 - static member, 667
- int, 33
 - literal, 38
- integral
 - constant expression, **65**
 - promotion, 134, **160**, 169
 - function matching, 246
 - type, **32**, 79
- integrated development environment, 3
- interface, **254**, 306
- internal, manipulator, 759
- interval, left-inclusive, 373
- invalid pointer, 52
- invalid_argument, 197
- invalidated iterator
 - and container operations, 354
 - undefined behavior, 353
- invalidates iterator
 - assign, 338
 - erase, 349
 - resize, 352
- IO
 - formatted, **761**, 769
 - unformatted, **761**, 770
- IO classes
 - condition state, **312**, 324
 - inheritance, 324
- IO stream, *see* stream
- iomanip header, 756
- iostate, 312
 - machine-dependent, 313

- iostream, 5
 - file marker, 765
 - header, 6, 27, 310
 - off_type, 766
 - pos_type, 766
 - random access, 765
 - random IO program, 766
 - seek and tell, 763–768
 - virtual base class, 810
- iota, 882
- is-a relationship, 637
- is_partitioned, 876
- is_permutation, 879
- is_sorted, 877
- is_sorted_until, 877
- isalnum, 92
- isalpha, 92
- isbn
 - Sales_data, 257
 - Sales_item, 23
- ISBN, 2
- isbn_mismatch, 783
- isctrl, 92
- isdigit, 92
- isgraph, 92
- islower, 92
- isprint, 92
- ispunct, 92
- isShorter program, 211
- isspace, 92
- istream, 5, 27, 311
 - see also* manipulator
 - >> (input operator), 8
 - precedence and associativity, 155
 - as condition, 15
 - chained input, 8
 - condition state, 312
 - conversion, 162
 - explicit conversion to bool, 583
 - file marker, 765
 - flushing input buffer, 314
 - format state, 753
 - gcount, 763
 - get, 761
 - multi-byte version, 762
 - returns int, 762, 764
 - getline, 87, 321, 762
 - ignore, 763
 - no copy or assign, 311
 - off_type, 766
 - peek, 761
 - pos_type, 766
 - put, 761
 - putback, 761
 - random access, 765
 - random IO program, 766
 - read, 763
 - seek and tell, 763–768
 - unformatted IO, 761
 - multi-byte, 763
 - single-byte, 761
 - unget, 761
- istream_iterator, 403, 418
 - >> (input operator), 403
 - algorithms, 404
 - initialization, 405
 - off-the-end iterator, 403
 - operations, 404
 - type requirements, 406
- istringstream, 311, 321, 321–323
 - see also* istream
 - word per line processing, 442
 - file marker, 765
 - getline, 321
 - initialization, 321
 - off_type, 766
 - phone number program, 321
 - pos_type, 766
 - random access, 765
 - random IO program, 766
 - seek and tell, 763–768
 - TextQuery constructor, 488
- isupper, 92
- isxdigit, 92
- iter_swap, 875
- iterator, 106, 106–112, 131
 - ++ (increment), 107, 132
 - (decrement), 107
 - * (dereference), 107
 - += (compound assignment), 111
 - + (addition), 111
 - (subtraction), 111
 - == (equality), 106, 107
 - != (inequality), 106, 107
 - algorithm type independence, 377
 - arithmetic, 111, 131
 - compared to reverse iterator, 409
 - destination, 413
 - insert, 401, 418
 - move, 401, 418, 543
 - uninitialized_copy, 543
 - off-the-beginning

- before_begin, 351
- forward_list, 351
- off-the-end, **106**, 132, 373
 - istream_iterator, 403
- parameter, 216
- regex, 734
- relational operators, 111
- reverse, **401**, 407–409, 418
- stream, **401**, 403–406, 418
- used as destination, 382

iterator

- compared to reverse_iterator, 408
- container, **108**, 332
- header, 119, 382, 401
- set iterators are const, 429

iterator category, **410**, 410–412, 418

- bidirectional iterator, **412**, 417
- forward iterator, **411**, 417
- input iterator, **411**, 418
- output iterator, **411**, 418
- random-access iterator, **412**, 418

iterator range, **331**, 331–332, 373

- algorithms, 376
- as initializer of container, 335
- container erase member, 349
- container insert member, 344
- left-inclusive, **331**
- off-the-end, 331

K

key concept

- algorithms
 - and containers, 378
 - iterator arguments, 381
- class user, 255
- classes define behavior, 20
- defining an assignment operator, 512
- dynamic binding in C++, 605
- elements are copies, 342
- encapsulation, 270
- headers for template code, 657
- indentation, 19
- inheritance and conversions, 604
- isA and hasA relationships, 637
- name lookup and inheritance, 619
- protected members, 614
- refactoring, 611
- respecting base class interface, 599
- specialization declarations, 708

- type checking, 46
- types define behavior, 3
- use concise expressions, 149

key_type

- associative container, 428, 447
- requirements
 - ordered container, 425
 - unordered container, 445

keyword table, 47

Koenig lookup, 797

L

L'c' (wchar_t literal), 38

label

- case, **179**, 199
- statement, 192

labeled statement, **192**, 200

lambda expression, **388**, 418

- arguments, 389
- biggies program, 391
 - reference capture, 393
- capture list, **388**, 417
 - capture by reference, 393
 - capture by value, 390, 392
 - implicit capture, 394
- inferred return type, 389, 396
- mutable, 395
- parameters, 389
- passed to find_if, 390
- passed to stable_sort, 389
- synthesized class type, 572–574
- trailing return type, 396

left, manipulator, 758

left-inclusive interval, **331**, 373

length_error, 197

less<T>, 575

less_equal<T>, 575

letter grade, program, 175

lexicographical_compare, 881

library function objects, 574

- as arguments to algorithms, 575

library names to header table, 866

library type, 5, 27, 82

lifetime, **204**, 252

- compared to scope, 204
- dynamically allocated objects, 450, 461
- global variable, 204
- local variable, 204
- parameter, 205

linkage directive, **858**, 863

- C++ to C, 860
- compound, 858
- overloaded function, 860
- parameter or return type, 859
- pointer to function, 859
- return type, 859
- single, 858
- linker, **208**, 252
 - template errors at link time, 657
- list, 373
 - see also* container
 - see also* sequential container
 - bidirectional iterator, 412
 - header, 329
 - initialization, 334–337
 - list initialization, 336
 - merge, 415
 - overview, 327
 - remove, 415
 - remove_if, 415
 - reverse, 415
 - splICE, 416
 - unique, 415
 - value initialization, 336
- list initialization, **43**, 79
 - = (assignment), 145
 - array, 337
 - associative container, 423
 - container, 336
 - dynamically allocated, object, 459
 - pair, 427, 431, 527
 - preferred, 99
 - prevents narrowing, 43
 - return value, **226**, 427, 527
 - sequential container, 336
 - vector, 98
- literal, **38**, 38–41, 79
 - bool, 41
 - in condition, 143
 - char, 39
 - decimal, 38
 - double (*numEnum* or *numenum*), 38
 - float (*numF* or *numf*), 41
 - floating-point, 38
 - hexadecimal (*0Xnum* or *0xnum*), 38
 - int, 38
 - long (*numL* or *numl*), 38
 - long double (*ddd.dddL* or *ddd.dddl*), 41
 - long long (*numLL* or *numll*), 38
 - octal (*0num*), 38
 - string, 7, 28, 39
 - unsigned (*numU* or *numu*), 41
 - wchar_t, 40
- literal type, 66
 - class type, 299
- local class, **852**, 863
 - access control, 853
 - name lookup, 853
 - nested class in, 854
 - restrictions, 852
- local scope, *see* block scope
- local static object, **205**, 252
- local variable, **204**, 252
 - destroyed during exception handling, 467, 773
 - destructor, 502
 - lifetime, 204
 - pointer, return value, 225
 - reference, return value, 225
 - return statement, 224
- lock, weak_ptr, 473
- logic_error, 197
- logical operators, 141, 142
 - condition, 141
 - function object, 574
- logical_and<T>, 575
- logical_not<T>, 575
- logical_or<T>, 575
- long, 33
 - literal (*numL* or *numl*), 38
- long double, 33
 - literal (*ddd.dddL* or *ddd.dddl*), 41
- long long, **33**
 - literal (*numLL* or *numll*), 38
- lookup, name, *see* name lookup
- low-level const, **64**, 79
 - argument and parameter, 213
 - conversion from, 163
 - conversion to, 162
 - overloaded function, 232
 - template argument deduction, 693
- low-order bits, **723**, 770
- lower_bound
 - algorithm, 873
 - ordered container, 438
- lround, 751
- lvalue, **135**, 169
 - cast to rvalue reference, 691
 - copy initialization, uses copy constructor, 539
 - decltype, 135

reference collapsing rule, 688
 result
 -> (arrow operator), 150
 ++ (increment) prefix, 148
 -- (decrement) prefix, 148
 * (dereference), 135
 [] (subscript), 135
 = (assignment), 145
 , (comma operator), 158
 ?: (conditional operator), 151
 cast, 163
 decltype, 71
 function reference return type, 226
 variable, 533
 lvalue reference, *see also* reference, 532, 549
 collapsing rule, 688
 compared to rvalue reference, 533
 function matching, 539
 initialization, 532
 member function, 546
 overloaded, 547
 move, 533
 template argument deduction, 687

M

machine-dependent
 bit-field layout, 854
 char representation, 34
 end-of-file character, 15
 enum representation, 835
 iostate, 313
 linkage directive language, 861
 nonzero return from main, 227
 random IO, 763
 reinterpret_cast, 164
 return from exception what, 198
 signed out-of-range value, 35
 signed types and bitwise operators,
 153
 size of arithmetic types, 32
 terminate function, 196
 type_info members, 831
 vector, memory management, 355
 volatile implementation, 856
 main, 2, 27
 not recursive, 228
 parameters, 218
 return type, 2
 return value, 2–4, 227
 make_move_iterator, 543

make_pair, 428
 make_plural program, 224
 make_shared, 451
 make_tuple, 718
 malloc library function, 823, 863
 manipulator, 7, 27, 753, 770
 boolalpha, 754
 change format state, 753
 dec, 754
 defaultfloat, 757
 endl, 314
 ends, 315
 fixed, 757
 flush, 315
 hex, 754
 hexfloat, 757
 internal, 759
 left, 758
 noboolalpha, 754
 noshowbase, 755
 noshowpoint, 758
 noskipws, 760
 nouppercase, 755
 oct, 754
 right, 758
 scientific, 757
 setfill, 759
 setprecision, 756
 setw, 758
 showbase, 755
 showpoint, 758
 skipws, 760
 unitbuf, 315
 uppercase, 755
 map, 420, 447
 see also ordered container
 * (dereference), 429
 [] (subscript), 435, 448
 adds element, 435
 at, 435
 definition, 423
 header, 420
 insert, 431
 key_type requirements, 425
 list initialization, 423
 lower_bound, 438
 map, initialization, 424
 TextQuery class, 485
 upper_bound, 438
 word_count program, 421

- mapped_type, associative container, 428, 448
- match
 - best, 251
 - no, 252
- match_flag_type, regex_constants, 743
- max, 881
- max_element, 881
- mem_fn, **843**, 863
 - generates callable, 843
- member, *see* class data member
- member access operators, 150
- member function, **23**, 27, 306
 - as friend, 281
 - base member hidden by derived, 619
 - class template
 - defined outside class body, 661
 - instantiation, 663
 - const, **258**, 305
 - () (call operator), 573
 - reference return, 276
 - declared but not defined, 509
 - defined outside class, 259
 - definition, 256–260
 - :: (scope operator), 259
 - name lookup, 285
 - parameter list, 282
 - return type, 283
 - explicitly inline, 273
 - function matching, 273
 - implicit this parameter, 257
 - implicitly inline, 257
 - inline and header, 273
 - move-enabled, **545**
 - name lookup, 287
 - overloaded, 273
 - on const, 276
 - on lvalue or rvalue reference, 547
 - overloaded operator, 500, 552
 - reference qualified, **546**, 550
 - returning *this, 260, 275
 - rvalue reference parameters, 544
 - scope, 282
 - template, *see* member template
- member template, **672**, 714
 - Blob, iterator constructor, 673
 - DebugDelete, 673
 - declaration, 673
 - defined outside class body, 674
 - instantiation, 674
 - template parameters, 673, 674
- memberwise
 - copy assignment, 500
 - copy constructor, 497
 - copy control, 267, 550
 - destruction is implicit, 503
 - move assignment, 538
 - move constructor, 538
- memory
 - see also* dynamically allocated
 - exhaustion, 460
 - leak, 462
- memory header, 450, 451, 481, 483
- merge, 874
 - list and forward_list, 415
- Message, 519–524
 - add_to_Folder, 522
 - class definition, 521
 - copy assignment, 523
 - copy constructor, 522
 - design, 520
 - destructor, 522
 - move assignment, 542
 - move constructor, 542
 - move_Folders, 542
 - remove_from_Folders, 523
- method, *see* member function
- Microsoft compiler, 5
- min, 881
- min_element, 881
- minmax, 881
- minus<T>, 575
- mismatch, 872
- mode, file, 324
- modulus<T>, 575
- move, **530**, **533**, 874
 - argument-dependent lookup, 798
 - binds rvalue reference to lvalue, 533
 - explained, 690–692
 - inherently dangerous, 544
 - Message, move operations, 541
 - moved from object has unspecified value, 533
 - reference collapsing rule, 691
 - StrVec reallocate, 530
 - remove_reference, 691
- move assignment, **536**, 550
 - copy and swap, 540
 - derived class, 626
 - HasPtr, valuelike, 540
 - memberwise, 538

Message, 542
 moved-from object destructible, 537
 noexcept, 535
 rule of three/five, virtual destructor
 exception, 622
 self-assignment, 537
 StrVec, 536
 synthesized
 deleted function, 538, 624
 derived class, 623
 multiple inheritance, 805
 sometimes omitted, 538
 move constructor, **529, 534**, 534–536, 550
 and copy initialization, 541
 derived class, 626
 HasPtr, valuelike, 540
 memberwise, 538
 Message, 542
 moved-from object destructible, 534,
 537
 noexcept, 535
 rule of three/five, virtual destructor
 exception, 622
 string, 529
 StrVec, 535
 synthesized
 deleted function, 624
 derived class, 623
 multiple inheritance, 805
 sometimes omitted, 538
 move iterator, 401, 418, **543**, 550
 make_move_iterator, 543
 StrVec, reallocate, 543
 uninitialized_copy, 543
 move operations, 531–548
 function matching, 539
 move, 533
 noexcept, 535
 rvalue references, 532
 valid but unspecified, 537
 move_backward, 875
 move_Folders, Message, 542
 multidimensional array, 125–130
 [] (subscript), 127
 argument and parameter, 218
 begin, 129
 conversion to pointer, 128
 definition, 126
 end, 129
 initialization, 126
 pointer, 128

 range for statement and, 128
 multimap, 448
 see also ordered container
 * (dereference), 429
 definition, 423
 has no subscript operator, 435
 insert, 431, 433
 key_type requirements, 425
 list initialization, 423
 lower_bound, 438
 map, initialization, 424
 upper_bound, 438
 multiple inheritance, **802, 817**
 see also virtual base class
 = (assignment), 805
 ambiguous conversion, 806
 ambiguous names, 808
 avoiding ambiguities, 809
 class derivation list, 803
 conversion, 805
 copy control, 805
 name lookup, 807
 object composition, 803
 order of initialization, 804
 scope, 807
 virtual function, 807
 multiplies<T>, 575
 multiset, 448
 see also ordered container
 insert, 433
 iterator, 429
 key_type requirements, 425
 list initialization, 423
 lower_bound, 438
 override comparison
 Basket class, 631
 using compareIsbn, 426
 upper_bound, 438
 used in Basket, 632
 mutable
 data member, **274**
 lambda expression, 395

N

\n (newline character), 39
 name lookup, **283, 306**
 : (scope operator), overrides, 286
 argument-dependent lookup, 797
 before type checking, 619
 multiple inheritance, 809

- block scope, 48
- class, 284
- class member
 - declaration, 284
 - definition, 285, 287
 - function, 284
- depends on static type, 617, 619
 - multiple inheritance, 806
- derived class, 617
 - name collisions, 618
- local class, 853
- multiple inheritance, 807
 - ambiguous names, 808
- namespace, 796
- nested class, 846
- overloaded virtual functions, 621
- templates, 657
- type checking, 235
- virtual base class, 812
- named cast, **162**
 - `const_cast`, 163, **163**
 - `dynamic_cast`, 163, **825**
 - `reinterpret_cast`, **163**, 164
 - `static_cast`, 163, **163**
- namespace, 7, 27, **785**, 817
 - alias, **792**, 817
 - argument-dependent lookup, 797
 - candidate function, 800
 - `cplusplus_primer`, 787
 - definition, 785
 - design, 786
 - discontiguous definition, 786
 - friend declaration scope, 799
 - function matching, 800
 - global, **789**, 817
 - inline, **790**, 817
 - member, 786
 - member definition, 788
 - outside namespace, 788
 - name lookup, 796
 - nested, 789
 - overloaded function, 800
 - placeholders, 399
 - scope, 785–790
 - `std`, 7
 - template specialization, 709, 788
 - unnamed, **791**, 818
 - local to file, 791
 - replace file `static`, 792
- namespace pollution, **785**, 817
- narrowing conversion, 43
- NDEBUG, 241
- `negate<T>`, 575
- nested class, **843**, 863
 - access control, 844
 - class defined outside enclosing class, 845
 - constructor, `QueryResult`, 845
 - in local class, 854
 - member defined outside class body, 845
 - name lookup, 846
 - `QueryResult`, 844
 - relationship to enclosing class, 844, 846
 - scope, 844
 - static member, 845
- nested namespace, 789
- nested type, *see* nested class
- `new`, **458**, 458–460, 491
 - execution flow, 820
 - failure, 460
 - header, 197, 460, 478, 821
 - initialization, 458
 - placement, 460, 491, **824**, 863
 - union with class type member, 851
 - `shared_ptr`, 464
 - `unique_ptr`, 470
 - with `auto`, 459
- `new []`, **477**, 477–478
 - initialization, 477
 - returns pointer to an element, 477
 - value initialization, 478
- newline (`\n`), character, 39
- `next_permutation`, 879
- no match, **234**, 252
 - see also* function matching
- `noboolalpha`, manipulator, 754
- `NoDefault`, 293
- `noexcept`
 - exception specification, **779**, 817
 - argument, 779–781
 - violation, 779
 - move operations, 535
 - operator, **780**, 817
- nonconst reference, *see* reference
- `none`, `bitset`, 726
- `none_of`, 871
- nonportable, 36, 863
- nonprintable character, **39**, 79
- nonthrowing function, **779**, 818
- nontype parameter, **654**, 714

- compare, 654
- must be constant expression, 655
- type requirements, 655
- normal_distribution, 751
- noshowbase, manipulator, 755
- noshowpoint, manipulator, 758
- noskipws, manipulator, 760
- not_equal_to<T>, 575
- NotQuery, 637
 - class definition, 642
 - eval function, 647
- nouppercase, manipulator, 755
- nth_element, 877
- NULL, 54
- null (\0), character, 39
- null pointer, 53, 79
 - delete of, 461
- null statement, 172, 200
- null-terminated character string, *see* C-style string
- nullptr, 54, 79
- numeric header, 376, 881
- numeric conversion, to and from string, 367
- numeric literal
 - float (*numF* or *numf*), 41
 - long (*numL* or *numl*), 41
 - long double (*ddd.dddL* or *ddd.dddl*), 41
 - long long (*numLL* or *numll*), 41
 - unsigned (*numU* or *numu*), 41

O

- object, 42, 79
 - automatic, 205, 251
 - dynamically allocated, 458–463
 - const object, 460
 - delete, 460
 - factory program, 461
 - initialization, 459
 - lifetime, 450
 - new, 458
 - lifetime, 204, 252
 - local static, 205, 252
 - order of destruction
 - class type object, 502
 - derived class object, 627
 - multiple inheritance, 805
 - virtual base classes, 815
 - order of initialization
 - class type object, 289
 - derived class object, 598, 623
 - multiple inheritance, 804
 - virtual base classes, 814
- object code, 252
- object file, 208, 252
- object-oriented programming, 650
- oct, manipulator, 754
- octal, literal (*0num*), 38
- octal escape sequence (*\nnn*), 39
- off-the-beginning iterator, 351, 373
 - before_begin, 351
 - forward_list, 351
- off-the-end
 - iterator, 106, 132, 373
 - iterator range, 331
 - pointer, 118
- ofstream, 311, 316–320, 324
 - see also* ostream
 - close, 318
 - file marker, 765
 - file mode, 319
 - initialization, 317
 - off_type, 766
 - open, 318
 - pos_type, 766
 - random access, 765
 - random IO program, 766
 - seek and tell, 763–768
- old-style, cast, 164
- open, file stream, 318
- operand, 134, 169
 - conversion, 159
- operator, 134, 169
- operator alternative name, 46
- operator delete
 - class member, 822
 - global function, 820, 863
- operator delete[]
 - class member, 822
 - compared to deallocate, 823
 - global function, 820
- operator new
 - class member, 822
 - global function, 820, 863
- operator new[]
 - class member, 822
 - compared to allocate, 823
 - global function, 820
- operator overloading, *see* overloaded operator

operators

- arithmetic, 139
- assignment, 12, 144–147
- binary, 134, 168
- bitwise, 152–156
 - bitset, 725
- comma (,), 157
- compound assignment, 12
- conditional (? :), 151
- decrement, 147–149
- equality, 18, 141
- increment, 12, 147–149
- input, 8
- iterator
 - addition and subtraction, 111
 - arrow, 110
 - dereference, 107
 - equality, 106, 108
 - increment and decrement, 107
 - relational, 111
- logical, 141
- member access, 150
- noexcept, 780
- output, 7
- overloaded, arithmetic, 560
- pointer
 - addition and subtraction, 119
 - equality, 120
 - increment and decrement, 118
 - relational, 120, 123
 - subscript, 121
- relational, 12, 141, 143
- Sales_data
 - += (compound assignment), 564
 - + (addition), 560
 - == (equality), 561
 - != (inequality), 561
 - >> (input operator), 558
 - << (output operator), 557
- Sales_item, 20
- scope, 82
- sizeof, 156
- sizeof . . . , 700
- string
 - addition, 89
 - equality and relational, 88
 - IO, 85
 - subscript, 93–95
- subscript, 116
- typeid, 826, 864
- unary, 134, 169

vector

- equality and relational, 102
- subscript, 103–105

options to main, 218

order of destruction

- class type object, 502
- derived class object, 627
- multiple inheritance, 805
- virtual base classes, 815

order of evaluation, 134, 169

- && (logical AND), 138
- || (logical OR), 138
- , (comma operator), 138
- ? : (conditional operator), 138

expression, 137

pitfalls, 149

order of initialization

- class type object, 289
- derived class object, 598
- multiple base classes, 816
- multiple inheritance, 804
- virtual base classes, 814

ordered container

- see also* container
- see also* associative container
- key_type requirements, 425
- lower_bound, 438
- override default comparison, 425
- upper_bound, 438

ordering, strict weak, 425, 448

OrQuery, 637

- class definition, 644
- eval function, 645

ostream, 5, 27, 311

- see also* manipulator
- << (output operator), 7
 - precedence and associativity, 155
- chained output, 7
- condition state, 312
- explicit conversion to bool, 583
- file marker, 765
- floating-point notation, 757
- flushing output buffer, 314
- format state, 753
- no copy or assign, 311
- not flushed if program crashes, 315
- off_type, 766
- output format, floating-point, 755
- pos_type, 766
- precision member, 756
- random access, 765

- random IO program, 766
- seek and tell, 763–768
- tie member, 315
- virtual base class, 810
- write, 763
- `ostream_iterator`, 403, 418
 - << (output operator), 405
 - algorithms, 404
 - initialization, 405
 - operations, 405
 - type requirements, 406
- `ostringstream`, 311, 321, 321–323
 - see also* `ostream`
 - file marker, 765
 - initialization, 321
 - `off_type`, 766
 - phone number program, 323
 - `pos_type`, 766
 - random access, 765
 - random IO program, 766
 - seek and tell, 763–768
 - `str`, 323
- `out` (file mode), 319
- out-of-range value, signed, 35
- `out_of_range`, 197
 - at function, 348
- `out_of__stock`, 783
- outer scope, 48, 79
- output, standard, 6
- output iterator, 411, 418
- overflow, 140
- `overflow_error`, 197
- overhead, function call, 238
- overload resolution, *see* function matching
- overloaded function, 230, 230–235, 252
 - see also* function matching
 - as friend, 281
 - compared to redeclaration, 231
 - compared to template specialization, 708
 - `const` parameters, 232
 - constructor, 262
 - function template, 694–699
 - linkage directive, 860
 - member function, 273
 - `const`, 276
 - move-enabled, 545
 - reference qualified, 547
 - virtual, 621
 - move-enabled, 545
 - namespace, 800
 - pointer to, 248
 - scope, 234
 - derived hides base, 619
 - using declaration, 800
 - in derived class, 621
 - using directive, 801
- overloaded operator, 135, 169, 500, 550, 552, 590
 - ++ (increment), 566–568
 - (decrement), 566–568
 - * (dereference), 569
 - `StrBlobPtr`, 569
 - & (address-of), 554
 - > (arrow operator), 569
 - `StrBlobPtr`, 569
 - [] (subscript), 564
 - `StrVec`, 565
 - () (call operator), 571
 - `absInt`, 571
 - `PrintString`, 571
 - = (assignment), 500, 563
 - `StrVec` initializer_list, 563
 - += (compound assignment), 555, 560
 - `Sales_data`, 564
 - + (addition), `Sales_data`, 560
 - == (equality), 561
 - `Sales_data`, 561
 - != (inequality), 562
 - `Sales_data`, 561
 - < (less-than), strict weak ordering, 562
 - >> (input operator), 558–559
 - `Sales_data`, 558
 - << (output operator), 557–558
 - `Sales_data`, 557
 - && (logical AND), 554
 - || (logical OR), 554
 - & (bitwise AND), `Query`, 644
 - | (bitwise OR), `Query`, 644
 - ~ (bitwise NOT), `Query`, 643
 - , (comma operator), 554
- ambiguous, 588
- arithmetic operators, 560
- associativity, 553
- binary operators, 552
- candidate function, 587
- consistency between relational and equality operators, 562
- definition, 500, 552
- design, 554–556

- equality operators, 561
- explicit call to, 553
 - postfix operators, 568
- function matching, 587–589
- member function, 500, 552
- member vs. nonmember function, 552, 555
- precedence, 553
- relational operators, 562
- requires class-type parameter, 552
- short-circuit evaluation lost, 553
- unary operators, 552

override, virtual function, 595, 650

- override specifier, 593, 596, 606

P

pair, **426**, 448

- default initialization, 427
- definition, 426
- initialization, 426
- list initialization, 427, 431, 527
- make_pair, 428
- map, * (dereference), 429
- operations, 427
- public data members, 427
- return value, 527

Panda, 803

parameter, **202**, 208, 252

- array, 214–219
 - buffer overflow, 215
 - to pointer conversion, 214
- C-style string, 216
- const, 212
- copy constructor, 496
- ellipsis, 222
- forwarding, 693
- function pointer, linkage directive, 859
- implicit this, **257**
- initialization, 203, 208
- iterator, 216
- lifetime, 205
- low-level const, 213
- main function, 218
- multidimensional array, 218
- nonreference, 209
 - uses copy constructor, 498
 - uses move constructor, 539
- pass by reference, **210**, 252
- pass by value, **209**, 252
- passing, 208–212
- pointer, 209, 214
 - pointer to const, 246
 - pointer to array, 218
 - pointer to function, 249
 - linkage directive, 859
 - reference, 210–214
 - to const, 213, 246
 - to array, 217
 - reference to const, 211
 - template, *see* template parameter
 - top-level const, 212

parameter list

- function, 2, 27, **202**
- template, 653, 714

parameter pack, 714

- expansion, **702**, 702–704, 714
- function template, 713
- sizeof..., 700
- variadic template, 699

parentheses, override precedence, 136

partial_sort, 877

partial_sort_copy, 877

partial_sum, 882

partition, 876

partition_copy, 876

partition_point, 876

pass by reference, **208**, 210, 252

pass by value, **209**, 252

- uses copy constructor, 498
- uses move constructor, 539

pattern, **702**, 714

- functional parameter pack, 704
- regular expression, phone number, 739
- template parameter pack, 703

peek, istream, 761

PersonInfo, 321

phone number, regular expression

- program, 738
- reformat program, 742
- valid, 740

pitfalls

- dynamic memory, 462
- order of evaluation, 149
- self-assignment, 512
- smart pointer, 469
- using directive, 795

placeholders, 399

placement new, 460, 491, **824**, 863

- union, class type member, 851

plus<T>, 575

- pointer, **52**, 52–58, 79
 - ++ (increment), 118
 - (decrement), 118
 - * (dereference), 53
 - [] (subscript), 121
 - = (assignment), 55
 - + (addition), 119
 - (subtraction), 119
 - == (equality), 55, 120
 - != (inequality), 55, 120
 - and array, 117
 - arithmetic, **119**, 132
 - const, **63**, 78
 - const pointer to const, 63
 - constexpr, 67
 - conversion
 - from array, 161
 - to bool, 162
 - to const, 62, 162
 - to void*, 161
 - dangling, **463**, 491
 - declaration style, 57
 - definition, 52
 - delete, 460
 - derived-to-base conversion, 597
 - under multiple inheritance, 805
 - dynamic_cast, 825
 - implicit this, **257**, 306
 - initialization, 52–54
 - invalid, 52
 - multidimensional array, 128
 - null, **53**, 79
 - off-the-end, **118**
 - parameter, 209, 214
 - relational operators, 123
 - return type, 204
 - return value, local variable, 225
 - smart, **450**, 491
 - to const, **62**
 - and typedef, 68
 - to array
 - parameter, 218
 - return type, 204
 - return type declaration, 229
 - to const, 79
 - overloaded parameter, 232, 246
 - to pointer, 58
 - typeid operator, 828
 - valid, 52
 - volatile, 856
- pointer to function, 247–250
 - auto, 249
 - callable object, 388
 - decltype, 249
 - exception specification, 779, 781
 - explicit template argument, 686
 - function template instantiation, 686
 - linkage directive, 859
 - overloaded function, 248
 - parameter, 249
 - return type, 204, 249
 - using decltype, 250
 - template argument deduction, 686
 - trailing return type, 250
 - type alias, 249
 - typedef, 249
- pointer to member, **835**, 863
 - arrow (->*), 837
 - definition, 836
 - dot (. *), 837
 - function, 838
 - and bind, 843
 - and function, 842
 - and mem_fn, 843
 - not callable object, 842
 - function call, 839
 - function table, 840
 - precedence, 838
- polymorphism, **605**, 650
- pop
 - priority_queue, 371
 - queue, 371
 - stack, 371
- pop_back
 - sequential container, 348
 - StrBlob, 457
- pop_front, sequential container, 348
- portable, **854**
- precedence, **134**, 136–137, 169
 - = (assignment), 146
 - ? : (conditional operator), 151
 - assignment and relational operators, 146
 - dot and dereference, 150
 - increment and dereference, 148
 - of IO operator, 156
 - overloaded operator, 553
 - parentheses overrides, 136
 - pointer to member and call operator, 838
- precedence table, 166
- precision member, ostream, 756

- predicate, 386, 418
 - binary, 386, 417
 - unary, 386, 418
- prefix, smatch, 736
- preprocessor, 76, 79
 - #include, 7
 - assert macro, 241, 251
 - header guard, 77
 - variable, 54, 79
- prev_permutation, 879
- print, Sales_data, 261
- print program
 - array parameter, 215
 - array reference parameter, 217
 - pointer and size parameters, 217
 - pointer parameter, 216
 - two pointer parameters, 216
 - variadic template, 701
- print_total
 - explained, 604
 - program, 593
- PrintString, 571
 - () (call operator), 571
- priority_queue, 371, 373
 - emplace, 371
 - empty, 371
 - equality and relational operators, 370
 - initialization, 369
 - pop, 371
 - push, 371
 - sequential container, 371
 - size, 371
 - swap, 371
 - top, 371
- private
 - access specifier, 268, 306
 - copy constructor and assignment, 509
 - inheritance, 612, 650
- program
 - addition
 - Sales_data, 74
 - Sales_item, 21, 23
 - alternative_sum, 682
 - biggies, 391
 - binops desk calculator, 577
 - book from author version 1, 438
 - book from author version 2, 439
 - book from author version 3, 440
 - bookstore
 - Sales_data, 255
 - Sales_data using algorithms, 406
 - Sales_item, 24
 - buildMap, 442
 - children's story, 383–391
 - compare, 652
 - count_calls, 206
 - debug_rep
 - additional nontemplate versions, 698
 - general template version, 695
 - nontemplate version, 697
 - pointer template version, 696
 - elimDups, 383–391
 - error_msg, 221
 - fact, 202
 - factorial, 227
 - factory
 - new, 461
 - shared_ptr, 453
 - file extension, 730
 - version 2, 738
 - find last word, 408
 - find_char, 211
 - findBook, 721
 - flip, 694
 - flip1, 692
 - flip2, 693
 - grade clusters, 103
 - grading
 - bitset, 728
 - bitwise operators, 154
 - i before e, 729
 - version 2, 734
 - isShorter, 211
 - letter grade, 175
 - make_plural, 224
 - message handling, 519
 - phone number
 - istream, 321
 - ostream, 323
 - reformat, 742
 - regular expression version, 738
 - valid, 740
 - print
 - array parameter, 215
 - array reference parameter, 217
 - pointer and size parameters, 217
 - pointer parameter, 216
 - two pointer parameters, 216
 - variadic template, 701
 - print_total, 593
 - Query, 635

- class design, 636–639
- random IO, 766
- reset
 - pointer parameters, 209
 - reference parameters, 210
- restricted `word_count`, 422
- sum, 682
- swap, 223
- `TextQuery`, 486
 - design, 485
- transform, 442
- valid, 740
- vector capacity, 357
- vowel counting, 179
- `word_count`
 - map, 421
 - `unordered_map`, 444
- `word_transform`, 441
- `ZooAnimal`, 802
- promotion, *see* integral promotion
- protected
 - access specifier, 595, 611, 650
 - inheritance, 612, 650
 - member, 611
- `ptr_fun` deprecated, 401
- `ptrdiff_t`, 120, 132
- public
 - access specifier, 268, 306
 - inheritance, 612, 650
- pure virtual function, 609, 650
 - `Disc_quote`, 609
 - `Query_base`, 636
- push
 - `priority_queue`, 371
 - queue, 371
 - stack, 371
- `push_back`
 - `back_inserter`, 382, 402
 - sequential container, 100, 132, 342
 - move-enabled, 545
 - `StrVec`, 527
 - move-enabled, 545
- `push_front`
 - `front_inserter`, 402
 - sequential container, 342
- `put`, `istream`, 761
- `putback`, `istream`, 761

Q

`Query`, 638

- `<<` (output operator), 641
- `&` (bitwise AND), 638
 - definition, 644
- `|` (bitwise OR), 638
 - definition, 644
- `~` (bitwise NOT), 638
 - definition, 643
- classes, 636–639
 - definition, 640
 - interface class, 637
 - operations, 635
 - program, 635
 - recap, 640
- `Query_base`, 636
 - abstract base class, 636
 - definition, 639
 - member function, 636
- `QueryResult`, 485
 - class definition, 489
 - nested class, 844
 - constructor, 845
 - `print`, 490
- `queue`, 371, 373
 - `back`, 371
 - `emplace`, 371
 - `empty`, 371
 - equality and relational operators, 370
 - `front`, 371
 - `header`, 371
 - initialization, 369
 - `pop`, 371
 - `push`, 371
 - sequential container, 371
 - `size`, 371
 - `swap`, 371
- `Quote`
 - class definition, 594
 - design, 592

R

- `Raccoon`, virtual base class, 812
- raise exception, *see* `throw`
- `rand` function, drawbacks, 745
- random header, 745
- random IO, 765
 - machine-dependent, 763
 - program, 766
- random-access iterator, 412, 418
- random-number library, 745
 - compared to `rand` function, 745

- distribution types, 745, 770
- engine, 745, 770
 - default_random_engine, 745
 - max, min, 747
 - retain state, 747
 - seed, 748, 770
- generator, 746, 770
- range, 747
- random_shuffle, 878
- range for statement, 91, 132, 187, 187–189, 200
 - can't add elements, 101, 188
 - multidimensional array, 128
 - not with dynamic array, 477
- range_error, 197
- rbegin, container, 333, 407
- rdstate, stream, 313
- read
 - istream, 763
 - Sales_data, 261
- reallocate, StrVec, 530
 - move iterator version, 543
- recursion loop, 228, 252, 608
- recursive function, 227, 252
- variadic template, 701
- ref, binds reference parameter, 400, 418
- refactoring, 611, 650
- reference, 50, 79
 - see also* lvalue reference
 - see also* rvalue reference
 - auto deduces referred to type, 69
 - collapsing rule, 688
 - forward, 694
 - lvalue arguments, 688
 - move, 691
 - rvalue reference parameters, 693
 - const, *see* reference to const
 - conversion
 - not from const, 61
 - to reference to const, 162
 - data member, initialization, 289
 - declaration style, 57
 - decltype yields reference type, 71
 - definition, 51
 - derived-to-base conversion, 597
 - under multiple inheritance, 805
 - dynamic_cast operator, 826
 - initialization, 51
 - member function, 546
 - parameter, 210–214
 - bind, 400
 - limitations, 214
 - template argument deduction, 687–689
 - remove_reference, 684
 - return type, 224
 - assignment operator, 500
 - is lvalue, 226
 - return value, local variable, 225
 - to array parameter, 217
- reference, container, 333
- reference count, 452, 491, 514, 550
 - copy assignment, 514
 - copy constructor, 514
 - design, 514
 - destructor, 514
 - HasPtr class, 514–516
- reference to const, 61, 80
 - argument, 211
 - initialization, 61
 - parameter, 211, 213
 - overloaded, 232, 246
 - return type, 226
- regex, 728, 770
 - error_type, 732
 - header, 728
 - regex_error, 732, 770
 - syntax_option_type, 730
- regex_constants, 743
 - match_flag_type, 743
- regex_error, 732, 770
- regex_match, 729, 770
- regex_replace, 742, 770
 - format flags, 744
 - format string, 742
- regex_search, 729, 730, 770
- regular expression library, 728, 770
 - case sensitive, 730
 - compiled at run time, 732
 - ECMAScript, 730
 - file extension program, 730
 - i before e program, 729
 - version 2, 734
 - match data, 735–737
 - pattern, 729
 - phone number, valid, 740
 - phone number pattern, 739
 - phone number program, 738
 - phone number reformat, program, 742
 - regex iterators, 734
 - search functions, 729

- smatch, provides context for a match, 735
- subexpression, **738**
 - file extension program version 2, 738
 - types, 733
 - valid, program, 740
- reinterpret_cast, **163**, 164
 - machine-dependent, 164
- relational operators, 141, 143
 - arithmetic conversion, 144
 - container adaptor, 370
 - container member, 340
 - function object, 574
 - iterator, 111
 - overloaded operator, 562
 - pointer, 120, 123
 - Sales_data, 563
 - string, 88
 - tuple, 720
 - vector, 102
- release, unique_ptr, 470
- remove, 878
 - list and forward_list, 415
- remove_copy, 878
- remove_copy_if, 878
- remove_from_Folders, Message, 523
- remove_if, 878
 - list and forward_list, 415
- remove_pointer, 685
- remove_reference, 684
 - move, 691
- rend, container, 333, 407
- replace, 383, 875
 - string, 362
- replace_copy, 383, 874
- replace_copy_if, 874
- replace_if, 875
- reserve
 - string, 356
 - vector, 356
- reserved identifiers, 46
- reset
 - bitset, 727
 - shared_ptr, 466
 - unique_ptr, 470
- reset program
 - pointer parameters, 209
 - reference parameters, 210
- resize
 - invalidates iterator, 352
 - sequential container, 352
 - value initialization, 352
- restricted word_count program, 422
- result, **134**, 169
 - * (dereference), lvalue, 135
 - [] (subscript), lvalue, 135
 - , (comma operator), lvalue, 158
 - ? : (conditional operator), lvalue, 151
 - cast, lvalue, 163
- rethrow, **776**
 - exception object, 777
 - throw, 776, 818
- return statement, **222**, 222–228
 - from main, 227
 - implicit return from main, 223
 - local variable, 224, 225
- return type, **2**, 27, **202**, 204, 252
 - array, 204
 - array using decltype, 230
 - function, 204
 - function pointer, 249
 - using decltype, 250
 - linkage directive, 859
 - main, 2
 - member function, 283
 - nonreference, 224
 - copy initialized, 498
 - pointer, 204
 - pointer to function, 204
 - reference, 224
 - reference to const, 226
 - reference yields lvalue, 226
 - trailing, **229**, 252, 396, 684
 - virtual function, 606
 - void, 223
- return value
 - conversion, 223
 - copy initialized, 498
 - initialization, 224
 - list initialization, **226**, 427, 527
 - local variable, pointer, 225
 - main, 2–4, 227
 - pair, 427, 527
 - reference, local variable, 225
 - *this, 260, 275
 - tuple, 721
 - type checking, 223
 - unique_ptr, 471
- reverse, 878
 - list and forward_list, 415
- reverse iterator, **401**, 407–409, 418

- ++ (increment), 407
- (decrement), 407, 408
- base, 409
- compared to iterator, 409
- reverse_copy, 414, 878
- reverse_copy_if, 414
- reverse_iterator
 - compared to iterator, 408
 - container, 332, 407
- rfind, string, 366
- right, manipulator, 758
- rotate, 878
- rotate_copy, 878
- rule of three/five, **505**, **541**
 - virtual destructor exception, 622
- run-time type identification, 825–831, 864
 - compared to virtual functions, 829
 - dynamic_cast, 825, **825**
 - bad_cast, 826
 - to pointer, 825
 - to reference, 826
 - type-sensitive equality, 829
 - typeid, **826**, 827
 - returns type_info, 827
- runtime binding, **594**, 650
- runtime_error, 194, 197
 - initialization from string, 196
- rvalue, **135**, 169
 - copy initialization, uses move constructor, 539
- result
 - ++ (increment) postfix, 148
 - (decrement) postfix, 148
 - function nonreference return type, 224
- rvalue reference, **532**, 550
 - cast from lvalue, 691
 - collapsing rule, 688
 - compared to lvalue reference, 533
 - function matching, 539
 - initialization, 532
 - member function, **546**
 - overloaded, 547
 - move, 533
 - parameter
 - forwarding, 693, 705
 - member function, 544
 - preserves argument type information, 693
 - template argument deduction, 687
 - variable, 533

S

- Sales_data
 - compareIsbn, 387
 - += (compound assignment), 564
 - + (addition), 560
 - == (equality), 561
 - != (inequality), 561
 - >> (input operator), 558
 - << (output operator), 557
 - add, 261
 - addition program, 74
 - avg_price, 259
 - bookstore program, 255
 - using algorithms, 406
 - class definition, 72, 268
 - combine, 259
 - compareIsbn, 425
 - with associative container, 426
 - constructors, 264–266
 - converting constructor, 295
 - default constructor, 262
 - exception classes, 783
 - exception version
 - += (compound assignment), 784
 - + (addition), 784
 - explicit constructor, 296
 - isbn, 257
 - operations, 254
 - print, 261
 - read, 261
 - relational operators, 563
- Sales_data.h header, 76
- Sales_item, 20
 - + (addition), 22
 - >> (input operator), 21
 - << (output operator), 21
 - addition program, 21, 23
 - bookstore program, 24
 - isbn, 23
 - operations, 20
- Sales_item.h header, 19
- scientific manipulator, 757
- scope, **48**, 80
 - base class, 617
 - block, **48**, 80, 173
 - class, 73, **282**, 282–287, 305
 - static member, 302
 - compared to object lifetime, 204
 - derived class, 617
 - friend, 270, 281

- function, 204
- global, 48, 80
- inheritance, 617–621
- member function, 282
 - parameters and return type, 283
- multiple inheritance, 807
- name collisions, using directive, 795
- namespace, 785–790
- nested class, 844
- overloaded function, 234
- statement, 174
- template parameter, 668
- template specialization, 708
- using directive, 794
- virtual function, 620
- scoped enumeration, 832, 864
 - enum class, 832
- Screen, 271
 - pos member, 272
 - concatenating operations, 275
 - do_display, 276
 - friends, 279
 - get, 273, 282
 - get_cursor, 283
 - Menu function table, 840
 - move, 841
 - move members, 275
 - set, 275
- search, 872
- search_n, 871
- seed, random-number engine, 748
- seekp, seekg, 763–768
- self-assignment
 - copy and swap assignment, 519
 - copy assignment, 512
 - explicit check, 542
- HasPtr
 - reference counted, 515
 - valuelike, 512
- Message, 523
- move assignment, 537
- pitfalls, 512
- StrVec, 528
- semicolon (;), 3
 - class definition, 73
 - null statement, 172
- separate compilation, 44, 80, 252
 - compiler options, 207
 - declaration vs. definition, 44
 - templates, 656
- sequential container, 326, 373
 - array, 326
 - deque, 326
 - forward_list, 326
 - initialization, 334–337
 - list, 326
 - list initialization, 336
 - members
 - assign, 338
 - back, 346
 - clear, 350
 - emplace, 345
 - emplace_back, 345
 - emplace_front, 345
 - erase, 349
 - front, 346
 - insert, 343
 - pop_back, 348
 - pop_front, 348
 - push_back, 132
 - push_back, 100, 342, 545
 - push_front, 342
 - resize, 352
 - value_type, 333
 - performance characteristics, 327
 - priority_queue, 371
 - queue, 371
 - stack, 370
 - value initialization, 336
 - vector, 326
- set, 420, 448
 - see also* ordered container
 - bitset, 727
 - header, 420
 - insert, 431
 - iterator, 429
 - key_type requirements, 425
 - list initialization, 423
 - lower_bound, 438
 - TextQuery class, 485
 - upper_bound, 438
 - word_count program, 422
- set_difference, 880
- set_intersection, 647, 880
- set_symmetric_difference, 880
- set_union, 880
- setfill, manipulator, 759
- setprecision, manipulator, 756
- setstate, stream, 313
- setw, manipulator, 758
- shared_ptr, 450, 450–457, 464–469, 491
 - * (dereference), 451

- copy and assignment, 451
- definition, 450
- deleter, 469, 491
 - bound at run time, 677
- derived-to-base conversion, 630
- destructor, 453
- dynamically allocated array, 480
- exception safety, 467
- factory program, 453
- initialization, 464
- make_shared, 451
- pitfalls, 469
- reset, 466
- StrBlob, 455
- TextQuery class, 485
- with new, 464
- short, 33
- short-circuit evaluation, 142, 169
 - && (logical AND), 142
 - || (logical OR), 142
 - not in overloaded operator, 553
- ShorterString, 573
 - () (call operator), 573
- shorterString, 224
- showbase, manipulator, 755
- showpoint, manipulator, 758
- shrink_to_fit
 - deque, 357
 - string, 357
 - vector, 357
- shuffle, 878
- signed, 34, 80
 - char, 34
 - conversion to unsigned, 34, 160
 - out-of-range value, 35
- signed type, 34
- single-line (//), comment, 9, 26
- size
 - container, 88, 102, 132, 340
 - priority_queue, 371
 - queue, 371
 - returns unsigned, 88
 - stack, 371
 - StrVec, 526
- size_t, 116, 132, 727
 - array subscript, 116
- size_type, container, 88, 102, 132, 332
- SizeComp, 573
 - () (call operator), 573
- sizeof, 156, 169
 - array, 157
 - data member, 157
- sizeof . . . , parameter pack, 700
- skipws, manipulator, 760
- sliced, 603, 650
- SmallInt
 - + (addition), 588
 - conversion operator, 580
- smart pointer, 450, 491
 - exception safety, 467
 - pitfalls, 469
- smatch, 729, 733, 769, 770
 - prefix, 736
 - provide context for a match, 735
 - suffix, 736
- sort, 384, 876
- source file, 4, 27
- specialization, *see* template specialization
- splice, list, 416
- splice_after, forward_list, 416
- sregex_iterator, 733, 770
 - i before e program, 734
- sstream
 - file marker, 765
 - header, 310, 321
 - off_type, 766
 - pos_type, 766
 - random access, 765
 - random IO program, 766
 - seek and tell, 763–768
- ssub_match, 733, 736, 770
 - example, 740
- stable_partition, 876
- stable_sort, 387, 876
- stack, 370, 373
 - emplace, 371
 - empty, 371
 - equality and relational operators, 370
 - header, 370
 - initialization, 369
 - pop, 371
 - push, 371
 - sequential container, 370
 - size, 371
 - swap, 371
 - top, 371
- stack unwinding, exception handling, 773, 818
- standard error, 6, 27
- standard header, #include, 6, 21
- standard input, 6, 27
- standard library, 5, 27

- standard output, 6, 27
- statement, 2, 27
 - block, *see* block
 - break, **190**, 199
 - compound, **173**, 199
 - continue, **191**, 199
 - do while, **189**, 200
 - expression, **172**, 200
 - for, **13**, 27, **185**, 185–187, 200
 - goto, **192**, 200
 - if, **17**, 27, **175**, 175–178, 200
 - labeled, **192**, 200
 - null, **172**, 200
 - range for, **91**, **187**, 187–189, 200
 - return, **222**, 222–228
 - scope, 174
 - switch, **178**, 178–182, 200
 - while, **11**, 28, **183**, 183–185, 200
- statement label, 192
- static (file static), **792**, 817
- static member
 - Account, 301
 - class template, 667
 - accessed through an instantiation, 667
 - definition, 667
 - const data member, initialization, 302
 - data member, 300
 - definition, 302
 - default argument, 304
 - definition, 302
 - inheritance, 599
 - instantiation, 667
 - member function, 301
 - nested class, 845
 - scope, 302
- static object, local, **205**, 252
- static type, **601**, 650
 - determines name lookup, 617, 619
 - multiple inheritance, 806
- static type checking, **46**
- static_cast, 163, **163**
 - lvalue to rvalue, 691
- std, **7**, 28
- std::forward, *see* forward
- std::move, *see* move
- stdexcept header, 194, 197
- stod, 368
- stof, 368
- stoi, 368
- stol, 368
- stold, 368
- stoll, 368
- store, free, **450**, 491
- stoul, 368
- stoull, 368
- str, string streams, 323
- StrBlob, 456
 - back, 457
 - begin, 475
 - check, 457
 - constructor, 456
 - end, 475
 - front, 457
 - pop_back, 457
 - shared_ptr, 455
- StrBlobPtr, 474
 - ++ (increment), 566
 - (decrement), 566
 - * (dereference), 569
 - > (arrow operator), 569
 - check, 474
 - constructor, 474
 - deref, 475
 - incr, 475
 - weak_ptr, 474
- strcat, 123
- strcmp, 123
- strcpy, 123
- stream
 - as condition, 15, 162, 312
 - clear, 313
 - explicit conversion to bool, 583
 - file marker, 765
 - flushing buffer, 314
 - format state, 753
 - istream_iterator, **403**
 - iterator, **401**, 403–406, 418
 - type requirements, 406
 - not flushed if program crashes, 315
 - ostream_iterator, **403**
 - random IO, 765
 - rdstate, 313
 - setstate, 313
- strict weak ordering, **425**, 448
- string, 80, 84–93, 132
 - see also* container
 - see also* sequential container
 - see also* iterator
 - [] (subscript), **93**, 132, 347
 - += (compound assignment), 89

- + (addition), 89
- >> (input operator), 85, 132
- >> (input operator) as condition, 86
- << (output operator), 85, 132
- and string literal, 89–90
- append, 362
- assign, 362
- at, 348
- C-style string, 124
- c_str, 124
- capacity, 356
- case sensitive, 365
- compare, 366
- concatenation, 89
- default initialization, 44
- difference_type, **112**
- equality and relational operators, 88
- erase, 362
- find, 364
- find_first_not_of, 365
- find_last_not_of, 366
- find_last_of, 366
- getline, 87, 321
- header, 74, 76, 84
- initialization, 84–85, 360–361
- initialization from string literal, 84
- insert, 362
- move constructor, 529
- numeric conversions, 367
- random-access iterator, 412
- replace, 362
- reserve, 356
- rfind, 366
- subscript range, 95
- substr, 361
- TextQuery class, 485
- string literal, 7, 28, 39
 - see also* C-style string
 - and string, 89–90
 - concatenation, 39
- stringstream, **321**, 321–323, 324
 - initialization, 321
- strlen, 122
- struct
 - see also* class
 - default access specifier, 268
 - default inheritance specifier, 616
- StrVec, 525
 - [] (subscript), 565
 - = (assignment), initializer_list, 563
 - alloc_n_copy, 527
 - begin, 526
 - capacity, 526
 - chk_n_alloc, 526
 - copy assignment, 528
 - copy constructor, 528
 - default constructor, 526
 - design, 525
 - destructor, 528
 - emplace_back, 704
 - end, 526
 - free, 528
 - memory allocation strategy, 525
 - move assignment, 536
 - move constructor, 535
 - push_back, 527
 - move-enabled, 545
 - reallocate, 530
 - move iterator version, 543
 - size, 526
- subexpression, 770
- subscript range, 93
 - array, 116
 - string, 95
 - validating, 104
 - vector, 105
- substr, string, 361
- suffix, smatch, 736
- sum, program, 682
- swap, 516
 - array, 339
 - container, 339
 - container nonmember version, 339
 - copy and swap assignment operator, 518
 - priority_queue, 371
 - queue, 371
 - stack, 371
 - typical implementation, 517–518
- swap program, 223
- swap_ranges, 875
- switch statement, **178**, 178–182, 200
 - default case label, **181**
 - break, 179–181, 190
 - compared to if, **178**
 - execution flow, 180
 - variable definition, 182
- syntax_option_type, regex, 730
- synthesized
 - copy assignment, **500**, 550
 - copy constructor, **497**, 550

- copy control, 267
 - as deleted function, 508
 - as deleted in derived class, 624
 - Bulk_quote, 623
 - multiple inheritance, 805
 - virtual base class, 815
 - virtual base classes, 815
 - volatile, 857
 - default constructor, 263, 306
 - derived class, 623
 - members of built-in type, 263
 - destructor, 503, 550
 - move operations
 - deleted function, 538
 - not always defined, 538
- T
- \t (tab character), 39
 - tellp, tellg, 763–768
 - template
 - see also* class template
 - see also* function template
 - see also* instantiation
 - declaration, 669
 - link time errors, 657
 - overview, 652
 - parameter, *see* template parameter
 - parameter list, 714
 - template argument, 653, 714
 - explicit, 660, 713
 - template member, *see* member template
 - type alias, 666
 - type transformation templates, 684, 714
 - type-dependencies, 658
 - variadic, *see* variadic template
 - template argument deduction, 678, 714
 - compare, 680
 - explicit template argument, 682
 - function pointer, 686
 - limited conversions, 679
 - low-level const, 693
 - lvalue reference parameter, 687
 - multiple function parameters, 680
 - parameter with nontemplate type, 680
 - reference parameters, 687–689
 - rvalue reference parameter, 687
 - top-level const, 679
 - template class, *see* class template
 - template function, *see* function template
 - template parameter, 653, 714
 - default template argument, 670
 - class template, 671
 - function template, 671
 - name, 668
 - restrictions on use, 669
 - nontype parameter, 654, 714
 - must be constant expression, 655
 - type requirements, 655
 - scope, 668
 - template argument deduction, 680
 - type parameter, 654, 654, 714
 - as friend, 666
 - used in template class, 660
 - template parameter pack, 699, 714
 - expansion, 703
 - pattern, 703
 - template specialization, 707, 706–712, 714
 - class template, 709–712
 - class template member, 711
 - compare function template, 706
 - compared to overloading, 708
 - declaration dependencies, 708
 - function template, 707
 - hash<key_type>, 709, 788
 - headers, 708
 - of namespace member, 709, 788
 - partial, class template, 711, 714
 - scope, 708
 - template<>, 707
 - template<>
 - default template argument, 671
 - template specialization, 707
 - temporary, 62, 80
 - terminate function, 773, 818
 - exception handling, 196, 200
 - machine-dependent, 196
 - terminology
 - const reference, 61
 - iterator, 109
 - object, 42
 - overloaded new and delete, 822
 - test, bitset, 727
 - TextQuery, 485
 - class definition, 487
 - constructor, 488
 - main program, 486
 - program design, 485
 - query, 489
 - revisited, 635

- this pointer, 257, 306
 - static members, 301
 - as argument, 266
 - in return, 260
 - overloaded
 - on const, 276
 - on lvalue or rvalue reference, 546
- throw, 193, **193**, 200, 772, 818
 - execution flow, 196, 773
 - pointer to local object, 774
 - rethrow, 776, 818
 - runtime_error, 194
- throw(), exception specification, 780
- tie member, ostream, 315
- to_string, 368
- Token, 849
 - assignment operators, 850
 - copy control, 851
 - copyUnion, 851
 - default constructor, 850
 - discriminant, 850
- tolower, 92
- top
 - priority_queue, 371
 - stack, 371
- top-level const, **64**, 80
 - and auto, 69
 - argument and parameter, 212
 - decltype, 71
 - parameter, 232
 - template argument deduction, 679
- toupper, 92
- ToyAnimal, virtual base class, 815
- trailing return type, **229**, 252
 - function template, 684
 - lambda expression, 396
 - pointer to array, 229
 - pointer to function, 250
- transform
 - algorithm, 396, 874
 - program, 442
- translation unit, 4
- trunc (file mode), 319
- try block, **193**, 194, 200, **773**, 818
- tuple, **718**, 770
 - findBook, program, 721
 - equality and relational operators, 720
 - header, 718
 - initialization, 718
 - make_tuple, 718
 - return value, 721
 - value initialization, 718
- type
 - alias, **67**, 80
 - template, 666
 - alias declaration, **68**
 - arithmetic, **32**, 78
 - built-in, 2, 26, 32–34
 - checking, **46**, 80
 - argument and parameter, 203
 - array reference parameter, 217
 - function return value, 223
 - name lookup, 235
 - class, **19**, 26
 - compound, **50**, 50–58, 78
 - conversion, *see* conversion
 - dynamic, **601**, 650
 - incomplete, **279**, 306
 - integral, **32**, 79
 - literal, 66
 - class type, 299
 - specifier, **41**, 80
 - static, **601**, 650
- type alias declaration, **68**, 78, 80
 - pointer, to array, 229
 - pointer to function, 249
 - pointer to member, 839
 - template type, 666
- type independence, algorithms, 377
- type member, class, 271
- type parameter, *see* template parameter
- type transformation templates, **684**, 714
 - type_traits, 685
- type_info, 864
 - header, 197
 - name, 831
 - no copy or assign, 831
 - operations, 831
 - returned from typeid, 827
- type_traits
 - header, 684
 - remove_pointer, 685
 - remove_reference, 684
 - and move, 691
 - type transformation templates, 685
- typedef, **67**, 80
 - const, 68
 - and pointer, to const, 68
 - pointer, to array, 229
 - pointer to function, 249
- typeid operator, **826**, 827, 864
 - returns type_info, 827

`TypeInfo` header, 826, 827, 831

`typename`

- compared to `class`, 654
- required for type member, 670
- template parameter, 654

U

unary operators, 134, 169

- overloaded operator, 552

unary predicate, 386, 418

`UnaryFunction` deprecated, 579

uncaught exception, 773

undefined behavior, 35, 80

- base class destructor not virtual, 622
- bitwise operators and signed values, 153

caching `end()` iterator, 355

`CString` functions, 122

dangling pointer, 463

default initialized members of built-in type, 263

`delete` of invalid pointer, 460

destination sequence too small, 382

element access empty container, 346

invalidated iterator, 107, 353

missing return statement, 224

misuse of smart pointer `get`, 466

omitting `[]` when deleting array, 479

operand order of evaluation, 138, 149

out-of-range subscript, 93

out-of-range value assigned to signed type, 35

overflow and underflow, 140

pointer casts, 163

pointer comparisons, 123

return reference or pointer to local variable, 225

string invalid initializer, 361

uninitialized

- dynamic object, 458

- local variable, 205

- pointer, 54

- variable, 45

using unconstructed memory, 482

using unmatched `match` object, 737

writing to a `const` object, 163

wrong deleter with smart pointer, 480

`UnderflowError`, 197

unformatted IO, 761, 770

- `istream`, 761

- multi-byte, `istream`, 763

- single-byte, `istream`, 761

`unget`, `istream`, 761

`UniformIntDistribution`, 746

`UniformRealDistribution`, 750

uninitialized, 8, 28, 44, 80

- pointer, undefined behavior, 54

- variable, undefined behavior, 45

`uninitialized_copy`, 483

- move iterator, 543

`uninitialized_fill`, 483

union, 847, 864

- anonymous, 848, 862

- class type member, 848

- assignment operators, 850

- copy control, 851

- default constructor, 850

- deleted copy control, 849

- placement `new`, 851

- definition, 848

- discriminant, 850

- restrictions, 847

`unique`, 384, 878

- `list` and `forward_list`, 415

`unique_copy`, 403, 878

`unique_ptr`, 450, 470–472, 491

- * (dereference), 451

- copy and assignment, 470

- definition, 470, 472

- deleter, 472, 491

- bound at compile time, 678

- dynamically allocated array, 479

- initialization, 470

- pitfalls, 469

- release, 470

- reset, 470

- return value, 471

- transfer ownership, 470

- with `new`, 470

`unitbuf`, manipulator, 315

unnamed namespace, 791, 818

- local to file, 791

- replace file `static`, 792

unordered container, 443, 448

- see also* container

- see also* associative container

- bucket management, 444

- `hash<key_type>` specialization, 709, 788

- compatible with `==` (equality), 710

- `key_type` requirements, 445

- override default hash, 446
 - unordered_map, 448
 - see also unordered container
 - * (dereference), 429
 - [] (subscript), 435, 448
 - adds element, 435
 - at, 435
 - definition, 423
 - header, 420
 - list initialization, 423
 - word_count program, 444
 - unordered_multimap, 448
 - see also unordered container
 - * (dereference), 429
 - definition, 423
 - has no subscript operator, 435
 - insert, 433
 - list initialization, 423
 - unordered_multiset, 448
 - see also unordered container
 - insert, 433
 - iterator, 429
 - list initialization, 423
 - override default hash, 446
 - unordered_set, 448
 - see also unordered container
 - header, 420
 - iterator, 429
 - list initialization, 423
 - unscoped enumeration, 832, 864
 - as union discriminant, 850
 - conversion to integer, 834
 - enum, 832
 - unsigned, 34, 80
 - char, 34
 - conversion, 36
 - conversion from signed, 34
 - conversion to signed, 160
 - literal (*numU* or *numu*), 41
 - size return type, 88
 - unsigned type, 34
 - unwinding, stack, 773, 818
 - upper_bound
 - algorithm, 873
 - ordered container, 438
 - used in *Basket*, 632
 - uppercase, manipulator, 755
 - use count, see reference count
 - user-defined conversion, see class type conversion
 - user-defined header, 76–77
 - const and *constexpr*, 76
 - default argument, 238
 - function declaration, 207
 - #include, 21
 - inline function, 240
 - inline member function definition, 273
 - template definition, 656
 - template specialization, 708
 - using =, see type alias declaration
 - using declaration, 82, 132, 793, 818
 - access control, 615
 - not in header files, 83
 - overloaded function, 800
 - overloaded inherited functions, 621
 - scope, 793
 - using directive, 793, 818
 - overloaded function, 801
 - pitfalls, 795
 - scope, 793, 794
 - name collisions, 795
 - utility header, 426, 530, 533, 694
- ## V
- valid, program, 740
 - valid but unspecified, 537
 - valid pointer, 52
 - value initialization, 98, 132
 - dynamically allocated, object, 459
 - map subscript operator, 435
 - new[], 478
 - resize, 352
 - sequential container, 336
 - tuple, 718
 - uses default constructor, 293
 - vector, 98
 - value_type
 - associative container, 428, 448
 - sequential container, 333
 - valuelike class, copy control, 512
 - varargs, 222
 - variable, 8, 28, 41, 41–49, 80
 - const, 59
 - constexpr*, 66
 - declaration, 45
 - class type, 294
 - define before use, 46
 - defined after label, 182, 192
 - definition, 41, 45
 - extern, 45

- extern and const, 60
 - initialization, 42, 43, 79
 - is lvalue, 533
 - lifetime, 204
 - local, **204**, 252
 - preprocessor, 79
 - variadic template, **699**, 714
 - declaration dependencies, 702
 - forwarding, 704
 - usage pattern, 706
 - function matching, 702
 - pack expansion, 702–704
 - parameter pack, 699
 - print program, 701
 - recursive function, 701
 - sizeof . . . , 700
 - vector, 96–105, 132, 373
 - see also* container
 - see also* sequential container
 - see also* iterator
 - [] (subscript), **103**, 132, 347
 - = (assignment), list initialization, 145
 - at, 348
 - capacity, 356
 - capacity program, 357
 - definition, 97
 - difference_type, **112**
 - erase, changes container size, 385
 - header, 96, 329
 - initialization, 97–101, 334–337
 - initialization from array, 125
 - list initialization, 98, 336
 - memory management, 355
 - overview, 326
 - push_back, invalidates iterator, 354
 - random-access iterator, 412
 - reserve, 356
 - subscript range, 105
 - TextQuery class, 485
 - value initialization, 98, 336
 - viable function, **243**, 252
 - see also* function matching
 - virtual base class, **811**, 818
 - ambiguities, 812
 - Bear, 812
 - class derivation list, 812
 - conversion, 812
 - derived class constructor, 813
 - iostream, 810
 - name lookup, 812
 - order of destruction, 815
 - order of initialization, 814
 - ostream, 810
 - Raccoon, 812
 - ToyAnimal, 815
 - ZooAnimal, 811
 - virtual function, **592**, 595, 603–610, 650
 - compared to run-time type identification, 829
 - default argument, 607
 - derived class, 596
 - destructor, 622
 - exception specification, 781
 - final specifier, 607
 - in constructor, destructor, 627
 - multiple inheritance, 807
 - overloaded function, 621
 - override, 595, 650
 - override specifier, 593, 596, 606
 - overriding run-time binding, 607
 - overview, 595
 - pure, **609**
 - resolved at run time, 604, 605
 - return type, 606
 - scope, 620
 - type-sensitive equality, 829
 - virtual inheritance, *see* virtual base class
 - Visual Studio, 5
 - void, **32**, 80
 - return type, 223
 - void*, **56**, 80
 - conversion from pointer, 161
 - volatile, **856**, 864
 - pointer, 856
 - synthesized copy-control members, 857
 - vowel counting, program, 179
- ## W
- wcerr, 311
 - wchar_t, 33
 - literal, 40
 - wchar_t streams, 311
 - wcin, 311
 - wcout, 311
 - weak ordering, strict, 448
 - weak_ptr, **450**, 473–475, 491
 - definition, 473
 - initialization, 473
 - lock, 473
 - StrBlobPtr, 474

- wfstream, 311
- what, exception, 195, 782
- while statement, **11**, 28, **183**, 183–185, 200
 - condition, 12, 183
- wide character streams, 311
- wifstream, 311
- window, console, 6
- Window_mgr, 279
- wiostream, 311
- wistream, 311
- wistringstream, 311
- wofstream, 311
- word, **33**, 80
- word_count program
 - map, 421
 - set, 422
 - unordered_map, 444
- word_transform program, 441
- WordQuery, 637, 642
- wostream, 311
- wostreamstringstream, 311
- wregex, 733
- write, ostream, 763
- wstringstream, 311

X

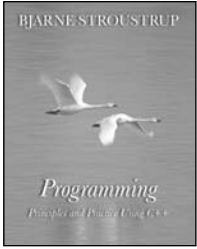
- \Xnm (hexadecimal escape sequence), 39

Z

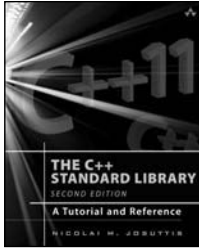
- ZooAnimal
 - program, 802
 - virtual base class, 811

This page intentionally left blank

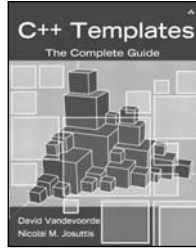
Take the Next Step to Mastering C++



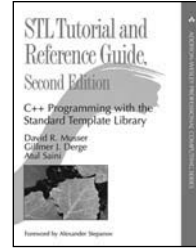
978-0-321-54372-1



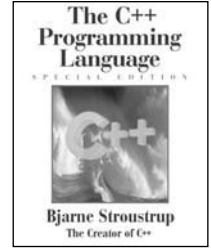
978-0-321-62321-8



978-0-201-73484-3



978-0-321-70212-8



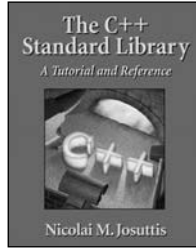
978-0-201-70073-2



978-0-13-704483-2



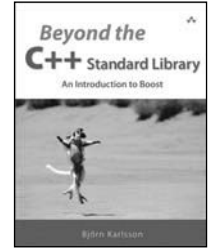
978-0-13-700130-9



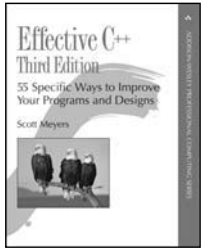
978-0-201-37926-6



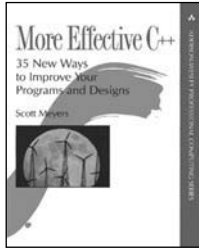
978-0-321-41299-7



978-0-321-13354-0



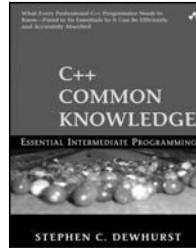
978-0-321-33487-9



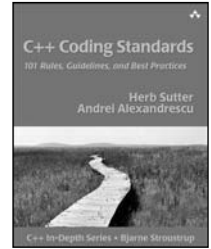
978-0-201-63371-9



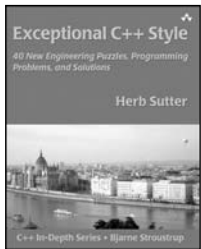
978-0-201-74962-5



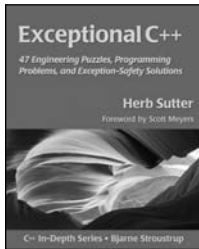
978-0-321-32192-3



978-0-321-11358-0



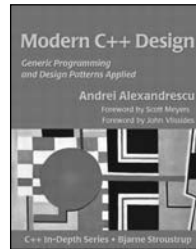
978-0-201-76042-2



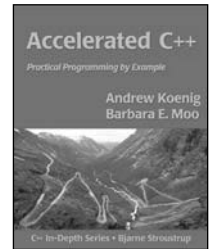
978-0-201-61562-3



978-0-201-70434-1



978-0-201-70431-0



978-0-201-70353-5



For more information on these titles visit informit.com



REGISTER

THIS PRODUCT

informit.com/register

Register the Addison-Wesley, Exam Cram, Prentice Hall, Que, and Sams products you own to unlock great benefits.

To begin the registration process, simply go to **informit.com/register** to sign in or create an account.

You will then be prompted to enter the 10- or 13-digit ISBN that appears on the back cover of your product.

Registering your products can unlock the following benefits:

- Access to supplemental content, including bonus chapters, source code, or project files.
- A coupon to be used on your next purchase.

Registration benefits vary by product. Benefits will be listed on your Account page under Registered Products.

About InformIT — THE TRUSTED TECHNOLOGY LEARNING SOURCE

INFORMIT IS HOME TO THE LEADING TECHNOLOGY PUBLISHING IMPRINTS Addison-Wesley Professional, Cisco Press, Exam Cram, IBM Press, Prentice Hall Professional, Que, and Sams. Here you will gain access to quality and trusted content and resources from the authors, creators, innovators, and leaders of technology. Whether you're looking for a book on a new technology, a helpful article, timely newsletters, or access to the Safari Books Online digital library, InformIT has a solution for you.

informIT.com

THE TRUSTED TECHNOLOGY LEARNING SOURCE

Addison-Wesley | Cisco Press | Exam Cram
IBM Press | Que | Prentice Hall | Sams

SAFARI BOOKS ONLINE

InformIT is a brand of Pearson and the online presence for the world's leading technology publishers. It's your source for reliable and qualified content and knowledge, providing access to the top brands, authors, and contributors from the tech community.

LearnIT at InformIT

Looking for a book, eBook, or training video on a new technology? Seeking timely and relevant information and tutorials? Looking for expert opinions, advice, and tips? **InformIT has the solution.**

- Learn about new releases and special promotions by subscribing to a wide variety of newsletters. Visit informit.com/newsletters.
- Access FREE podcasts from experts at informit.com/podcasts.
- Read the latest author articles and sample chapters at informit.com/articles.
- Access thousands of books and videos in the Safari Books Online digital library at safari.informit.com.
- Get tips from expert blogs at informit.com/blogs.

Visit informit.com/learn to discover all the ways you can access the hottest technology content.

Are You Part of the IT Crowd?

Connect with Pearson authors and editors via RSS feeds, Facebook, Twitter, YouTube, and more! Visit informit.com/socialconnect.



Try Safari Books Online FREE for 15 days

Get online access to Thousands of Books and Videos



Safari
Books Online

FREE 15-DAY TRIAL + 15% OFF*
informit.com/safaritrial

➤ Feed your brain

Gain unlimited access to thousands of books and videos about technology, digital media and professional development from O'Reilly Media, Addison-Wesley, Microsoft Press, Cisco Press, McGraw Hill, Wiley, WROX, Prentice Hall, Que, Sams, Apress, Adobe Press and other top publishers.

➤ See it, believe it

Watch hundreds of expert-led instructional videos on today's hottest topics.

WAIT, THERE'S MORE!

➤ Gain a competitive edge

Be first to learn about the newest technologies and subjects with Rough Cuts pre-published manuscripts and new technology overviews in Short Cuts.

➤ Accelerate your project

Copy and paste code, create smart searches that let you know when new books about your favorite topics are available, and customize your library with favorites, highlights, tags, notes, mash-ups and more.

* Available to new subscribers only. Discount applies to the Safari Library and is valid for first 12 consecutive monthly billing cycles. Safari Library is not available in all countries.

