

Advanced R

Hadley Wickham

To Jeff, who makes me happy,
and who made sure I had a life outside this book.

Contents

Preface	5
1 Introduction	9
1.1 Why R?	9
1.2 Who should read this book	11
1.3 What you will get out of this book	12
1.4 What you will not learn	13
1.5 Meta-techniques	13
1.6 Recommended reading	14
1.7 Getting help	14
1.8 Acknowledgments	15
1.9 Conventions	18
1.10 Colophon	19
I Foundations	23
Introduction	25
2 Names and values	27
2.1 Introduction	27
2.2 Binding basics	29
2.3 Copy-on-modify	32
2.4 Object size	38
2.5 Modify-in-place	40
2.6 Unbinding and the garbage collector	44
2.7 Answers	46
3 Vectors	47
3.1 Introduction	47
3.2 Atomic vectors	48
3.3 Attributes	52

3.4	S3 atomic vectors	56
3.5	Lists	61
3.6	Data frames and tibbles	65
3.7	NULL	75
3.8	Answers	76
4	Subsetting	79
4.1	Introduction	79
4.2	Selecting multiple elements	80
4.3	Selecting a single element	87
4.4	Subsetting and assignment	92
4.5	Applications	93
4.6	Answers	100
5	Functions	101
5.1	Introduction	101
5.2	Function fundamentals	103
5.3	Function composition	107
5.4	Lexical scoping	108
5.5	Lazy evaluation	114
5.6	... (dot-dot-dot)	120
5.7	Exiting a function	123
5.8	Function forms	128
5.9	Invoking a function	135
5.10	Quiz answers	136
6	Environments	137
6.1	Introduction	137
6.2	Environment basics	138
6.3	Recursing over environments	147
6.4	Special environments	150
6.5	The call stack	160
6.6	As data structures	164
6.7	Quiz answers	165
7	Conditions	167
7.1	Introduction	167
7.2	Signalling conditions	169
7.3	Ignoring conditions	174
7.4	Handling conditions	176
7.5	Custom conditions	185
7.6	Applications	190

CONTENTS	5
7.7 Quiz answers	200
II Functional programming	201
Introduction	203
Functional programming languages	203
Functional style	204
8 Functionals	207
8.1 Introduction	207
8.2 My first functional: <code>map()</code>	209
8.3 Purrr style	219
8.4 Map variants	220
8.5 Reduce	231
8.6 Predicate functionals	236
8.7 Base functionals	239
9 Function factories	243
9.1 Introduction	243
9.2 Factory fundamentals	245
9.3 Graphical factories	252
9.4 Statistical factories	256
9.5 Function factories + functionals	263
10 Function operators	267
10.1 Introduction	267
10.2 Existing FOs	268
10.3 Case study: creating your own FOs	274
III Object oriented programming	279
Introduction	281
OOP systems	282
OOP in R	284
sloop	285
11 Base types	287
11.1 Introduction	287
11.2 Base vs OO objects	288
11.3 Base types	289
12 S3	293

12.1	Introduction	293
12.2	Basics	294
12.3	Classes	298
12.4	Generics and methods	305
12.5	Object styles	309
12.6	Inheritance	310
12.7	Dispatch details	315
13	R6	321
13.1	Introduction	321
13.2	Classes and methods	322
13.3	Controlling access	328
13.4	Reference semantics	332
13.5	Why R6?	336
14	S4	337
14.1	Introduction	337
14.2	Basics	339
14.3	Classes	340
14.4	Generics and methods	345
14.5	Method dispatch	348
14.6	S4 and S3	355
15	Trade-offs	359
15.1	Introduction	359
15.2	S4 vs S3	360
15.3	R6 vs S3	361
IV	Metaprogramming	367
Introduction		369
15.4	Big ideas	370
	Overview	378
16	Expressions	379
16.1	Introduction	379
16.2	Abstract syntax trees	380
16.3	Expressions	385
16.4	Parsing and grammar	392
16.5	Walking the AST with recursive functions	396
16.6	Specialised data structures	404

17 Quasiquotation	407
17.1 Introduction	407
17.2 Motivation	408
17.3 Quoting	412
17.4 Unquoting	417
17.5 Non-quoting in base R	426
17.6 Dot-dot-dot (...)	428
17.7 Case studies	434
18 Evaluation	443
18.1 Introduction	443
18.2 Evaluation basics	444
18.3 Quosures	450
18.4 Data masks	454
18.5 Using tidy evaluation	460
18.6 Base evaluation	464
19 Translating R code	473
19.1 Introduction	473
19.2 HTML	474
19.3 LaTeX	483
V Techniques	493
20 Debugging	495
20.1 Introduction	495
20.2 Techniques	496
20.3 Tools	498
21 Performance	505
21.1 Why is R slow?	506
21.2 Microbenchmarking	507
21.3 Language performance	509
21.4 Implementation performance	514
21.5 Alternative R implementations	517
22 Optimising code	521
22.1 Introduction	521
22.2 Measuring performance	523
22.3 Memory profiling with lineprof	527
22.4 Improving performance	530
22.5 Code organisation	530

22.6 Has someone already solved the problem?	532
22.7 Do as little as possible	533
22.8 Vectorise	540
22.9 Avoid copies	542
22.10 Byte code compilation	544
22.11 Case study: t-test	544
22.12 Parallelise	547
22.13 Other techniques	549
23 Rewriting R code in C++	551
23.1 Introduction	551
23.2 Getting started with C++	553
23.3 Attributes and other classes	562
23.4 Missing values	565
23.5 Rcpp sugar	569
23.6 The STL	571
23.7 Case studies	578
23.8 Using Rcpp in a package	583
23.9 Learning more	584
23.10 Acknowledgments	585
References	587

Preface

Welcome to the 2nd edition of Advanced R. I had three main goals for this edition:

- Improve coverage of important concepts that I fully understood only after the publication of the 1st edition.
- Reduce coverage of topics time has shown to be less useful, or that I think are really exciting but turn out not to be that practical.
- Generally make the material easier to understand with better text, clearer code, and many more diagrams.

If you're familiar with the 1st edition, this preface describes the major changes so that you can focus your reading on the new areas (but I really do encourage you to skim throughout the book).

If you're reading a printed version of this book you'll notice one big change very quickly: Advanced R is now in colour! This has considerably improved the syntax highlighting of code chunks, and made it much easier to create helpful diagrams. I have taken advantage of this and included over 100 new diagrams throughout the book.

Another big change in this version is the use of packages, particularly `rlang` (<http://rlang.r-lib.org>), which provides a clean interface to low-level data structures and operations. The 1st edition used base R functions almost exclusively, which created some pedagogical challenges because many functions evolved independently over multiple years, making it hard to see the big underlying ideas hidden amongst the incidental variations in function names and arguments. I continue to show base equivalents in sidebars, footnotes, and where needed, in individual sections, but if you want to see the purest base R expression of the ideas in this book, I recommend reading the 1st edition, which you can find online at <http://adv-r.had.co.nz>.

The foundations of R have not changed in the five years since the 1st edition, but my understanding of them certainly has. Thus, the overall structure of “Founda-

tions” has remained roughly the same, but many of the individual chapters have been considerably improved:

- Chapter 2, “Names and values”, is a brand new chapter that helps you understand the difference between objects and names of objects. This helps you more accurately predict when R will make a copy of a data structure, and lays important groundwork to understand functional programming.
- Chapter 3, “Vectors” (previously called data structures), and has been rewritten to focus on vector types like integers, factors, and data frames. It contains more details of important S3 vectors (like dates and date-times), and discusses the data frame variation provided by the `tibble` (<https://tibble.tidyverse.org>) package.
- Chapter 4, “Subsetting”, now distinguishes between `[` and `[[` by their intention: `[` extracts many values and `[[` extracts a single value (previously they were characterised by whether they “simplified” or “preserved”). Section 4.3 draws the “train” to help you understand how `[[` works with lists, and introduces the new `purrr::pluck()` and `purrr::chuck()` functions that provide more consistent behaviour for out-of-bounds indices.
- Chapter 5, “Functions”, has an improved ordering, introduces the pipe (`%>%`) as a third way to compose functions (Section 5.3), and has considerably improved coverage of function forms (Section 5.8).
- Chapter 6, “Environments”, has a reorganised treatment of special environments (Section 6.4), and a much improved discussion of the call stack (Section 6.5).
- Chapter 7, “Conditions”, contains material previously in “Exceptions and debugging”, and much new content on how R’s condition system works. It also shows you how to create your own custom condition classes (Section 7.5).

The chapters following foundations have been re-organised around the three most important programming paradigms in R: functional programming, object oriented programming, and metaprogramming.

- Functional programming is now more cleanly divided into the three main techniques: “Functionals” (Chapter 8), “Function factories” (Chapter 9), and “Function operators” (Chapter 10). I’ve focussed in on ideas that have practical applications in data science and reduced the amount of pure theory.

These chapters now use functions provided by the `purrr` package, which allow me to focus more on the underlying ideas and less on the incidental

variations. This also lead to a considerable simplification of the function operators chapter since a major use was to work around the absence of . . . in base functionals.

- Object oriented programming (OOP) now forms a major section of the book with completely new chapters on base types (Chapter 11), S3 (Chapter 12), S4 (Chapter 14), R6 (Chapter 13), and the tradeoffs between the systems (Chapter 15).

These chapters focus on how the different object systems work, not how to use them effectively. This is unfortunate, but necessary, because many of the technical details are not described elsewhere, and effective use of OOP needs a whole book of its own.

- Metaprogramming (previously called “computing on the language”) describes the suite of tools that you can use to generate code with code. Compared to the 1st edition this material has been substantially expanded and now focusses on “tidy evaluation”, a set of ideas and theory that make metaprogramming safe, well-principled, and accessible to many more R programmers. Chapter 16, “Expressions”, describes the underlying data structures; Chapter 17, “Quasiquotation”, quoting and unquoting; Chapter 18, “Evaluation”, evaluating code in special environments; and Chapter 19, “Translations”, pulls all the themes together to show how you might translate from one (programming) language to another.

The final section of the book collects chapters on programming techniques, including debugging, profiling, improving performance, and connecting R and C++.

While the 2nd edition has mostly expanded coverage of existing material, there were four chapters that have been removed:

- The vocabulary chapter has been removed because it was always a bit of an odd duck, and there are more effective ways to present vocabulary lists than in a book chapter.
- The style chapter has been replaced with an online style guide, <http://style.tidyverse.org/>. The style guide is paired with the new styler (<http://styler.r-lib.org/>) package which can automatically apply many of the rules.
- The C chapter has been moved to a new repo, <https://github.com/hadley/r-internals>, which, over time, will provide a guide to writing C code that work’s with R’s data structures.
- The memory chapter has been removed. Much of the material has been integrated into Chapter 2 and the remainder felt excessively technical and not that important to understand.

Chapter 1

Introduction

I have now been programming in R for over 15 years, and have been doing it full-time for the last five years. This has given me the luxury of time to spend on understanding how the language works. This book is my attempt to pass on what I've learned so that you can understand the intricacies of R as quickly and painlessly as possible. Reading it will help you avoid the mistakes I've made and dead ends I've gone down, and will teach you useful tools, techniques, and idioms that can help you to attack many types of problems. In the process, I hope to show that, despite its sometimes frustrating quirks, R is, at its heart, an elegant and beautiful language, well tailored for data science.

1.1 Why R?

If you are new to R, you might wonder what makes learning such a quirky language worthwhile. To me, some of the best features are:

- It's free, open source, and available on every major platform. As a result, if you do your analysis in R, anyone can easily replicate it, regardless of where they live or how much money they earn.
- R has a diverse and welcoming community, both online (e.g. the #rstats twitter community (<https://twitter.com/search?q=%23rstats>)) and in person (like the many R meetups (<https://www.meetup.com/topics/r-programming-language/>)). Two particularly inspiring community groups are the rweekly newsletter (<https://rweekly.org>) which makes it easy to keep up to date with R, and the R-Ladies (<http://r-ladies.org>) organization

which has made a wonderfully welcoming community for women and gender minorities.

- A massive set of packages for statistical modelling, machine learning, visualisation, and importing and manipulating data. Whatever model or graphic you’re trying to do, chances are that someone has already tried to do it and you can learn from their efforts.
- Powerful tools for communicating your results. RMarkdown (<https://rmarkdown.rstudio.com>) makes it easy to turn your results into R packages into HTML, PDFs, word documents, powerpoint presentations, dashboards and more. Shiny (<http://shiny.rstudio.com>) allows you to make beautiful interactive apps without any knowledge of HTML or javascript.
- RStudio, the IDE (<http://www.rstudio.com/ide/>), which is tailored to the needs of data science, interactive data analysis, and statistical programming.
- Cutting edge tools. Researchers in statistics and machine learning will often publish an R package to accompany their articles. This means immediate access to the very latest statistical techniques and implementations.
- Deep-seated language support for data analysis. This includes features like missing values, data frames, and subsetting.
- A strong foundation of functional programming. The ideas of functional programming are well suited to the challenges of data science, and the R language is functional at heart, and provides many primitives needed for effective functional programming.
- RStudio, the company (<https://www.rstudio.com>), which makes money by selling professional products to teams of R users, and turns around and invests much of that money back into the open source community. I work for RStudio because I fundamentally believe in its mission.
- Powerful metaprogramming facilities. R’s metaprogramming capabilities allow you to write magically succinct and concise functions and provide an excellent environment for designing domain-specific languages like ggplot2, dplyr, data.table, and more.
- The ease with which R can connect to high-performance programming languages like C, Fortran, and C++.

Of course, R is not perfect. R’s biggest challenge (and opportunity!) is that most R users are not programmers. This means that:

- Much of the R code you'll see in the wild is written in haste to solve a pressing problem. As a result, code is not very elegant, fast, or easy to understand. Most users do not revise their code to address these shortcomings.
- Compared to other programming languages, the R community is more focussed on results than processes. Knowledge of software engineering best practices is patchy: for instance, not enough R programmers use source code control or automated testing.
- Metaprogramming is a double-edged sword. Too many R functions use tricks to reduce the amount of typing at the cost of making code that is hard to understand and that can fail in unexpected ways.
- Inconsistency is rife across contributed packages, and even within base R. You are confronted with over 20 years of evolution every time you use R, and this can make learning R tough because there are so many special cases to remember.
- R is not a particularly fast programming language, and poorly written R code can be terribly slow. R is also a profligate user of memory.

Personally, I think these challenges create a great opportunity for experienced programmers to have a profound positive impact on R and the R community. R users do care about writing high quality code, particularly for reproducible research, but they don't yet have the skills to do so. I hope this book will not only help more R users to become R programmers, but also encourage programmers from other languages to contribute to R.

1.2 Who should read this book

This book is aimed at two complementary audiences:

- Intermediate R programmers who want to dive deeper into R and learn new strategies for solving diverse problems.
- Programmers from other languages who are learning R and want to understand why R works the way it does.

To get the most out of this book, you'll need to have written a decent amount of code in R or another programming language. You should be familiar with the basics of data analysis (i.e. data import, manipulation, and visualisation), have written a number of functions, and be familiar with the installation and use of CRAN packages.

This book works the narrow line between being a reference book (primarily used for lookup), and being linearly readable. This involves some tradeoffs, because it's difficult to linearise material while still keeping related materials together, whereas some concepts are much easier to explain if you're already familiar with specific technical vocabulary. I've tried to use footnotes and cross-references to make sure you can still make sense even if you just dip your toes in the occasional chapter.

1.3 What you will get out of this book

This book delivers the knowledge that I think an advanced R programmer should possess: a deep understanding of the fundamentals coupled with a broad vocabulary that means that you can tactically learn more about a topic when needed.

After reading this book, you will:

- Be familiar with the fundamentals of R. You will understand complex data types and the best ways to perform operations on them. You will have a deep understanding of how functions work, and be able to recognise and use the four object systems in R.
- Understand what functional programming means, and why it is a useful tool for data science. You'll be able to quickly learn how to use existing tools, and have the knowledge to create your own functional tools when needed.
- Appreciate the double-edged sword of metaprogramming. You'll be able to create functions that use tidy evaluation, saving typing and creating elegant code to express important operations. You'll also understand the dangers and when to avoid it.
- Have a good intuition for which operations in R are slow or use a lot of memory. You'll know how to use profiling to pinpoint performance bottlenecks, and you'll know enough C++ to convert slow R functions to fast C++ equivalents.
- Be comfortable reading and understanding the majority of R code. You'll recognise common idioms (even if you wouldn't use them yourself) and be able to critique others' code.

1.4 What you will not learn

This book is about R the programming language, not R the data analysis tool. If you are looking to improve your data science skills, I instead recommend that you learn about the tidyverse (<https://www.tidyverse.org/>), a collection of consistent packages developed by me and my colleagues. In this book you'll learn the techniques used to develop the tidyverse package; if you want to instead learn how to use them, I recommend "R for Data Science" (<http://r4ds.had.co.nz/>).

If you want to share your R code with others, you will need to make an R package. This allows you to bundle code along with documentation and unit tests, and easily distribute it via CRAN. In my opinion, the easiest way to develop packages is with devtools (<http://devtools.r-lib.org>), roxygen2 (<http://klutometis.github.io/roxygen/>), testthat (<http://testthat.r-lib.org>), and usethis (<http://usethis.r-lib.org>). You can learn about using them to make your own package in "R packages" (<http://r-pkgs.had.co.nz/>).

1.5 Meta-techniques

There are two meta-techniques that are tremendously helpful for improving your skills as an R programmer: reading source code and adopting a scientific mindset.

Reading source code is important because it will help you write better code. A great place to start developing this skill is to look at the source code of the functions and packages you use most often. You'll find things that are worth emulating in your own code and you'll develop a sense of taste for what makes good R code. You will also see things that you don't like, either because its virtues are not obvious or it offends your sensibilities. Such code is nonetheless valuable, because it helps make concrete your opinions on good and bad code.

A scientific mindset is extremely helpful when learning R. If you don't understand how something works, develop a hypothesis, design some experiments, run them, and record the results. This exercise is extremely useful since if you can't figure something out and need to get help, you can easily show others what you tried. Also, when you learn the right answer, you'll be mentally prepared to update your world view.

1.6 Recommended reading

Because the R community mostly consists of data scientists, not computer scientists, there are relatively few books that go deep in the technical underpinnings of R. In my personal journey to understand R, I've found it particularly helpful to use resources from other programming languages. R has aspects of both functional and object-oriented (OO) programming languages. Learning how these concepts are expressed in R will help you leverage your existing knowledge of other programming languages, and will help you identify areas where you can improve.

To understand why R's object systems work the way they do, I found “The Structure and Interpretation of Computer Programs”¹ (Abelson, Sussman, and Sussman 1996) (SICP) by Harold Abelson and Gerald Jay Sussman, to be particularly helpful. It's a concise but deep book, and after reading it, I felt for the first time that I could actually design my own object-oriented system. The book was my first introduction to the encapsulated paradigm of object oriented programming found in R, and it helped me understand the strengths and weaknesses of this system. SICP also teaches the functional mindset where you create functions that are simple individually, and which become powerful when composed together.

To understand the trade-offs that R has made compared to other programming languages, I found “Concepts, Techniques and Models of Computer Programming” (Van-Roy and Haridi 2004) extremely helpful. It helped me understand that R's copy-on-modify semantics make it substantially easier to reason about code, and that while its current implementation is not particularly efficient, it is a solvable problem.

If you want to learn to be a better programmer, there's no place better to turn than “The Pragmatic Programmer” (Hunt and Thomas 1990) by Andrew Hunt and David Thomas. This book is language agnostic, and provides great advice for how to be a better programmer.

1.7 Getting help

Currently, there are three main venues to get help when you're stuck and can't figure out what's causing the problem: RStudio Community (<https://community.rstudio.com/>), stackoverflow (<http://stackoverflow.com>) and the R-help mailing

¹You can read it online for free at <https://mitpress.mit.edu/sites/default/files/sicp/full-text/book/book.html>

list (<https://stat.ethz.ch/mailman/listinfo/r-help>). You can get fantastic help in each venue, but they do have their own cultures and expectations. It's usually a good idea to spend a little time lurking, learning about community expectations, before you put up your first post.

Some good general advice:

- Make sure you have the latest version of R and of the package (or packages) you are having problems with. It may be that your problem is the result of a recently fixed bug.
- Spend some time creating a **reproducible example**, or reprex. This will help others help you, and often leads to a solution without asking others, because in the course of making the problem reproducible you often figure out the root cause. I highly recommend learning and using the reprex (<https://reprex.tidyverse.org/>) package.

1.8 Acknowledgments

I would like to thank the many contributors to R-devel and R-help and, more recently, Stack Overflow and RStudio Community. There are too many to name individually, but I'd particularly like to thank Luke Tierney, John Chambers, Dirk Eddelbuettel, JJ Allaire, and Brian Ripley for generously giving their time and correcting my countless misunderstandings.

This book was written in the open (<https://github.com/hadley/adv-r/>), and chapters were advertised on twitter (<https://twitter.com/hadleywickham>) when complete. It is truly a community effort: many people read drafts, fixed typos, suggested improvements, and contributed content. Without those contributors, the book wouldn't be nearly as good as it is, and I'm deeply grateful for their help. Special thanks go to Jeff Hammerbacher, Peter Li, Greg Wilson, who all read the book from cover-to-cover and provided many fixes and suggestions. Other consistently helpful contributors were Aaron Schumacher, @crtahlin, Lingbing Feng, @juancentro, @johnbaums, and .

Thanks go to all contributors in alphabetical order: Aaron Wolen (@aaronwolen), @absolutelyNoWarranty, Adam Hunt (@adamphunt), @agrabovsky, Alexander Grueneberg (@agrueneberg), Anthony Damico (@ajdamico), James Manton (@ajdm), Aaron Schumacher (@ajschumacher), Alan Dipert (@alandipert), Alex Brown (@alexbbrown), @alexperrone, Alex Whitworth (@alexWhitworth), Alexandros Kokkalis (@alko989), @amarchin, Amelia McNamara (@AmeliaMN), Bryce Mecum (@amoeba), Andrew Laucius (@andrewlwa), Andrew Bray (@andrewpbray), Andrie de Vries (@andrie), @aranlunzer, Ari

Lamstein (@arilamstein), @asnr, Andy Teucher (@ateucher), Albert Vilella (@avilella), baptiste (@baptiste), Brian G. Barkley (@BarkleyBG), Mara Averick (@batpigandme), Barbara Borges Ribeiro (@bborgesr), Brandon Greenwell (@bgreenwell), Brandon Hurr (@bhive01), Jason Knight (@binarybana), Brett Klamer (@bklamer), Jesse Anderson (@blindjesse), Brian Mayer (@blmayer), Benjamin L. Moore (@blmoore), Brian Diggs (@BrianDiggs), Brian S. Yandell (@byandell), @carey1024, Chip Hogg (@chiphogg), Chris Muir (@ChrisMuir), Christopher Gandrud (@christophergandrud), Clay Ford (@clayford), Colin Fay (@ColinFay), @cortinah, Cameron Plouffe (@cplouffe), Carson Sievert (@cpsiever), Craig Citro (@craigcitro), Craig Grabowski (@craiggrabowski), Christopher Roach (@croach), Peter Meilstrup (@crowding), Crt Ahlin (@crtahlin), Carlos Scheidegger (@cscheid), Colin Gillespie (@csgillespie), Christopher Brown (@ctbrown), Davor Cubranic (@cubranic), Darren Cusanovich (@cusanovich), Christian G. Warden (@cwarden), Charlotte Wickham (@cwickham), Dean Attali (@daattali), Dan Sullivan (@dan87134), Daniel Barnett (@daniel-barnett), Kenny Darrell (@darrkj), Tracy Nance (@datapixie), Dave Childers (@dav-echilders), David Rubinger (@davidrubinger), David Chudzicki (@dchudz), Daisuke ICHIKAWA (@dichika), david kahle (@dkahle), David LeBauer (@le-bauer), David Schweizer (@dlschweizer), David Montaner (@dmontaner), Zhuoer Dong (@dongzhuoer), Doug Mitarotonda (@dougmitarotonda), Jonathan Hill (@Dripdrop12), Julian During (@duju211), @duncanwadsworth, @eaurele, Dirk Eddelbuettel (@eddelbuettel), @EdFineOKL, Edwin Thoen (@EdwinTh), Ethan Heinzen (@eheinzen), @eijoac, Joel Schwartz (@eipi10), Eric Ronald Legrand (@elegrand), Ellis Valentiner (@ellisvalentiner), Emil Hvitfeldt (@EmilHvitfeldt), Emil Rehnberg (@EmilRehnberg), Daniel Lee (@erget), Eric C. Anderson (@eriqande), Enrico Spinielli (@espinielli), @etb, David Hajage (@eusebe), Fabian Scheipl (@fabian-s), @flammy0530, François Michonneau (@fmichonneau), Francois Pepin (@fpepin), Frank Farach (@frankfarach), @freezby, Frans van Dunné (@FvD), @fyears, @gagnagaman, Garrett Grolemund (@garrettgman), Gavin Simpson (@gavinsimpson), @gezakiss7, @gggtest, Gökçen Eraslan (@gokceneraslan), Georg Russ (@gr650), @grasshoppermouse, Gregor Thomas (@gregorp), Garrett See (@gsee), Ari Friedman (@gsk3), Gunnlaugur Thor Briem (@gthb), Hadley Wickham (@hadley), Hamed (@hamedbh), Harley Day (@harleyday), @hassaad85, @helmingstay, Henning (@henningsway), Henrik Bengtsson (@HenrikBengtsson), Ching Boon (@hoscb), Iain Dillingham (@iaindillingham), @IanKopacka, Ian Lyttle (@ijlyttle), Ilan Man (@ilanman), Imanuel Costigan (@imanuelcostigan), Thomas Bürli (@initdch), Os Keyes (@Ironholds), @irudnyts, i (@isomorphisms), Irene Steves (@isteves), Jan Gleixner (@jan-glx), Jason Asher (@jasonasher), Jason Davies (@jasondavies), Chris (@jastingo), jcborras (@jcborras), John Blischak (@jdblischak), @je-harmse, Lukas Burk (@jemus42), Jennifer (Jenny) Bryan (@jennybc), Justin

Jent (@jentjr), Jeston (@JestonBlu), Jim Hester (@jimhester), @JimInNashville, @jimmyliu2017, Jim Vine (@jimvine), Jinlong Yang (@jinlong25), J.J. Allaire (@jjallaire), @JMHay, Jochen Van de Velde (@jochenvdv), Johann Hibschnan (@johannh), John Baumgartner (@johnbaums), John Horton (@johnjosephhorton), @johnthomas12, Jon Calder (@jonmcalder), Jon Harmon (@jonthegEEK), Julia Gustavsen (@joolia), JorneBicler (@JorneBicler), Jeffrey Arnold (@jrnold), Joyce Robbins (@jtr13), Juan Manuel Truppia (@juancentro), Kevin Markham (@justmarkham), john verzani (@jverzani), Michael Kane (@kaneplus-plus), Bart Kastermans (@kasterma), Kevin D'Auria (@kdauria), Karandeep Singh (@kdpsingh), Ken Williams (@kenahoo), Kendon Bell (@kendonB), Kent Johnson (@kent37), Kevin Ushey (@kevinushey), (@kfeng123), Karl Forner (@kforner), Kirill Sevastyanenko (@kirillseva), Brian Knaus (@knausb), Kirill Müller (@krlmlr), Kriti Sen Sharma (@ksens), Kevin Wright (@kwstat), suo.lawrence.liu@gmail.com (mailto:suo.lawrence.liu@gmail.com) (@Lawrence-Liu), @ldfmrails, Rachel Severson (@leighseverson), Laurent Gatto (@lgatto), C. Jason Liang (@liangcj), Steve Lianoglou (@lianatos), @lindbrook, Lingbing Feng (@Lingbing), Marcel Ramos (@LiNk-NY), Zhongpeng Lin (@linzhp), Lionel Henry (@lionel-), myq (@lrcg), Luke W Johnston (@lwjohnst86), Kevin Lynagh (@lynaghk), Malcolm Barrett (@malcolmbarrett), @mannyishere, Matt (@mattbaggott), Matthew Grogan (@mattgrogan), @matthewhillary, Matthieu Gomez (@matthieugomez), Matt Malin (@mattmalin), Mauro Lepore (@maurolepo), Max Ghenis (@MaxGhenis), Maximilian Held (@maxheld83), Michal Bojanowski (@mbojan), Mark Rosenstein (@mbrmbr), Michael Sumner (@mdsumner), Jun Mei (@meijun), merkliopas (@merkliopas), mfrasco (@mfrasco), Michael Bach (@michaelbach), Michael Bishop (@MichaelMBishop), Michael Buckley (@michaelmikebuckley), Michael Quinn (@michaelquinn32), @miguelmorin, Michael (@mikekaminsky), Mine Cetinkaya-Rundel (@minecetinkaya-rundel), @mjsduncan, Mamoun Benghezal (@MoBeng), Matt Pettis (@mpettis), Martin Morgan (@mtmorgan), Guy Dawson (@Mullefa), Nacho Caballero (@nachocab), Natalya Rapstine (@natalya-patrikeeva), Nick Carchedi (@ncarchedi), Noah Greifer (@ngreifer), Nicholas Vasile (@nickv9), Nikos Ignatiadis (@nignatiadis), Xavier Laviron (@norival), Nick Pullen (@nstjhp), Oge Nnadi (@ogennadi), Oliver Paisley (@oliverpaisley), Pariksheet Nanda (@omsai), Øystein Sørensen (@osorensen), Paul (@otepoti), Otho Mantegazza (@othomantegazza), Dewey Dunnington (@paleolimbot), Parker Abercrombie (@parkerabercrombie), Patrick Hausmann (@patperu), Patrick Miller (@patr1ckm), Patrick Werkmeister (@Patrick01), @paulponcet, @pdb61, Tom Crockett (@pelotom), @pengyu, Jeremiah (@perryjer1), Peter Hickey (@Pete-Haitch), Phil Chalmers (@philchalmers), Jose Antonio Magaña Mesa (@picarus), Pierre Casadebaig (@picasa), Antonio Piccolboni (@piccolbo), Pierre Roudier (@pierreroudier), Poor Yorick (@pooryorick), Marie-Helene Burle (@prosoitos),

Peter Schulam (@pschulam), John (@quantbo), Quyu Kong (@qykong), Ramiro Magno (@ramiromagno), Ramnath Vaidyanathan (@ramnathv), Kun Ren (@renkun-ken), Richard Reeve (@richardreeve), Richard Cotton (@richierocks), Robert M Flight (@rmflight), R. Mark Sharp (@rmsharp), Robert Krzyzanowski (@robertzk), @robiRagan, Romain François (@romainfrancois), Ross Holmberg (@rossholmberg), Ricardo Pietrobon (@rpietro), @rrunner, Ryan Walker (@rtwalker), @rubenfcasal, Rob Weyant (@rweyant), Rumen Zarev (@rzarev), Nan Wang (@sailingwave), @sbgraves237, Scott Kostyshak (@scottkosty), Scott Leishman (@sctl), Sean Hughes (@seaaan), Sean Anderson (@seananderson), Sean Carmody (@seancarmody), Sebastian (@sebastian-c), Matthew Sedaghatfar (@sedaghatfar), @see24, Sven E. Templer (@setempler), @sflippl, @shabbybanks, Steven Pav (@shabbychef), Shannon Rush (@shannonrush), S'busiso Mkhondwane (@sibusiso16), Sigfried Gold (@Sigfried), Simon O'Hanlon (@simonohanlon101), Simon Potter (@sjp), Steve (@SplashDance), Scott Ritchie (@sritchie73), Tim Cole (@statist7), @ste-fan, @stephens999, Steve Walker (@stevencarlislewalker), Stefan Widgren (@stewid), Homer Strong (@strongh), Dirk (@surmann), Sebastien Vigneau (@svigneau), Scott Warchal (@Swarchal), Steven Nydick (@swnydick), Taekyun Kim (@taekyunk), Tal Galili (@talgalili), @Tazinho, Tom B (@tbuckl), @tdenes, @thomasherbig, Thomas (@thomaskern), Thomas Lin Pedersen (@thomasp85), Thomas Zumbrunn (@thomaszumbrunn), Tim Waterhouse (@timwaterhouse), TJ Mahr (@tjmahr), Anton Antonov (@tonytonov), Ben Torvaney (@Torvaney), Jeff Allen (@trestletech), Terence Teo (@tdeo), Tim Triche, Jr. (@ttriche), @tyhenkaline, Tyler Ritchie (@tylerritchie), Varun Agrawal (@varun729), Vijay Barve (@vijaybarve), Victor (@vkryukov), Vaidotas Zemlys-Balevičius (@vzemlys), Winston Chang (@wch), Linda Chin (@wchi144), Welliton Souza (@Welliton309), Gregg Whitworth (@whitwort), Will Beasley (@wibeasley), William R Bauer (@WilCrofter), William Doane (@WilDoane), Sean Wilkinson (@wilkinson), Christof Winter (@winterschlaefer), Bill Carver (@wmc3), Wolfgang Huber (@wolfganghuber), Krishna Sankar (@xsankar), Yihui Xie (@yihui), yang (@yiluhehei), Yoni Ben-Meshulam (@yoni), @yuchouchen, @zachcp, @zackham, Edward Cho (@zerokarmaleft), Albert Zhao (@zxzb).

1.9 Conventions

Throughout this book I use `f()` to refer to functions, `g` to refer to variables and function parameters, and `h/` to paths.

Larger code blocks intermingle input and output. Output is commented so that if you have an electronic version of the book, e.g., <https://adv-r.hadley.nz/>, you can easily copy and paste examples into R. Output comments look like `#>` to

distinguish them from regular comments.

Many examples use random numbers. These are made reproducible by `set.seed(1014)`, which is executed automatically at the start of each chapter.

1.10 Colophon

This book was written in bookdown (<http://bookdown.org/>) inside RStudio (<http://www.rstudio.com/ide/>). The website (<https://adv-r.hadley.nz/>) is hosted with netlify (<http://netlify.com/>), and automatically updated after every commit by travis-ci (<https://travis-ci.org/>). The complete source is available from github (<https://github.com/hadley/adv-r>). Code in the printed book is set in inconsolata (<http://levien.com/type/myfonts/inconsolata.html>). Emoji come from the open-licensed Twitter Emoji (<https://github.com/twitter/twemoji>).

This version of the book was built with the following version of R and packages.

setting	value
version	R version 3.5.1 (2017-01-27)
os	Ubuntu 14.04.5 LTS
system	x86_64, linux-gnu
ui	X11
language	(EN)
collate	en_US.UTF-8
ctype	en_US.UTF-8
tz	UTC
date	2018-11-19

package	version	source
assertthat	0.2.0	CRAN (R 3.5.1)
backports	1.1.2	CRAN (R 3.5.1)
base64enc	0.1-3	CRAN (R 3.5.1)
bench	1.0.1	CRAN (R 3.5.1)
BH	1.66.0-1	CRAN (R 3.5.1)
bindr	0.1.1	CRAN (R 3.5.1)
bindrcpp	0.2.2	CRAN (R 3.5.1)
bit	1.1-14	CRAN (R 3.5.1)
bit64	0.9-7	CRAN (R 3.5.1)
blob	1.1.1	CRAN (R 3.5.1)
bookdown	0.7	CRAN (R 3.5.1)

package	version	source
cli	1.0.1	CRAN (R 3.5.1)
codetools	0.2-15	CRAN (R 3.5.1)
colorspace	1.3-2	CRAN (R 3.5.1)
crayon	1.3.4	CRAN (R 3.5.1)
DBI	1.0.0	CRAN (R 3.5.1)
dbplyr	1.2.2	CRAN (R 3.5.1)
desc	1.2.0	CRAN (R 3.5.1)
digest	0.6.18	CRAN (R 3.5.1)
dplyr	0.7.8	CRAN (R 3.5.1)
emo	0.0.0.9000	Github (hadley/emo@02a5206)
evaluate	0.12	CRAN (R 3.5.1)
fansi	0.4.0	CRAN (R 3.5.1)
furrr	0.1.0	CRAN (R 3.5.1)
future	1.10.0	CRAN (R 3.5.1)
ggplot2	3.1.0	CRAN (R 3.5.1)
globals	0.12.4	CRAN (R 3.5.1)
glue	1.3.0	Github (tidyverse/glue@35c61e9)
gttable	0.2.0	CRAN (R 3.5.1)
highr	0.7	CRAN (R 3.5.1)
hms	0.4.2	CRAN (R 3.5.1)
htmltools	0.3.6	CRAN (R 3.5.1)
httpuv	1.4.5	CRAN (R 3.5.1)
inline	0.3.15	CRAN (R 3.5.1)
jsonlite	1.5	CRAN (R 3.5.1)
knitr	1.20	CRAN (R 3.5.1)
labeling	0.3	CRAN (R 3.5.1)
later	0.7.5	CRAN (R 3.5.1)
lattice	0.20-35	CRAN (R 3.5.1)
lazyeval	0.2.1	CRAN (R 3.5.1)
lineprof	0.1.9001	Github (hadley/lineprof@972e71d)
listenv	0.7.0	CRAN (R 3.5.1)
lobstr	0.0.0.9000	Github (r-lib/lobstr@2ab73e8)
lubridate	1.7.4	CRAN (R 3.5.1)
magrittr	1.5	CRAN (R 3.5.1)
markdown	0.8	CRAN (R 3.5.1)
MASS	7.3-50	CRAN (R 3.5.1)
Matrix	1.2-14	CRAN (R 3.5.1)
memoise	1.1.0	CRAN (R 3.5.1)
mgcv	1.8-24	CRAN (R 3.5.1)
microbenchmark	1.4-6	CRAN (R 3.5.1)

package	version	source
mime	0.6	CRAN (R 3.5.1)
munsell	0.5.0	CRAN (R 3.5.1)
nlme	3.1-137	CRAN (R 3.5.1)
pillar	1.3.0	CRAN (R 3.5.1)
pkgconfig	2.0.2	CRAN (R 3.5.1)
plogr	0.2.0	CRAN (R 3.5.1)
plyr	1.8.4	CRAN (R 3.5.1)
png	0.1-7	CRAN (R 3.5.1)
praise	1.0.0	CRAN (R 3.5.1)
prettyunits	1.0.2	CRAN (R 3.5.1)
profmem	0.5.0	CRAN (R 3.5.1)
promises	1.0.1	CRAN (R 3.5.1)
pryr	0.1.4	CRAN (R 3.5.1)
purrr	0.2.5	CRAN (R 3.5.1)
R6	2.3.0	CRAN (R 3.5.1)
RColorBrewer	1.1-2	CRAN (R 3.5.1)
Rcpp	1.0.0	CRAN (R 3.5.1)
readr	1.1.1	CRAN (R 3.5.1)
reshape2	1.4.3	CRAN (R 3.5.1)
rlang	0.3.0.1	CRAN (R 3.5.1)
rmarkdown	1.10	CRAN (R 3.5.1)
rprojroot	1.3-2	CRAN (R 3.5.1)
RSQLite	2.1.1	CRAN (R 3.5.1)
scales	1.0.0	CRAN (R 3.5.1)
sessioninfo	1.1.1	CRAN (R 3.5.1)
shiny	1.2.0	CRAN (R 3.5.1)
sloop	1.0.0	CRAN (R 3.5.1)
sourcetools	0.1.7	CRAN (R 3.5.1)
stringi	1.2.4	CRAN (R 3.5.1)
stringr	1.3.1	CRAN (R 3.5.1)
testthat	2.0.1	CRAN (R 3.5.1)
tibble	1.4.2	CRAN (R 3.5.1)
tidyselect	0.2.5	CRAN (R 3.5.1)
tinytex	0.9	CRAN (R 3.5.1)
utf8	1.1.4	CRAN (R 3.5.1)
vctrs	0.0.0.9000	Github (r-lib/vctrs@688707c)
viridisLite	0.3.0	CRAN (R 3.5.1)
withr	2.1.2	CRAN (R 3.5.1)
xfun	0.4	CRAN (R 3.5.1)
xtable	1.8-3	CRAN (R 3.5.1)

package	version	source
yaml	2.2.0	CRAN (R 3.5.1)
zeallot	0.1.0	CRAN (R 3.5.1)

```
ruler()  
#> -----+---1---+---2---+---3---+---4---+---5---+---6---+---  
#> 12345678901234567890123456789012345678901234567890123456789
```

Part I

Foundations

Introduction

To start your journey in mastering R, the following six chapters will help you learn what I consider to be the foundational components of R. I expect that you've already seen many of these pieces before, but you probably have not studied them deeply. To help check your existing knowledge, each chapter starts with a quiz; if you get all the questions right, feel free to skip to the next chapter!

1. In Chapter 2, you'll learn about one of the most important distinctions you haven't previously needed to grapple with: the difference between an object and its name. Improving your mental model here will help you make better predictions about when R copies data and hence which basic operations are cheap and which are expensive.
2. Every day you've used R, you've used vectors, so Chapter 3 will dive into the details, helping you learn how the different types of vector fit together. You'll also learn about attributes, which allow you to store arbitrary metadata, and form the basis for two of R's object oriented programming toolkits
3. To write concise and performant R code it is important to fully appreciate the power of subsetting with `[`, `[[` and `$`, as described in Chapter 4. Understanding the fundamental components of subsetting will allow you to solve new problems by combining the building blocks in novel ways.
4. Functions are the most important building block of R code, and in Chapter 5, you'll learn exactly how they work, including the **scoping** rules, which govern how R looks up values from names. You'll also learn more of the details behind R's lazy evaluation, and how you can control what happens when you exit a function.
5. In Chapter 6, you'll learn about a data structure that is crucial for understanding how R works, but quite unimportant for data analysis: the environment. Environments are the data structure that binds names to values, and they power tools like package namespaces. Unlike most programming languages, environments in R are "first class" which means that

you can manipulate them just like other objects.

6. Chapter 7 concludes this section of the book with a discussion of “conditions”, the umbrella term used to describe errors, warnings, and messages. You’ve certainly encountered these before, so in this chapter you learn how to signal them appropriately in your own functions, and how to handle them when signalled elsewhere.

Chapter 2

Names and values

2.1 Introduction

In R, it is important to understand the distinction between an object and its name. Doing so will help you:

- More accurately predict the performance and memory usage of your code.
- Write faster code by avoiding accidental copies, a major source of slow code.
- Better understand R’s functional programming tools.

The goal of this chapter is to help you understand the distinction between names and values, and when R will copy an object.

Quiz

Answer the following questions to see if you can safely skip this chapter. You can find the answers at the end of the chapter in Section 2.7.

1. Given the following data frame, how do I create a new column called “3” that contains the sum of 1 and 2? You may only use \$, not [[. What makes 1, 2, and 3 challenging as variable names?

```
df <- data.frame(runif(3), runif(3))
names(df) <- c(1, 2)
```

2. In the following code, how much memory does y occupy?

```
x <- runif(1e6)
y <- list(x, x, x)
```

3. On which line does `a` get copied in the following example?

```
a <- c(1, 5, 3, 2)
b <- a
b[[1]] <- 10
```

Outline

- Section 2.2 introduces you to the distinction between names and values, and discusses how `<-` creates a binding, or reference, between a name and a value.
- Section 2.3 describes when R makes a copy: whenever you modify a vector, you’re almost certainly creating a new, modified vector. You’ll learn how to use `tracemem()` to figure out when a copy actually occurs. Then you’ll explore the implications as they apply to function calls, lists, data frames, and character vectors.
- Section 2.4 explores the implications of the previous two sections on how much memory an object occupies. Since your intuition may be profoundly wrong and since `utils::object.size()` is unfortunately inaccurate, you’ll learn how to use `lobstr::obj_size()`.
- Section 2.5 describes the two important exceptions to copy-on-modify: with environments and values with a single name, objects are actually modified in place.
- Section 2.6 concludes the chapter with a discussion of the garbage collector, which frees up the memory used by objects no longer referenced by a name.

Prerequisites

We’ll use the development version of `lobstr` (<https://github.com/r-lib/lobstr>) to dig into the internal representation of R objects.

```
# devtools::install_github("r-lib/lobstr")
library(lobstr)
```

Sources

The details of R’s memory management are not documented in a single place. Much of the information in this chapter was gleaned from a

close reading of the documentation (particularly `?Memory` and `?gc`), the memory profiling (<http://cran.r-project.org/doc/manuals/R-exts.html#Profiling-R-code-for-memory-use>) section of “Writing R extensions” (R Core Team 2018b), and the SEXPs (<http://cran.r-project.org/doc/manuals/R-ints.html#SEXPs>) section of “R internals” (R Core Team 2018a). The rest I figured out by reading the C source code, performing small experiments, and asking questions on R-devel. Any mistakes are entirely mine.

2.2 Binding basics

Consider this code:

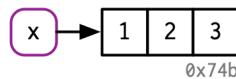
```
x <- c(1, 2, 3)
```

It’s easy to read it as: “create an object named ‘x’, containing the values 1, 2, and 3”. Unfortunately, that’s a simplification that will lead to inaccurate predictions about what R is actually doing behind the scenes. It’s more accurate to say that this code is doing two things:

- It’s creating an object, a vector of values, `c(1, 2, 3)`.
- And it’s binding that object to a name, `x`.

In other words, the object, or value, doesn’t have a name; it’s actually the name that has a value.

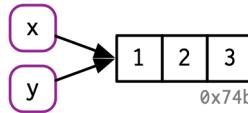
To further clarify this distinction, I’ll draw diagrams like this:



The name, `x`, is drawn with a rounded rectangle. It has an arrow that points to (or binds or references) the value, the vector `c(1, 2, 3)`. Note that the arrow points in opposite direction to the assignment arrow: `<-` creates a binding from the name on the left-hand side to the object on the right-hand side.

Thus, you can think of a name as a reference to a value. For example, if you run this code, you don’t get another copy of the value `c(1, 2, 3)`, you get another binding to the existing object:

```
y <- x
```



You might have noticed that the value `c(1, 2, 3)` has a label: `0x74b`. While the vector doesn't have a name, I'll occasionally need to refer to an object independent of its bindings. To make that possible, I'll label values with a unique identifier. These identifiers have a special form that looks like the object's memory "address", i.e. the location in memory where the object is stored. But because the actual memory addresses changes every time the code is run, we use these identifiers instead.

You can access an object's identifier with `lobstr::obj_addr()`. Doing so allows you to see that both `x` and `y` point to the same identifier:

```
obj_addr(x)
#> [1] "0x4411748"
obj_addr(y)
#> [1] "0x4411748"
```

These identifiers are long, and change every time you restart R.

It can take some time to get your head around the distinction between names and values, but understanding this is really helpful in functional programming where functions can have different names in different contexts.

2.2.1 Non-syntactic names

R has strict rules about what constitutes a valid name. A **syntactic** name must consist of letters¹, digits, . and _ but can't begin with _ or a digit. Additionally, you can't use any of the **reserved words** like `TRUE`, `NULL`, `if`, and `function` (see the complete list in `?Reserved`). A name that doesn't follow these rules is a **non-syntactic** name; if you try to use them, you'll get an error:

```
_abc <- 1
#> Error: unexpected input in "_"

if <- 10
#> Error: unexpected assignment in "if <-"
```

¹Surprisingly, what constitutes a letter is determined by your current locale. That means that the syntax of R code can actually differ from computer to computer, and that it's possible for a file that works on one computer to not even parse on another!

It's possible to override these rules and use any name, i.e., any sequence of characters, by surrounding it with backticks:

```
`_abc` <- 1
`_abc`
#> [1] 1

`if` <- 10
`if`
#> [1] 10
```

While it's unlikely you'd deliberately create such crazy names, you need to understand how these crazy names work because you'll come across them, most commonly when you load data that has been created outside of R.

You *can* also create non-syntactic bindings using single or double quotes (e.g. `"_abc" <- 1`) instead of backticks, but you shouldn't, because you'll have to use a different syntax to retrieve the values. The ability to use strings on the left hand side of the assignment arrow is an historical artefact, used before R supported backticks.

2.2.2 Exercises

1. Explain the relationship between `a`, `b`, `c` and `d` in the following code:

```
a <- 1:10
b <- a
c <- b
d <- 1:10
```

2. The following code accesses the `mean` function in multiple ways. Do they all point to the same underlying function object? Verify this with `lobstr::obj_addr()`.

```
mean
base::mean
get("mean")
evalq(mean)
match.fun("mean")
```

3. By default, base R data import functions, like `read.csv()`, will automatically convert non-syntactic names to syntactic ones. Why might this be problematic? What option allows you to suppress this behaviour

4. What rules does `make.names()` use to convert non-syntactic names into syntactic ones?
5. I slightly simplified the rules that govern syntactic names. Why is `.123e1` not a syntactic name? Read `?make.names` for the full details.

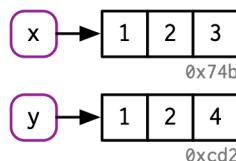
2.3 Copy-on-modify

Consider the following code. It binds `x` and `y` to the same underlying value, then modifies `y`.²

```
x <- c(1, 2, 3)
y <- x

y[[3]] <- 4
x
#> [1] 1 2 3
```

Modifying `y` clearly didn't modify `x`. So what happened to the shared binding? While the value associated with `y` changed, the original object did not. Instead, R created a new object, `0xcd2`, a copy of `0x74b` with one value changed, then rebinded `y` to that object.



This behaviour is called **copy-on-modify**. Understanding it will radically improve your intuition about the performance of R code. A related way to describe this behaviour is to say that R objects are unchangeable, or **immutable**. However, I'll generally avoid that term because there are a couple of important exceptions to copy-on-modify that you'll learn about in Section 2.5.

When exploring copy-on-modify behaviour interactively, be aware that you'll get different results inside of RStudio. That's because the environment pane must make a reference to each object in order to display information about it. This distorts your interactive exploration but doesn't affect code inside of functions, and so doesn't affect performance during data analysis. For experimentation, I

²You may be surprised to see `[[` used to subset a numeric vector. We'll come back to this in Section 4.3, but in brief, I think you should always use `[[` when you are getting or setting a single element.

recommend either running R directly from the terminal, or using RMarkdown (like this book).

2.3.1 `tracemem()`

You can see when an object gets copied with the help of `base::tracemem()`. Once you call that function with an object, you'll get the object's current address:

```
x <- c(1, 2, 3)
cat(tracemem(x), "\n")
#> <0x7f80c0e0ffc8>
```

From then on, whenever that object is copied, `tracemem()` will print a message telling you which object was copied, its new address, and the sequence of calls that led to the copy:

```
y <- x
y[[3]] <- 4L
#> tracemem[0x7f80c0e0ffc8 -> 0x7f80c4427f40]:
```

Note that if you modify `y` again, it won't get copied. That's because the new object now only has a single name bound to it, so R applies modify-in-place optimisation. We'll come back to this shortly.

```
y[[3]] <- 5L

untracemem(y)
```

`untracemem()` is the opposite of `tracemem()`; it turns tracing off.

2.3.2 Function calls

The same rules for copying also apply to function calls. Take this code:

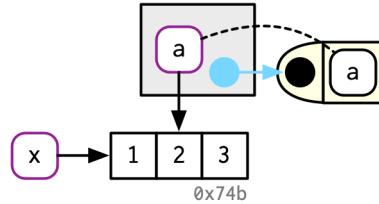
```
f <- function(a) {
  a
}

x <- c(1, 2, 3)
cat(tracemem(x), "\n")
#> <0x465a7f8>

z <- f(x)
```

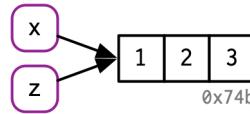
```
# there's no copy here!
untracemem(x)
```

While `f()` is running, the `a` inside the function points to the same value as the `x` does outside the function:



(You'll learn more about the conventions used in this diagram in Execution environments.)

Once `f()` completes, `x` and `z` will point to the same object. `0x74b` never gets copied because it never gets modified. If `f()` did modify `x`, R would create a new copy, and then `z` would bind that object.

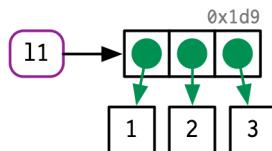


2.3.3 Lists

It's not just names (i.e. variables) that point to values; elements of lists do too. Take this list, which is superficially very similar to the vector above:

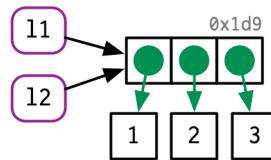
```
l1 <- list(1, 2, 3)
```

The internal representation of a list is actually quite different from that of a vector. A list is really a vector of references:

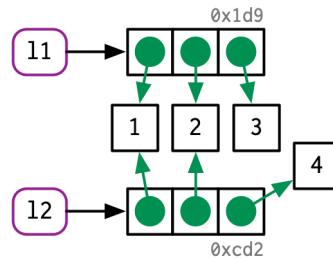


This is particularly important when we modify a list:

```
12 <- 11
```



```
12[[3]] <- 4
```



Like vectors, lists use copy-on-modify behaviour; the original list is left unchanged, and R creates a modified copy. This, however, is a **shallow** copy: the list object and its bindings are copied, but the values pointed to by the bindings are not. The opposite of a shallow copy is a deep copy where the contents of every reference are copied. Prior to R 3.1.0, copies were always deep copies.

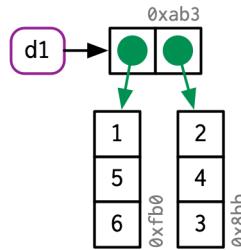
To see values that are shared across lists, use `lobstr::ref()`. `ref()` prints the memory address of each object, along with a local ID so that you can easily cross-reference shared components.

```
ref(11, 12)
#> [1:0x6ee2bb8] <list>
#> [2:0x6d42838] <dbl>
#> [3:0x6d42800] <dbl>
#> [4:0x6d427c8] <dbl>
#>
#> [5:0x792fc78] <list>
#> [2:0x6d42838]
#> [3:0x6d42800]
#> [6:0x783d5c8] <dbl>
```

2.3.4 Data frames

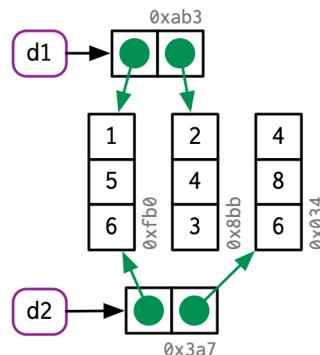
Data frames are lists of vectors, so copy-on-modify has important consequences when you modify a data frame. Take this data frame as an example:

```
d1 <- data.frame(x = c(1, 5, 6), y = c(2, 4, 3))
```



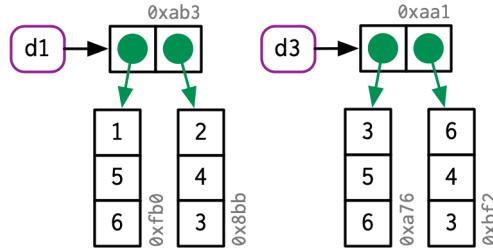
If you modify a column, only *that* column needs to be modified; the others will still point to their original references:

```
d2 <- d1
d2[, 2] <- d2[, 2] * 2
```



However, if you modify a row, there is no way to share data with the previous version of the data frame: every column must be copied-and-modified.

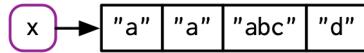
```
d3 <- d1
d3[1, ] <- d3[1, ] * 3
```



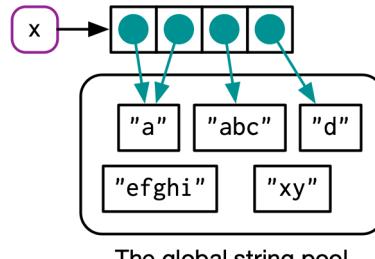
2.3.5 Character vectors

The final place that R uses references is with character vectors. I usually draw character vectors like this:

```
x <- c("a", "a", "abc", "d")
```



But this is a polite fiction. R actually uses a **global string pool** where each element of a character vector is a pointer to a unique string in the pool:



The global string pool

You can request that `ref()` show these references by setting the `character` argument to `TRUE`:

```
ref(x, character = TRUE)
#> [1:0x4246ed8] <chr>
#> [2:0x13ee788] <string: "a">
#> [2:0x13ee788]
#> [3:0x1f0ed10] <string: "abc">
#> [4:0x18a4b28] <string: "d">
```

This has a profound impact on the amount of memory a character vector uses but is otherwise generally unimportant, so elsewhere in the book I'll draw character vectors as if the strings lived inside a vector.

2.3.6 Exercises

1. Why is `tracemem(1:10)` not useful?
2. Explain why `tracemem()` shows two copies when you run this code. Hint: carefully look at the difference between this code and the code shown earlier in the section.

```
x <- c(1L, 2L, 3L)
tracemem(x)

x[[3]] <- 4
```

3. Sketch out the relationship between the following objects:

```
a <- 1:10
b <- list(a, a)
c <- list(b, a, 1:10)
```

4. What happens when you run this code?

```
x <- list(1:10)
x[[2]] <- x
```

Draw a picture.

2.4 Object size

You can find out how much memory an object takes with `lobstr::obj_size()`³:

```
obj_size(letters)
#> 1,712 B
obj_size(ggplot2::diamonds)
#> 3,456,344 B
```

Since the elements of lists are references to values, the size of a list might be much smaller than you expect:

```
x <- runif(1e6)
obj_size(x)
#> 8,000,048 B

y <- list(x, x, x)
```

³Beware of the `utils::object.size()` function. It does not correctly account for shared references and will return sizes that are too large.

```
obj_size(y)
#> 8,000,128 B
```

y is only 80 bytes⁴ bigger than x. That's the size of an empty list with three elements:

```
obj_size(list(NULL, NULL, NULL))
#> 80 B
```

Similarly, because R uses a global string pool character vectors take up less memory than you might expect: repeating a string 1000 times does not make it take up 1000 times as much memory.

```
banana <- "bananas bananas bananas"
obj_size(banana)
#> 136 B
obj_size(rep(banana, 100))
#> 928 B
```

References also make it challenging to think about the size of individual objects. `obj_size(x) + obj_size(y)` will only equal `obj_size(x, y)` if there are no shared values. Here, the combined size of x and y is the same as the size of y:

```
obj_size(x, y)
#> 8,000,128 B
```

Finally, R 3.5.0 and later have a feature that might lead to surprises: ALTREP, short for **alternative representation**. This allows R to represent certain types of vectors very compactly. The place you are most likely to see this is with : because instead of storing every single number in the sequence, R just stores the first and last number. This means that every sequence, no matter how large, is the same size:

```
obj_size(1:3)
#> 680 B
obj_size(1:1e3)
#> 680 B
obj_size(1:1e6)
#> 680 B
obj_size(1:1e9)
#> 680 B
```

⁴If you're running the 32-bit version of R you'll see slightly different sizes.

2.4.1 Exercises

1. In the following example, why are `object.size(y)` and `obj_size(y)` so radically different? Consult the documentation of `object.size()`.

```
y <- rep(list(runif(1e4)), 100)

object.size(y)
#> 8005648 bytes
obj_size(y)
#> 80,896 B
```

2. Take the following list. Why is its size somewhat misleading?

```
x <- list(mean, sd, var)
obj_size(x)
#> 17,608 B
```

3. Predict the output of the following code:

```
x <- runif(1e6)
obj_size(x)

y <- list(x, x)
obj_size(y)
obj_size(x, y)

y[[1]][[1]] <- 10
obj_size(y)
obj_size(x, y)

y[[2]][[1]] <- 10
obj_size(y)
obj_size(x, y)
```

2.5 Modify-in-place

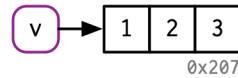
As we've seen above, modifying an R object usually creates a copy. There are two exceptions:

- Objects with a single binding get a special performance optimisation.
- Environments, a special type of object, are always modified in place.

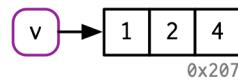
2.5.1 Objects with a single binding

If an object has a single name bound to it, R will modify it in place:

```
v <- c(1, 2, 3)
```



```
v[[3]] <- 4
```



(Note the object IDs here: `v` continues to bind to the same object, `0x207`.)

Two complications make predicting exactly when R applies this optimisation challenging:

- When it comes to bindings, R can currently⁵ only count 0, 1, or many. That means that if an object has two bindings, and one goes away, the reference count does not go back to 1: one less than many is still many.
- Whenever you call any regular function, it makes a reference to the object. The only exception are specially written C functions. These occur mostly in the base package.

Together, these two complications make it hard to predict whether or not a copy will occur. Instead, it's better to determine it empirically with `tracemem()`.

Let's explore the subtleties with a case study using for loops. For loops have a reputation for being slow in R, but often that slowness is caused by every iteration of the loop creating a copy. Consider the following code. It subtracts the median from each column of a large data frame:

```
x <- data.frame(matrix(runif(5 * 1e4), ncol = 5))
medians <- vapply(x, median, numeric(1))

for (i in seq_along(medians)) {
  x[[i]] <- x[[i]] - medians[[i]]
}
```

This loop is surprisingly slow because each iteration of the loop copies the data frame. You can see this by using `tracemem()`:

⁵By the time you read this, this may have changed, as plans are afoot to improve reference counting: <https://developer.r-project.org/RefCnt.html>

```

cat(tracemem(x), "\n")
#> <0x7f80c429e020>

for (i in 1:5) {
  x[[i]] <- x[[i]] - medians[[i]]
}
#> tracemem[0x7f80c429e020 -> 0x7f80c0c144d8]:
#> tracemem[0x7f80c0c144d8 -> 0x7f80c0c14540]: [[<-.data.frame [[<-
#> tracemem[0x7f80c0c14540 -> 0x7f80c0c145a8]: [[<-.data.frame [[<-
#> tracemem[0x7f80c0c145a8 -> 0x7f80c0c14610]:
#> tracemem[0x7f80c0c14610 -> 0x7f80c0c14678]: [[<-.data.frame [[<-
#> tracemem[0x7f80c0c14678 -> 0x7f80c0c146e0]: [[<-.data.frame [[<-
#> tracemem[0x7f80c0c146e0 -> 0x7f80c0c14748]:
#> tracemem[0x7f80c0c14748 -> 0x7f80c0c147b0]: [[<-.data.frame [[<-
#> tracemem[0x7f80c0c147b0 -> 0x7f80c0c14818]: [[<-.data.frame [[<-
#> tracemem[0x7f80c0c14818 -> 0x7f80c0c14880]:
#> tracemem[0x7f80c0c14880 -> 0x7f80c0c148e8]: [[<-.data.frame [[<-
#> tracemem[0x7f80c0c148e8 -> 0x7f80c0c14950]: [[<-.data.frame [[<-
#> tracemem[0x7f80c0c14950 -> 0x7f80c0c149b8]:
#> tracemem[0x7f80c0c149b8 -> 0x7f80c0c14a20]: [[<-.data.frame [[<-
#> tracemem[0x7f80c0c14a20 -> 0x7f80c0c14a88]: [[<-.data.frame [[<-

untracemem(x)

```

In fact, each iteration copies the data frame not once, not twice, but three times! Two copies are made by `[[.data.frame`, and a further copy⁶ is made because `[[.data.frame` is a regular function that increments the reference count of `x`.

We can reduce the number of copies by using a list instead of a data frame. Modifying a list uses internal C code, so the refs are not incremented and only a single copy is made:

```

y <- as.list(x)
cat(tracemem(y), "\n")
#> <0x7f80c5c3de20>

for (i in 1:5) {
  y[[i]] <- y[[i]] - medians[[i]]
}
#> tracemem[0x7f80c5c3de20 -> 0x7f80c48de210]:

```

⁶Note that these copies are shallow: they only copy the reference to each individual column, not the contents of the columns. This means the performance isn't terrible, but it's obviously not as good as it could be.

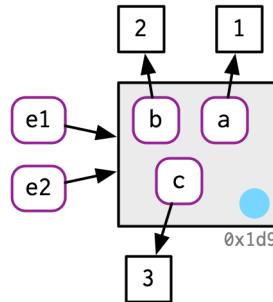
While it's not hard to determine when a copy is made, it is hard to prevent it. If you find yourself resorting to exotic tricks to avoid copies, it may be time to rewrite your function in C++, as described in Chapter 23.

2.5.2 Environments

You'll learn more about environments in Chapter 6, but it's important to mention them here because their behavior is different from that of other objects: environments are always modified in place. This property is sometimes described as **reference semantics** because when you modify an environment all existing bindings to that environment continue to have the same reference.

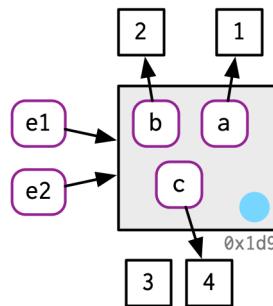
Take this environment, which we bind to `e1` and `e2`:

```
e1 <- rlang::env(a = 1, b = 2, c = 3)
e2 <- e1
```



If we change a binding, the environment is modified in place:

```
e1$c <- 4
e2$c
#> [1] 4
```



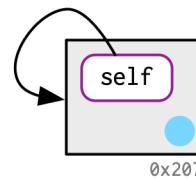
This basic idea can be used to create functions that “remember” their previous

state. See Section 9.2.3 for more details. This property is also used to implement the R6 object oriented programming system, the topic of Chapter 13.

One consequence of this is that environments can contain themselves:

```
e <- rlang::env()
e$self <- e

ref(e)
#> [1:0x993aa40] <env>
#> self = [1:0x993aa40]
```



This is a unique property of environments!

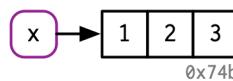
2.5.3 Exercises

1. Wrap the two methods for subtracting medians into two functions, then use the ‘bench’ package (Hester 2018) to carefully compare their speeds. How does performance change as the number of columns increase?
2. What happens if you attempt to use `tracemem()` on an environment?

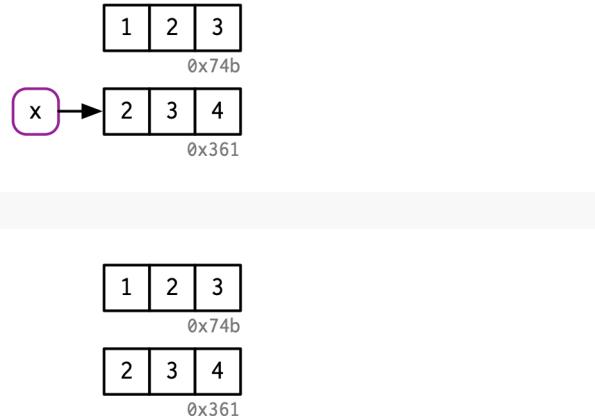
2.6 Unbinding and the garbage collector

Consider this code:

```
x <- 1:3
```



```
x <- 2:4
```



We created two objects, but by the time the code finishes, neither object is bound to a name. How do these objects get deleted? That's the job of the **garbage collector**, or GC for short. The GC frees up memory by deleting R objects that are no longer used, and by requesting more memory from the operating system if needed.

R uses a **tracing** GC. This means it traces every object that's reachable from the global⁷ environment, and all objects that are, in turn, reachable from those objects (i.e. the references in lists and environments are searched recursively). The garbage collector does not use the modify-in-place reference count described above. While these two ideas are closely related, the internal data structures are optimised for different use cases.

The garbage collector (GC) runs automatically whenever R needs more memory to create a new object. Looking from the outside, it's basically impossible to predict when the GC will run. In fact, you shouldn't even try. If you want to find out when the GC runs, call `gcinfo(TRUE)` and GC will print a message to the console every time it runs.

You can force garbage collection by calling `gc()`. But despite what you might have read elsewhere, there's never any *need* to call `gc()` yourself. The only reasons you might *want* to call `gc()` is to ask R to return memory to your operating system, or is for the side-effect that tells you how much memory is currently being used:

```
gc()
#>           used (Mb) gc trigger (Mb) max used (Mb)
#> Ncells  584035 31.2    1296008 69.3  1296008 69.3
#> Vcells 3128452 23.9   13394499 102.2 11684299 89.2
```

`lobstr::mem_used()` is a wrapper around `gc()` that prints the total number of

⁷And every environment in the current call stack.

bytes used:

```
mem_used()
#> 57,733,256 B
```

This number won't agree with the amount of memory reported by your operating system. There are three reasons:

1. It includes objects created by R but not by the R interpreter.
2. Both R and the operating system are lazy: they won't reclaim memory until it's actually needed. R might be holding on to memory because the OS hasn't yet asked for it back.
3. R counts the memory occupied by objects but there may be empty gaps due to deleted objects. This problem is known as memory fragmentation.

2.7 Answers

1. You must quote non-syntactic names with backticks: ``: for example, the variables 1, 2, and 3.

```
df <- data.frame(runif(3), runif(3))
names(df) <- c(1, 2)

df$`3` <- df$`1` + df$`2`
```

2. It occupies about 8 MB.

```
x <- runif(1e6)
y <- list(x, x, x)
obj_size(y)
#> 8,000,128 B
```

3. `a` is copied when `b` is modified, `b[[1]] <- 10.`

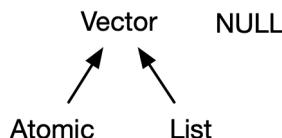
Chapter 3

Vectors

3.1 Introduction

This chapter discusses the most important family of data types in base R: the vector types¹. You've probably used many (if not all) of the vectors before, but you may not have thought deeply about how they are interrelated. In this chapter, I won't cover individual vectors types in too much depth. Instead, I'll show you how they fit together as a whole. If you need more details, you can find them in R's documentation.

Vectors come in two flavours: atomic vectors and lists². They differ in the types of their elements: all elements of an atomic vector must be the same type, whereas the elements of a list can have different types. Closely related to vectors is `NULL`; `NULL` is not a vector, but often serves the role of a generic 0-length vector. Throughout this chapter we'll expand on this diagram:



Every vector can also have **attributes**, which you can think of as a named

¹Collectively, all other data types are known as the “node” data types, and include things like functions and environments. This is a highly technical term used in only a few places. The place where you're most likely to encounter it is the output of `gc()`: the “N” in `Ncells` stands for nodes, and the “V” in `Vcells` stands for vectors.

²A few places in R's documentation call lists generic vectors to emphasise their difference from atomic vectors.

list containing arbitrary metadata. Two attributes are particularly important because they create important vector variants. The **dimension** attribute turns vectors into matrices and arrays. The **class** attribute powers the S3 object system. You’ll learn how to use S3 in Chapter 12, but here, you’ll learn about a handful of the most important S3 vectors: factors, date/times, data frames, and tibbles. Matrices and data frames are not necessarily what you think of as vectors, so you’ll learn why these 2d structures are considered to be vectors in R.

Quiz

Take this short quiz to determine if you need to read this chapter. If the answers quickly come to mind, you can comfortably skip this chapter. You can check your answers in [answers](#).

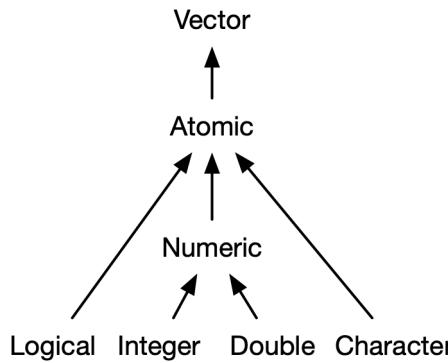
1. What are the four common types of atomic vectors? What are the two rare types?
2. What are attributes? How do you get them and set them?
3. How is a list different from an atomic vector? How is a matrix different from a data frame?
4. Can you have a list that is a matrix? Can a data frame have a column that is a matrix?
5. How do tibbles behave differently from data frames?

Outline

3.2 Atomic vectors

There are four common types of atomic vectors: logical, integer, double, and character. Collectively integer and double vectors are known as numeric vectors³. There are two rare types that I won’t discuss further: complex and raw. Complex numbers are rarely needed for statistics, and raw vectors are a special type only needed when handling binary data.

³This is a slight simplification as R does not use “numeric” consistently, which we’ll come back to in Section 11.3.1.



3.2.1 Scalars

Each of the four primary atomic vectors has special syntax to create an individual value, aka a **scalar**⁴, and its own missing value.:

- Strings are surrounded by " ("hi") or ' ('bye'). The string missing value is `NA_character_`. Special characters are escaped with \\; see `?Quotes` for full details.
- Doubles can be specified in decimal (0.1234), scientific (1.23e4), or hexadeciml (0xcafe) forms. There are three special values unique to doubles: `Inf`, `-Inf`, and `NaN`. The double missing value is `NA_real_`.
- Integers are written similarly to doubles but must be followed by L⁵ (1234L, 1e4L, or 0xcafeL), and can not include decimals. The integer missing value is `NA_integer_`.
- Logicals can be spelled out (TRUE or FALSE), or abbreviated (T or F). The logical missing value is `NA`.

3.2.2 Making longer vectors with `c()`

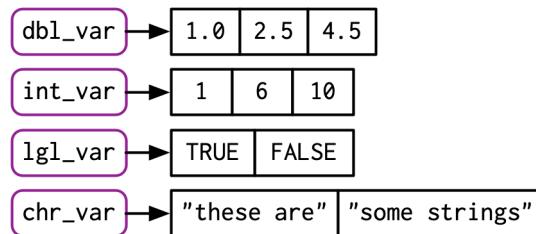
To create longer vectors from shorter ones, use `c()`, short for combine:

⁴Technically, the R language does not possess scalars, and everything that looks like a scalar is actually a vector of length one. This however, is mainly a theoretical distinction, and blurring the distinction between scalar and length-1 vector is unlikely to harm your code.

⁵L is not intuitive, and you might wonder where it comes from. At the time L was added to R, R's integer type was equivalent to a long integer in C, and C code could use a suffix of 1 or L to force a number to be a long integer. It was decided that 1 was too visually similar to i (used for complex numbers in R), leaving L.

```
dbl_var <- c(1, 2.5, 4.5)
int_var <- c(1L, 6L, 10L)
lgl_var <- c(TRUE, FALSE)
chr_var <- c("these are", "some strings")
```

In diagrams, I'll depict vectors as connected rectangles, so the above code could be drawn as follows:



You can determine the type of a vector with `typeof()` and its length with `length()`.

```
typeof(dbl_var)
#> [1] "double"
typeof(int_var)
#> [1] "integer"
typeof(lgl_var)
#> [1] "logical"
typeof(chr_var)
#> [1] "character"
```

3.2.3 Testing and coercing

Generally, you can **test** if a vector is of a given type with an `is.` function, but they need to be used with care. `is.character()`, `is.double()`, `is.integer()`, and `is.logical()` do what you might expect: they test if a vector is a character, double, integer, or logical. Beware `is.vector()`, `is.atomic()`, and `is.numeric()`: they don't test if you have a vector, atomic vector, or numeric vector, and you'll need to carefully read the docs to figure out what they do do.

The type is a property of the entire atomic vector, so all elements of an atomic must be the same type. When you attempt to combine different types they will be **coerced** to the most flexible one (character >> double >> integer >> logical). For example, combining a character and an integer yields a character:

```
str(c("a", 1))
#> chr [1:2] "a" "1"
```

Coercion often happens automatically. Most mathematical functions (+, `log`, `abs`, etc.) will coerce to numeric. This coercion is particularly useful for logical vectors because `TRUE` becomes 1 and `FALSE` becomes 0.

```
x <- c(FALSE, FALSE, TRUE)
as.numeric(x)
#> [1] 0 0 1
```

```
# Total number of TRUES
sum(x)
#> [1] 1
```

```
# Proportion that are TRUE
mean(x)
#> [1] 0.333
```

Vectorised logical operations (`&`, `!`, `any`, etc) will coerce to a logical, but since this might lose information, it's always accompanied by a warning.

Generally, you can deliberately coerce by using an `as.` function, like `as.character()`, `as.double()`, `as.integer()`, or `as.logical()`. Failed coercions from strings generate a warning and a missing value:

```
as.integer(c("1", "1.5", "a"))
#> Warning: NAs introduced by coercion
#> [1] 1 1 NA
```

3.2.4 Exercises

1. How do you create scalars of type `raw` and `complex`? (See `?raw` and `?complex`)
2. Test your knowledge of vector coercion rules by predicting the output of the following uses of `c()`:

```
c(1, FALSE)
c("a", 1)
c(TRUE, 1L)
```

3. Why is `1 == "1"` true? Why is `-1 < FALSE` true? Why is `"one" < 2` false?

4. Why is the default missing value, `NA`, a logical vector? What's special about logical vectors? (Hint: think about `c(FALSE, NA_character_)`.)
5. Precisely what do `is.atomic()`, `is.numeric()`, and `is.vector()` test for?

3.3 Attributes

You might have noticed that the set of atomic vectors does not include a number of important data structures like matrices and arrays, factors and date/times. These types are built on top of atomic vectors by adding attributes. In this section, you'll learn the basics of attributes, and how the `dim` attribute makes matrices and arrays. In the next section you'll learn how the `class` attribute is used to create S3 vectors, including factors, dates, and date-times.

3.3.1 Getting and setting

You can think of attributes as a named list⁶ used to attach metadata to an object. Individual attributes can be retrieved and modified with `attr()`, or retrieved en masse with `attributes()`, and set en masse with `structure()`.

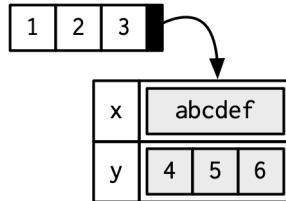
```
a <- 1:3
attr(a, "x") <- "abcdef"
attr(a, "x")
#> [1] "abcdef"

attr(a, "y") <- 4:6
str(attributes(a))
#> List of 2
#> $ x: chr "abcdef"
#> $ y: int [1:3] 4 5 6

# Or equivalently
a <- structure(
  1:3,
  x = "abcdef",
  y = 4:6
)
str(attributes(a))
```

⁶The reality is a little more complicated: attributes are actually stored in pairlists. Pairlists are functionally indistinguishable from lists, but are profoundly different under the hood, and you'll learn more about them in Section 16.6.1.

```
#> List of 2
#> $ x: chr "abcdef"
#> $ y: int [1:3] 4 5 6
```



Attributes should generally be thought of as ephemeral. For example, most attributes are lost by most operations:

```
attributes(a[1])
#> NULL
attributes(sum(a))
#> NULL
```

There are only two attributes that are routinely preserved:

- **names**, a character vector giving each element a name.
- **dim**, short for dimensions, an integer vector, used to turn vectors into matrices and arrays.

To preserve additional attributes, you'll need to create your own S3 class, the topic of Chapter 12.

3.3.2 Names

You can name a vector in three ways:

```
# When creating it:
x <- c(a = 1, b = 2, c = 3)

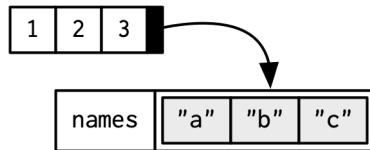
# By assigning names() to an existing vector:
x <- 1:3
names(x) <- c("a", "b", "c")

# Inline, with setNames():
x <- setNames(1:3, c("a", "b", "c"))
```

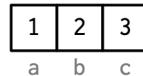
Avoid using `attr(x, "names")` as it requires more typing and is less readable than `names(x)`. You can remove names from a vector by using `unname(x)` or

```
names(x) <- NULL.
```

To be technically correct, when drawing the named vector `x`, I should draw it like so:



However, names are so special and so important, that unless I'm trying specifically to draw attention to the attributes data structure, I'll use them to label the vector directly:



To be maximally useful for character subsetting (e.g. Section 4.5.1) names should be unique, and non-missing, but this is not enforced by R. Depending on how the names are set, missing names may be either `""` or `NA_character_`. If all names are missing, `names()` will return `NULL`.

3.3.3 Dimensions

Adding a `dim` attribute to a vector allows it to behave like a 2-dimensional **matrix** or multi-dimensional **array**. Matrices and arrays are primarily a mathematical/statistical tool, not a programming tool, so will be used infrequently in this book, and only covered briefly. Their most important feature is multidimensional subsetting, which is covered in Section 4.2.3.

You can create matrices and arrays with `matrix()` and `array()`, or by using the assignment form of `dim()`:

```
# Two scalar arguments specify row and column sizes
a <- matrix(1:6, nrow = 2, ncol = 3)
a
#>      [,1] [,2] [,3]
#> [1,]     1     3     5
#> [2,]     2     4     6

# One vector argument to describe all dimensions
b <- array(1:12, c(2, 3, 2))
```

```

b
#> , , 1
#>
#>      [,1] [,2] [,3]
#> [1,]    1    3    5
#> [2,]    2    4    6
#>
#> , , 2
#>
#>      [,1] [,2] [,3]
#> [1,]    7    9   11
#> [2,]    8   10   12

# You can also modify an object in place by setting dim()
c <- 1:6
dim(c) <- c(3, 2)
c
#>      [,1] [,2]
#> [1,]    1    4
#> [2,]    2    5
#> [3,]    3    6

```

Many of the functions for working with vectors have generalisations for matrices and arrays:

Vector	Matrix	Array
names()	rownames(), colnames()	dimnames()
length()	nrow(), ncol()	dim()
c()	rbind(), cbind()	abind::abind()
—	t()	aperm()
is.null(dim(x))	is.matrix()	is.array()

A vector without a `dim` attribute set is often thought of as 1-dimensional, but actually has `NULL` dimensions. You also can have matrices with a single row or single column, or arrays with a single dimension. They may print similarly, but will behave differently. The differences aren't too important, but it's useful to know they exist in case you get strange output from a function (`tapply()` is a frequent offender). As always, use `str()` to reveal the differences.

```
str(1:3) # 1d vector  
#> int [1:3] 1 2 3
```

```
str(matrix(1:3, ncol = 1)) # column vector
#>  int [1:3, 1] 1 2 3
str(matrix(1:3, nrow = 1)) # row vector
#>  int [1, 1:3] 1 2 3
str(array(1:3, 3))          # "array" vector
#>  int [1:3(1d)] 1 2 3
```

3.3.4 Exercises

1. How is `setNames()` implemented? How is `unname()` implemented? Read the source code.
2. What does `dim()` return when applied to a 1d vector? When might you use `NROW()` or `NCOL()`?
3. How would you describe the following three objects? What makes them different to `1:5`?

```
x1 <- array(1:5, c(1, 1, 5))
x2 <- array(1:5, c(1, 5, 1))
x3 <- array(1:5, c(5, 1, 1))
```

4. An early draft used this code to illustrate `structure()`:

```
structure(1:5, comment = "my attribute")
#> [1] 1 2 3 4 5
```

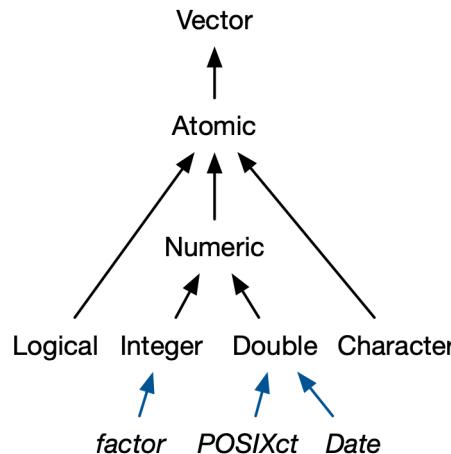
But when you print that object you don't see the comment attribute. Why? Is the attribute missing, or is there something else special about it? (Hint: try using `help()`.)

3.4 S3 atomic vectors

One of the most important attributes is `class`, which defines the S3 object system. Having a `class` attribute makes an object an **S3 object**, which means that it will behave differently when passed to a **generic** function. Every S3 object is built on top of a base type, and often stores additional information in other attributes. You'll learn the details of the S3 object system, and how to create your own S3 classes, in Chapter 12.

In this section, we'll discuss four important S3 vectors used in base R:

- Categorical data, where values can only come from a fixed set of levels, are recorded in **factor** vectors.
- Dates (with day resolution) are recorded in **Date** vectors.
- Date-times (with second or sub-second resolution) are stored in **POSIXct** vectors.
- Durations are stored in **difftime** vectors.



3.4.1 Factors

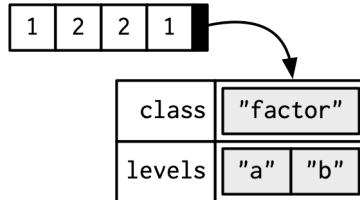
A factor is a vector that can contain only predefined values, and is used to store categorical data. Factors are built on top of integer vectors with two attributes: the `class`, “factor”, which makes them behave differently from regular integer vectors, and the `levels`, which defines the set of allowed values.

```

x <- factor(c("a", "b", "b", "a"))
x
#> [1] a b b a
#> Levels: a b

typeof(x)
#> [1] "integer"
attributes(x)
#> $levels
#> [1] "a" "b"
#>
#> $class
  
```

```
#> [1] "factor"
```



Factors are useful when you know the set of possible values, even if you don't see them all in a given dataset. Compared to a character vector, this means that tabulating a factor can yield counts of 0:

```
sex_char <- c("m", "m", "m")
sex_factor <- factor(sex_char, levels = c("m", "f"))

table(sex_char)
#> sex_char
#> m
#> 3
table(sex_factor)
#> sex_factor
#> m f
#> 3 0
```

A minor variation of factors is **ordered** factors, which generally behave similarly, but declare that the order of the levels is meaningful (a fact which is used automatically in some models and visualisations).

```
grade <- ordered(c("b", "b", "a", "c"), levels = c("c", "b", "a"))
grade
#> [1] b b a c
#> Levels: c < b < a
```

With base R⁷ you tend to encounter factors very frequently, because many base R functions (like `read.csv()` and `data.frame()`) automatically convert character vectors to factors. This is suboptimal, because there's no way for those functions to know the set of all possible levels or their optimal order: the levels are a property of the experimental design, not the data. Instead, use the argument `stringsAsFactors = FALSE` to suppress this behaviour, and then manually convert character vectors to factors using

⁷The tidyverse never automatically coerce characters to factor, and provides the `forcats` (Wickham 2018) package specifically for working with factors.

your knowledge of the data. To learn about the historical context of this behaviour, I recommend *stringsAsFactors: An unauthorized biography* (<http://simplystatistics.org/2015/07/24/stringsasfactors-an-unauthorized-biography/>) by Roger Peng, and *stringsAsFactors = <sigh>* (<http://notstatschat.tumblr.com/post/124987394001/stringsasfactors-sigh>) by Thomas Lumley.

While factors look like (and often behave like) character vectors, they are built on top of integers. Be careful when treating them like strings. Some string methods (like `gsub()` and `grep1()`) will coerce factors to strings automatically, while others (like `nchar()`) will throw an error, and still others (like `c()`) will use the underlying integer values. For this reason, it's usually best to explicitly convert factors to character vectors if you need string-like behaviour.

3.4.2 Dates

Date vectors are built on top of double vectors. They have class “Date” and no other attributes:

```
today <- Sys.Date()

typeof(today)
#> [1] "double"
attributes(today)
#> $class
#> [1] "Date"
```

The value of the double (which can be seen by stripping the class), represents the number of days since 1970-01-01:

```
date <- as.Date("1970-02-01")
unclass(date)
#> [1] 31
```

3.4.3 Date-times

Base R⁸ provides two ways of storing date-time information, `POSIXct`, and `POSIXlt`. These are admittedly odd names: “POSIX” is short for Portable Operating System Interface which is a family of cross-platform standards. “ct” standards for calendar time (the `time_t` type in C), and “lt” for local time (the

⁸The tidyverse provides the `lubridate` (Grolmund and Wickham 2011) package for working with date-times. It provides a number of convenient helpers which work with the base `POSIXct` type.

`struct tm` type in C). Here we'll focus on `POSIXct`, because it's the simplest, is built on top of an atomic vector, and is most appropriate for use in data frames. `POSIXct` vectors are built on top of double vectors, where the value represents the number of seconds since 1970-01-01.

```
now_ct <- as.POSIXct("2018-08-01 22:00", tz = "UTC")
now_ct
#> [1] "2018-08-01 22:00:00 UTC"

typeof(now_ct)
#> [1] "double"
attributes(now_ct)
#> $class
#> [1] "POSIXct" "POSIXt"
#>
#> $tzone
#> [1] "UTC"
```

The `tzone` attribute controls how the date-time is formatted, not the instant of time represented by the vector. Note that the time is not printed if it is midnight.

```
structure(now_ct, tzone = "Asia/Tokyo")
#> [1] "2018-08-02 07:00:00 JST"
structure(now_ct, tzone = "America/New_York")
#> [1] "2018-08-01 18:00:00 EDT"
structure(now_ct, tzone = "Australia/Lord_Howe")
#> [1] "2018-08-02 08:30:00 +1030"
structure(now_ct, tzone = "Europe/Paris")
#> [1] "2018-08-02 CEST"
```

3.4.4 Durations

Durations, the amount of time between two dates or date times, are stored in `difftime`s. `Difftimes` are built on top of doubles, and have a `units` attribute which determines how the integer should be interpreted:

```
one_week_1 <- as.difftime(1, units = "weeks")
one_week_1
#> Time difference of 1 weeks

typeof(one_week_1)
#> [1] "double"
attributes(one_week_1)
```

```

#> $class
#> [1] "difftime"
#>
#> $units
#> [1] "weeks"

one_week_2 <- as.difftime(7, units = "days")
one_week_2
#> Time difference of 7 days

typeof(one_week_2)
#> [1] "double"
attributes(one_week_2)
#> $class
#> [1] "difftime"
#>
#> $units
#> [1] "days"

```

3.4.5 Exercises

1. What sort of object does `table()` return? What is its type? What attributes does it have? How does the dimensionality change as you tabulate more variables?
2. What happens to a factor when you modify its levels?

```

f1 <- factor(letters)
levels(f1) <- rev(levels(f1))

```

3. What does this code do? How do `f2` and `f3` differ from `f1`?

```

f2 <- rev(factor(letters))

f3 <- factor(letters, levels = rev(letters))

```

3.5 Lists

Lists are a step up in complexity from atomic vectors because an element of a list can be any type (not just vectors). An element of a list can even be another list!

3.5.1 Creating

Construct lists with `list()`:

```
11 <- list(
  1:3,
  "a",
  c(TRUE, FALSE, TRUE),
  c(2.3, 5.9)
)

typeof(11)
#> [1] "list"

str(11)
#> List of 4
#> $ : int [1:3] 1 2 3
#> $ : chr "a"
#> $ : logi [1:3] TRUE FALSE TRUE
#> $ : num [1:2] 2.3 5.9
```

As described in Section 2.3.3, the elements of a list are references. Creating a list does not copy the components in, so the total size of a list might be smaller than you expect.

```
lobstr::obj_size(mtcars)
#> 7,208 B

12 <- list(mtcars, mtcars, mtcars, mtcars)
lobstr::obj_size(12)
#> 7,288 B
```

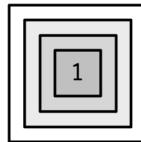
Lists can contain complex objects so it's not possible to pick one visual style that works for every list. Generally I'll draw lists like vectors, using colour to remind you of the hierarchy.



Lists are sometimes called **recursive** vectors, because a list can contain other lists. This makes them fundamentally different from atomic vectors.

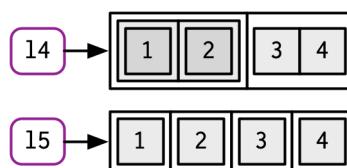
```
13 <- list(list(list(1)))
str(13)
```

```
#> List of 1
#> $ :List of 1
#> ..$ :List of 1
#> ...$ : num 1
```



`c()` will combine several lists into one. If given a combination of atomic vectors and lists, `c()` will coerce the vectors to lists before combining them. Compare the results of `list()` and `c()`:

```
14 <- list(list(1, 2), c(3, 4))
15 <- c(list(1, 2), c(3, 4))
str(14)
#> List of 2
#> $ :List of 2
#> ..$ : num 1
#> ..$ : num 2
#> $ : num [1:2] 3 4
str(15)
#> List of 4
#> $ : num 1
#> $ : num 2
#> $ : num 3
#> $ : num 4
```



3.5.2 Testing and coercing

The `typeof()` a list is `list`. You can test for a list with `is.list()`, and coerce to a list with `as.list()`.

```
list(1:3)
#> [[1]]
```

```
#> [1] 1 2 3
as.list(1:3)
#> [[1]]
#> [1] 1
#>
#> [[2]]
#> [1] 2
#>
#> [[3]]
#> [1] 3
```

You can turn a list into an atomic vector with `unlist()`. The rules for the resulting type are complex, not well documented, and not always equivalent to `c()`.

3.5.3 Matrices and arrays

While atomic vectors are most commonly turned into matrices, the dimension attribute can also be set on lists to make list-matrices or list-arrays:

```
l <- list(1:3, "a", TRUE, 1.0)
dim(l) <- c(2, 2)
l
#>      [,1]      [,2]
#> [1,] Integer,3 TRUE
#> [2,] "a"        1
l[[1, 1]]
#> [1] 1 2 3
```

These are relatively esoteric data structures, but can be useful if you want to arrange objects into a grid-like structure. For example, if you're running models on a spatio-temporal grid, it might be natural to preserve the grid structure by storing the models in a 3d array.

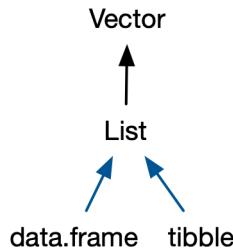
3.5.4 Exercises

1. List all the ways that a list differs from an atomic vector.
2. Why do you need to use `unlist()` to convert a list to an atomic vector? Why doesn't `as.vector()` work?

3. Compare and contrast `c()` and `unlist()` when combining a date and date-time into a single vector.

3.6 Data frames and tibbles

There are two important S3 vectors that are built on top of lists: data frames and tibbles.



A data frame is the most common way of storing data in R, and is crucial for effective data analysis. A data frame is a named list of equal-length vectors. It has attributes providing the (column) `names`, `row.names`⁹, and a class of “data.frame”:

```

df1 <- data.frame(x = 1:3, y = letters[1:3])
typeof(df1)
#> [1] "list"

attributes(df1)
#> $names
#> [1] "x" "y"
#>
#> $class
#> [1] "data.frame"
#>
#> $row.names
#> [1] 1 2 3
  
```

Because each element of the list has the same length, data frames have a rectangular structure, and hence shares properties of both the matrix and the list:

⁹Row names are one of the most surprisingly complex data structures in R, because they've been a persistent performance issue over many years. The most straightforward representations are character or integer vectors, with one element for each row. There's also a compact representation for “automatic” row names (consecutive integers), created by `.set_row_names()`. R 3.5 has a special way of deferring integer to character conversions specifically to speed up `lm()`; see https://svn.r-project.org/R/branches/ALTREP/ALTREP.html#deferred_string_conversions for details.

- A data frame has 1d `names()`, and 2d `colnames()` and `rownames()`¹⁰. The `names()` and `colnames()` are identical.
- A data frame has 1d `length()`, and 2d `ncol()` and `nrow()`. The `length()` is the number of columns.

Data frames are one of the biggest and most important ideas in R, and one of the things that makes R different from other programming languages. However, in the over 20 years since their creation, the ways people use R have changed, and some of the design decisions that made sense at the time data frames were created now cause frustration.

This frustration lead to the creation of the tibble (Müller and Wickham 2018), a modern reimagining of the data frame. Tibbles are designed to be (as much as possible) drop-in replacements for data frames, while still fixing the greatest frustrations. A concise, and fun, way to summarise the main differences is that tibbles are lazy and surly: they tend to do less and complain more. You'll see what that means as you work through this section.

Tibbles are provided by the tibble package and share the same structure as data frames. The only difference is that the class vector is longer, and includes `tbl_df`. This allows tibbles to behave differently in the key ways which we'll discuss below.

```
library(tibble)

df2 <- tibble(x = 1:3, y = letters[1:3])
typeof(df2)
#> [1] "list"

attributes(df2)
#> $names
#> [1] "x"  "y"
#>
#> $row.names
#> [1] 1 2 3
#>
#> $class
#> [1] "tbl_df"     "tbl"        "data.frame"
```

¹⁰Technically, you are encouraged to use `row.names()`, not `rownames()` with data frames, but this distinction is rarely important.

3.6.1 Creating

You create a data frame by supplying name-vector pairs to `data.frame()`:

```
df <- data.frame(
  x = 1:3,
  y = c("a", "b", "c")
)
str(df)
#> 'data.frame': 3 obs. of 2 variables:
#> $ x: int 1 2 3
#> $ y: Factor w/ 3 levels "a","b","c": 1 2 3
```

Beware the default conversion of strings to factors. Use `stringsAsFactors = FALSE` to suppress it and keep character vectors as character vectors:

```
df1 <- data.frame(
  x = 1:3,
  y = c("a", "b", "c"),
  stringsAsFactors = FALSE
)
str(df1)
#> 'data.frame': 3 obs. of 2 variables:
#> $ x: int 1 2 3
#> $ y: chr "a" "b" "c"
```

Creating a tibble is similar, but tibbles never coerce their input (this is one feature that makes them lazy):

```
df2 <- tibble(
  x = 1:3,
  y = c("a", "b", "c")
)
str(df2)
#> Classes 'tbl_df', 'tbl' and 'data.frame': 3 obs. of 2 variables:
#> $ x: int 1 2 3
#> $ y: chr "a" "b" "c"
```

Additionally, while data frames automatically transform non-syntactic names (unless `check.names = FALSE`), tibbles do not (although they do print non-syntactic names surrounded by `).

```
names(data.frame(`1` = 1))
#> [1] "X1"
```

```
names(tibble(`1` = 1))
#> [1] "1"
```

While every element of a data frame (or tibble) must have the same length, both `data.frame()` and `tibble()` can recycle shorter inputs. Data frames automatically recycle columns that are an integer multiple of the longest column; tibbles only ever recycle vectors of length 1.

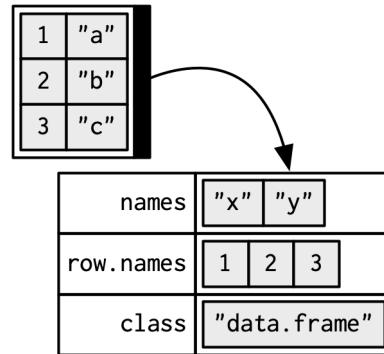
```
data.frame(x = 1:4, y = 1:2)
#>   x y
#> 1 1 1
#> 2 2 2
#> 3 3 1
#> 4 4 2
data.frame(x = 1:4, y = 1:3)
#> Error in data.frame(x = 1:4, y = 1:3):
#>   arguments imply differing number of rows: 4, 3

tibble(x = 1:4, y = 1)
#> # A tibble: 4 x 2
#>       x     y
#>   <int> <dbl>
#> 1     1     1
#> 2     2     1
#> 3     3     1
#> 4     4     1
tibble(x = 1:4, y = 1:2)
#> Error: Column `y` must be length 1 or 4, not 2
```

There is one final difference: `tibble()` allows you to refer to newly created variables:

```
tibble(
  x = 1:3,
  y = x * 2
)
#> # A tibble: 3 x 2
#>       x     y
#>   <int> <dbl>
#> 1     1     2
#> 2     2     4
#> 3     3     6
```

When drawing data frames and tibbles, rather than focussing on the implementation details, i.e. the attributes:



I'll draw them in the same way as a named list, but arranged to emphasise their columnar structure.

x	y
1	"a"
2	"b"
3	"c"

3.6.2 Row names

Data frames allow you to label each row with a “name”, a character vector containing only unique values:

```
df3 <- data.frame(
  age = c(35, 27, 18),
  hair = c("blond", "brown", "black"),
  row.names = c("Bob", "Susan", "Sam")
)
df3
#>      age  hair
#> Bob    35 blond
#> Susan  27 brown
#> Sam    18 black
```

You can get and set row names with `rownames()`, and you can use them to subset rows:

```
rownames(df3)
#> [1] "Bob"    "Susan"   "Sam"

df3["Bob", ]
#>      age  hair
#> Bob  35 blond
```

Row names arise naturally if you think of data frames as 2d structures like matrices: the columns (variables) have names so the rows (observations) should too. Most matrices are numeric, so having a place to store character labels is important. But this analogy to matrices is misleading because matrices possess an important property that data frames do not: they are transposable. In matrices the rows and columns are interchangeable, and transposing a matrix gives you another matrix (and transposing again gives you back the original matrix). With data frames, however, the rows and columns are not interchangeable, and the transpose of a data frame is not a data frame.

There are three reasons that row names are suboptimal:

- Metadata is data, so storing it in a different way to the rest of the data is fundamentally a bad idea. It also means that you need to learn a new set of tools to work with row names; you can't use what you already know about manipulating columns.
- Row names are poor abstraction for labelling rows because they only work when a row can be identified by a single string. This fails in many cases, for example when you want to identify a row by a non-character vector (e.g. a time point), or with multiple vectors (e.g. position, encoded by latitude and longitude).
- Row names must be unique, so any replication of rows (e.g. from bootstrapping) will create new row names. If you want to match rows from before and after the transformation you'll need to perform complicated string surgery.

```
df3[c(1, 1, 1), ]
#>      age  hair
#> Bob    35 blond
#> Bob.1  35 blond
#> Bob.2  35 blond
```

For these reasons, tibbles do not support row names. Instead the `tibble` package provides tools to easily convert row names into a regular column with either `rownames_to_column()`, or the `rownames` argument to `as_tibble()`:

```
as_tibble(df3, rownames = "name")
#> # A tibble: 3 x 3
#>   name    age hair
#>   <chr> <dbl> <fct>
#> 1 Bob     35  blond
#> 2 Susan   27  brown
#> 3 Sam     18  black
```

3.6.3 Printing

One of the most obvious differences between tibbles and data frames is how they are printed. I assume that you're already familiar with how data frames are printed, so here I'll highlight some of the biggest differences using an example dataset included in the dplyr package:

```
dplyr::starwars
#> # A tibble: 87 x 13
#>   name    height  mass hair_color skin_color eye_color birth_year
#>   <chr> <int> <dbl> <chr>      <chr>      <chr>      <dbl>
#> 1 Luke~    172     77 blond     fair       blue        19
#> 2 C-3PO~   167     75 <NA>      gold       yellow     112
#> 3 R2-D2~   96      32 <NA>      white, bl~ red        33
#> 4 Dart~    202     136 none      white      yellow      41.9
#> 5 Leia~    150     49 brown     light      brown       19
#> 6 Owen~    178     120 brown, gr~ light      blue        52
#> 7 Beru~    165     75 brown     light      blue        47
#> 8 R5-D4~   97      32 <NA>      white, red red       NA
#> 9 Bigg~    183     84 black     light      brown       24
#> 10 Obi-~   182     77 auburn, w~ fair      blue-gray    57
#> # ... with 77 more rows, and 6 more variables: gender <chr>,
#> #   homeworld <chr>, species <chr>, films <list>, vehicles <list>,
#> #   starships <list>
```

Tibbles:

- Only show the first 10 rows and all the columns that will fit on screen. Additional columns are shown at the bottom.
- Each column is labelled with its type, abbreviated to three or four letters.
- Wide columns are truncated to avoid a single long string occupying an entire row. (This is still a work in progress: it's tricky to get the tradeoff

right between showing as many columns as possible and showing a single wide column fully.)

- When used in console environments that support it, colour is used judiciously to highlight important information, and de-emphasise supplemental details.

3.6.4 Subsetting

As you will learn in Chapter 4, you can subset a data frame or a tibble like a 1d structure (where it behaves like a list), or a 2d structure (where it behaves like a matrix).

In my opinion, data frames have two suboptimal subsetting behaviours:

- When you subset columns with `df[, vars]`, you will get a vector if `vars` selects one variable, otherwise you'll get a data frame. This is a frequent source of bugs when using `[` in a function, unless you always remember to do `df[, vars, drop = FALSE]`.
- When you attempt to extract a single column with `df$x` and there is no column `x`, a data frame will instead select any variable that starts with `x`. If no variable starts with `x`, `df$x` will return `NULL`. This makes it easy to select the wrong variable or to select a variable that doesn't exist.

Tibbles tweak these behaviours so that `[` always returns a tibble, and `$` doesn't partial match, and warns if it can't find a variable (this is what makes tibbles surly).

```
df1 <- data.frame(xyz = "a")
df2 <- tibble(xyz = "a")

str(df1$x)
#> Factor w/ 1 level "a": 1
str(df2$x)
#> Warning: Unknown or uninitialised column: 'x'.
#> NULL
```

A tibble's insistence on returning a data frame from `[` can cause problems with legacy code, which often uses `df[, "col"]` to extract a single column. To fix this, use `df[["col"]]` instead; this is more expressive (since `[` always extracts a single element) and works with both data frames and tibbles.

3.6.5 Testing and coercing

To check if an object is a data frame or tibble, use `is.data.frame()`:

```
is.data.frame(df1)
#> [1] TRUE
is.data.frame(df2)
#> [1] TRUE
```

Typically, it should not matter if you have a tibble or data frame, but if you do need to distinguish, use `is_tibble()`:

```
is_tibble(df1)
#> [1] FALSE
is_tibble(df2)
#> [1] TRUE
```

You can coerce an object to a data frame with `as.data.frame()` or to a tibble with `as_tibble()`.

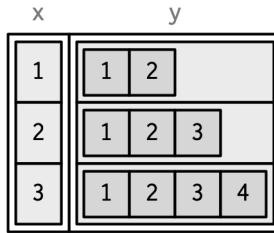
3.6.6 List columns

Since a data frame is a list of vectors, it is possible for a data frame to have a column that is a list. This is very useful because a list can contain any other object, which means that you can put any object in a data frame. This allows you to keep related objects together in a row, no matter how complex the individual objects are. You can see an application of this in the “Many Models” chapter of “R for Data Science”, <http://r4ds.had.co.nz/many-models.html>.

List-columns are allowed in data frames but you have to do a little extra work, either adding the list-column after creation, or wrapping the list in `I()`.

```
df <- data.frame(x = 1:3)
df$y <- list(1:2, 1:3, 1:4)

data.frame(
  x = 1:3,
  y = I(list(1:2, 1:3, 1:4))
)
#>   x           y
#> 1 1           1, 2
#> 2 2           1, 2, 3
#> 3 3           1, 2, 3, 4
```



List columns are easier to use with tibbles because you can provide them inside `tibble()`, and they are handled specially when printing:

```
tibble(
  x = 1:3,
  y = list(1:2, 1:3, 1:4)
)
#> # A tibble: 3 x 2
#>   x     y
#>   <int> <list>
#> 1     1 <int [2]>
#> 2     2 <int [3]>
#> 3     3 <int [4]>
```

3.6.7 Matrix and data frame columns

It's also possible to have a column of a data frame that's a matrix or array, as long as the number of rows matches the data frame. (This requires a slight extension to our definition of a data frame: it's not the `length()` of each column that must be equal, but the `NROW()`.) Like with list-columns, you must either add after creation, or wrap in `I()`.

```
dfm <- data.frame(
  x = 1:3 * 10
)
dfm$y <- matrix(1:9, nrow = 3)
dfm$z <- data.frame(a = 3:1, b = letters[1:3], stringsAsFactors = FALSE)

str(dfm)
#> 'data.frame':   3 obs. of  3 variables:
#>   $ x: num  10 20 30
#>   $ y: int [1:3, 1:3] 1 2 3 4 5 6 7 8 9
#>   $ z:'data.frame':   3 obs. of  2 variables:
#>     ..$ a: int  3 2 1
```

```
#> ...$b: chr  "a" "b" "c"
```

x	y	z
10	1 4 7	a
20	2 5 8	"b"
30	3 6 9	"c"

Matrix and data frame columns require a little caution. Many functions that work with data frames assume that all columns are vectors, and the printed display can be confusing.

```
dfm[1, ]
#> x y.1 y.2 y.3 z.a z.b
#> 1 10 1 4 7 3 a
```

3.6.8 Exercises

1. Can you have a data frame with 0 rows? What about 0 columns?
2. What happens if you attempt to set rownames that are not unique?
3. If `df` is a data frame, what can you say about `t(df)`, and `t(t(df))`? Perform some experiments, making sure to try different column types.
4. What does `as.matrix()` do when applied to a data frame with columns of different types? How does it differ from `data.matrix()`?

3.7 *NULL*

To finish up the chapter, I wanted to talk about a final important data structure that's closely related to vectors: `NULL`. `NULL` is special because it has a unique type, is always length 0, and can't have any attributes:

```
typeof(NULL)
#> [1] "NULL"

length(NULL)
#> [1] 0
```

```
x <- NULL
attr(x, "y") <- 1
#> Error in attr(x, "y") <- 1:
#>   attempt to set an attribute on NULL
```

You can test for `NULL`s with `is.null()`:

```
is.null(NULL)
#> [1] TRUE
```

There are two common uses of `NULL`:

- To represent an empty vector (a vector of length 0) of arbitrary type. For example, if you use `c()` but don't include any arguments, you get `NULL`, and concatenating `NULL` to a vector leaves it unchanged¹¹:

```
c()
#> NULL
```

- To represent an absent vector. For example, `NULL` is often used as a default function argument, when the argument is optional but the default value requires some computation (see Section 5.5.4 for more on this idea). Contrast this with `NA` which is used to indicate that an *element* of a vector is absent.

If you're familiar with SQL, you know about relational `NULL` and might expect it to be the same as R's. However, the database `NULL` is actually equivalent to `NA`.

3.8 Answers

1. The four common types of atomic vector are logical, integer, double and character. The two rarer types are complex and raw.
2. Attributes allow you to associate arbitrary additional metadata to any object. You can get and set individual attributes with `attr(x, "y")` and `attr(x, "y") <- value`; or get and set all attributes at once with `attributes()`.
3. The elements of a list can be any type (even a list); the elements of an atomic vector are all of the same type. Similarly, every element of a matrix must be the same type; in a data frame, the different columns can have different types.

¹¹Algebraically, this makes `NULL` the identity element under vector concatenation.

4. You can make “list-array” by assigning dimensions to a list. You can make a matrix a column of a data frame with `df$x <- matrix()`, or using `I()` when creating a new data frame `data.frame(x = I(matrix()))`.
5. Tibbles have an enhanced print method, never coerce strings to factors, and provide stricter subsetting methods.

Chapter 4

Subsetting

4.1 Introduction

R’s subsetting operators are powerful and fast. Mastery of subsetting allows you to succinctly express complex operations in a way that few other languages can match. Subsetting is easy to learn but hard to master because you need to internalise a number of interrelated concepts:

- The six types of thing that you can subset with.
- The three subsetting operators, `[[`, `[`, and `$`.
- How the subsetting operators interact with vector types (e.g., atomic vectors, lists, factors, matrices, and data frames).
- The use of subsetting together with assignment.

This chapter helps you master subsetting by starting with the simplest type of subsetting: subsetting an atomic vector with `[`. It then gradually extends your knowledge, first to more complicated data types (like arrays and lists), and then to the other subsetting operators, `[[` and `$`. You’ll then learn how subsetting and assignment can be combined to modify parts of an object, and, finally, you’ll see a large number of useful applications.

Subsetting is a natural complement to `str()`. `str()` shows you the structure of any object, and subsetting allows you to pull out the pieces that you’re interested in. For large, complex objects, I also highly recommend the interactive RStudio Viewer, which you can activate with `View(my_object)`.

Quiz

Take this short quiz to determine if you need to read this chapter. If the answers quickly come to mind, you can comfortably skip this chapter. Check your answers in Section 4.6.

1. What is the result of subsetting a vector with positive integers, negative integers, a logical vector, or a character vector?
2. What's the difference between `[`, `[[`, and `$` when applied to a list?
3. When should you use `drop = FALSE`?
4. If `x` is a matrix, what does `x[] <- 0` do? How is it different to `x <- 0`?
5. How can you use a named vector to relabel categorical variables?

Outline

- Section 4.2 starts by teaching you about `[`. You'll start by learning the six types of data that you can use to subset atomic vectors. You'll then learn how those six data types act when used to subset lists, matrices, and data frames.
- Section 4.3 expands your knowledge of subsetting operators to include `[[` and `$`, focussing on the important principles of simplifying vs. preserving.
- In Section 4.4 you'll learn the art of subassignment, combining subsetting and assignment to modify parts of an object.
- Section 4.5 leads you through eight important, but not obvious, applications of subsetting to solve problems that you often encounter in a data analysis.

4.2 Selecting multiple elements

It's easiest to learn how subsetting works for atomic vectors, and then how it generalises to higher dimensions and other more complicated objects. We'll start with `[`, the most commonly used operator which allows you to extract any number of elements. Section 4.3 will cover `[[` and `$`, used to extract a single element from a data structure.

4.2.1 Atomic vectors

Let's explore the different types of subsetting with a simple vector, `x`.

```
x <- c(2.1, 4.2, 3.3, 5.4)
```

Note that the number after the decimal point gives the original position in the vector.

There are six things that you can use to subset a vector:

- **Positive integers** return elements at the specified positions:

```
x[c(3, 1)]
#> [1] 3.3 2.1
x[order(x)]
#> [1] 2.1 3.3 4.2 5.4

# Duplicated indices yield duplicated values
x[c(1, 1)]
#> [1] 2.1 2.1

# Real numbers are silently truncated to integers
x[c(2.1, 2.9)]
#> [1] 4.2 4.2
```

- **Negative integers** omit elements at the specified positions:

```
x[-c(3, 1)]
#> [1] 4.2 5.4
```

You can't mix positive and negative integers in a single subset:

```
x[c(-1, 2)]
#> Error in x[c(-1, 2)]:
#>   only 0's may be mixed with negative subscripts
```

- **Logical vectors** select elements where the corresponding logical value is `TRUE`. This is probably the most useful type of subsetting because you can write an expression that creates the logical vector:

```
x[c(TRUE, TRUE, FALSE, FALSE)]
#> [1] 2.1 4.2
x[x > 3]
#> [1] 4.2 3.3 5.4
```

If the logical vector is shorter than the vector being subsetted, it will be

silently **recycled** to be the same length.

```
x[c(TRUE, FALSE)]
#> [1] 2.1 3.3
# Equivalent to
x[c(TRUE, FALSE, TRUE, FALSE)]
#> [1] 2.1 3.3
```

A missing value in the index always yields a missing value in the output:

```
x[c(TRUE, TRUE, NA, FALSE)]
#> [1] 2.1 4.2 NA
```

- **Nothing** returns the original vector. This is not useful for 1d vectors, but as you'll see shortly, is very useful for matrices, data frames, and arrays. It can also be useful in conjunction with assignment.

```
x[]
#> [1] 2.1 4.2 3.3 5.4
```

- **Zero** returns a zero-length vector. This is not something you usually do on purpose, but it can be helpful for generating test data.

```
x[0]
#> numeric(0)
```

- If the vector is named, you can also use **character vectors** to return elements with matching names.

```
(y <- setNames(x, letters[1:4]))
#> a   b   c   d
#> 2.1 4.2 3.3 5.4
y[c("d", "c", "a")]
#> d   c   a
#> 5.4 3.3 2.1

# Like integer indices, you can repeat indices
y[c("a", "a", "a")]
#> a   a   a
#> 2.1 2.1 2.1

# When subsetting with [, names are always matched exactly
z <- c(abc = 1, def = 2)
z[c("a", "d")]
#> <NA> <NA>
```

```
#> NA NA
```

NB: factors are not treated specially when subsetting. This means that subsetting will use the underlying integer vector, not the character levels. This is typically unexpected, so you should avoid subsetting with factors:

```
y[factor("b")]
#> a
#> 2.1
```

4.2.2 Lists

Subsetting a list works in the same way as subsetting an atomic vector. Using `[` will always return a list; `[[` and `$`, as described in Section 4.3, let you pull out the components of the list.

4.2.3 Matrices and arrays

You can subset higher-dimensional structures in three ways:

- With multiple vectors.
- With a single vector.
- With a matrix.

The most common way of subsetting matrices (2d) and arrays (>2d) is a simple generalisation of 1d subsetting: you supply a 1d index for each dimension, separated by a comma. Blank subsetting is now useful because it lets you keep all rows or all columns.

```
a <- matrix(1:9, nrow = 3)
colnames(a) <- c("A", "B", "C")
a[1:2, ]
#>      A B C
#> [1,] 1 4 7
#> [2,] 2 5 8
a[c(TRUE, FALSE, TRUE), c("B", "A")]
#>      B A
#> [1,] 4 1
#> [2,] 6 3
a[0, -2]
#>      A C
```

By default, `[` will simplify the results to the lowest possible dimensionality. You'll learn how to avoid this in Section 4.2.5.

Because matrices and arrays are just vectors with special attributes, you can subset them with a single vector, as if they were a 1d vector. Arrays in R are stored in column-major order:

```
vals <- outer(1:5, 1:5, FUN = "paste", sep = ",")  
vals  
#>      [,1]  [,2]  [,3]  [,4]  [,5]  
#> [1,] "1,1" "1,2" "1,3" "1,4" "1,5"  
#> [2,] "2,1" "2,2" "2,3" "2,4" "2,5"  
#> [3,] "3,1" "3,2" "3,3" "3,4" "3,5"  
#> [4,] "4,1" "4,2" "4,3" "4,4" "4,5"  
#> [5,] "5,1" "5,2" "5,3" "5,4" "5,5"  
  
vals[c(4, 15)]  
#> [1] "4,1" "5,3"
```

You can also subset higher-dimensional data structures with an integer matrix (or, if named, a character matrix). Each row in the matrix specifies the location of one value, and each column corresponds to a dimension in the array being subsetted. This means that you can use a 2 column matrix to subset a matrix, a 3 column matrix to subset a 3d array, and so on. The result is a vector of values:

```
select <- rbind(  
  c(1, 1),  
  c(3, 1),  
  c(2, 4)  
)  
vals[select]  
#> [1] "1,1" "3,1" "2,4"
```

4.2.4 Data frames and tibbles

Data frames possess the characteristics of both lists and matrices: if you subset with a single vector, they behave like lists; if you subset with two vectors, they behave like matrices.

```
df <- data.frame(x = 1:3, y = 3:1, z = letters[1:3])  
  
df[df$x == 2, ]  
#>   x y z
```

```

#> 2 2 2 b
df[c(1, 3), ]
#> x y z
#> 1 1 3 a
#> 3 3 1 c

# There are two ways to select columns from a data frame
# Like a list
df[c("x", "z")]
#> x z
#> 1 1 a
#> 2 2 b
#> 3 3 c
# Like a matrix
df[, c("x", "z")]
#> x z
#> 1 1 a
#> 2 2 b
#> 3 3 c

# There's an important difference if you select a single
# column: matrix subsetting simplifies by default, list
# subsetting does not.
str(df["x"])
#> 'data.frame': 3 obs. of 1 variable:
#> $ x: int 1 2 3
str(df[, "x"])
#> int [1:3] 1 2 3

```

Subsetting a tibble with [always returns a tibble:

```

df <- tibble::tibble(x = 1:3, y = 3:1, z = letters[1:3])

str(df["x"])
#> Classes 'tbl_df', 'tbl' and 'data.frame': 3 obs. of 1 variable:
#> $ x: int 1 2 3
str(df[, "x"])
#> Classes 'tbl_df', 'tbl' and 'data.frame': 3 obs. of 1 variable:
#> $ x: int 1 2 3

```

4.2.5 Preserving dimensionality

By default, subsetting a 2d data structures with a single number, single name, or a logical vector containing a single `TRUE` will simplify the returned output, i.e. it will return an object with lower dimensionality. To preserve the original dimensionality, you must use `drop = FALSE`

- For matrices and arrays, any dimensions with length 1 will be dropped:

```
a <- matrix(1:4, nrow = 2)
str(a[1, ])
#>  int [1:2] 1 3

str(a[1, , drop = FALSE])
#>  int [1, 1:2] 1 3
```

- Data frames with a single column will return just that column:

```
df <- data.frame(a = 1:2, b = 1:2)
str(df[, "a"])
#>  int [1:2] 1 2

str(df[, "a", drop = FALSE])
#> 'data.frame': 2 obs. of 1 variable:
#> $ a: int 1 2
```

- Tibbles default to `drop = FALSE`, and `[` will never return a single vector.

The default `drop = TRUE` behaviour is a common source of bugs in functions: you check your code with a data frame or matrix with multiple columns, and it works. Six months later you (or someone else) uses it with a single column data frame and it fails with a mystifying error. When writing functions, get in the habit of always using `drop = FALSE` when subsetting a 2d object.

Factor subsetting also has a `drop` argument, but the meaning is rather different. It controls whether or not levels are preserved (not the dimensionality), and it defaults to `FALSE` (levels are preserved, not simplified by default). If you find you are using `drop = TRUE` a lot it's often a sign that you should be using a character vector instead of a factor.

```
z <- factor(c("a", "b"))
z[1]
#> [1] a
#> Levels: a b
z[1, drop = TRUE]
```

```
#> [1] a
#> Levels: a
```

4.2.6 Exercises

1. Fix each of the following common data frame subsetting errors:

```
mtcars[mtcars$cyl = 4, ]
mtcars[-1:4, ]
mtcars[mtcars$cyl <= 5]
mtcars[mtcars$cyl == 4 | 6, ]
```

2. Why does the following code yield five missing values? (Hint: why is it different from `x[NA_real_]`?)

```
x <- 1:5
x[NA]
#> [1] NA NA NA NA NA
```

3. What does `upper.tri()` return? How does subsetting a matrix with it work? Do we need any additional subsetting rules to describe its behaviour?

```
x <- outer(1:5, 1:5, FUN = "*")
x[upper.tri(x)]
```

4. Why does `mtcars[1:20]` return an error? How does it differ from the similar `mtcars[1:20,]`?
5. Implement your own function that extracts the diagonal entries from a matrix (it should behave like `diag(x)` where `x` is a matrix).
6. What does `df[is.na(df)] <- 0` do? How does it work?

4.3 Selecting a single element

There are two other subsetting operators: `[[` and `$`. `[[` is used for extracting single items, and `x$y` is a useful shorthand for `x[["y"]]`.

4.3.1 `[[`

`[[` is most important working with lists because subsetting a list with `[` always returns a smaller list. To help make this easier to understand we can use a

metaphor:

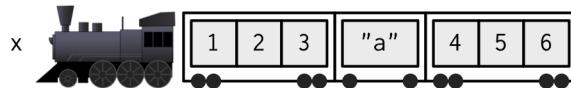
“If list `x` is a train carrying objects, then `x[[5]]` is the object in car 5; `x[4:6]` is a train of cars 4-6.”

— @RLangTip,

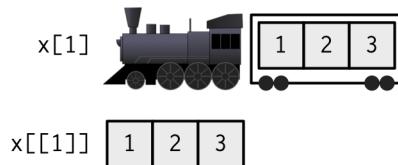
<https://twitter.com/RLangTip/status/268375867468681216>

Let’s make a simple list and draw it as a train:

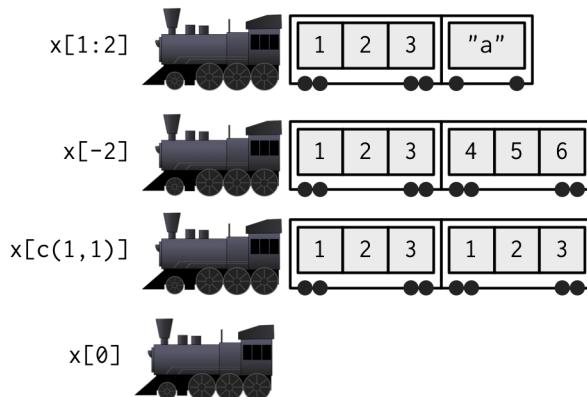
```
x <- list(1:3, "a", 4:6)
```



When extracting a single element, you have two options: you can create a smaller train, or you can extract the contents of a carriage. This is the difference between `[` and `[[`:



When extracting multiple elements (or zero!), you have to make a smaller train:



Because it can return only a single item, you must use `[[` with either a single positive integer or a string. If you use a vector with `[[`, it will subset recursively:

```
b <- list(a = list(b = list(c = list(d = 1))))
b[[c("a", "b", "c", "d")]]
#> [1] 1
```

```
# Equivalent to
b[["a"]][["b"]][["c"]][["d"]]
#> [1] 1
```

[[is crucial for working with lists, but I recommend using it whenever you want your code to clearly express that it's working with a single item. That frequently arises in for loops, e.g., instead of writing:

```
for (i in 2:length(x)) {
  out[i] <- fun(x[i], out[i - 1])
}
```

It's better to write:

```
for (i in 2:length(x)) {
  out[[i]] <- fun(x[[i]], out[[i - 1]])
}
```

That reinforces to the reader that you expect to get and set individual values.

4.3.2 \$

\$ is a shorthand operator: x\$y is roughly equivalent to x[["y"]]. It's often used to access variables in a data frame, as in mtcars\$cyl or diamonds\$carat. One common mistake with \$ is to use it when you have the name of a column stored in a variable:

```
var <- "cyl"
# Doesn't work - mtcars$var translated to mtcars[["var"]]
mtcars$var
#> NULL

# Instead use [[
mtcars[[var]]
#> [1] 6 6 4 6 8 6 8 4 4 6 6 8 8 8 8 8 4 4 4 4 8 8 8 8 4 4 4 8 6 8 4
```

There's one important difference between \$ and [[. \$ does partial matching:

```
x <- list(abc = 1)
x$a
#> [1] 1
x[["a"]]
#> NULL
```

To help avoid this behaviour I highly recommend setting the global option `warnPartialMatchDollar` to `TRUE`:

```
options(warnPartialMatchDollar = TRUE)
x$a
#> Warning in x$a: partial match of 'a' to 'abc'
#> [1] 1
```

(For data frames, you can also avoid this problem by using tibbles instead: they never do partial matching.)

4.3.3 Missing/out of bounds indices

It's useful to understand what happens with `[[` when you use an “invalid” index. The following tables summarise what happens when you subset a logical vector, list, and `NULL` with an out-of-bounds value (OOB), a missing value (e.g. `NA_integer_`), and a zero-length object (like `NULL` or `logical()`) with `[[`. Each cell shows the result of subsetting the data structure named in the row by the type of index described in the column. I've only shown the results for logical vectors, but other atomic vectors behave similarly, returning elements of the same type.

row <code>[[col]]</code>	Zero-length	OOB (int)	OOB (chr)	Missing
<code>NULL</code>	<code>NULL</code>	<code>NULL</code>	<code>NULL</code>	<code>NULL</code>
Atomic	Error	Error	Error	Error
List	Error	Error	<code>NULL</code>	<code>NULL</code>

If the input vector is named, then the names of OOB, missing, or `NULL` components will be "`<NA>`".

The inconsistency of the `[[` table above led to the development of `purrr::pluck()` and `purrr::chuck()`. `pluck()` always returns `NULL` (or the value of the `.default` argument) when the element is missing; `chuck()` always throws an error:

<code>pluck(row, col)</code>	Zero-length	OOB (int)	OOB (chr)	Missing
<code>NULL</code>	<code>NULL</code>	<code>NULL</code>	<code>NULL</code>	<code>NULL</code>
Atomic	<code>NULL</code>	<code>NULL</code>	<code>NULL</code>	<code>NULL</code>
List	<code>NULL</code>	<code>NULL</code>	<code>NULL</code>	<code>NULL</code>

chuck(row, col)	Zero-length	OOB (int)	OOB (chr)	Missing
NULL	Error	Error	Error	Error
Atomic	Error	Error	Error	Error
List	Error	Error	Error	Error

The behaviour of `pluck()` makes it well suited for indexing into deeply nested data structures where the component you want does not always exist (as is common when working with JSON data from web APIs). `pluck()` also allows you to mingle integer and character indexes, and to provide an alternative default value if the item does not exist:

```
x <- list(
  a = list(1, 2, 3),
  b = list(3, 4, 5)
)

purrr::pluck(x, "a", 1)
#> [1] 1

purrr::pluck(x, "c", 1)
#> NULL

purrr::pluck(x, "c", 1, .default = NA)
#> [1] NA
```

4.3.4 `@@` and `slot()`

There are also two additional subsetting operators that are needed for S4 objects: `@@` (equivalent to `$`), and `slot()` (equivalent to `[[`). `@@` is more restrictive than `$` in that it will return an error if the slot does not exist. These are described in more detail in S4.

4.3.5 Exercises

1. Brainstorm as many ways as possible to extract the third value from the `cyl` variable in the `mtcars` dataset.
2. Given a linear model, e.g., `mod <- lm(mpg ~ wt, data = mtcars)`, extract the residual degrees of freedom. Extract the R squared from the model summary (`summary(mod)`)

4.4 Subsetting and assignment

All subsetting operators can be combined with assignment to modify selected values of the input vector, so called subassignment. The basic form is `x[i] <- value`:

```
x <- 1:5
x[c(1, 2)] <- c(101, 102)
x
#> [1] 101 102  3  4  5
```

I recommend ensuring that `length(value)` and `length(x[i])` are equal, and that `i` is unique. R does recycle if needed, but the rules are complex (particularly if `i` contains missing or duplicated values).

With lists, you can use `x[[i]] <- NULL` to remove a component. To add a literal `NULL`, use `x[i] <- list(NULL)`:

```
x <- list(a = 1, b = 2)
x[["b"]] <- NULL
str(x)
#> List of 1
#> $ a: num 1

y <- list(a = 1, b = 2)
y[["b"]] <- list(NULL)
str(y)
#> List of 2
#> $ a: num 1
#> $ b: NULL
```

Subsetting with nothing can be useful in conjunction with assignment because it will preserve the structure of the original object. Compare the following two expressions. In the first, `mtcars` will remain as a data frame. In the second, `mtcars` will become a list.

```
mtcars[] <- lapply(mtcars, as.integer)
is.data.frame(mtcars)
#> [1] TRUE

mtcars <- lapply(mtcars, as.integer)
is.data.frame(mtcars)
#> [1] FALSE
```

4.5 Applications

The basic principles described above give rise to a wide variety of useful applications. Some of the most important are described below. Many of these basic techniques are wrapped up into more concise functions (e.g., `subset()`, `merge()`, `dplyr::arrange()`), but it is useful to understand how they are implemented with basic subsetting. This will allow you to adapt to new situations not handled by existing functions.

4.5.1 Lookup tables (character subsetting)

Character matching provides a powerful way to make lookup tables. Say you want to convert abbreviations:

```
x <- c("m", "f", "u", "f", "f", "m", "m")
lookup <- c(m = "Male", f = "Female", u = NA)
lookup[x]
#>      m      f      u      f      f      m      m
#> "Male" "Female" NA "Female" "Female" "Male" "Male"

unname(lookup[x])
#> [1] "Male"  "Female" NA      "Female" "Female" "Male"  "Male"
```

If you don't want names in the result, use `unname()` to remove them.

4.5.2 Matching and merging by hand (integer subsetting)

You may have a more complicated lookup table which has multiple columns of information. Suppose we have a vector of integer grades, and a table that describes their properties:

```
grades <- c(1, 2, 2, 3, 1)

info <- data.frame(
  grade = 3:1,
  desc = c("Excellent", "Good", "Poor"),
  fail = c(F, F, T)
)
```

We want to duplicate the `info` table so that we have a row for each value in `grades`. An elegant way to do this is by combining `match()` and integer subsetting:

```
id <- match(grades, info$grade)
info[id, ]
#>     grade      desc  fail
#> 3      1      Poor  TRUE
#> 2      2      Good FALSE
#> 2.1    2      Good FALSE
#> 1      3 Excellent FALSE
#> 3.1    1      Poor  TRUE
```

If you have multiple columns to match on, you'll need to first collapse them to a single column (with e.g. `interaction()`), but typically you are better off switching to a function designed specifically for joining multiple tables like `merge()`, or `dplyr::left_join()`.

4.5.3 Random samples/bootstraps (integer subsetting)

You can use integer indices to perform random sampling or bootstrapping of a vector or data frame. `sample()` generates a vector of indices, then subsetting accesses the values:

```
df <- data.frame(x = c(1, 2, 3, 1, 2), y = 5:1, z = letters[1:5])

# Randomly reorder
df[sample(nrow(df)), ]
#>   x y z
#> 1 1 5 a
#> 4 1 2 d
#> 2 2 4 b
#> 5 2 1 e
#> 3 3 3 c

# Select 3 random rows
df[sample(nrow(df), 3), ]
#>   x y z
#> 3 3 3 c
#> 2 2 4 b
#> 1 1 5 a

# Select 6 bootstrap replicates
df[sample(nrow(df), 6, replace = TRUE), ]
#>   x y z
```

```
#> 4 1 2 d
#> 4.1 1 2 d
#> 5 2 1 e
#> 1 1 5 a
#> 1.1 1 5 a
#> 2 2 4 b
```

The arguments of `sample()` control the number of samples to extract, and whether sampling is performed with or without replacement.

4.5.4 Ordering (integer subsetting)

`order()` takes a vector as input and returns an integer vector describing how the subsetted vector should be ordered:

```
x <- c("b", "c", "a")
order(x)
#> [1] 3 1 2
x[order(x)]
#> [1] "a" "b" "c"
```

To break ties, you can supply additional variables to `order()`, and you can change from ascending to descending order using `decreasing = TRUE`. By default, any missing values will be put at the end of the vector; however, you can remove them with `na.last = NA` or put at the front with `na.last = FALSE`.

For two or more dimensions, `order()` and integer subsetting makes it easy to order either the rows or columns of an object:

```
# Randomly reorder df
df2 <- df[sample(nrow(df)), 3:1]
df2
#> z y x
#> 3 c 3 3
#> 1 a 5 1
#> 2 b 4 2
#> 4 d 2 1
#> 5 e 1 2

df2[order(df2$x), ]
#> z y x
#> 1 a 5 1
#> 4 d 2 1
```

```
#> 2 b 4 2
#> 5 e 1 2
#> 3 c 3 3
df2[, order(names(df2))]
#> x y z
#> 3 3 3 c
#> 1 1 5 a
#> 2 2 4 b
#> 4 1 2 d
#> 5 2 1 e
```

You can sort vectors directly with `sort()`, or use `dplyr::arrange()` or similar to sort a data frame.

4.5.5 Expanding aggregated counts (integer subsetting)

Sometimes you get a data frame where identical rows have been collapsed into one and a count column has been added. `rep()` and integer subsetting make it easy to uncollapse the data by subsetting with a repeated row index:

```
df <- data.frame(x = c(2, 4, 1), y = c(9, 11, 6), n = c(3, 5, 1))
rep(1:nrow(df), df$n)
#> [1] 1 1 1 2 2 2 2 2 3

df[rep(1:nrow(df), df$n), ]
#> x y n
#> 1 2 9 3
#> 1.1 2 9 3
#> 1.2 2 9 3
#> 2 4 11 5
#> 2.1 4 11 5
#> 2.2 4 11 5
#> 2.3 4 11 5
#> 2.4 4 11 5
#> 3 1 6 1
```

4.5.6 Removing columns from data frames (character subsetting)

There are two ways to remove columns from a data frame. You can set individual columns to `NULL`:

```
df <- data.frame(x = 1:3, y = 3:1, z = letters[1:3])
df$z <- NULL
```

Or you can subset to return only the columns you want:

```
df <- data.frame(x = 1:3, y = 3:1, z = letters[1:3])
df[c("x", "y")]
#>   x y
#> 1 1 3
#> 2 2 2
#> 3 3 1
```

If you only know the columns you don't want, use set operations to work out which columns to keep:

```
df[setdiff(names(df), "z")]
#>   x y
#> 1 1 3
#> 2 2 2
#> 3 3 1
```

4.5.7 Selecting rows based on a condition (logical subsetting)

Because logical subsetting allows you to easily combine conditions from multiple columns, it is probably the most commonly used technique for extracting rows out of a data frame.

```
mtcars[mtcars$gear == 5, ]
#>           mpg cyl  disp  hp drat    wt  qsec vs am gear carb
#> Porsche 914-2 26.0   4 120.3 91 4.43 2.14 16.7  0  1    5    2
#> Lotus Europa  30.4   4  95.1 113 3.77 1.51 16.9  1  1    5    2
#> Ford Pantera L 15.8   8 351.0 264 4.22 3.17 14.5  0  1    5    4
#> Ferrari Dino  19.7   6 145.0 175 3.62 2.77 15.5  0  1    5    6
#> Maserati Bora  15.0   8 301.0 335 3.54 3.57 14.6  0  1    5    8

mtcars[mtcars$gear == 5 & mtcars$cyl == 4, ]
#>           mpg cyl  disp  hp drat    wt  qsec vs am gear carb
#> Porsche 914-2 26.0   4 120.3 91 4.43 2.14 16.7  0  1    5    2
#> Lotus Europa  30.4   4  95.1 113 3.77 1.51 16.9  1  1    5    2
```

Remember to use the vector boolean operators `&` and `|`, not the short-circuiting scalar operators `&&` and `||` which are more useful inside if statements. Don't for-

get De Morgan's laws (http://en.wikipedia.org/wiki/De_Morgan's_laws), which can be useful to simplify negations:

- $!(X \ \& \ Y)$ is the same as $!X \ | \ !Y$
- $!(X \ | \ Y)$ is the same as $!X \ \& \ !Y$

For example, $!(X \ \& \ !(Y \ | \ Z))$ simplifies to $!X \ | \ !(Y \ | \ Z)$, and then to $!X \ | \ Y \ | \ Z$.

4.5.8 Boolean algebra vs. sets (logical & integer subsetting)

It's useful to be aware of the natural equivalence between set operations (integer subsetting) and boolean algebra (logical subsetting). Using set operations is more effective when:

- You want to find the first (or last) TRUE.
- You have very few TRUEs and very many FALSEs; a set representation may be faster and require less storage.

`which()` allows you to convert a boolean representation to an integer representation. There's no reverse operation in base R but we can easily create one:

```
x <- sample(10) <- 4
which(x)
#> [1] 2 5 8

unwhich <- function(x, n) {
  out <- rep_len(FALSE, n)
  out[x] <- TRUE
  out
}
unwhich(which(x), 10)
#> [1] FALSE  TRUE FALSE FALSE  TRUE FALSE FALSE  TRUE FALSE FALSE
```

Let's create two logical vectors and their integer equivalents and then explore the relationship between boolean and set operations.

```
(x1 <- 1:10 %% 2 == 0)
#> [1] FALSE  TRUE FALSE  TRUE FALSE  TRUE FALSE  TRUE FALSE  TRUE
(x2 <- which(x1))
#> [1] 2 4 6 8 10
(y1 <- 1:10 %% 5 == 0)
#> [1] FALSE FALSE FALSE FALSE  TRUE FALSE FALSE FALSE FALSE  TRUE
(y2 <- which(y1))
```

```

#> [1] 5 10

#  $X \& Y \leftrightarrow \text{intersect}(x, y)$ 
x1 & y1
#> [1] FALSE FALSE FALSE FALSE FALSE FALSE FALSE FALSE TRUE
intersect(x2, y2)
#> [1] 10

#  $X \mid Y \leftrightarrow \text{union}(x, y)$ 
x1 | y1
#> [1] FALSE TRUE FALSE TRUE TRUE TRUE FALSE TRUE FALSE TRUE
union(x2, y2)
#> [1] 2 4 6 8 10 5

#  $X \& \neg Y \leftrightarrow \text{setdiff}(x, y)$ 
x1 & !y1
#> [1] FALSE TRUE FALSE TRUE FALSE TRUE FALSE TRUE FALSE FALSE
setdiff(x2, y2)
#> [1] 2 4 6 8

#  $\text{xor}(X, Y) \leftrightarrow \text{setdiff}(\text{union}(x, y), \text{intersect}(x, y))$ 
xor(x1, y1)
#> [1] FALSE TRUE FALSE TRUE TRUE TRUE FALSE TRUE FALSE FALSE
setdiff(union(x2, y2), intersect(x2, y2))
#> [1] 2 4 6 8 5

```

When first learning subsetting, a common mistake is to use `x[which(y)]` instead of `x[y]`. Here the `which()` achieves nothing: it switches from logical to integer subsetting but the result will be exactly the same. In more general cases, there are two important differences.

- When the logical vector contains `NA`, logical subsetting replaces these values by `NA` while `which()` drops these values. It's not uncommon to use `which()` for this side-effect, but that's
- `x[-which(y)]` is **not** equivalent to `x[!y]`: if `y` is all `FALSE`, `which(y)` will be `integer(0)` and `-integer(0)` is still `integer(0)`, so you'll get no values, instead of all values.

In general, avoid switching from logical to integer subsetting unless you want, for example, the first or last `TRUE` value.

4.5.9 Exercises

1. How would you randomly permute the columns of a data frame? (This is an important technique in random forests.) Can you simultaneously permute the rows and columns in one step?
2. How would you select a random sample of m rows from a data frame? What if the sample had to be contiguous (i.e., with an initial row, a final row, and every row in between)?
3. How could you put the columns in a data frame in alphabetical order?

4.6 Answers

1. Positive integers select elements at specific positions, negative integers drop elements; logical vectors keep elements at positions corresponding to TRUE; character vectors select elements with matching names.
2. `[` selects sub-lists. It always returns a list; if you use it with a single positive integer, it returns a list of length one. `[[` selects an element within a list. `$` is a convenient shorthand: `x$y` is equivalent to `x[["y"]]`.
3. Use `drop = FALSE` if you are subsetting a matrix, array, or data frame and you want to preserve the original dimensions. You should almost always use it when subsetting inside a function.
4. If `x` is a matrix, `x[] <- 0` will replace every element with 0, keeping the same number of rows and columns. `x <- 0` completely replaces the matrix with the value 0.
5. A named character vector can act as a simple lookup table: `c(x = 1, y = 2, z = 3)[c("y", "z", "x")]`

Chapter 5

Functions

5.1 Introduction

If you’re reading this book, you’ve probably already created many R functions and know how to use them to reduce duplication in your code. In this chapter, you’ll learn how to turn that informal, working knowledge into more rigorous, theoretical understanding. And while you’ll see some interesting tricks and techniques along the way, keep in mind that what you’ll learn here will be important for understanding the more advanced topics discussed later in the book.

Quiz

Answer the following questions to see if you can safely skip this chapter. You can find the answers in Section 5.10.

1. What are the three components of a function?
2. What does the following code return?

```
x <- 10
f1 <- function(x) {
  function() {
    x + 10
  }
}
f1(1)()
```

3. How would you usually write this code?

```
~+(1, ~*(2, 3))
```

4. How could you make this call easier to read?

```
mean(, TRUE, x = c(1:10, NA))
```

5. Does the following code throw an error when executed? Why/why not?

```
f2 <- function(a, b) {
  a * 10
}
f2(10, stop("This is an error!"))
```

6. What is an infix function? How do you write it? What's a replacement function? How do you write it?

7. How do you ensure that cleanup action occurs regardless of how a function exits?

Outline

- Section 5.2 describes the basics of creating a function, the three main components of a function, and the exception to many function rules: primitive functions (which are implemented in C, not R).
- Section 5.3 discusses the strengths and weaknesses of the three forms of function composition commonly used in R code.
- Section 5.4 shows you how R finds the value associated with a given name, i.e. the rules of lexical scoping.
- Section 5.5 is devoted to an important property of function arguments: they are only evaluated when used for the first time.
- Section 5.6 discusses the special `...` argument, which allows you to pass on extra arguments to another function.
- Section 5.7 discusses the two primary ways that a function can exit, and how to define an exit handler, code that is run on exit, regardless of what triggers it.
- Section 5.8 shows you the various ways in which R disguises ordinary function calls, and how you can use the standard prefix form to better understand what's going on.

5.2 Function fundamentals

To understand functions in R you need to internalise two important ideas:

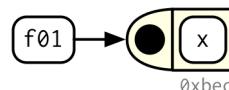
- Functions are objects, just as vectors are objects.
- Functions can be broken down into three components: arguments, body, and environment.

There are exceptions to every rule, and in this case, there is a small selection of “primitive” base functions that are implemented purely in C.

5.2.1 First-class functions

The most important thing to understand about R is that functions are objects in their own right, a language property often called “first-class functions”. Unlike in many other languages, there is no special syntax for defining and naming a function: you simply create a function object (with `function`) and bind it to a name with `<-`:

```
f01 <- function(x) {
  sin(1 / x ^ 2)
}
```



While you almost always create a function and then bind it to a name, the binding step is not compulsory. If you choose not to give a function a name, you get an **anonymous function**. This is useful when it’s not worth the effort to figure out a name:

```
lapply(mtcars, function(x) length(unique(x)))
Filter(function(x) !is.numeric(x), mtcars)
integrate(function(x) sin(x) ^ 2, 0, pi)
```

A final option is to put functions in a list:

```
funcs <- list(
  half = function(x) x / 2,
  double = function(x) x * 2
)
```

```
fun$double(10)
#> [1] 20
```

In R, you'll often see functions called **closures**. This name reflects the fact that R functions capture, or **enclose**, their environments.

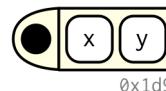
```
typeof(f01)
#> [1] "closure"
```

5.2.2 Function components

A function has three parts:

- The **formals()**, the list of arguments that control how you call the function.
- The **body()**, the code inside the function.
- The **environment()**, the data structure that determines how the function finds the values associated with the names.

I'll draw functions as in the following diagram. The black dot on the left is the environment. The two blocks to the right are the function arguments. I won't draw the body, because it's usually large, and doesn't help you understand the "shape" of the function.



While the formals and body are specified explicitly when you create a function, the environment is specified implicitly, based on *where* you defined the function. The function environment always exists, but it is only printed when the function isn't defined in the global environment.

```
f02 <- function(x) {
  # A comment
  x ^ 2
}

formals(f02)
#> $x

body(f02)
#> {
```

```
#>     x ^ 2
#> }

environment(f02)
#> <environment: R_GlobalEnv>
```

Like all objects in R, functions can also possess any number of additional `attributes()`. One attribute used by base R is “srcref”, short for source reference. It points to the source code used to create the function. The srcref is used for printing because, unlike `body()`, it contains code comments and other formatting.

```
attr(f02, "srcref")
#> function(x) {
#>   # A comment
#>   x ^ 2
#> }
```

5.2.3 Primitive functions

There is one exception to the rule that a function has three components. Primitive functions, like `sum()` and `[`, call C code directly.

```
sum
#> function (...) na.rm = FALSE) .Primitive("sum")
`[`
#> .Primitive("[")
```

They have type “builtin” or “special”:

```
typeof(sum)
#> [1] "builtin"
typeof(`[`)
#> [1] "special"
```

These functions exist primarily in C, not R, so their `formals()`, `body()`, and `environment()` are all `NULL`:

```
formals(sum)
#> NULL
body(sum)
#> NULL
environment(sum)
#> NULL
```

Primitive functions are only found in the base package. While they have certain performance advantages, this benefit comes at a price: they are harder to write. For this reason, R-core generally avoids creating them unless there is no other option.

5.2.4 Exercises

- Given a function, like "mean", `match.fun()` lets you find a function. Given a function, can you find its name? Why doesn't that make sense in R?
- It's possible (although typically not useful) to call an anonymous function. Which of the two approaches below is correct? Why?

```
function(x) 3()
#> function(x) 3()
(function(x) 3)()
#> [1] 3
```

- A good rule of thumb is that an anonymous function should fit on one line and shouldn't need to use `{}`. Review your code. Where could you have used an anonymous function instead of a named function? Where should you have used a named function instead of an anonymous function?
- What function allows you to tell if an object is a function? What function allows you to tell if a function is a primitive function?
- This code makes a list of all functions in the base package.

```
objs <- mget(ls("package:base"), inherits = TRUE)
funs <- Filter(is.function, objs)
```

Use it to answer the following questions:

- Which base function has the most arguments?
 - How many base functions have no arguments? What's special about those functions?
 - How could you adapt the code to find all primitive functions?
- What are the three important components of a function?
 - When does printing a function not show the environment it was created in?

5.3 Function composition

Base R provides two ways to compose multiple function calls. For example, imagine you want to compute the population standard deviation using `sqrt()` and `mean()` as building blocks:

```
square <- function(x) x^2
deviation <- function(x) x - mean(x)
```

You either nest the function calls:

```
x <- runif(100)

sqrt(mean(square(deviation(x))))
#> [1] 0.274
```

Or you save the intermediate results as variables:

```
out <- deviation(x)
out <- square(out)
out <- mean(out)
out <- sqrt(out)
out
#> [1] 0.274
```

The magrittr package (Bache and Wickham 2014) provides a third option: the binary operator `%>%`, which is called the pipe and is pronounced as “and then”.

```
library(magrittr)

x %>%
  deviation() %>%
  square() %>%
  mean() %>%
  sqrt()
#> [1] 0.274
```

`x %>% f()` is equivalent to `f(x)`; `x %>% f(y)` is equivalent to `f(x, y)`. The pipe is related to **tacit** or **point-free programming**¹. In this style of programming, you don’t explicitly refer to variables. Instead, you focus on the high-level composition of functions rather than the low-level flow of data; the focus is on what’s being done (the verbs), rather than on what’s being modified (the nouns). This

¹Point-free programming is related to point-free topology. It’s just a coincidence that many forms of point-free programming use `.` extensively. Point-free programming is sometimes humorously called pointless programming.

style is common in Haskell and F#, the main inspiration for magrittr, and is the default style in stack based programming languages like Forth and Factor.

Each of the three options has its own strengths and weaknesses:

- Nesting, `f(g(x))`, is concise, and well suited for short sequences. But longer sequences are hard to read because they are read inside out and right to left. As a result, arguments can get spread out over long distances creating the “Dagwood sandwich (https://en.wikipedia.org/wiki/Dagwood_sandwich)” problem.
- Intermediate objects, `y <- f(x); g(y)`, requires you to name intermediate objects. This is a strength when objects are important, but a weakness when values are truly intermediate.
- Piping, `x %>% f() %>% g()`, allows you to read code in straightforward left-to-right fashion and doesn’t require you to name intermediate objects. But you can only use it with linear sequences of transformations of a single object. It also requires an additional third party package and assumes that the reader understands piping.

Most code will use a combination of all three styles. Piping is more common in data analysis code, as much of an analysis consists of a sequence of transformations of an object (like a data frame or plot). I tend to use piping infrequently in packages; not because it is a bad idea, but because it’s often a less natural fit.

5.4 Lexical scoping

In Names and values, we discussed assignment, the act of binding a name to a value. Here we’ll discuss **scoping**, the act of finding the value associated with a name.

The basic rules of scoping are quite intuitive, and you’ve probably already internalised them, even if you never explicitly studied them. For example, what will the following code return, 10 or 20?²

```
x <- 10
g01 <- function() {
  x <- 20
  x
}
```

²I’ll “hide” the answers to these challenges in the footnotes. Try solving them before looking at the answer; this will help you to better remember the correct answer. In this case, `g01()` will return 20.

g01()

In this section, you'll learn the formal rules of scoping as well as some of its more subtle details. A deeper understanding of scoping will help you to use more advanced functional programming tools, and eventually, even to write tools that translate R code into other languages.

R uses **lexical scoping**³: it looks up the values of names based on how a function is defined, not how it is called. “Lexical” here is not the English adjective “relating to words or a vocabulary”. It's a technical CS term that tells us that the scoping rules use a parse-time, rather than a run-time structure.

R's lexical scoping follows four primary rules:

- Name masking
- Functions vs. variables
- A fresh start
- Dynamic lookup

5.4.1 Name masking

The basic principle of lexical scoping is that names defined inside a function mask names defined outside a function. This is illustrated in the following example.

```
x <- 10
y <- 20
g02 <- function() {
  x <- 1
  y <- 2
  c(x, y)
}
g02()
#> [1] 1 2
```

If a name isn't defined inside a function, R looks one level up.

```
x <- 2
g03 <- function() {
  y <- 1
  c(x, y)
```

³Functions that automatically quote one or more arguments (sometimes called NSE functions) can override the default scoping rules to implement other varieties of scoping. You'll learn more about that in metaprogramming.

```

}
g03()
#> [1] 2 1

```

The same rules apply if a function is defined inside another function. First, R looks inside the current function. Then, it looks where that function was defined (and so on, all the way up to the global environment). Finally, it looks in other loaded packages.

Run the following code in your head, then confirm the result by running the code.⁴

```

x <- 1
g04 <- function() {
  y <- 2
  i <- function() {
    z <- 3
    c(x, y, z)
  }
  i()
}
g04()

```

The same rules also apply to functions created by other functions, which I call manufactured functions, and are the topic of Chapter 9. Here I'll focus on how they interact with scoping. The following function, `g05()`, returns a function. What do you think this function will return when it's called?⁵

```

x <- 10
y <- 20

g05 <- function() {
  y <- 2
  function() {
    c(x, y)
  }
}
g06 <- g05()
g06()

```

This seems a little magical: how does R know what the value of `y` is after `g05()` is returned? R knows because `g06()` preserves the environment where it was

⁴`g04()` returns `c(1, 2, 3)`.

⁵`g06()` returns `c(10, 2)`.

defined and that environment includes the value of `y`. You'll learn more about how environments work in Chapter 6.

5.4.2 Functions vs. variables

In R, functions are ordinary objects. This means the scoping rules described above also apply to functions:

```
g07 <- function(x) x + 1
g08 <- function() {
  g07 <- function(x) x + 100
  g07(10)
}
g08()
#> [1] 110
```

However, when a function and a non-function share the same name (they must, of course, reside in different environments), applying these rules gets a little more complicated. When you use a name in a function call, R ignores non-function objects when looking for that value. For example, in the code below, `g09` takes on two different values:

```
g09 <- function(x) x + 100
g10 <- function() {
  g09 <- 10
  g09(g09)
}
g10()
#> [1] 110
```

Note that for the record, using the same name for two different things makes for confusing code, and is something best avoided!

5.4.3 A fresh start

What happens to values between invocations of a function? Consider the example below. What will happen the first time you run this function? What will happen the second time?⁶ (If you haven't seen `exists()` before, it returns `TRUE` if there's a variable with that name and returns `FALSE` if not.)

⁶`g11()` returns `1` every time it's called.

```
g11 <- function() {
  if (!exists("a")) {
    a <- 1
  } else {
    a <- a + 1
  }
  a
}

g11()
g11()
```

You might be surprised that `g11()` always returns the same value. This happens because every time a function is called a new environment is created to host its execution. This means that a function has no way to tell what happened the last time it was run; each invocation is completely independent. (We'll see some ways to get around this in Section 9.2.3)

5.4.4 Dynamic lookup

Lexical scoping determines where, but not when to look for values. R looks for values when the function is run, not when the function is created. Together, these two properties tell us that the output of a function can differ depending on the objects outside the function's environment:

```
g12 <- function() x + 1
x <- 15
g12()
#> [1] 16

x <- 20
g12()
#> [1] 21
```

This behaviour can be quite annoying. If you make a spelling mistake in your code, you won't get an error message when you create the function. And depending on the variables defined in the global environment, you might not even get an error message when you run the function.

To detect this problem, use `codetools::findGlobals()`. This function lists all the external dependencies (unbound symbols) within a function:

```
codetools::findGlobals(g12)
#> [1] "+" "x"
```

To solve this problem, you can manually change the function's environment to the `emptyenv()`, an environment which contains nothing:

```
environment(g12) <- emptyenv()
g12()
#> Error in x + 1:
#>   could not find function "+"
```

The problem and its solution reveal why this seemingly undesirable behaviour exists: R relies on lexical scoping to find *everything*, from the obvious, like `mean()`, to the less obvious, like `+` or even `{`. This gives R's scoping rules a rather beautiful simplicity.

5.4.5 Exercises

1. What does the following code return? Why? Describe how each of the three `c`'s is interpreted.

```
c <- 10
c(c = c)
```

2. What are the four principles that govern how R looks for values?
3. What does the following function return? Make a prediction before running the code yourself.

```
f <- function(x) {
  f <- function(x) {
    f <- function() {
      x ^ 2
    }
    f() + 1
  }
  f(x) * 2
}
f(10)
```

5.5 Lazy evaluation

In R, function arguments are **lazily evaluated**: they're only evaluated if accessed. For example, this code doesn't generate an error because `x` is never used:

```
h01 <- function(x) {
  10
}
h01(stop("This is an error!"))
#> [1] 10
```

This is an important feature because it allows you to do things like include potentially expensive computations in function arguments that will only be evaluated if needed.

5.5.1 Forcing evaluation

To **compel** the evaluation of an argument, use `force()`:

```
h02 <- function(x) {
  force(x)
  10
}
h02(stop("This is an error!"))
#> Error in force(x):
#>   This is an error!
```

It's usually not necessary to force evaluation. However, it is important for certain functional programming techniques, like the one we'll cover in detail in function operators. Here, I'm just going to show you what the basic issue is.

Consider this small but surprisingly tricky function. It takes a single argument `x`, and returns a function that returns `x` when called.

```
capture1 <- function(x) {
  function() {
    x
  }
}
```

The subtlety here is that the value of `x` will be captured not when you call `capture1()`, but when you call the function that `capture1()` returns:

```

x <- 10
h03 <- capture1(x)
h04 <- capture1(x)

h03()
#> [1] 10

x <- 20
h04()
#> [1] 20

```

Even more confusingly this only happens once: the value is locked in after you have called `h03()`/`h04()` for the first time.

```

x <- 30
h03()
#> [1] 10
h04()
#> [1] 20

```

This behaviour is a consequence of lazy evaluation. The `x` argument is evaluated once `h03()`/`h04()` is called, and then its value is cached. We can avoid the confusion by forcing `x`:

```

capture2 <- function(x) {
  force(x)

  function() {
    x
  }
}

x <- 10
h05 <- capture2(x)

x <- 20
h05()
#> [1] 10

```

5.5.2 Promises

Lazy evaluation is powered by a data structure called a **promise**, or (less commonly) a thunk. It's one of the features that makes R such an interesting programming language (we'll return to promises again in metaprogramming).

A promise has three components:

- The expression, like `x + y` which gives rise to the delayed computation.
- The environment where the expression should be evaluated.
- The value, which is computed and cached the first time a promise is accessed when the expression is evaluated in the specified environment.

The value cache ensures that the promise always returns the same value, even when it's accessed multiple times. For example, you can see in the following code that `runif(1)` is only evaluated once:

```
h06 <- function(x) {
  c(x, x, x)
}

h06(runif(1))
#> [1] 0.806 0.806 0.806
```

You can also create promises “by hand” using `delayedAssign()`:

```
delayedAssign("x", {print("Executing code"); runif(1)})

x
#> [1] "Executing code"
#> [1] 0.814
x
#> [1] 0.814
```

You'll see this idea again in advanced bindings.

You cannot manipulate promises with R code. Promises are like a quantum state: any attempt to inspect them with R code will force an immediate evaluation, making the promise disappear. Later, in Section 18.3, you'll learn about quosures, which reify promises into an R object where you can easily inspect the expression and the environment.

5.5.3 Default arguments

Thanks to lazy evaluation, default values can be defined in terms of other arguments, or even in terms of variables defined later in the function:

```
h07 <- function(x = 1, y = x * 2, z = a + b) {
  a <- 10
  b <- 100

  c(x, y, z)
}

h07()
#> [1] 1 2 110
```

Many base R functions use this technique, but I don't recommend it. It makes the code harder to understand: to predict *what* will be returned, you need to know the exact order in which default arguments are evaluated.

The evaluation environment is slightly different for default and user supplied arguments, as default arguments are evaluated inside the function. This means that seemingly identical calls can yield different results. It's easiest to see this with an extreme example:

```
h08 <- function(x = ls()) {
  a <- 1
  x
}

# ls() evaluated inside h08:
h08()
#> [1] "a" "x"

# ls() evaluated in global environment:
h08(ls())
#> [1] "h08"
```

5.5.4 Missing arguments

To determine if an argument's value comes from the user or from a default, you can use `missing()`:

```

h09 <- function(x = 10) {
  list(missing(x), x)
}
str(h09())
#> List of 2
#> $ : logi TRUE
#> $ : num 10
str(h09(10))
#> List of 2
#> $ : logi FALSE
#> $ : num 10

```

`missing()` is best used sparingly, however. Take `sample()`, for example. How many arguments are required?

```

args(sample)
#> function (x, size, replace = FALSE, prob = NULL)
#> NULL

```

It looks like both `x` and `size` are required, but in fact if it's not supplied, `sample()` uses `missing()` to provide a default for `size`. If I were to rewrite `sample`, I'd use an explicit `NULL` to indicate that `size` is not required but can be supplied:

```

sample <- function(x, size = NULL, replace = FALSE, prob = NULL) {
  if (is.null(size)) {
    size <- length(x)
  }

  x[sample.int(length(x), size, replace = replace, prob = prob)]
}

```

With the binary pattern created by the `%||%` infix function, which uses the LHS if it's not `NULL` and the RHS otherwise, we can further simplify `sample()`:

```

`%||%` <- function(lhs, rhs) {
  if (!is.null(lhs)) {
    lhs
  } else {
    rhs
  }
}

sample <- function(x, size = NULL, replace = FALSE, prob = NULL) {
  size <- size %||% length(x)
}

```

```
x[sample.int(length(x), size, replace = replace, prob = prob)]  
}
```

Because of lazy evaluation, you don't need to worry about unnecessary computation: the RHS of `%||%` will only be evaluated if the LHS is `NULL`.

5.5.5 Exercises

1. What important property of `&&` makes `x_ok()` work?

```
x_ok <- function(x) {  
  !is.null(x) && length(x) == 1 && x > 0  
}  
  
x_ok(NULL)  
#> [1] FALSE  
x_ok(1)  
#> [1] TRUE  
x_ok(1:3)  
#> [1] FALSE
```

What is different with this code? Why is this behaviour undesirable here?

```
x_ok <- function(x) {  
  !is.null(x) & length(x) == 1 & x > 0  
}  
  
x_ok(NULL)  
#> logical(0)  
x_ok(1)  
#> [1] TRUE  
x_ok(1:3)  
#> [1] FALSE FALSE FALSE
```

2. The definition of `force()` is simple:

```
force  
#> function (x)  
#> x  
#> <bytecode: 0x1a65cd8>  
#> <environment: namespace:base>
```

Why is it better to `force(x)` instead of just `x`?

3. What does this function return? Why? Which principle does it illustrate?

```
f2 <- function(x = z) {
  z <- 100
  x
}
f2()
```

4. What does this function return? Why? Which principle does it illustrate?

```
y <- 10
f1 <- function(x = {y <- 1; 2}, y = 0) {
  c(x, y)
}
f1()
y
```

5. In `hist()`, the default value of `xlim` is `range(breaks)`, the default value for `breaks` is "Sturges", and

```
range("Sturges")
#> [1] "Sturges" "Sturges"
```

Explain how `hist()` works to get a correct `xlim` value.

6. Explain why this function works. Why is it confusing?

```
show_time <- function(x = stop("Error!")) {
  stop <- function(...) Sys.time()
  print(x)
}
show_time()
#> [1] "2018-09-28 10:19:00 UTC"
```

7. How many arguments are required when calling `library()`?

5.6 ... (dot-dot-dot)

Functions can have a special argument `...` (pronounced dot-dot-dot). With it, a function can take any number of additional arguments. In other programming languages, this type of argument is often called a varargs, and a function that uses it is said to be variadic.

You can also use `...` to pass those additional arguments on to another function.

```
i01 <- function(y, z) {
  list(y = y, z = z)
}

i02 <- function(x, ...) {
  i01(...)
}

str(i02(x = 1, y = 2, z = 3))
#> List of 2
#> $ y: num 2
#> $ z: num 3
```

Using a special syntax, it's possible (but rarely useful) to refer to elements of `...` by position:

```
i03 <- function(...) {
  list(first = ..1, third = ..3)
}
str(i03(1, 2, 3))
#> List of 2
#> $ first: num 1
#> $ third: num 3
```

More useful is `list(...)`, which evaluates the arguments and stores them in a list:

```
i04 <- function(...) {
  list(...)
}
str(i04(a = 1, b = 2))
#> List of 2
#> $ a: num 1
#> $ b: num 2
```

(See also `rlang::list2()` to support splicing and to silently ignore trailing commas, and `rlang::enquos()` to capture unevaluated arguments, the topic of quasiquotation.)

There are two primary uses of `...`, both of which we'll come back to later in the book:

- If your function takes a function as an argument, you want some way to pass additional arguments to that function. In this example, `lapply()` uses

... to pass `na.rm` on to `mean()`:

```
x <- list(c(1, 3, NA), c(4, NA, 6))
str(lapply(x, mean, na.rm = TRUE))
#> List of 2
#>  $ : num 2
#>  $ : num 5
```

We'll come back to this technique in Section 8.2.3.

- If your function is an S3 generic, you need some way to allow methods to take arbitrary extra arguments. For example, take the `print()` function. Because there are different options for printing depending on the type of object, there's no way to pre-specify every possible argument. ... is what allow individual methods to have different arguments:

```
print(factor(letters), max.levels = 4)

print(y ~ x, showEnv = TRUE)
```

We'll come back to this use of ... in Section 12.4.3.

Using ... comes with two downsides:

- When you use it to pass arguments to another function, you have to carefully explain to the user where those arguments go. This makes it hard to understand what you can do with functions like `lapply()` and `plot()`.
- A misspelled argument will not raise an error. This makes it easy for typos to go unnoticed:

```
sum(1, 2, NA, na_rm = TRUE)
#> [1] NA
```

... is a powerful tool, but be aware of the downsides.

5.6.1 Exercises

1. Explain the following results:

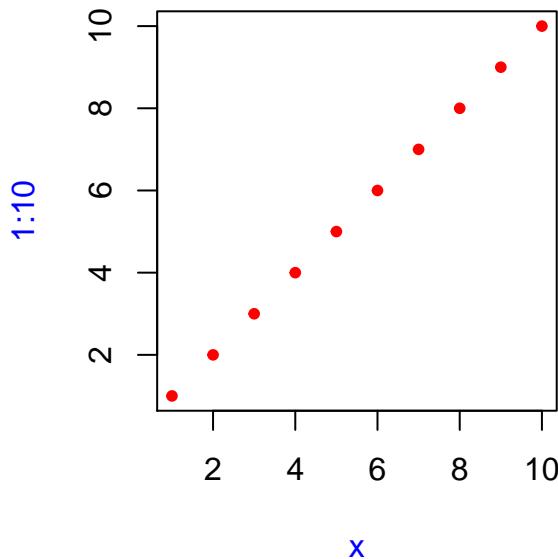
```
sum(1, 2, 3)
#> [1] 6
mean(1, 2, 3)
#> [1] 1

sum(1, 2, 3, na.omit = TRUE)
```

```
#> [1] 7
mean(1, 2, 3, na.omit = TRUE)
#> [1] 1
```

2. In the following call, explain how to find the documentation for the named arguments in the following function call:

```
plot(1:10, col = "red", pch = 20, xlab = "x", col.lab = "blue")
```



3. Why does `plot(1:10, col = "red")` only colour the points, not the axes or labels? Read the source code of `plot.default()` to find out.

5.7 Exiting a function

Most functions exit in one of two ways⁷: they either return a value, indicating success, or they throw an error, indicating failure. This section describes return values (implicit vs. explicit; visible vs. invisible), briefly discusses errors, and introduces exit handlers, which allow you to run code when a function exits.

5.7.1 Implicit vs. explicit returns

There are two ways that a function can return a value:

⁷Functions can exit in other more esoteric ways like signalling a condition that is caught by an exit handler, invoking a restart, or pressing “Q” in an interactive browser.

- Implicitly, where the last evaluated expression is the return value:

```
j01 <- function(x) {
  if (x < 10) {
    0
  } else {
    10
  }
}
j01(5)
#> [1] 0
j01(15)
#> [1] 10
```

- Explicitly, by calling `return()`:

```
j02 <- function(x) {
  if (x < 10) {
    return(0)
  } else {
    return(10)
  }
}
```

5.7.2 Invisible values

Most functions return visibly: calling the function in an interactive context prints the result.

```
j03 <- function() 1
j03()
#> [1] 1
```

However, you can prevent automatic printing by applying `invisible()` to the last value:

```
j04 <- function() invisible(1)
j04()
```

To verify that this value does indeed exist, you can explicitly print it or wrap it in parentheses:

```
print(j04())
#> [1] 1
```

```
(j04())
#> [1] 1
```

Alternatively, you can use `withVisible()` to return the value and a visibility flag:

```
str(withVisible(j04()))
#> List of 2
#> $ value  : num 1
#> $ visible: logi FALSE
```

The most common function that returns invisibly is `<-:`

```
a <- 2
(a <- 2)
#> [1] 2
```

This is what makes it possible to chain assignments:

```
a <- b <- c <- d <- 2
```

In general, any function called primarily for a side effect (like `<-`, `print()`, or `plot()`) should return an invisible value (typically the value of the first argument).

5.7.3 Errors

If a function cannot complete its assigned task, it should throw an error with `stop()`, which immediately terminates the execution of the function.

```
j05 <- function() {
  stop("I'm an error")
  return(10)
}
j05()
#> Error in j05():
#>   I'm an error
```

An error indicates that something has gone wrong, and forces the user to deal with the problem. Some languages (like C, Go, and Rust) rely on special return values to indicate problems, but in R you should always throw an error. You'll learn more about errors, and how to handle them, in Conditions.

5.7.4 Exit handlers

Sometimes a function needs to make temporary changes to the global state. But having to cleanup those changes can be painful (what happens if there's an error?). To ensure that your changes are undone and that the global state is restored when the function completes, set up an **exit handler**. You do so by calling `on.exit()` with the code to be run. When the function exits, this code executes regardless of whether the function returns a value or throws an error.

To setup an exit handler:

```
j06 <- function(x) {
  cat("Hello\n")
  on.exit(cat("Goodbye!\n"), add = TRUE)

  if (x) {
    return(10)
  } else {
    stop("Error")
  }
}

j06(TRUE)
#> Hello
#> Goodbye!
#> [1] 10

j06(FALSE)
#> Hello
#> Error in j06(FALSE):
#>   Error
#> Goodbye!
```

Always set `add = TRUE` when using `on.exit()`. If you don't, each call to `on.exit()` will overwrite the previous exit handler. Even when only registering a single handler, it's good practice to set `add = TRUE` so that you won't get any unpleasant surprises if you later add more exit handlers

`on.exit()` is important because it allows you to place clean-up actions next to other actions.

```
cleanup <- function(dir, code) {
  old_dir <- setwd(dir)
  on.exit(setwd(old_dir), add = TRUE)
```

```
old_opt <- options(stringsAsFactors = FALSE)
on.exit(options(old_opt), add = TRUE)
}
```

Coupled with lazy evaluation, this creates a very useful pattern for running a block of code in an altered environment:

```
with_dir <- function(dir, code) {
  old <- setwd(dir)
  on.exit(setwd(old), add = TRUE)

  force(code)
}

getwd()
#> [1] "/home/travis/build/liao961120/adv-r"
with_dir("~/", getwd())
#> [1] "/home/travis"
```

See the `withr` package (<http://withr.r-lib.org>) for a collection of functions of this nature.

In R 3.4 and earlier, `on.exit()` expressions are always run in order of creation:

```
f <- function() {
  on.exit(message("a"), add = TRUE)
  on.exit(message("b"), add = TRUE)
}
f()
#> a
#> b
```

This can make cleanup a little tricky if some actions need to happen in a specific order; typically you want the most recent added expression to be run first. In R 3.5 and later, you can control this by setting `after = FALSE`:

```
f <- function() {
  on.exit(message("a"), add = TRUE, after = FALSE)
  on.exit(message("b"), add = TRUE, after = FALSE)
}
f()
#> b
#> a
```

5.7.5 Exercises

1. What does `load()` return? Why don't you normally see these values?
2. What does `write.table()` return? What would be more useful?
3. How does the `chdir` parameter of `source()` compare to `in_dir()`? Why might you prefer one to the other?
4. Write a function that opens a graphics device, runs the supplied code, and closes the graphics device (always, regardless of whether or not the plotting code works).
5. We can use `on.exit()` to implement a simple version of `capture.output()`.

```
capture.output2 <- function(code) {
  temp <- tempfile()
  on.exit(file.remove(temp), add = TRUE, after = TRUE)

  sink(temp)
  on.exit(sink(), add = TRUE, after = TRUE)

  force(code)
  readLines(temp)
}

capture.output2(cat("a", "b", "c", sep = "\n"))
#> [1] "a" "b" "c"
```

Compare `capture.output()` to `capture.output2()`. How do the functions differ? What features have I removed to make the key ideas easier to see? How have I rewritten the key ideas so they're easier to understand?

5.8 Function forms

“To understand computations in R, two slogans are helpful:

- Everything that exists is an object.
- Everything that happens is a function call.”

— John Chambers

While everything that happens in R is a result of a function call, not all calls look the same. Function calls come in four varieties:

- **prefix**: the function name comes before its arguments, like `foofy(a, b, c)`. These constitute of the majority of function calls in R.
- **infix**: the function name comes in between its arguments, like `x + y`. Infix forms are used for many mathematical operators, and for user-defined functions that begin and end with %.
- **replacement**: functions that replace values by assignment, like `names(df) <- c("a", "b", "c")`. They actually look like prefix functions.
- **special**: functions like `[[`, `if`, and `for`. While they don't have a consistent structure, they play important roles in R's syntax.

While there are four forms, you actually only need one because any call can be written in prefix form. I'll demonstrate this property, and then you'll learn about each of the forms in turn.

5.8.1 Rewriting to prefix form

An interesting property of R is that every infix, replacement, or special form can be rewritten in prefix form. Doing so is useful because it helps you better understand the structure of the language, it gives you the real name of every function, and it allows you to modify those functions for fun and profit.

The following example shows three pairs of equivalent calls, rewriting an infix form, replacement form, and a special form into prefix form.

```
x + y
`+`(x, y)

names(df) <- c("x", "y", "z")
`names<-`(df, c("x", "y", "z"))

for(i in 1:10) print(i)
`for`(i, 1:10, print(i))
```

Knowing the function name of a non-prefix function allows you to override its behaviour. For example, if you're ever feeling particularly evil, run the following code while a friend is away from their computer. It will introduce a fun bug: 10% of the time, it will add 1 to any numeric calculation inside the parentheses.

```
`(` <- function(e1) {
  if (is.numeric(e1) && runif(1) < 0.1) {
    e1 + 1
  } else {
```

Of course, overriding built-in functions like this is a bad idea, but, as you'll learn in metaprogramming, it's possible to apply it only to selected code blocks. This provides a clean and elegant approach to writing domain specific languages and translators to other languages.

A more useful application comes up when using functional programming tools. For example, you could use `sapply()` to add 3 to every element of a list by first defining a function `add()`:

```
add <- function(x, y) x + y
sapply(1:10, add, 3)
#> [1] 4 5 6 7 8 9 10 11 12 13
```

But we can also get the same result simply by relying on the existing `+` function:

```
sapply(1:5, `+`, 3)  
#> [1] 4 5 6 7 8
```

We'll explore this idea in detail in functionals.

5.8.2 Prefix form

The prefix form is the most common form in R code, and indeed in the majority of programming languages. Prefix calls in R are a little special because you can specify arguments in three ways:

- By position, like `help(mean)`.
 - Using partial matching, like `help(to = mean)`.
 - By name, like `help(topic = mean)`.

As illustrated by the following chunk, arguments are matched by exact name, then with unique prefixes, and finally by position.

```
k01 <- function(abcdef, bcde1, bcde2) {  
  list(a = abcdef, b1 = bcde1, b2 = bcde2)  
}
```

```

str(k01(1, 2, 3))
#> List of 3
#> $ a : num 1
#> $ b1: num 2
#> $ b2: num 3
str(k01(2, 3, abcdef = 1))
#> List of 3
#> $ a : num 1
#> $ b1: num 2
#> $ b2: num 3

# Can abbreviate long argument names:
str(k01(2, 3, a = 1))
#> List of 3
#> $ a : num 1
#> $ b1: num 2
#> $ b2: num 3

# But this doesn't work because abbreviation is ambiguous
str(k01(1, 3, b = 1))
#> Error in k01(1, 3, b = 1):
#>   argument 3 matches multiple formal arguments

```

In general, use positional matching only for the first one or two arguments; they will be the most commonly used, and most readers will know what they are. Avoid using positional matching for less commonly used arguments, and never use partial matching. See the tidyverse style guide, <http://style.tidyverse.org/syntax.html#argument-names>, for more advice.

5.8.3 Infix functions

Infix functions get their name from the fact the function name comes **in**between its arguments, and hence have two arguments. R comes with a number of built-in infix operators: `:`, `::`, `:::`, `$`, `@`, `^`, `*`, `/`, `+`, `-`, `>`, `>=`, `<`, `<=`, `==`, `!=`, `!`, `&`, `&&`, `|`, `||`, `~`, `<-`, and `<<-`. You can also create your own infix functions that start and end with `%`. Base R uses this pattern to define `%%`, `%*%`, `%/%`, `%in%`, `%o%`, and `%x%`.

Defining your own infix function is simple. You create a two argument function and bind it to a name that starts and ends with `%`:

```
`%+%` <- function(a, b) paste0(a, b)
"new " %+% "string"
#> [1] "new string"
```

The names of infix functions are more flexible than regular R functions: they can contain any sequence of characters except “%”. You will need to escape any special characters in the string used to define the function, but not when you call it:

```
% % <- function(a, b) paste(a, b)
%/%\% <- function(a, b) paste(a, b)

"a" % % "b"
#> [1] "a b"
"a" %/% "b"
#> [1] "a b"
```

R’s default precedence rules mean that infix operators are composed left to right:

```
%-% <- function(a, b) paste0("(", a, " %-% ", b, ")")
"a" %-% "b" %-% "c"
#> [1] "((a %-% b) %-% c)"
```

There are two special infix functions that can be called with a single argument: `+` and `-`.

```
-1
#> [1] -1
+10
#> [1] 10
```

5.8.4 Replacement functions

Replacement functions act like they modify their arguments in place, and have the special name `xxx<-`. They must have arguments named `x` and `value`, and must return the modified object. For example, the following function modifies the second element of a vector:

```
second<- <- function(x, value) {
  x[2] <- value
  x
}
```

Replacement functions are used by placing the function call on the LHS of `<-`:

```
x <- 1:10
second(x) <- 5L
x
#> [1] 1 5 3 4 5 6 7 8 9 10
```

I say they “act” like they modify their arguments in place, because, as discussed in Modify-in-place, they actually create a modified copy. We can see that by using `tracemem()`:

```
x <- 1:10
tracemem(x)
#> <0x7ffae71bd880>

second(x) <- 6L
#> tracemem[0x7ffae71bd880 -> 0x7ffae61b5480]:
#> tracemem[0x7ffae61b5480 -> 0x7ffae73f0408]: second<-
```

If you want to supply additional arguments, place them between `x` and `value`:

```
~modify<-` <- function(x, position, value) {
  x[position] <- value
  x
}
modify(x, 1) <- 10
x
#> [1] 10 5 3 4 5 6 7 8 9 10
```

When you write `modify(x, 1) <- 10`, behind the scenes R turns it into:

```
x <- `modify<-` (x, 1, 10)
```

Combining replacement with other functions requires more complex translation. For example:

```
x <- c(a = 1, b = 2, c = 3)
names(x)
#> [1] "a" "b" "c"

names(x)[2] <- "two"
names(x)
#> [1] "a" "two" "c"
```

Is translated into:

```

`*tmp*` <- x
x <- `names`<-`(`*tmp*`, `<`(`names`(`*tmp*`), 2, "two"))
rm(`*tmp*`)

```

(Yes, it really does create a local variable named *tmp*, which is removed afterwards.)

5.8.5 Special forms

Finally, there are a bunch of language features that are usually written in special ways, but also have prefix forms. These include parentheses:

- (x) ((``(x)))
- $\{x\}$ ((```(x)).)

The subsetting operators:

- $x[i]$ ((```(x, i)))
- $x[[i]]$ ((```[``(x, i)))

And the tools of control flow:

- if (cond) true ($\text{(`if``(cond, true))}$)
- $\text{if (cond) true else false}$ ($\text{(`if``(cond, true, false))}$)
- $\text{for(var in seq) action}$ ($\text{(`for``(var, seq, action))}$)
- $\text{while(cond) action}$ ($\text{(`while``(cond, action))}$)
- repeat expr ((`repeat``(expr)))
- next ((`next``()))
- break ((`break``()))

Finally, the most complex is the “function” function:

- $\text{function(arg1, arg2) \{body\}}$ ($\text{(`function``(alist(arg1, arg2), body, env))}$)

Knowing the name of the function that underlies a special form is useful for getting documentation: $?(`$ is a syntax error; $?(``$ will give you the documentation for parentheses.

Note that all special forms are implemented as primitive functions (i.e. in C); this means printing these functions is not informative:

```

`for`
#> .Primitive("for")

```

5.9 Invoking a function

Suppose you had a list of function arguments:

```
args <- list(1:10, na.rm = TRUE)
```

How could you then send that list to `mean()`? In base R, you'd use `do.call()`:

```
do.call(mean, args)
#> [1] 5.5
# Equivalent to
mean(1:10, na.rm = TRUE)
#> [1] 5.5
```

5.9.1 Exercises

1. Rewrite the following code snippets into prefix form:

```
1 + 2 + 3
```

```
1 + (2 + 3)
```

```
if (length(x) <= 5) x[[5]] else x[[n]]
```

2. Clarify the following list of odd function calls:

```
x <- sample(replace = TRUE, 20, x = c(1:10, NA))
y <- runif(min = 0, max = 1, 20)
cor(m = "k", y = y, u = "p", x = x)
```

3. Explain why the following code fails:

```
modify(get("x"), 1) <- 10
#> Error: target of assignment expands to non-language object
```

4. Create a replacement function that modifies a random location in a vector.

5. Write your own version of `+` that pastes its inputs together if they are character vectors but behaves as usual otherwise. In other words, make this code work:

```
1 + 2
#> [1] 3
```

```
"a" + "b"  
#> [1] "ab"
```

6. Create a list of all the replacement functions found in the base package. Which ones are primitive functions? (Hint: use `apropos()`)
7. What are valid names for user-created infix functions?
8. Create an infix `xor()` operator.
9. Create infix versions of the set functions `intersect()`, `union()`, and `setdiff()`. You might call them `%n%`, `%u%`, and `%/%` to match conventions from mathematics.

5.10 Quiz answers

1. The three components of a function are its body, arguments, and environment.
2. `f1(1)()` returns 11.
3. You'd normally write it in infix style: `1 + (2 * 3)`.
4. Rewriting the call to `mean(c(1:10, NA), na.rm = TRUE)` is easier to understand.
5. No, it does not throw an error because the second argument is never used so it's never evaluated.
6. See infix and replacement functions.
7. You use `on.exit()`; see `on.exit` for details.

Chapter 6

Environments

6.1 Introduction

The environment is the data structure that powers scoping. This chapter dives deep into environments, describing their structure in depth, and using them to improve your understanding of the four scoping rules described in lexical scoping. Understanding environments is not necessary for day-to-day use of R. But they are important to understand because they power many important R features like lexical scoping, namespaces, and R6 classes, and interact with evaluation to give you powerful tools for making domain specific languages, like dplyr and ggplot2.

Quiz

If you can answer the following questions correctly, you already know the most important topics in this chapter. You can find the answers at the end of the chapter in answers.

1. List at least three ways that an environment is different to a list.
2. What is the parent of the global environment? What is the only environment that doesn't have a parent?
3. What is the enclosing environment of a function? Why is it important?
4. How do you determine the environment from which a function was called?
5. How are `<-` and `<<-` different?

Outline

- Environment basics introduces you to the basic properties of an environment and shows you how to create your own.
- Recursing over environments provides a function template for computing with environments, illustrating the idea with a useful function.
- Explicit environments briefly discusses three places where environments are useful data structures for solving other problems.

Prerequisites

This chapter will use `rlang` functions for working with environments, because it allows us to focus on the essence of environments, rather than the incidental details.

```
library(rlang)

# Some API changes that haven't made it in rlang yet
search_envs <- function() {
  rlang:::new_environments(c(
    list(global_env()),
    head(env_parents(global_env()), -1)
  ))
}
```

Note that the `env_` functions in `rlang` are designed to work with the pipe: all take an environment as the first argument, and many also return an environment. I won't use the pipe in this chapter in the interest of keeping the code as simple as possible, but you should consider it for your own code.

6.2 Environment basics

Generally, an environment is similar to a named list, with four important exceptions:

- Every name must be unique.
- The names in an environment are not ordered (i.e. it doesn't make sense to ask what the first element of an environment is).
- An environment has a parent.

- Environments are not copied when modified.

Let's explore these ideas with code and pictures.

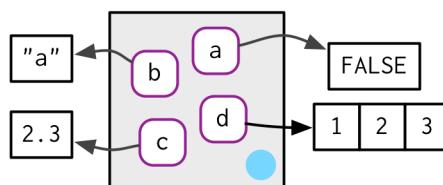
6.2.1 Basics

To create an environment, use `rlang::env()`. It works like `list()`, taking a set of name-value pairs:

```
e1 <- env(
  a = FALSE,
  b = "a",
  c = 2.3,
  d = 1:3,
)
```

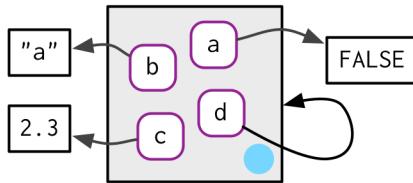
Use `new.env()` to create a new environment. Ignore the `hash` and `size` parameters; they are not needed. Note that you cannot simultaneously create and define values; use `$<-`, as shown below.

The job of an environment is to associate, or **bind**, a set of names to a set of values. You can think of an environment as a bag of names, with no implied order (i.e. it doesn't make sense to ask which is the first element in an environment). For that reason, we'll draw the environment as so:



As discussed in names and values, environments have reference semantics: unlike most R objects, when you modify them, you modify them in place, and don't create a copy. One important implication is that environments can contain themselves. This means that environments go one step further in their level of recursion than lists: an environment can contain any object, including itself!

```
e1$d <- e1
```



Printing an environment just displays its memory address, which is not terribly useful:

```
e1
#> <environment: 0x28a7be8>
```

Instead, we'll use `env_print()` which gives us a little more information:

```
env_print(e1)
#> <environment: 0x28a7be8>
#>   parent: <environment: global>
#>   bindings:
#>     * a: <lgl>
#>     * b: <chr>
#>     * c: <dbl>
#>     * d: <env>
```

You can use `env_names()` to get a character vector giving the current bindings

```
env_names(e1)
#> [1] "a" "b" "c" "d"
```

In R 3.2.0 and greater, use `names()` to list the bindings in an environment. If your code needs to work with R 3.1.0 or earlier, use `ls()`, but note that the default value of `all.names` is `FALSE` so you don't see any bindings that start with `..`.

6.2.2 Important environments

We'll talk in detail about special environments in Special environments, but for now we need to mention two. The current environment, or `current_env()` is the environment in which code is currently executing. When you're experimenting interactively, that's usually the global environment, or `global_env()`. The global environment is sometimes called your "workspace", as it's where all interactive (i.e. outside of a function) computation takes place.

Note that to compare environments, you need to use `identical()` and not `==`:

```
identical(global_env(), current_env())
#> [1] TRUE

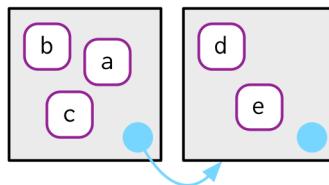
global_env() == current_env()
#> Error in global_env() == current_env():
#>   comparison (1) is possible only for atomic and list types
```

Access the global environment with `globalenv()` and the current environment with `environment()`. The global environment is printed as `Rf_GlobalEnv` and `.GlobalEnv`.

6.2.3 Parents

Every environment has a **parent**, another environment. In diagrams, the parent is shown as a small pale blue circle and arrow that points to another environment. The parent is what's used to implement lexical scoping: if a name is not found in an environment, then R will look in its parent (and so on). You can set the parent environment by supplying an unnamed argument to `env()`. If you don't supply it, it defaults to the current environment.

```
e2a <- env(d = 4, e = 5)
e2b <- env(e2a, a = 1, b = 2, c = 3)
```



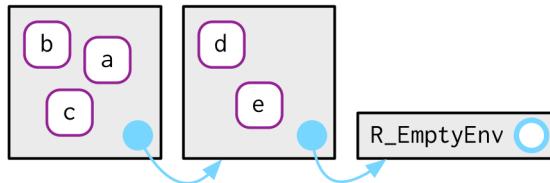
We use the metaphor of a family to name environments relative to one another. The grandparent of an environment is the parent's parent, and the ancestors include all parent environments up to the empty environment. To save space, I typically won't draw all the ancestors; just remember whenever you see a pale blue circle, there's a parent environment somewhere.

You can find the parent of an environment with `env_parent()`:

```
env_parent(e2b)
#> <environment: 0x5406938>
env_parent(e2a)
#> <environment: R_GlobalEnv>
```

Only one environment doesn't have a parent: the `empty` environment. I draw the empty environment with a hollow parent environment, and where space allows I'll label it with `R_EmptyEnv`, the name R uses.

```
e2c <- env(empty_env(), d = 4, e = 5)
e2d <- env(e2c, a = 1, b = 2, c = 3)
```



You'll get an error if you try to find the parent of the empty environment:

```
env_parent(empty_env())
#> Error: The empty environment has no parent
#> Call `rlang::last_error()` to see a backtrace
```

You can list all ancestors of an environment with `env_parents()`:

```
env_parents(e2b)
#> [[1]] <env: 0x5406938>
#> [[2]] $ <env: global>

env_parents(e2d)
#> [[1]] <env: 0x5e88690>
#> [[2]] $ <env: empty>
```

By default, `env_parents()` continues until it hits either the global environment or the empty environment. You can control this behaviour with the `last` environment.

Use `parent.env()` to find the parent of an environment. No base function returns all ancestors.

6.2.4 Super assignment, <<-

The ancestors of an environment have an important relationship to `<<-`. Regular assignment, `<-`, always creates a variable in the current environment. Super assignment, `<<-`, never creates a variable in the current environment, but instead modifies an existing variable found in a parent environment.

```
x <- 0
f <- function() {
  x <<- 1
}
f()
x
#> [1] 1
```

If `<<-` doesn't find an existing variable, it will create one in the global environment. This is usually undesirable, because global variables introduce non-obvious dependencies between functions. `<<-` is most often used in conjunction with a function factory, as described in Section 9.2.3.

6.2.5 Getting and setting

You can get and set elements of an environment with `$` and `[[` in the same way as a list:

```
e3 <- env(x = 1, y = 2)
e3$x
#> [1] 1
e3$z <- 3
e3[["z"]]
#> [1] 3
```

But you can't use `[[` with numeric indices, and you can't use `[`:

```
e3[[1]]
#> Error in e3[[1]]:
#>   wrong arguments for subsetting an environment

e3[c("x", "y")]
#> Error in e3[c("x", "y")]:
#>   object of type 'environment' is not subsettable
```

`$` and `[[` will return `NULL` if the binding doesn't exist. Use `env_get()` if you want an error:

```
e3$xyz
#> NULL

env_get(e3, "xyz")
#> Error in env_get(e3, "xyz"):
```

```
#> object 'xyz' not found
```

If you want to use a default value if the binding doesn't exist, you can use the `default` argument.

```
env_get(e3, "xyz", default = NA)
#> [1] NA
```

There are two other ways to add bindings to an environment:

- `env_poke()`¹ takes a name (as string) and a value:

```
env_poke(e3, "a", 100)
e3$a
#> [1] 100
```

- `env_bind()` allows you to bind multiple values:

```
env_bind(e3, a = 10, b = 20)
env_names(e3)
#> [1] "x" "y" "z" "a" "b"
```

You can determine if an environment has a binding with `env_has()`:

```
env_has(e3, "a")
#> a
#> TRUE
```

Unlike lists, setting an element to `NULL` does not remove it. Instead, use `env_unbind()`:

```
e3$a <- NULL
env_has(e3, "a")
#> a
#> TRUE

env_unbind(e3, "a")
env_has(e3, "a")
#> a
#> FALSE
```

Unbinding a name doesn't delete the object. That's the job of the garbage collector, which automatically removes objects with no names binding to them. This process is described in more detail in GC.

¹You might wonder why rlang has `env_poke()` instead of `env_set()`. This is for consistency: `_set()` functions return a modified copy; `_poke()` functions modify in place.

See `get()`, `assign()`, `exists()`, and `rm()`. These are designed interactively for use with the current environment, so working with other environments is a little clunky. Also beware the `inherits` argument: it defaults to `TRUE` meaning that the base equivalents will inspect the supplied environment and all its ancestors.

6.2.6 Finalisers

Add something once rlang has an API. Also mention in data structures below

6.2.7 Advanced bindings

There are two more exotic variants of `env_bind()`:

- `env_bind_exprs()` creates **delayed bindings**, which are evaluated the first time they are accessed. Behind the scenes, delayed bindings create promises, so behave in the same way as function arguments.

```
env_bind_exprs(current_env(), b = {Sys.sleep(1); 1})
#> Warning: `env_bind_exprs()` is soft-deprecated as of rlang 0.3.0.
#> Please use `env_bind_lazy()` instead.
#> This warning is displayed once per session.

system.time(print(b))
#> [1] 1
#>   user  system elapsed
#>       0       0       1
system.time(print(b))
#> [1] 1
#>   user  system elapsed
#>       0       0       0
```

Delayed bindings are used to implement `autoload()`, which makes R behave as if the package data is in memory, even though it's only loaded from disk when you ask for it.

- `env_bind_fns()` creates **active bindings** which are re-computed every time they're accessed:

```
env_bind_fns(current_env(), z1 = function(val) runif(1))
#> Warning: `env_bind_fns()` is soft-deprecated as of rlang 0.3.0.
#> Please use `env_bind_active()` instead.
#> This warning is displayed once per session.
```

```

z1
#> [1] 0.0808
z1
#> [1] 0.834

```

The argument to the function allows you to also override behaviour when the variable is set:

```

env_bind_fns(current_env(), z2 = function(val) {
  if (missing(val)) {
    2
  } else {
    stop("Don't touch z2!", call. = FALSE)
  }
})

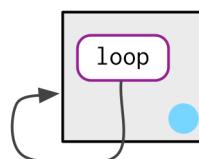
z2
#> [1] 2
z2 <- 3
#> Error: Don't touch z2!

```

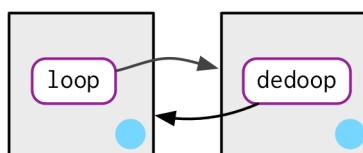
See `?delayedAssign()` and `?makeActiveBinding()`.

6.2.8 Exercises

1. List three ways in which an environment differs from a list.
2. Create an environment as illustrated by this picture.



3. Create a pair of environments as illustrated by this picture.



4. Explain why `e[[1]]` and `e[c("a", "b")]` don't make sense when `e` is an environment.
5. Create a version of `env_poke()` that will only bind new names, never rebind old names. Some programming languages only do this, and are known as single assignment languages ([http://en.wikipedia.org/wiki/Assignment_\(computer_science\)#Single_assignment](http://en.wikipedia.org/wiki/Assignment_(computer_science)#Single_assignment)).
6. What does this function do? How does it differ from `<-` and why might you prefer it?

```
rebind <- function(name, value, env = caller_env()) {
  if (identical(env, empty_env())) {
    stop("Can't find `", name, "``", call. = FALSE)
  } else if (env_has(env, name)) {
    env_poke(env, name, value)
  } else {
    rebind(name, value, env_parent(env))
  }
}
rebind("a", 10)
#> Error: Can't find `a`
a <- 5
rebind("a", 10)
a
#> [1] 10
```

6.3 Recursing over environments

If you want to operate on every ancestor of an environment, it's often convenient to write a recursive function. This section shows you how, applying your new knowledge of environments to write a function that given a name, finds the environment `where()` that name is defined, using R's regular scoping rules.

The definition of `where()` is straightforward. It has two arguments: the name to look for (as a string), and the environment in which to start the search. (We'll learn why `caller_env()` is a good default in calling environments.)

```
where <- function(name, env = caller_env()) {
  if (identical(env, empty_env())) {
    # Base case
    stop("Can't find ", name, call. = FALSE)
  } else if (env_has(env, name)) {
```

```

# Success case
env
} else {
  # Recursive case
  where(name, env_parent(env))
}
}

```

There are three cases:

- The base case: we've reached the empty environment and haven't found the binding. We can't go any further, so we throw an error.
- The successful case: the name exists in this environment, so we return the environment.
- The recursive case: the name was not found in this environment, so try the parent.

These three cases are illustrated with these three examples:

```

where("yyy")
#> Error: Can't find yyy

x <- 5
where("x")
#> <environment: R_GlobalEnv>

where("mean")
#> <environment: base>

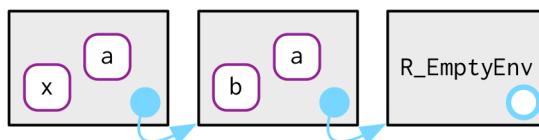
```

It might help to see a picture. Imagine you have two environments, as in the following code and diagram:

```

e4a <- env(empty_env(), a = 1, b = 2)
e4b <- env(e4a, x = 10, a = 11)

```



- `where("a", e4b)` will find `a` in `e4b`.
- `where("b", e4b)` doesn't find `b` in `e4b`, so it looks in its parent, `e4a`, and finds it there.

- `where("c", e4b)` looks in `e4b`, then `e4a`, then hits the empty environment and throws an error.

It's natural to work with environments recursively, so `where()` provides a useful template. Removing the specifics of `where()` shows the structure more clearly:

```
f <- function(..., env = caller_env()) {
  if (identical(env, empty_env())) {
    # base case
  } else if (success) {
    # success case
  } else {
    # recursive case
    f(..., env = env_parent(env))
  }
}
```

Iteration vs recursion

It's possible to use a loop instead of recursion. I think it's harder to understand than the recursive version, but I include it because you might find it easier to see what's happening if you haven't written many recursive functions.

```
f2 <- function(..., env = caller_env()) {
  while (!identical(env, empty_env())) {
    if (success) {
      # success case
      return()
    }
    # inspect parent
    env <- env_parent(env)
  }

  # base case
}
```

6.3.1 Exercises

1. Modify `where()` to return *all* environments that contain a binding for `name`. Carefully think through what type of object the function will need to return.
2. Write a function called `fget()` that finds only function objects. It should

have two arguments, `name` and `env`, and should obey the regular scoping rules for functions: if there's an object with a matching name that's not a function, look in the parent. For an added challenge, also add an `inherits` argument which controls whether the function recurses up the parents or only looks in one environment.

6.4 Special environments

Most environments are not created by you (e.g. with `env()`) but are instead created by R. In this section, you'll learn about the most important environments, starting with the package environments. You'll then learn about the function environment bound to the function when it is created, and the (usually) ephemeral execution environment created every time the function is called. Finally, you'll see how the package and function environments interact to support namespaces, which ensure that a package always behaves the same way, regardless of what other packages the user has loaded.

6.4.1 Package environments and the search path

Each package attached by `library()` or `require()` becomes one of the parents of the global environment. The immediate parent of the global environment is the last package you attached²:

```
env_parent(global_env())
#> <environment: package:rlang>
#> attr(,"name")
#> [1] "package:rlang"
#> attr(,"path")
#> [1] "/home/travis/R/Library/rlang"
```

And the parent of that package is the second to last package you attached:

```
env_parent(env_parent(global_env()))
#> <environment: package:stats>
#> attr(,"name")
#> [1] "package:stats"
#> attr(,"path")
#> [1] "/home/travis/R-bin/lib/R/library/stats"
```

²Note the difference between attached and loaded. A package is loaded automatically if you access one of its functions using `::`; it is only **attached** to the search path by `library()` or `require()`.

If you follow all the parents back, you see the order in which every package has been attached. This is known as the **search path** because all objects in these environments can be found from the top-level interactive workspace.

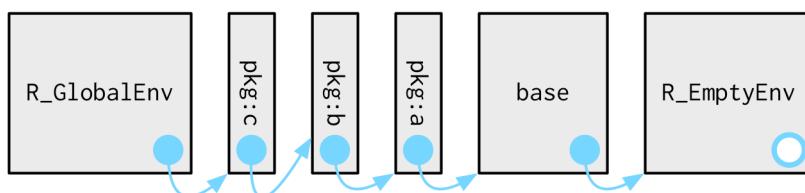
```
search_envs()
#> [[1]] $ <env: global>
#> [[2]] $ <env: package:rlang>
#> [[3]] $ <env: package:stats>
#> [[4]] $ <env: package:graphics>
#> [[5]] $ <env: package:grDevices>
#> [[6]] $ <env: package:utils>
#> [[7]] $ <env: package:datasets>
#> [[8]] $ <env: package:methods>
#> [[9]] $ <env: Autoloads>
#> [[10]] $ <env: package:base>
```

You can access the names of the environments on the search path with `search()`

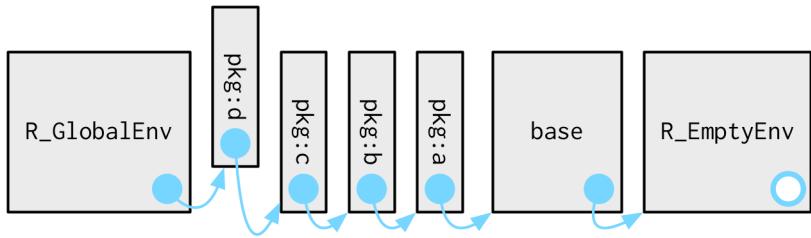
The last two environments on the search path are always the same:

- The **Autoloads** environment uses delayed bindings to save memory by only loading package objects (like big datasets) when needed.
- The base environment, `package:base` or sometimes just `base`, is the environment of the base package. It is special because it has to be able to bootstrap the loading of all other packages. You can access it directly with `base_env()`.

Graphically, the search path looks like this:



When you attach another package with `library()`, the parent environment of the global environment changes:



6.4.2 The function environment

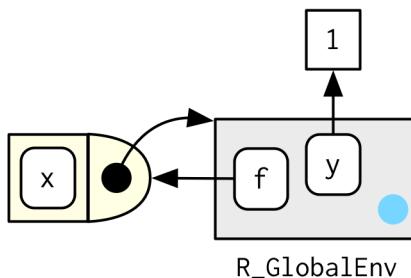
A function binds the current environment when it is created. This is called the **function environment**, and is used for lexical scoping. Across computer languages, functions that capture their environments are called **closures**, which is why this term is often used interchangeably with function in R's documentation.

You can get the function environment with `fn_env()`:

```
y <- 1
f <- function(x) x + y
fn_env(f)
#> <environment: R_GlobalEnv>
```

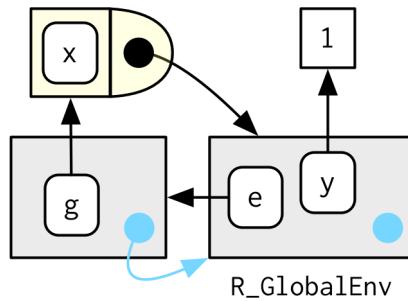
Use `environment(f)` to access the environment of function `f`.

In diagrams, I'll depict functions as rectangles with a rounded end that binds an environment.



In this case, `f()` binds the environment that binds the name `f` to the function. But that's not always the case: in the following example `g` is bound in a new environment `e`, but `g()` binds the global environment. The distinction between binding and being bound by is subtle but important; the difference is how we find `g` vs. how `g` finds its variables.

```
e <- env()
e$g <- function() 1
```



6.4.3 Namespaces

In the diagram above, you saw that the parent environment of a package varies based on what other packages have been loaded. This seems worrying: doesn't that mean that the package will find different functions if packages are loaded in a different order? The goal of **namespaces** is to make sure that this does not happen, and that every package works the same way regardless of what packages are attached by the user.

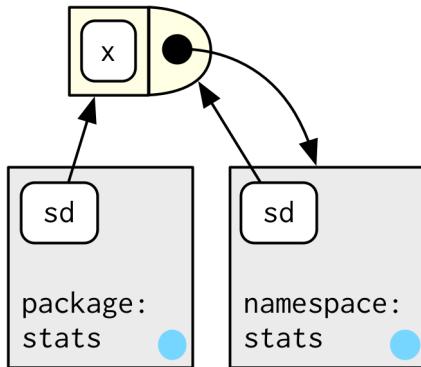
For example, take `sd()`:

```
sd
#> function (x, na.rm = FALSE)
#> sqrt(var(if (is.vector(x) || is.factor(x)) x else as.double(x),
#>           na.rm = na.rm))
#> <bytecode: 0x4a5cf30>
#> <environment: namespace:stats>
```

`sd()` is defined in terms of `var()`, so you might worry that the result of `sd()` would be affected by any function called `var()` either in the global environment, or in one of the other attached packages. R avoids this problem by taking advantage of the function vs. binding environment described above. Every function in a package is associated with a pair of environments: the package environment, which you learned about earlier, and the **namespace** environment.

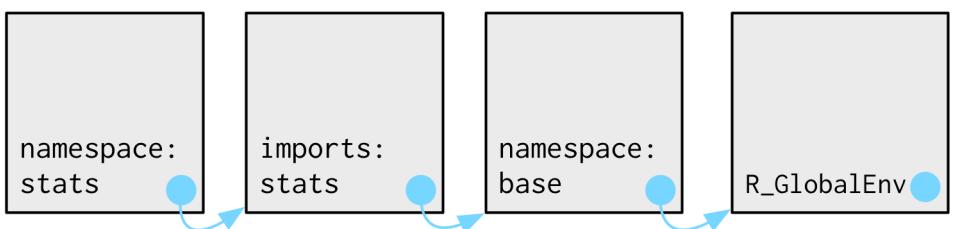
- The package environment is the external interface to the package. It's how you, the R user, find a function in an attached package or with `::`. Its parent is determined by search path, i.e. the order in which packages have been attached.
- The namespace environment is the internal interface to the package. The package environment controls how we find the function; the namespace controls how the function finds its variables.

Every binding in the package environment is also found in the namespace environment; this ensures every function can use every other function in the package. But some bindings only occur in the namespace environment. These are known as internal or non-exported objects, which make it possible to hide internal implementation details from the user.

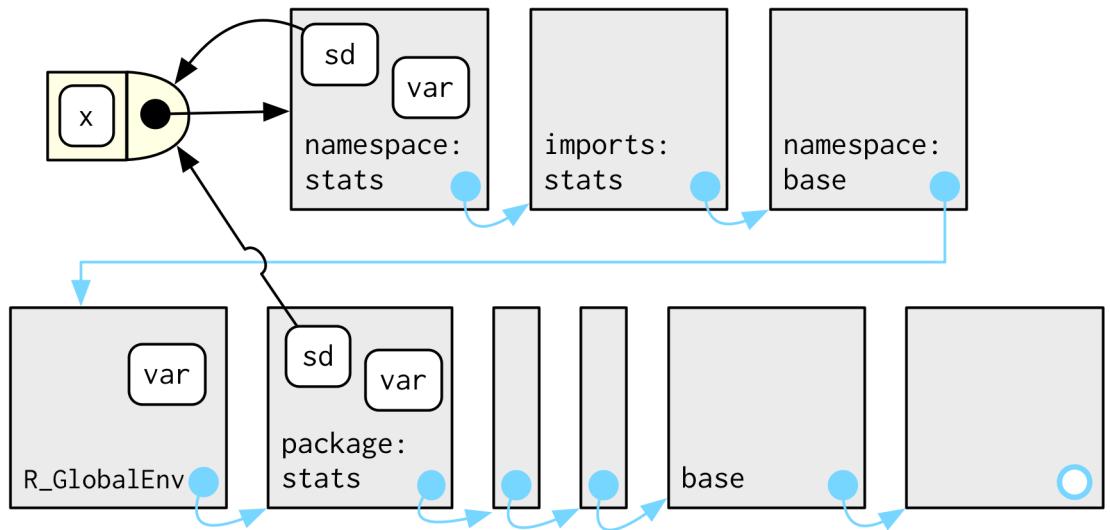


Every namespace environment has the same set of ancestors:

- Each namespace has an **imports** environment that contains bindings to all the functions used by the package. The imports environment is controlled by the package developer with the **NAMESPACE** file.
- Explicitly importing every base function would be tiresome, so the parent of the imports environment is the base **namespace**. The base namespace contains the same bindings as the base environment, but it has a different parent.
- The parent of the base namespace is the global environment. This means that if a binding isn't defined in the imports environment the package will look for it in the usual way. This is usually a bad idea (because it makes code depend on other loaded packages), so **R CMD check** automatically warns about such code. It is needed primarily for historical reasons, particularly due to how S3 method dispatch works.



Putting all these diagrams together we get:



So when `sd()` looks for the value of `var` it always finds it in a sequence of environments determined by the package developer, but not by the package user. This ensures that package code always works the same way regardless of what packages have been attached by the user.

Note that there's no direct link between the package and namespace environments; the link is defined by the function environments.

6.4.4 Execution environments

The last important topic we need to cover is the **execution** environment. What will the following function return the first time it's run? What about the second?

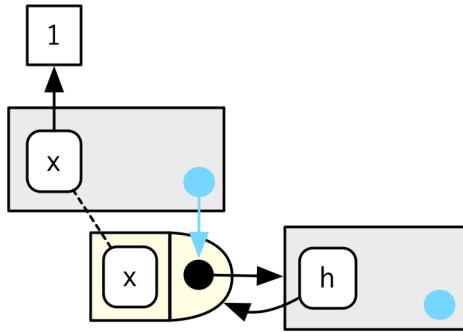
```
g <- function(x) {
  if (!env_has(current_env(), "a")) {
    message("Defining a")
    a <- 1
  } else {
    a <- a + 1
  }
  a
}
```

Think about it for a moment before you read on.

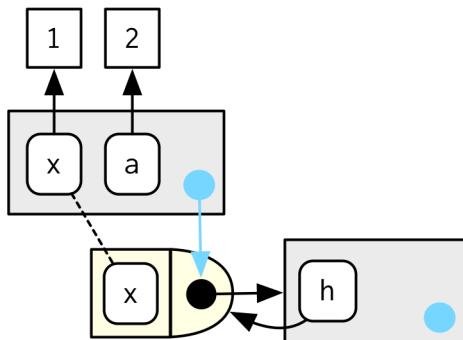
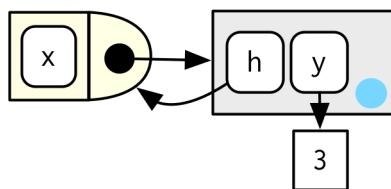
```
g(10)
#> Defining a
#> [1] 1
g(10)
#> Defining a
#> [1] 1
```

This function returns the same value every time because of the fresh start principle, described in a fresh start. Each time a function is called, a new environment is created to host execution. This is called the execution environment, and its parent is the function environment. Let's illustrate that process with a simpler function. I'll draw execution environments with an indirect parent; the parent environment is found via the function environment.

```
h <- function(x) {
  # 1.
  a <- 2 # 2.
  x + a
}
y <- h(1) # 3.
```

1. Function called with $x = 1$ 

2. a bound to value 2

3. Function completes returning value 3.
Execution environment goes away.

An execution environment is usually ephemeral; once the function has completed, the environment will be GC'd. There are several ways to make it stay around for longer. The first is to explicitly return it:

```
h2 <- function(x) {  
  a <- x * 2
```

```

  current_env()
}

e <- h2(x = 10)
env_print(e)
#> <environment: 0x482ab40>
#>   parent: <environment: global>
#>   bindings:
#>     * a: <dbl>
#>     * x: <dbl>
fn_env(h2)
#> <environment: R_GlobalEnv>

```

Another way to capture it is to return an object with a binding to that environment, like a function. The following example illustrates that idea with a function factory, `plus()`. We use that factory to create a function called `plus_one()`.

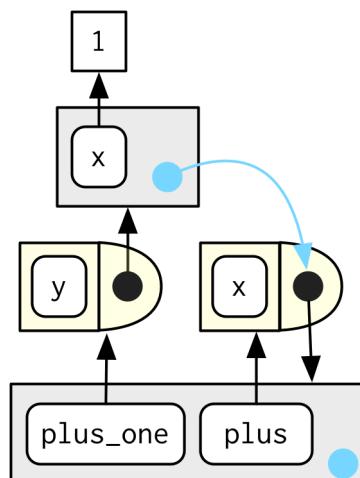
There's a lot going on in the diagram because the enclosing environment of `plus_one()` is the execution environment of `plus()`.

```

plus <- function(x) {
  function(y) x + y
}

plus_one <- plus(1)
plus_one
#> function(y) x + y
#> <environment: 0x3202d60>

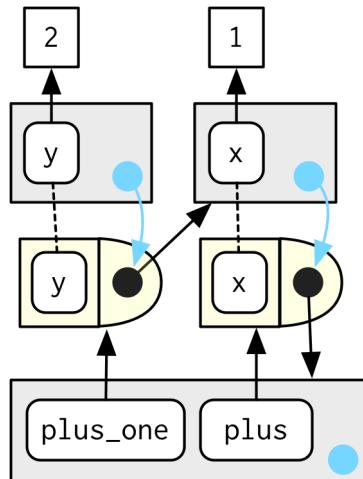
```



What happens when we call `plus_one()`? Its execution environment will have the captured execution environment of `plus()` as its parent:

```
plus_one(2)
```

```
#> [1] 3
```



You'll learn more about function factories in functional programming.

6.4.5 Exercises

1. How is `search_envs()` different to `env_parents(global_env())`?
2. Draw a diagram that shows the enclosing environments of this function:

```
f1 <- function(x1) {
  f2 <- function(x2) {
    f3 <- function(x3) {
      x1 + x2 + x3
    }
    f3(3)
  }
  f2(2)
}
f1(1)
```

3. Write an enhanced version of `str()` that provides more information about functions. Show where the function was found and what environment it was defined in.

6.5 The call stack

There is one last environment we need to explain, the **caller** environment, accessed with `rlang::caller_env()`. This provides the environment from which the function was called, and hence varies based on how the function is called, not how the function was created. As we saw above this is a useful default whenever you write a function that takes an environment as an argument.

`parent.frame()` is equivalent to `caller_env()`; just note that it returns an environment, not a frame.

To fully understand the caller environment we need to discuss two related concepts: the **call stack**, which is made up of **frames**. Executing a function creates two types of context. You've learned about one already: the execution environment is a child of the function environment, which is determined by where the function was created. There's another type of context created by where the function was called: this is called the call stack.

6.5.1 Simple call stacks

Let's illustrate this with a simple sequence of calls: `f()` calls `g()` calls `h()`.

```
f <- function(x) {
  g(x = 2)
}
g <- function(x) {
  h(x = 3)
}
h <- function(x) {
  stop()
}
```

The way you most commonly see a call stack in R is by looking at the `traceback()` after an error has occurred:

```
f(x = 1)
#> Error:
traceback()
#> 4: stop()
#> 3: h(x = 3)
#> 2: g(x = 2)
#> 1: f(x = 1)
```

Instead of `stop()` + `traceback()` to understand the call stack, we're going to use `lobstr::cst()` to print out the call stack tree:

```
h <- function(x) {
  lobstr::cst()
}
f(x = 1)
#>
#>   f(x = 1)
#>   g(x = 2)
#>   h(x = 3)
#>   lobstr::cst()
```

This shows us that `cst()` was called from `h()`, which was called from `g()`, which was called from `f()`. Note that the order is the opposite from `traceback()`. As the call stacks get more complicated, I think it's easier to understand the sequence of calls if you start from the beginning, rather than the end (i.e. `f()` calls `g()`; rather than `g()` was called by `f()`).

6.5.2 Lazy evaluation

The call stack above is simple - while you get a hint that there's some tree-like structure involved, everything happens on a single branch. This is typical of a call stack when all arguments are eagerly evaluated.

Let's create a more complicated example that involves some lazy evaluation. We'll create a sequence of functions, `a()`, `b()`, `c()`, that pass along an argument `x`.

```
a <- function(x) b(x)
b <- function(x) c(x)
c <- function(x) x

a(f())
#>
#>   a(f())
#>   b(x)
#>   c(x)
#>   f()
#>   g(x = 2)
#>   h(x = 3)
#>   lobstr::cst()
```

`x` is lazily evaluated so this tree gets two branches. In the first branch `a()`

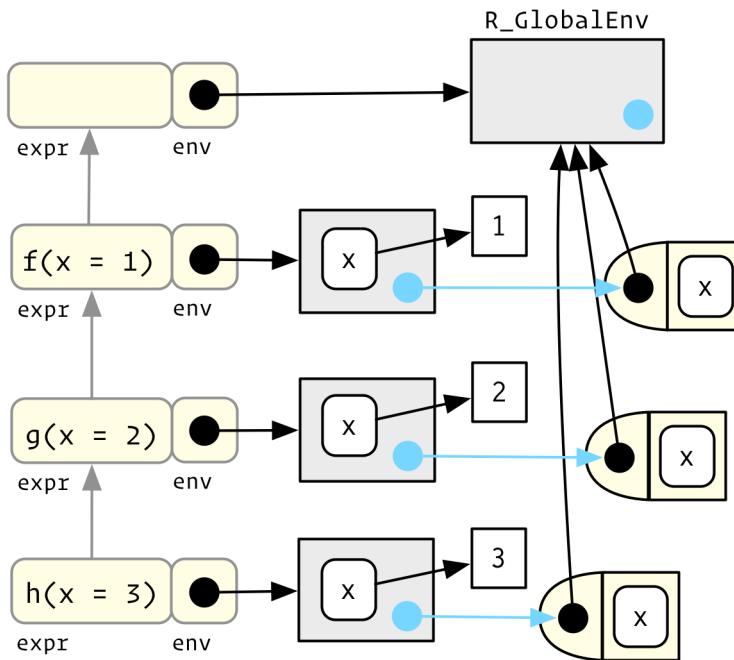
calls `b()`, then `b()` calls `c()`. The second branch starts when `c()` evaluates its argument `x`. This argument is evaluated in a new branch because the environment in which it is evaluated is the global environment, not the environment of `c()`.

6.5.3 Frames

Each element of the call stack is a **frame**³, also known as an evaluation context. The frame is an extremely important internal data structure, and R code can only access a small part of the data structure because it's so critical. A frame has three main components that are accessible from R:

- An expression (labelled with `expr`) giving the function call. This is what `traceback()` prints out.
- An environment (labelled with `env`), which is typically the execution environment of a function. There are two main exceptions: the environment of the global frame is the global environment, and calling `eval()` also generates frames, where the environment can be anything.
- A parent, the previous call in the call stack (shown by a grey arrow).

³NB: `?environment` uses frame in a different sense: “Environments consist of a *frame*, or collection of named objects, and a pointer to an enclosing environment.”. We avoid this sense of frame, which comes from S, because it’s very specific and not widely used in base R. For example, the “frame” in `parent.frame()` is an execution context, not a collection of named objects.



(To focus on the calling environments, I have omitted the bindings in the global environment from `f`, `g`, and `h` to the respective function objects.)

The frame also holds exit handlers created with `on.exit()`, restarts and handlers for the condition system, and which context to `return()` to when a function completes. These are important for the internal operation of R, but are not directly accessible.

6.5.4 Dynamic scope

Looking up variables in the calling stack rather than in the enclosing environment is called **dynamic scoping**. Few languages implement dynamic scoping (Emacs Lisp is a notable exception (<http://www.gnu.org/software/emacs/emacs-paper.html#SEC15>).) This is because dynamic scoping makes it much harder to reason about how a function operates: not only do you need to know how it was defined, you also need to know the context in which it was called. Dynamic scoping is primarily useful for developing functions that aid interactive data analysis. It is one of the topics discussed in non-standard evaluation.

6.5.5 Exercises

1. Write a function that lists all the variables defined in the environment in which it was called. It should return the same results as `ls()`.

6.6 As data structures

As well as powering scoping, environments are also useful data structures in their own right because they have reference semantics. There are three common problems that they can help solve:

- **Avoiding copies of large data.** Since environments have reference semantics, you'll never accidentally create a copy. This makes it a useful vessel for large objects. Bare environments are not that pleasant to work with; I recommend using R6 objects instead. Learn more in R6.
- **Managing state within a package.** Explicit environments are useful in packages because they allow you to maintain state across function calls. Normally, objects in a package are locked, so you can't modify them directly. Instead, you can do something like this:

```
my_env <- new.env(parent = emptyenv())
my_env$a <- 1

get_a <- function() {
  my_env$a
}

set_a <- function(value) {
  old <- my_env$a
  my_env$a <- value
  invisible(old)
}
```

Returning the old value from setter functions is a good pattern because it makes it easier to reset the previous value in conjunction with `on.exit()` (see more in `on.exit`).

- **As a hashmap.** A hashmap is a data structure that takes constant, $O(1)$, time to find an object based on its name. Environments provide this behaviour by default, so can be used to simulate a hashmap. See the CRAN package `hash` for a complete development of this idea.

6.7 Quiz answers

1. There are four ways: every object in an environment must have a name; order doesn't matter; environments have parents; environments have reference semantics.
2. The parent of the global environment is the last package that you loaded. The only environment that doesn't have a parent is the empty environment.
3. The enclosing environment of a function is the environment where it was created. It determines where a function looks for variables.
4. Use `caller_env()` or `parent.frame()`.
5. `<-` always creates a binding in the current environment; `<<-` rebinds an existing name in a parent of the current environment.

Chapter 7

Conditions

7.1 Introduction

The **condition** system provides a paired set of tools that allow the author of a function to indicate that something unusual is happening, and the user of that function to deal with it. The function author **signals** conditions with functions like `stop()` (for errors), `warning()` (for warnings), and `message()` (for messages), then the function user can handle them with functions like `tryCatch()` and `withCallingHandlers()`. Understanding the condition system is important because you'll often need to play both roles: signalling conditions from the functions you create, and handle conditions signalled by the functions you call.

R offers a very powerful condition system based on ideas from Common Lisp. Like R's approach to object oriented programming, it is rather different to currently popular programming languages so it is easy to misunderstand, and there has been relatively little written about how to use it effectively. Historically, this has led to few people (including me!) taking full advantage of its power. The goal of this chapter is to remedy that situation. Here you will learn about the big ideas of R's condition system, as well as learning a bunch of practical tools that will make your code stronger.

I found two resources particularly useful when writing this chapter. You may also want to read them if you want to learn more about the inspirations and motivations for the system:

- *A prototype of a condition system for R* (<http://homepage.stat.uiowa.edu/~luke/R/exceptions/simpcond.html>) by Robert Gentleman and Luke Tierney. This describes an early version of R's condition system. While the

implementation has changed somewhat since this document was written, it provides a good overview of how the pieces fit together, and some motivation for its design.

- *Beyond exception handling: conditions and restarts* (<http://www.gigamonkeys.com/book/beyond-exception-handling-conditions-and-restarts.html>) by Peter Seibel. This describes exception handling in Lisp, which happens to be very similar to R's approach. It provides useful motivation and more sophisticated examples. I have provided an R translation of the chapter at <http://adv-r.had.co.nz/beyond-exception-handling.html>.

I also found it helpful to work through the underlying C code that implements these ideas. If you're interested in understanding how it all works, you might find my notes (<https://gist.github.com/hadley/4278d0a6d3a10e42533d59905fbed0ac>) to be useful.

Quiz

Want to skip this chapter? Go for it, if you can answer the questions below. Find the answers at the end of the chapter in answers.

1. What are the three most important types of condition?
2. What function do you use to ignore errors in block of code?
3. What's the main difference between `tryCatch()` and `withCallingHandlers()`?
4. Why might you want to create a custom error object?

Overview

- Signalling conditions introduces the basic tools for signalling conditions, and discusses when it is appropriate to use each type.
- Ignoring conditions teaches you about the simplest tools for handling conditions: functions like `try()` and `suppressMessages()` that swallow conditions and prevent them from getting to the top level.
- Handling conditions introduces the condition **object**, and the two fundamental tools of condition handling: `tryCatch()` for error conditions, and `withCallingHandlers()` for everything else.
- Custom conditions shows you how to extend the built-in condition objects to store useful data that condition handlers can use to make more informed decisions.

- Applications closes out the chapter with a grab bag of practical applications based on the low-level tools found in earlier sections.

7.1.1 Prerequisites

As well as base R functions, this chapter uses condition signalling and handling functions from `rlang`.

```
library(rlang)
```

7.2 Signalling conditions

There are three conditions that you can signal in code: errors, warnings, and messages.

- Errors are the most severe; they indicate that there is no way for a function to continue and execution must stop.
- Warnings fall somewhat in between errors and warnings, and typically indicate that something has gone wrong but the function has been able to at least partially recover.
- Messages are the mildest; they are way of informing the user that some action has been performed on their behalf.

There is a final condition that can only be generated interactively: an interrupt, which indicates that the user has “interrupted” execution by pressing Escape, Ctrl + Break, or Ctrl + C (depending on the platform).

Conditions are usually displayed prominently, in a bold font or coloured red, depending on the R interface. You can tell them apart because errors always start with “Error”, warnings with “Warning message”, and messages with nothing.

```
stop("This is what an error looks like")
#> Error in eval(expr, envir, enclos):
#>   This is what an error looks like

warning("This is what a warning looks like")
#> Warning: This is what a warning looks like

message("This is what a message looks like")
#> This is what a message looks like
```

The following three sections describe errors, warnings, and message in more detail.

7.2.1 Errors

In base R, errors are signalled, or **thrown**, by `stop()`:

```
f <- function() g()
g <- function() h()
h <- function() stop("This is an error!")

f()
#> Error in h():
#>   This is an error!
```

By default, the error message includes the call, but this is typically not useful (and recapitulates information that you can easily get from `traceback()`), so I think it's good practice to use `call. = FALSE`:

```
h <- function() stop("This is an error!", call. = FALSE)
f()
#> Error: This is an error!
```

The rlang equivalent to `stop()`, `rlang::abort()`, does this automatically. We'll use `abort()` throughout this chapter, but we won't get to its most compelling feature, the ability to add additional metadata to the condition object, until we're near the end of the chapter.

```
h <- function() abort("This is an error!")
f()
#> Error: This is an error!
#> Call `rlang::last_error()` to see a backtrace
```

(Note that `stop()` pastes together multiple inputs, while `abort()` does not. To create complex error messages with `abort`, I recommend using `glue::glue()`. This allows us to use other arguments to `abort()` for useful features that you'll learn about in custom conditions.)

The best error messages tell you what is wrong and point you in the right direction to fix the problem. Writing good error messages is hard because errors usually occur when the user has a flawed mental model of the function. As a developer, it's hard to imagine how the user might be thinking incorrectly about your function, and thus it's hard to write a message that will steer the user in the correct direction. That said, the tidyverse style guide discusses a few general principles that we have found useful: <http://style.tidyverse.org/error-messages.html>.

7.2.2 Warnings

Warnings, signalled by `warning()`, are weaker than errors: they signal that something has gone wrong, but the code has been able to recover and continue. Unlike errors, you can have multiple warnings from a single function call:

```
fw <- function() {
  cat("1\n")
  warning("W1")
  cat("2\n")
  warning("W2")
  cat("3\n")
  warning("W3")
}
```

By default, warnings are cached and printed only when control returns to the top level:

```
fw()
#> 1
#> 2
#> 3
#> Warning messages:
#> 1: In f() : W1
#> 2: In f() : W2
#> 3: In f() : W3
```

You can control this behaviour with the `warn` option:

- To make warnings appear immediately, set `options(warn = 1)`.
- To turn warnings into errors, set `options(warn = 2)`. This is usually the easiest way to debug a warning, as once it's an error you can use tools like `traceback()` to find the source.
- Restore the default behaviour with `option(warn = 0)`.

Like `stop()`, `warning()` also has a `call` argument. It is slightly more useful (since warnings are often more distant from their source), but I still generally suppress it with `call. = FALSE`. Like `rlang::abort()`, the `rlang` equivalent of `warning()`, `rlang::warn()`, also suppresses the `call.` by default.

Warnings occupy a somewhat challenging place between messages (“you should know about this”) and errors (“you must fix this!”), and it’s hard to give precise advice on when to use them. Generally, be restrained, as warnings are easy to miss if there’s a lot of other output, and you don’t want your function to

recover too easily from clearly invalid input. In my opinion, base R tends to overuse warnings, and many warnings in base R would be better off as errors. For example, I think these warnings would be more helpful as errors:

```
formals(1)
#> Warning in formals(fun): argument is not a function
#> NULL

file.remove("this-file-doesn't-exist")
#> Warning in file.remove("this-file-doesn't-exist"): cannot remove file
#> 'this-file-doesn't-exist', reason 'No such file or directory'
#> [1] FALSE

lag(1:3, k = 1.5)
#> Warning in lag.default(1:3, k = 1.5): 'k' is not an integer
#> [1] 1 2 3
#> attr(,"tsp")
#> [1] -1 1 1
```

There only a couple of cases where using a warning is clearly appropriate:

- When you **deprecate** a function you want to allow older code to continue to work (so ignoring the warning is OK) but you want to encourage the user to switch to a new function.
- When you are reasonably certain you can recover from a problem: If you were 100% certain that you could fix the problem, you wouldn't need any message; if you were more uncertain that you could correctly fix the issue, you'd throw an error.

Otherwise use warnings with restraint, and carefully consider if an error would be more appropriate.

7.2.3 Messages

Messages, signalled by `message()`, are informational; use them to tell the user that you've done something on their behalf. Good messages are a balancing act: you want to provide just enough information so the user knows what's going on, but not so much that they're overwhelmed.

`messages()` are displayed immediately and do not have a `call.` argument:

```
fm <- function() {
  cat("1\n")
```

```

  message("M1")
  cat("2\n")
  message("M2")
  cat("3\n")
  message("M3")
}

fm()
#> 1
#> M1
#> 2
#> M2
#> 3
#> M3

```

Good places to use a message are:

- When a default argument requires some non-trivial amount of computation and you want to tell the user what value was used. For example, `ggplot2` reports the number of bins used if you don't supply a `binwidth`.
- In functions that are called primarily for their side-effects which would otherwise be silent. For example, when writing files to disk, calling a web API, or writing to a database, it's useful provide regular status messages telling the user what's happening.
- When you're about to start a long running process with no intermediate output. A progress bar (e.g. with `progress` (<https://github.com/r-lib/progress>)) is better, but a message is a good place start.
- When writing a package, you sometimes want to display a message when your package is loaded (i.e. in `.onAttach()`); here you must use `packageStartupMessage()`.

Generally any function that produces a message should have some way to suppress it, like a `quiet = TRUE` argument. It is possible to suppress all messages with `suppressMessages()`, as you'll learn shortly, but it is nice to also give finer grained control.

It's important to compare `message()` to the closely related `cat()`. In terms of usage and result, they appear quite similar¹:

¹But note that `cat()` requires an explicit trailing "\n" to print a new line.

```
cat("Hi!\n")
#> Hi!

message("Hi!")
#> Hi!
```

However, the *purposes* of `cat()` and `message()` are different. Use `cat()` when the primary role of the function is to print to the console, like `print()` or `str()` methods. Use `message()` as a side-channel to print to the console when the primary purpose of the function is something else. In other words, `cat()` is for when the user *asks* for something to be printed and `message()` is for when the developer *elects* to print something.

7.2.4 Exercises

1. Write a wrapper around `file.remove()` that throws an error if the file to be deleted does not exist.
2. What does the `appendLF` argument to `message()` do? How is it related to `cat()`?
3. What does `options(error = recover)` do? Why might you use it?
4. What does `options(error = quote(dump.frames(to.file = TRUE)))` do? Why might you use it?

7.3 Ignoring conditions

The simplest way of handling conditions in R is to simply ignore them:

- Ignore errors with `try()`.
- Ignore warnings with `suppressWarnings()`.
- Ignore messages with `suppressMessages()`.

These functions are heavy handed as you can't use them to suppress a single type of condition that you know about, while allowing everything else to pass through. We'll come back to that challenge later in the chapter.

`try()` allows execution to continue even after an error has occurred. Normally if you run a function that throws an error, it terminates immediately and doesn't return a value:

```
f1 <- function(x) {
  log(x)
  10
}
f1("x")
#> Error in log(x):
#>   non-numeric argument to mathematical function
```

However, if you wrap the statement that creates the error in `try()`, the error message will be displayed² but execution will continue:

```
f2 <- function(x) {
  try(log(x))
  10
}
f2("a")
#> Error in log(x) : non-numeric argument to mathematical function
#> [1] 10
```

It is possible, but not recommended, to save the result of `try()` and perform different actions based on whether or not the code succeeded or failed³. Instead, it is better to use `tryCatch()` or a higher-level helper; you'll learn about those shortly.

A simple, but useful, pattern is to do assignment inside the call: this lets you define a default value to be used if the code does not succeed.

```
default <- NULL
try(default <- read.csv("possibly-bad-input.csv"), silent = TRUE)
```

`suppressWarnings()` and `suppressMessages()` suppress all warnings and messages. Unlike errors, messages and warnings don't terminate execution, so there may be multiple signalled in a single block.

```
suppressWarnings({
  warning("Uhoh!")
  warning("Another warning")
  1
})
#> [1] 1

suppressMessages({
```

²You can suppress the message with `try(..., silent = TRUE)`.

³You can tell if the expression failed because the result will have class `try-error`.

```

  message("Hello there")
  2
})
#> [1] 2

suppressWarnings({
  message("You can still see me")
  3
})
#> You can still see me
#> [1] 3

```

7.4 Handling conditions

Every condition has default behaviour: errors stop execution and return to the top level, warnings are captured and displayed in aggregate, and messages are immediately displayed. Condition **handlers** allow us to temporarily override or supplement the default behaviour.

Two functions, `tryCatch()` and `withCallingHandlers()`, allow us to register handlers, functions that take the signalled condition as their single argument. The registration functions have the same basic form:

```

tryCatch(
  error = function(cnd) {
    # code to run when error is thrown
  },
  code_to_run_while_handlers_are_active
)

withCallingHandlers(
  warning = function(cnd) {
    # code to run when warning is signalled
  },
  message = function(cnd) {
    # code to run when message is signalled
  },
  code_to_run_while_handlers_are_active
)

```

They differ in the type of handlers that they create:

- `tryCatch()` defines **existing** handlers; after the condition is handled, control returns to the context where `tryCatch()` was called. This makes `tryCatch()` most suitable for working with errors and interrupts, as these have to exit anyway.
- `withCallingHandlers()` defines **calling** handlers; after the condition is captured control returns to the context where the condition was signalled. This makes it most suitable for working with non-error conditions.

But before we can learn about and use these handlers, we need to talk a little bit about condition **objects**. These are created implicitly whenever you signal a condition, but become explicit inside the handler.

7.4.1 Condition objects

So far we've just signalled conditions, and not looked at the objects that are created behind the scenes. The easiest way to see a condition object is to catch one from a signalled condition. That's the job of `rlang::catch_cnd()`:

```
cond <- catch_cnd_abort("An error")
str(cond)
#> List of 4
#> $ message: chr "An error"
#> $ call   : NULL
#> $ trace  :List of 3
#>   ..$ calls :List of 31
#>     ...$ : language local({      args = commandArgs(TRUE) ...
#>     ...$ : language eval.parent(substitute(eval(quote(expr), envir)))
#>     ...$ : language eval(expr, p)
#>     ...$ : language eval(expr, p)
#>     ...$ : language eval(quote({      args = commandArgs(TRUE) ...
#>     ...$ : language eval(quote({      args = commandArgs(TRUE) ...
#>     ...$ : language do.call(rmarkdown::render, c(args[1], readRDS("..
#>     ...$ : language (function (input, output_format = NULL, output_..
#>     ...$ : language knitr::knit(knit_input, knit_output, envir = en..
#>     ...$ : language process_file(text, output)
#>     ...$ : language withCallingHandlers(if (tangle) process_tangle(...
#>     ...$ : language process_group(group)
#>     ...$ : language process_group.block(group)
#>     ...$ : language call_block(x)
#>     ...$ : language block_exec(params)
#>     ...$ : language in_dir(input_dir(), evaluate(code, envir = env, ..
```

```

#> ... .$.language evaluate(code, envir = env, new_device = FALSE, ..
#> ... .$.language evaluate::evaluate(...)
#> ... .$.language evaluate_call(expr, parsed$src[[i]], envir = en...
#> ... .$.language timing_fn(handle(ev <- withCallingHandlers(with...
#> ... .$.language handle(ev <- withCallingHandlers(withVisible(ev...
#> ... .$.language withCallingHandlers(withVisible(eval(expr, envi...
#> ... .$.language withVisible(eval(expr, envir, enclos)))
#> ... .$.language eval(expr, envir, enclos)
#> ... .$.language eval(expr, envir, enclos)
#> ... .$.language catch_cnd(abort("An error"))
#> ... .$.language tryCatch(condition = identity, { force(expr...
#> ... .$.language tryCatchList(expr, classes, parentenv, handlers)
#> ... .$.language tryCatchOne(expr, names, parentenv, handlers[[1...
#> ... .$.language doTryCatch(return(expr), name, parentenv, handl..
#> ... .$.language force(expr)
#> ... $.parents: int [1:31] 0 1 2 3 0 5 6 6 8 9 ...
#> ... $.envs :List of 31
#> ... .$.language chr "0x3e725e0"
#> ... .$.language chr "0x3e72490"
#> ... .$.language chr "0x3e72148"
#> ... .$.language chr "global"
#> ... .$.language chr "0x3e71ab8"
#> ... .$.language chr "0x3e71620"
#> ... .$.language chr "0x3e73818"
#> ... .$.language chr "0x3fdf588"
#> ... .$.language chr "0x2cf9638"
#> ... .$.language chr "0x2b3b390"
#> ... .$.language chr "0x786e328"
#> ... .$.language chr "0x786de20"
#> ... .$.language chr "0x786db80"
#> ... .$.language chr "0x786daa0"
#> ... .$.language chr "0x7855608"
#> ... .$.language chr "0x78d0828"
#> ... .$.language chr "0x78d3190"
#> ... .$.language chr "0x78d57b0"
#> ... .$.language chr "0x7964180"
#> ... .$.language chr "0x79845a8"
#> ... .$.language chr "0x79844c8"
#> ... .$.language chr "0x79841b8"
#> ... .$.language chr "0x7983c08"
#> ... .$.language chr "0x79839d8"

```

```
#> ...$ : chr "global"
#> ...$ : chr "0x79875a8"
#> ...$ : chr "0x79873b0"
#> ...$ : chr "0x7986d20"
#> ...$ : chr "0x79869d8"
#> ...$ : chr "0x7986690"
#> ...$ : chr "0x7986348"
#> ...- attr(*, "class")= chr "rlang_trace"
#> $ parent : NULL
#> - attr(*, "class")= chr [1:3] "rlang_error" "error" "condition"
```

Built-in conditions are lists with two elements:

- **message**, a length-1 character vector containing the text to display to a user. To extract the message, use `conditionMessage(cnd)`.
- **call**, the call which triggered the condition. As described above, we don't use the call, so it will often be `NULL`. To extract it, use `conditionCall(cnd)`.

Custom conditions may contain other components, which we'll discuss in custom conditions.

Conditions also have a `class` attribute, which makes them S3 objects. We won't discuss S3 until S3, but fortunately, even if you don't know about S3, condition objects are quite simple. The most important thing to know is that the `class` attribute is a character vector, and it determines which handlers will match the condition.

7.4.2 Exiting handlers

`tryCatch()` registers exiting handlers, and is typically used to handle error conditions. It allows you to override the default error behaviour. For example, the following code will return 10 instead of displaying an error:

```
tryCatch(
  error = function(cnd) 10,
  stop("This is an error!")
)
#> [1] 10
```

If no conditions are signalled, or the class of the signalled condition does not match the handler name, the code executes normally:

```
tryCatch(
  error = function(cnd) 10,
  1 + 1
)
#> [1] 2

tryCatch(
  error = function(cnd) 10,
{
  message("Hi!")
  1 + 1
}
)
#> Hi!
#> [1] 2
```

The handlers set up by `tryCatch()` are called **exiting** handlers because after the condition is signalled, control passes to the handler and never returns to the original code, effectively meaning that the code “exits”:

```
tryCatch(
  message = function(cnd) "There",
{
  message("Here")
  stop("This code is never run!")
}
)
#> [1] "There"
```

Note that the code is evaluated in the environment of `tryCatch()`, but the handler code is not, because the handlers are functions. This is important to remember if you’re trying to modify objects in the parent environment.

The handler functions are called with a single argument, the condition object. I call this argument `cnd`, by convention. This value is only moderately useful for the base conditions because they contain relatively little data. It’s more useful when you make your own custom conditions, as you’ll see shortly.

```
tryCatch(
  error = function(cnd) {
    paste0("--", conditionMessage(cnd), "--")
  },
  stop("This is an error")
```

```
)  
#> [1] "--This is an error--"
```

`tryCatch()` has one other argument: `finally`. It specifies a block of code (not a function) to run regardless of whether the initial expression succeeds or fails. This can be useful for clean up, like deleting files, or closing connections. This is functionally equivalent to using `on.exit()` (and indeed that's how it's implemented) but it can wrap smaller chunks of code than an entire function.

7.4.3 Calling handlers

The handlers set up by `tryCatch()` are called exiting handlers, because they cause code to exit once the condition has been caught. By contrast, `withCallingHandlers()` sets up calling handlers: code execution continues normally once the handler returns. This tends to make `withCallingHandlers()` a more natural pairing with the non-error conditions.

Compare the results of `tryCatch()` and `withCallingHandlers()` in the example below. The messages are not printed in the first case, because the code is terminated once the exiting handler completes. They are printed in the second case, because a calling handler does not exit.

```
tryCatch(  
  message = function(cnd) cat("Caught a message!\n"),  
  {  
    message("Someone there?")  
    message("Why, yes!")  
  }  
)  
#> Caught a message!  
  
withCallingHandlers(  
  message = function(c) cat("Caught a message!\n"),  
  {  
    message("Someone there?")  
    message("Why, yes!")  
  }  
)  
#> Caught a message!  
#> Someone there?  
#> Caught a message!  
#> Why, yes!
```

Handlers are applied in order, so you don't need to worry getting caught in an infinite loop:

```
withCallingHandlers(
  message = function(cnd) message("Second message"),
  message("First message")
)
#> Second message
#> First message
```

(But beware if you have multiple handlers, and some handlers signal conditions that could be captured by another handler: you'll need to think through the order carefully.)

The return value of a calling handler is ignored because the code continues to execute after the handler completes; where would the return value go? That means that calling handlers are only useful for their side-effects.

One important side-effect unique to calling handlers is the ability to **muffle** the signal. By default, a condition will continue to propagate to parent handlers, all the way up to the default handler (or an exiting handler, if provided):

```
# Bubbles all the way up to default handler which generates the message
withCallingHandlers(
  message = function(cnd) cat("Level 2\n"),
  withCallingHandlers(
    message = function(cnd) cat("Level 1\n"),
    message("Hello")
  )
)
#> Level 1
#> Level 2
#> Hello

# Bubbles up to tryCatch
tryCatch(
  message = function(cnd) cat("Level 2\n"),
  withCallingHandlers(
    message = function(cnd) cat("Level 1\n"),
    message("Hello")
  )
)
#> Level 1
#> Level 2
```

If you want to prevent the condition “bubbling up” but still run the rest of the code in the block, you need to explicitly muffle it with `rlang::cnd_muffle()`:

```
# Muffles the default handler which prints the messages
withCallingHandlers(
  message = function(cnd) {
    cat("Level 2\n")
    cnd_muffle(cnd)
  },
  withCallingHandlers(
    message = function(cnd) cat("Level 1\n"),
    message("Hello")
  )
)
#> Level 1
#> Level 2

# Muffles level 2 handler and the default handler
withCallingHandlers(
  message = function(cnd) cat("Level 2\n"),
  withCallingHandlers(
    message = function(cnd) {
      cat("Level 1\n")
      cnd_muffle(cnd)
    },
    message("Hello")
  )
)
#> Level 1
```

7.4.4 Call stacks

To complete the section, there are some important differences between the call stacks of exiting and calling handlers. These differences are generally not important but I’m including it here because I’ve occassionally found it useful, and don’t want to forget about it!

It’s easiest to see the difference by setting up a small example that uses `lobstr::cst()`:

```
f <- function() g()
g <- function() h()
```

```
h <- function() message("!")
```

Calling handlers are called in the context of the call that signalled the condition:

```
withCallingHandlers(f(), message = function(cnd) {
  lobstr::cst()
  cnd_muffle(cnd)
})
#> x
#> +-withCallingHandlers(...)
#> +-f()
#> / \-g()
#> / \-h()
#> / \-message("!")
#> / +-withRestarts(...)
#> / / \-withOneRestart(expr, restarts[[1L]])
#> / / \-doWithOneRestart(return(expr), restart)
#> / \-signalCondition(cnd)
#> \-(function (cnd) ...
#> \-lobstr::cst()
```

Whereas exiting handlers are called in the context of the call to `tryCatch()`:

```
tryCatch(f(), message = function(cnd) lobstr::cst())
#> x
#> \-tryCatch(f(), message = function(cnd) lobstr::cst())
#> \-tryCatchList(expr, classes, parentenv, handlers)
#> \-tryCatchOne(expr, names, parentenv, handlers[[1L]])
#> \-value[[3L]](cnd)
#> \-lobstr::cst()
```

7.4.5 Exercises

- Predict the results of evaluating the following code

```
show_condition <- function(code) {
  tryCatch(
    error = function(cnd) "error",
    warning = function(cnd) "warning",
    message = function(cnd) "message",
  {
    code
```

```

        NULL
    }
)
}

show_condition(stop("!"))
show_condition(10)
show_condition(warning("?!"))
show_condition({
  10
  message("?")
  warning("?!")
})

```

2. Explain the results of running this code:

```

withCallingHandlers(
  message = function(cnd) message("b"),
  withCallingHandlers(
    message = function(cnd) message("a"),
    message("c")
  )
)
#> b
#> a
#> b
#> c

```

3. Read the source code for `catch_cnd()` and explain how it works.
4. How could you rewrite `show_condition()` to use a single handler?

7.5 Custom conditions

One of the challenges of error handling in R is that most functions generate one of the built-in conditions, which contain only a `message` and a `call`. That means that if you want to detect a specific type of error, you can only work with the text of the error message. This is error prone, not only because the message might change over time, but also because messages can be translated into other languages.

Fortunately R has a powerful, but little used feature: the ability to create custom

conditions that can contain additional metadata. Creating custom conditions is a little fiddly in base R, but `rlang::abort()` makes it very easy as you can supply a custom `.subclass` and additional metadata.

The following example shows the basic pattern. I recommend using the following call structure for custom conditions. This takes advantage of R’s flexible argument matching so that the name of the “type” of error comes first, followed by the user facing text, followed by custom metadata.

```
abort(
  "error_not_found",
  message = "Path `blah.csv` not found",
  path = "blah.csv"
)
#> Error: Path `blah.csv` not found
#> Call `rlang::last_error()` to see a backtrace
```

Custom conditions work just like regular conditions when used interactively, but allow handlers to do much more.

7.5.1 Motivation

To explore these ideas in more depth, let’s take `base:::log()`. It does the minimum when throwing errors caused by invalid arguments:

```
log(letters)
#> Error in log(letters):
#>   non-numeric argument to mathematical function
log(1:10, base = letters)
#> Error in log(1:10, base = letters):
#>   non-numeric argument to mathematical function
```

I think we can do better by being explicit about which argument is the problem (i.e. `x` or `base`), and saying what the problematic input is (not just what it isn’t).

```
my_log <- function(x, base = exp(1)) {
  if (!is.numeric(x)) {
    abort(paste0("`x` must be a numeric vector; not ", typeof(x), "."))
  }
  if (!is.numeric(base)) {
    abort(paste0("`base` must be a numeric vector; not ", typeof(base), "."))
  }
}
```

```
base::log(x, base = base)
}
```

This gives us:

```
my_log(letters)
#> Error: `x` must be a numeric vector; not character.
#> Call `rlang::last_error()` to see a backtrace
my_log(1:10, base = letters)
#> Error: `base` must be a numeric vector; not character.
#> Call `rlang::last_error()` to see a backtrace
```

This is an improvement for interactive usage as the error messages are more likely to guide the user towards a correct fix. However, they're no better if you want to programmatically handle the errors: all the useful metadata about the error is jammed into a single string.

7.5.2 Signalling

Let's build some infrastructure to improve this situation. We'll start by providing a custom `abort()` function for bad arguments. This is a little over-generalised for the example at hand, but it reflects common patterns that I've seen across other functions. The pattern is fairly simple. We create a nice error message for the user, using `glue::glue()`, and store metadata in the condition call for the developer.

```
abort_bad_argument <- function(arg, must, not = NULL) {
  msg <- glue::glue(`{arg}` must {must}`)
  if (!is.null(not)) {
    not <- typeof(not)
    msg <- glue::glue("{msg}; not {not}.")
  }

  abort("error_bad_argument",
    message = msg,
    arg = arg,
    must = must,
    not = not
  )
}
```

If you want to throw a custom error without adding a dependency on `rlang`, you

can create a condition object “by hand” and then pass it to `stop()`:

```
stop_custom <- function(.subclass, message, call = NULL, ...) {
  err <- structure(
    list(
      message = message,
      call = call,
      ...
    ),
    class = c(.subclass, "error", "condition")
  )
  stop(err)
}

err <- catch_cnd(stop_custom("error_new", "This is a custom error", x = 10))
class(err)
err$x
```

We can now rewrite `my_log()` to use this new helper:

```
my_log <- function(x, base = exp(1)) {
  if (!is.numeric(x)) {
    abort_bad_argument("x", must = "be numeric", not = x)
  }
  if (!is.numeric(base)) {
    abort_bad_argument("base", must = "be numeric", not = base)
  }

  base::log(x, base = base)
}
```

`my_log()` itself is not much shorter, but is a little more meaningful, and it ensures that error messages for bad arguments are consistent across functions. It yields the same interactive error messages as before:

```
my_log(letters)
#> Error: `x` must be numeric; not character.
#> Call `rlang::last_error()` to see a backtrace
my_log(1:10, base = letters)
#> Error: `base` must be numeric; not character.
#> Call `rlang::last_error()` to see a backtrace
```

7.5.3 Handling

These structured condition objects are much easier to program with. The first place you might want to use this capability is when testing your function. Unit testing is not a subject of this book (see R packages (<http://r-pkgs.had.co.nz/>) for details), but the basics are easy to understand. The following code captures the error, and then asserts it has the structure that we expect.

```
library(testthat)
#>
#> Attaching package: 'testthat'
#> The following objects are masked from 'package:rlang':
#>
#>     is_false, is_null, is_true

err <- catch_cnd(my_log("a"))
expect_s3_class(err, "error_bad_argument")
expect_equal(err$arg, "x")
expect_equal(err$not, "character")
```

We can also use the class (`error_bad_argument`) in `tryCatch()` to only handle that specific error:

```
tryCatch(
  error_bad_argument = function(cnd) "bad_argument",
  error = function(cnd) "other error",
  my_log("a")
)
#> [1] "bad_argument"
```

Note that when using `tryCatch()` with multiple handlers and custom classes, the first handler to match any class in the signal's class vector is called, not the best match. For this reason, you need to make sure to put the most specific handlers first. The following code does not do what you might hope:

```
tryCatch(
  error = function(cnd) "other error",
  error_bad_argument = function(cnd) "bad_argument",
  my_log("a")
)
#> [1] "other error"
```

7.5.4 Exercises

1. Inside a package, it's occassionally useful to check that a package is installed before using it. Write a function that checks if a package is installed (with `requireNamespace("pkg", quietly = FALSE)`) and if not, throws a custom condition that includes the package name in the metadata.
2. Inside a package you often need to stop with an error when something is not right. Other packages that depend on your package might be tempted to check these errors in their unit tests. How could you help these packages to avoid relying on the error message which is part of the user interface rather than the API and might change without notice?

7.6 Applications

Now that you've learned the basic tools of R's condition system, it's time to dive into some applications. The goal of this section is not to show every possible usage of `tryCatch()` and `withCallingHandlers()` but to illustrate some common patterns that frequently crop up. Hopefully these will get your creative juices flowing, so when you encounter a new problem you can come up with a useful solution.

7.6.1 Failure value

There are a few simple, but useful, `tryCatch()` patterns based on returning a value from the error handler. The simplest case is a wrapper to return a “default” value if an error occurs:

```
fail_with <- function(expr, value = NULL) {
  tryCatch(
    error = function(cnd) value,
    expr
  )
}

fail_with(log(10), NA_real_)
#> [1] 2.3
fail_with(log("x"), NA_real_)
#> [1] NA
```

A more sophisticated application is `base::try()`. Below, `try2()` extracts the essence of `base::try()`; the real function is more complicated in order to make the error message look more like what you'd see if `tryCatch()` wasn't used.

```
try2 <- function(expr, silent = FALSE) {
  tryCatch(
    error = function(cnd) {
      msg <- conditionMessage(cnd)
      if (!silent) {
        message("Error: ", msg)
      }
      structure(msg, class = "try-error")
    },
    expr
  )
}

try2(1)
#> [1] 1
try2(stop("Hi"))
#> Error: Hi
#> [1] "Hi"
#> attr(,"class")
#> [1] "try-error"
try2(stop("Hi"), silent = TRUE)
#> [1] "Hi"
#> attr(,"class")
#> [1] "try-error"
```

7.6.2 Success and failure values

We can extend this pattern to returns one value if the code evaluates successfully (`success_val`), and another if it fails (`error_val`). This pattern just requires one small trick: evaluating the user supplied code, then `success_val`. If the code throws an error, we'll never get to `success_val` and will instead return `error_val`.

```
foo <- function(expr) {
  tryCatch(
    error = function(cnd) error_val,
    {
      expr
```

```

        success_val
    }
)
}
}
```

We can use this to determine if an expression fails:

```
does_error <- function(expr) {
  tryCatch(
    error = function(cnd) TRUE,
  {
    expr
    FALSE
  }
)
}
```

Or to capture any condition, like just `rlang::catch_cnd()`:

```
catch_cnd <- function(expr) {
  tryCatch(
    condition = function(cnd) cnd,
  {
    expr
    NULL
  }
)
}
```

We can also use this pattern to create a `try()` variant. One challenge with `try()` is that it's slightly challenging to determine if the code succeeded or failed. Rather than returning an object with a special class, I think it's slightly nicer to return a list with two components `result` and `error`.

```
safety <- function(expr) {
  tryCatch(
    error = function(cnd) {
      list(result = NULL, error = cnd)
    },
    list(result = expr, error = NULL)
  )
}

str(safety(1 + 10))
```

```

#> List of 2
#> $ result: num 11
#> $ error : NULL
str(safetyabort("Error!")))
#> List of 2
#> $ result: NULL
#> $ error :List of 4
#>   ..$ message: chr "Error!"
#>   ..$ call   : NULL
#>   ..$ trace  :List of 3
#>     ...$ calls  :List of 31
#>       ... . . . $ : language local({      args = commandArgs(TRUE) ...
#>       ... . . . $ : language eval.parent(substitute(eval(quote(expr), env..
#>       ... . . . $ : language eval(expr, p)
#>       ... . . . $ : language eval(expr, p)
#>       ... . . . $ : language eval(quote({      args = commandArgs(TRUE) ...
#>       ... . . . $ : language eval(quote({      args = commandArgs(TRUE) ...
#>       ... . . . $ : language do.call(rmarkdown::render, c(args[1], readR"..
#>       ... . . . $ : language (function (input, output_format = NULL, outp..
#>       ... . . . $ : language knitr::knit(knit_input, knit_output, envir = ..
#>       ... . . . $ : language process_file(text, output)
#>       ... . . . $ : language withCallingHandlers(if (tangle) process_tang..
#>       ... . . . $ : language process_group(group)
#>       ... . . . $ : language process_group.block(group)
#>       ... . . . $ : language call_block(x)
#>       ... . . . $ : language block_exec(params)
#>       ... . . . $ : language in_dir(input_dir(), evaluate(code, envir = e..
#>       ... . . . $ : language evaluate(code, envir = env, new_device = FAL..
#>       ... . . . $ : language evaluate::evaluate(...)
#>       ... . . . $ : language evaluate_call(expr, parsed$src[[i]], envir = ..
#>       ... . . . $ : language timing_fn(handle(ev <- withCallingHandlers(w..
#>       ... . . . $ : language handle(ev <- withCallingHandlers(withVisible..
#>       ... . . . $ : language withCallingHandlers(withVisible(eval(expr, e..
#>       ... . . . $ : language withVisible(eval(expr, envir, enclos))
#>       ... . . . $ : language eval(expr, envir, enclos)
#>       ... . . . $ : language eval(expr, envir, enclos)
#>       ... . . . $ : language str(safetyabort("Error!")))
#>       ... . . . $ : language safetyabort("Error!"))
#>       ... . . . $ : language tryCatch(error = function(cnd) {      list(re..
#>       ... . . . .- attr(*, "srcref")= 'srcref' int [1:8] 2 3 7 3 3 3 2 7
#>       ... . . . .- attr(*, "srcfile")=Classes 'srcfilecopy', 'srcfil..

```

```

#> ... . . . $ : language tryCatchList(expr, classes, parentenv, handl..
#> ... . . . $ : language tryCatchOne(expr, names, parentenv, handlers..
#> ... . . . $ : language doTryCatch(return(expr), name, parentenv, ha..
#> ... . . $ parents: int [1:31] 0 1 2 3 0 5 6 6 8 9 ...
#> ... . . $ envs   :List of 31
#> ... . . . $ : chr "0x3e725e0"
#> ... . . . $ : chr "0x3e72490"
#> ... . . . $ : chr "0x3e72148"
#> ... . . . $ : chr "global"
#> ... . . . $ : chr "0x3e71ab8"
#> ... . . . $ : chr "0x3e71620"
#> ... . . . $ : chr "0x3e73818"
#> ... . . . $ : chr "0x3fdf588"
#> ... . . . $ : chr "0x2cf9638"
#> ... . . . $ : chr "0x2b3b390"
#> ... . . . $ : chr "0x5c91870"
#> ... . . . $ : chr "0x5c91368"
#> ... . . . $ : chr "0x5c910c8"
#> ... . . . $ : chr "0x5c90fe8"
#> ... . . . $ : chr "0x5cd6960"
#> ... . . . $ : chr "0x5d24278"
#> ... . . . $ : chr "0x5d26be0"
#> ... . . . $ : chr "0x5d29200"
#> ... . . . $ : chr "0x5f66c20"
#> ... . . . $ : chr "0x5f815d0"
#> ... . . . $ : chr "0x5f814f0"
#> ... . . . $ : chr "0x5f811e0"
#> ... . . . $ : chr "0x5f80c30"
#> ... . . . $ : chr "0x5f80a00"
#> ... . . . $ : chr "global"
#> ... . . . $ : chr "0x5f80808"
#> ... . . . $ : chr "0x5f80680"
#> ... . . . $ : chr "0x60d1460"
#> ... . . . $ : chr "0x60d0d60"
#> ... . . . $ : chr "0x60d0a18"
#> ... . . . $ : chr "0x60d06d0"
#> ... . . - attr(*, "class")= chr "rlang_trace"
#> ... $ parent : NULL
#> ... - attr(*, "class")= chr [1:3] "rlang_error" "error" "condition"

```

(This is closely related to `purrr::safely()`, a function operator, which we'll

come back to in Section 10.2.1.)

7.6.3 Resignal

As well as returning default values when a condition is signalled, handlers can be used to make more informative error messages. One simple application is to make a function that works like `option(warn = 2)` for a single block of code. The idea is simple: we handle warnings by throwing an error:

```
warning2error <- function(expr) {
  withCallingHandlers(
    warning = function(cnd) abort(conditionMessage(cnd)),
    expr
  )
}

warning2error({
  x <- 2 ^ 4
  warn("Hello")
})
#> Error: Hello
```

You could write a similar function if you were trying to find the source of an annoying message.

7.6.4 Record

Another common pattern is to record conditions for later investigation. The new challenge here is that calling handlers are called only for their side-effects so we can't return values, but instead need to modify some object in place.

```
catch_cnds <- function(expr) {
 conds <- list()
add_cond <- function(cnd) {
 conds <- append(conds, list(cnd))
  cnd_muffle(cnd)
}

withCallingHandlers(
  message = add_cond,
  warning = add_cond,
  expr
```

```

  )
  conds
}

catch_cnds({
  inform("a")
  warn("b")
  inform("c")
})
#> [[1]]
#> <message: a
#> >
#>
#> [[2]]
#> <warning: b>
#>
#> [[3]]
#> <message: c
#> >

```

What if you also want to capture errors? You'll need to wrap the `withCallingHandlers()` in a `tryCatch()`. If an error occurs, it will be the last condition.

```

catch_cnds <- function(expr) {
  conds <- list()
  add_cond <- function(cnd) {
    conds <-> append(conds, list(cnd))
    cnd_muffle(cnd)
  }

  tryCatch(
    error = function(cnd) {
      conds <-> append(conds, list(cnd))
    },
    withCallingHandlers(
      message = add_cond,
      warning = add_cond,
      expr
    )
  )
}

```

```

conds
}

catch_cnds({
  inform("a")
  warn("b")
  abort("C")
})
#> [[1]]
#> <message: a
#> >
#>
#> [[2]]
#> <warning: b>
#>
#> [[3]]
#> <error>
#> * Message: "C"
#> * Class: `rlang_error`
#> * Backtrace:
#> -local(...)
#> -catch_cnds(...)
#> -withCallingHandlers(message = add_cond, warning = add_cond, expr)

```

This is the key idea underlying the `evaluate` (<https://github.com/r-lib/evaluate>) package which powers knitr: it captures every output into a special data structure so that it can be later replayed. As a whole, the `evaluate` package is quite a lot more complicated than the code here because it also needs to handle plots and text output.

7.6.5 No default behaviour

A final useful pattern is to signal a condition that doesn't inherit from `message`, `warning` or `error`. Because there is no default behaviour, this means the condition has no effect unless the user specifically requests it. For example, you could imagine a logging system based on conditions:

```

log <- function(message, level = c("info", "error", "fatal")) {
  level <- match.arg(level)
  signal(message, "log", level = level)
}

```

When you call `log()` a condition is signalled, but nothing happens because it has no default handler:

```
log("This code was run")
```

To “activate” logging you need a handler that does something with the `log` condition. Below I define a `record_log()` function that will record all logging messages to a path:

```
record_log <- function(expr, path = stdout()) {
  withCallingHandlers(
    log = function(cnd) {
      cat(
        "[", cnd$level, "] ", cnd$message, "\n", sep = "",
        file = path, append = TRUE
      )
    },
    expr
  )
}

record_log(log("Hello"))
#> [info] Hello
```

You could even imagine layering with another function that allows you to selectively suppress some logging levels.

```
ignore_log_levels <- function(expr, levels) {
  withCallingHandlers(
    log = function(cnd) {
      if (cnd$level %in% levels) {
        cnd_muffle(cnd)
      }
    },
    expr
  )
}

record_log(ignore_log_levels(log("Hello"), "info"))
```

If you create a condition object by hand, and signal it with `signalCondition()`, `cnd_muffle()` will not work. Instead you need to call it with a muffle restart defined, like this:

```
withRestarts(signalCondition(cond), muffle = function() NULL)
```

Restarts are currently beyond the scope of the book, but I suspect will be included in the 3rd edition.

7.6.6 Exercises

1. Create `suppressConditions()` that works like `suppressMessages()` and `suppressWarnings()` but suppresses everything. Think carefully about how you should handle errors.
2. Compare the following two implementations of `message2error()`. What is the main advantage of `withCallingHandlers()` in this scenario? (Hint: look carefully at the traceback.)

```
message2error <- function(code) {
  withCallingHandlers(code, message = function(e) stop(e))
}
message2error <- function(code) {
  tryCatch(code, message = function(e) stop(e))
}
```

3. How would you modify the `catch_cnds()` definition if you wanted to recreate the original intermingling of warnings and messages?
4. Why is catching interrupts dangerous? Run this code to find out.

```
bottles_of_beer <- function(i = 99) {
  message("There are ", i, " bottles of beer on the wall, ", i, " bottles of be
  while(i > 0) {
    tryCatch(
      Sys.sleep(1),
      interrupt = function(err) {
        i <- i - 1
        if (i > 0) {
          message(
            "Take one down, pass it around, ", i,
            " bottle", if (i > 1) "s", " of beer on the wall."
          )
        }
      }
    )
  }
}
```

```
  message("No more bottles of beer on the wall, no more bottles of beer."  
}
```

7.7 Quiz answers

1. `error`, `warning`, and `message`.
2. You could use `try()` or `tryCatch()`.
3. `tryCatch()` creates exiting handlers which will terminate the execution of wrapped code; `withCallingHandlers()` creates calling handlers which don't affect the execution of wrapped code.
4. Because you can then capture specific types of error with `tryCatch()`, rather than relying on the comparison of error strings, which is risky, especially when messages are translated.

Part II

Functional programming

Introduction

R, at its heart, is a **functional** language. This means that it has certain technical properties, but more importantly that it lends itself to a style of problem solving centered on functions. Below I'll give a brief overview of the technical definition of a functional *language*, but in this book I will primarily focus on the functional *style* of programming, because I think it is an extremely good fit to the types of problem you commonly encounter when doing data analysis.

Recently, functional techniques have experienced a surge in interest because they can produce efficient and elegant solutions to many modern problems. A functional style tends to create functions that can easily be analysed in isolation (i.e. using only local information), and hence is often much easier to automatically optimise or parallelise. The traditional weaknesses of functional languages, poorer performance and sometimes unpredictable memory usage, have been much reduced in recent years. Functional programming is complementary to object oriented programming, which has been the dominant programming paradigm for the last several decades.

Functional programming languages

Every programming language has functions, so what makes a programming language functional? There are many definitions for precisely what makes a language “functional”, but there are two common threads.

Firstly, functional languages have **first-class functions**, functions that behave like any other data structure. In R, this means that you can do anything with a function that you can do with a vector: you can assign them to variables, store them in lists, pass them as arguments to other functions, create them inside functions, and even return them as the result of a function.

Secondly, many functional languages require functions to be **pure**. A function is pure if it satisfies two properties:

- The output only depends on the inputs, i.e. if you call it again with the same inputs, you get the same outputs. This excludes functions like `runif()`, `read.csv()`, or `Sys.time()` that can return different values.
- The function has no side-effects, like changing the value of a variable, writing to disk, or displaying to the screen. This excludes functions like `print()`, `write.csv()` and `<-`.

Pure functions are much easier to reason about, but obviously have significant downsides: imagine doing a data analysis where you couldn't generate random numbers or read files from disk.

Strictly speaking, R isn't a functional programming *language* because it doesn't require that you write pure functions. However, you can certainly adopt a functional style in parts of your code: you don't *have* to write pure functions, but you often *should*. In my experience, partitioning code into functions that are either extremely pure or extremely impure tends to lead to code that is easier to understand and extends to new situations.

Functional style

It's hard to describe exactly what a functional *style* is, but generally I think it means decomposing a big problem into smaller pieces, then solving each piece with a function or combination of functions. When using a functional style, you strive to decompose components of the problem into isolated functions that operate independently. Each function taken by itself is simple and straightforward to understand; complexity is handled by composing functions in various ways.

The following three chapters discuss the three key functional techniques that help you to decompose problems into smaller pieces:

- Chapter 8 shows you how to replace many for loops with **functionals** which are functions (like `lapply()`) that take another function as an argument. Functionals allow you to take a function that solves the problem for a single input and generalise it to handle any number of inputs. Functionals are by far and away the most important technique and you'll use them all the time in data analysis.
- Chapter 9 introduces **function factories**: functions that create functions. Function factories are less useful than functionals, but often allow you to elegantly partition work between different parts of your code.
- Chapter 10 shows you how to create **function operators**: functions that take functions as input and produce functions as output. They are like

adverbs, because they typically modify the operation of a function.

Collectively, these types of function are called **higher-order functions** and they fill out a two-by-two table:

In	Out	
Vector	Vector	Function
Function	Functional	Function operator

Chapter 8

Functionals

8.1 Introduction

“To become significantly more reliable, code must become more transparent. In particular, nested conditions and loops must be viewed with great suspicion. Complicated control flows confuse programmers. Messy code often hides bugs.”

— Bjarne Stroustrup

A **functional** is a function that takes a function as an input and returns a vector as output. Here’s a simple functional: it calls the function provided as input with 1000 random uniform numbers.

```
randomise <- function(f) f(runif(1e3))
randomise(mean)
#> [1] 0.506
randomise(mean)
#> [1] 0.501
randomise(sum)
#> [1] 489
```

The chances are that you’ve already used a functional. You might have used for-loop replacement like base R’s `lapply()`, `apply()`, or `tapply()`, or maybe `purrr`’s `map()`; or maybe you’ve used a mathematical functional like `integrate()` or `optim()`.

A common use of functionals is as an alternative to for loops. For loops have a

bad rap in R, because many people believe they are slow¹, but the real downside of for loops is that they're very flexible, and hence not very expressive. A for loop conveys that it's iterating over something, but doesn't clearly convey what you are trying to achieve. Instead of using a for loop, it's better to use a functional. Each functional is tailored for a specific task, so when you recognise the functional you immediately know why it's being used.

Using functionals is a pattern matching exercise. You look at the for loop, and find a functional that matches the basic form. If one doesn't exist, don't try and torture an existing functional to fit the form you need. Instead, just leave it as a for loop! (Or once you've repeated the same loop two or more times, maybe think about writing your own functional).

Outline

- Section 8.2 introduces your first functional: `purrr::map()`.
- Section 8.3 demonstrates how you can combine multiple simple functional to solve a more complex problem, and discusses how purrr style differs from other approaches.
- Section 8.4 teaches you about 18 (!!) important variants of `purrr::map()`. Fortunately, their orthogonal design makes them easy to learn, remember, and master.
- Section 8.5 introduces a new style of functional: `purrr::reduce()`. `reduce()` systematically reduces a vector to a single result by applying a function that takes two inputs.
- Section 8.6 teaches you about predicates, functions that return a single `TRUE` or `FALSE`, and the family of functionals that use them to solve common problems.
- Section 8.7 reviews some functionals in base R that are not members of the map, reduce, or predicate families.

Prerequisites

This chapter will focus on functionals provided by the `purrr` package. These functions have a consistent interface that makes it easier to understand the key

¹Typically it's not the for loop itself that's slow, but what you're doing inside of it. A common culprit of slow loops is modifying a data structure, where each modification generates a copy. See Section 2.5.1 for more details.

ideas than their base equivalents, which have grown organically over many years. I'll compare and contrast base R functions as we go, and then wrap up the chapter with a discussion of base functionals that don't have `purrr` equivalents.

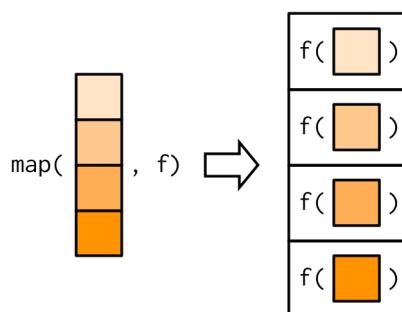
```
library(purrr)
```

8.2 My first functional: `map()`

The most fundamental functional is `purrr::map()`². It takes a vector and a function, calls the function once for each element of the vector, and returns the results in a list. In other words, `map(1:3, f)` is equivalent to `list(f(1), f(2), f(3))`.

```
triple <- function(x) x * 3
map(1:3, triple)
#> [[1]]
#> [1] 3
#>
#> [[2]]
#> [1] 6
#>
#> [[3]]
#> [1] 9
```

Or, graphically:



You might wonder why this function is called `map()`. What does it have to do with depicting physical features of land or sea ? In fact, the meaning comes from mathematics where `map` refers to “an operation that associates each element of a given set with one or more elements of a second set”. This makes sense here because `map()` defines a mapping from one vector to another. (“Map” also has

²Not to be confused with `base:::Map()`, which is considerably more complex. I'll discuss `Map()` in Section 8.4.5.

the nice property of being short, which is useful for such a fundamental building block.)

The implementation of `map()` is quite simple. We allocate a list the same length as the input, and then fill in the list with a for loop. A basic implementation is only a handful of lines of code:

```
simple_map <- function(x, f, ...) {
  out <- vector("list", length(x))
  for (i in seq_along(x)) {
    out[[i]] <- f(x[[i]], ...)
  }
  out
}
```

The real `purrr::map()` function has a few differences: it is written in C to eke out every last iota of performance, preserves names, and supports a few shortcuts that you'll learn about in Section 8.2.2.

The base equivalent to `map()` is `lapply()`. The only difference is that `lapply()` does not support the helpers that you'll learn about below, so if you're only using `map()` from `purrr`, you can skip the additional dependency and use `lapply()` directly.

8.2.1 Producing atomic vectors

`map()` returns a list, which makes it the most general of the “map” family because you can put anything in a list. But it is inconvenient to return a list when a simpler data structure would do, so there are four more specific variants: `map_lgl()`, `map_int()`, `map_dbl()`, and `map_chr()`. Each returns an atomic vector of the specified type:

```
map_chr(mtcars, typeof)
#>      mpg      cyl      disp      hp      drat      wt      qsec
#> "double" "double" "double" "double" "double" "double" "double"
#>      vs      am      gear      carb
#> "double" "double" "double" "double"

map_lgl(mtcars, is.double)
#> mpg cyl disp hp drat wt qsec vs am gear carb
#> TRUE TRUE TRUE TRUE TRUE TRUE TRUE TRUE TRUE

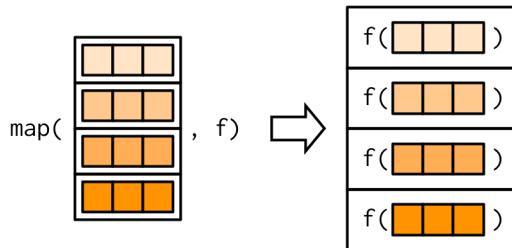
map_dbl(mtcars, mean)
```

```
#>      mpg      cyl      disp      hp      drat      wt      qsec      vs
#> 20.091  6.188 230.722 146.688  3.597  3.217 17.849  0.438
#>      am      gear      carb
#>  0.406  3.688  2.812

n_unique <- function(x) length(unique(x))
map_int(mtcars, n_unique)
#> mpg cyl disp hp drat wt qsec vs am gear carb
#> 25 3 27 22 22 29 30 2 2 3 6
```

purrr generally adopts the convention that suffixes, like `_dbl()`, refer to the output. All `map_*`() functions can take any type of vector as input.

These examples rely on the fact that data frames are lists containing vectors of the same length. This is more obvious if we draw a data frame with the same orientation as vector:



All map functions always return an output vector the same length as the input. This means that you'll get an error if the function you are mapping returns multiple results:

```
pair <- function(x) c(x, x)
map_dbl(1:3, pair)
#> Error: Result 1 is not a length 1 atomic vector
```

When debugging problems like this, it's often useful to switch back to `map()` so you can see what the problematic output is.

```
map(1:3, pair)
#> [[1]]
#> [1] 1 1
#>
#> [[2]]
#> [1] 2 2
#>
#> [[3]]
```

```
#> [1] 3 3
```

Base R has two apply functions that can return atomic vectors: `sapply()` and `vapply()`.

`sapply()` tries to simplify the result to an atomic vector wherever possible. But this simplification depends on the result, so sometimes you'll get a list, sometimes a vector, and sometimes a matrix. This makes it difficult to program with, and it should be avoided in non-interactive settings.

`vapply()` allows you to provide a template, `FUN.VALUE`, that describes the output shape. If you want to use only base R code you should always use `vapply()` in your functions, not `sapply()`. The primary downside of `vapply()` is its verbosity: the equivalent to `map_dbl(x, mean, na.rm = TRUE)` is `vapply(x, mean, na.rm = TRUE, FUN.VALUE = double(1))`.

8.2.2 Anonymous functions and shortcuts

Instead of using `map()` with an existing function, you can create an inline anonymous function (as mentioned in Section 5.2.1):

```
map_dbl(mtcars, function(x) length(unique(x)))
#> mpg cyl disp hp drat wt qsec vs am gear carb
#> 25 3 27 22 22 29 30 2 2 3 6
```

Anonymous functions are very useful, but the syntax is verbose. So purrr supports a special shortcut:

```
map_dbl(mtcars, ~ length(unique(.x)))
#> mpg cyl disp hp drat wt qsec vs am gear carb
#> 25 3 27 22 22 29 30 2 2 3 6
```

This works because all purrr functions translate formulas, created by `~` (pronounced “twiddle”), into functions. You can see what's happening behind the scenes by calling `as_mapper()`:

```
as_mapper(~ length(unique(.x)))
#> <lambda>
#> function (... , .x = ..1, .y = ..2, . = ..1)
#> length(unique(.x))
#> attr("class")
#> [1] "rlang_lambda_function"
```

The function arguments look a little quirky but allow you to refer to `.` for one argument functions, `.x` and `.y`. for two argument functions, and `..1`, `..2`, `..3`,

etc, for functions with an arbitrary number of arguments. `.` remains for backward compatibility but I don't recommend using it because it's easily confused with the `.` use by magrittr's pipe.

This shortcut is particularly useful for generating random data:

```
x <- map(1:3, ~ runif(2))
str(x)
#> List of 3
#> $ : num [1:2] 0.281 0.53
#> $ : num [1:2] 0.433 0.917
#> $ : num [1:2] 0.0275 0.8249
```

Reserve this syntax for short and simple functions. A good rule of thumb is that if your function spans lines or uses `{}`, it's time to give it a name.

The map functions also have shortcuts for extracting elements from a vector, powered by `purrr::pluck()`. You can use a character vector to select elements by name, an integer vector to select by position, or a list to select by both name and position. These are very useful for working with deeply nested lists, which often arise when working with JSON.

```
x <- list(
  list(-1, x = 1, y = c(2), z = "a"),
  list(-2, x = 4, y = c(5, 6), z = "b"),
  list(-3, x = 8, y = c(9, 10, 11)))
)

# Select by name
map_dbl(x, "x")
#> [1] 1 4 8

# Or by position
map_dbl(x, 1)
#> [1] -1 -2 -3

# Or by both
map_dbl(x, list("y", 1))
#> [1] 2 5 9

# You'll get an error if a component doesn't exist:
map_chr(x, "z")
#> Error: Result 3 is not a length 1 atomic vector
```

```
# Unless you supply a .default value
map_chr(x, "z", .default = NA)
#> [1] "a" "b" NA
```

In base R functions, like `lapply()`, you can provide the name of the function as a string. This isn't tremendously useful as `lapply(x, "f")` is almost always equivalent to `lapply(x, f)` and is more typing.

8.2.3 Passing arguments with ...

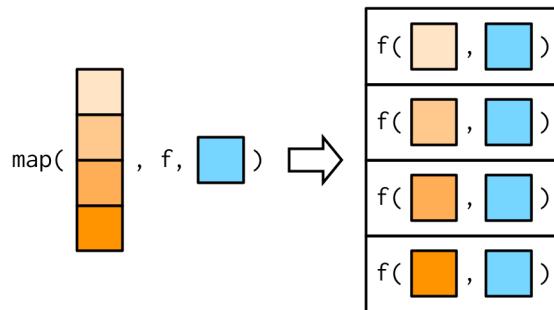
It's often convenient to pass along additional arguments to the function that you're calling. For example, you might want to pass `na.rm = TRUE` along to `mean()`. One way to do that is with an anonymous function:

```
x <- list(1:5, c(1:10, NA))
map_dbl(x, ~ mean(.x, na.rm = TRUE))
#> [1] 3.0 5.5
```

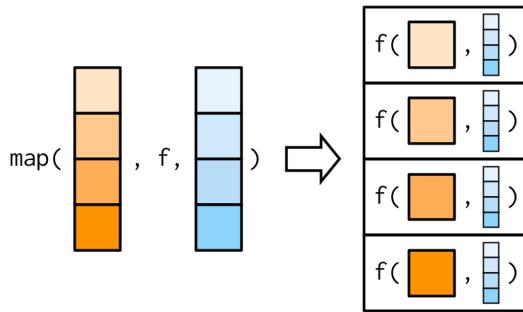
But because the map functions pass `...` along, there's a simpler form available:

```
map_dbl(x, mean, na.rm = TRUE)
#> [1] 3.0 5.5
```

This is easiest to understand with a picture: any arguments that come after `f` in the call to `map()` are inserted *after* the data in individual calls to `f()`:



It's important to note that these arguments are not decomposed; or said another way, `map()` is only vectorised over its first argument. If an argument after `f` is a vector, it will be passed along as is:



(You'll learn about map variants that *are* vectorised over multiple arguments in Sections 8.4.2 and 8.4.5.)

Note there's a subtle difference between placing extra arguments inside an anonymous function compared with passing them to `map()`. Putting them in an anonymous function means that they will be evaluated every time `f()` is executed, not just once when you call `map()`. This is easiest to see if we make the additional argument random:

```
plus <- function(x, y) x + y

x <- c(0, 0, 0, 0)
map_dbl(x, plus, runif(1))
#> [1] 0.0625 0.0625 0.0625 0.0625
map_dbl(x, ~ plus(.x, runif(1)))
#> [1] 0.903 0.132 0.629 0.945
```

8.2.4 Argument names

In the diagrams, I've omitted argument names to focus on the overall structure. But I recommend writing out the full names in your code, as it makes it easier to read. `map(x, mean, 0.1)` is perfectly valid code, but will call `mean(x[[1]], 0.1)` so it relies on the reader remembering that the second argument to `mean()` is `trim`. To avoid unnecessary burden on the brain of the reader³, be kind and write `map(x, mean, trim = 0.1)`.

This is the reason why the arguments to `map()` are a little odd: instead of being `x` and `f`, they are `.x` and `.f`. It's easiest to see the problem that leads to these names using `simple_map()` defined above. `simple_map()` has arguments `x` and `f` so you'll have problems whenever the function you are calling has arguments `x` or `f`:

³Who is highly likely to be future you!

```
bootstrap_summary <- function(x, f) {
  f(sample(x, replace = TRUE))
}

simple_map(mtcars, bootstrap_summary, f = mean)
#> Error in mean.default(x[[i]], ...):
#>   'trim' must be numeric of length one
```

The error is a little bewildering until you remember that the call to **simple_map()** is equivalent to **simple_map(x = mtcars, f = mean, bootstrap_summary)** because named matching beats positional matching.

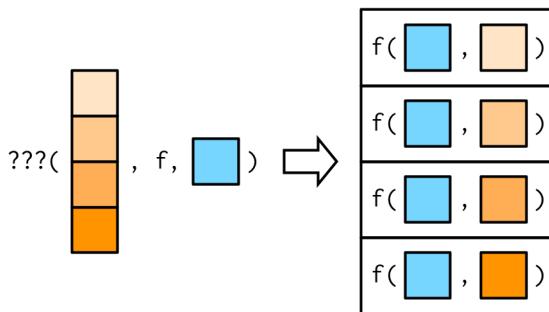
purrr functions reduce the likelihood of such a clash by using **.f** and **.x** instead of the more common **f** and **x**. Of course this technique isn't perfect (because the function you are calling might still use **.f** and **.x**), but it avoids 99% of issues. The remaining 1% of the time, use an anonymous function.

Base functions that pass along **...** use a variety of naming conventions to prevent undesired argument matching:

- The apply family mostly uses capital letters (e.g. **X** and **FUN**).
- **transform()** uses the more exotic prefix **_**: this makes the name non-syntactic so it must always be surrounded in **`**, as described in Section 2.2.1. This makes undesired matches extremely unlikely.
- Other functionals like **uniroot()** and **optim()** make no effort to avoid clashes but they tend to be used with specially created functions so clashes are less likely.

8.2.5 Varying another argument

So far the first argument to **map()** has always become the first argument to the function. But what happens if the first argument should be constant, and you want to vary a different argument? How do you get the result in this picture?



It turns out that there's no way to do it directly, but there are two tricks you can use instead. To illustrate them, imagine I have a vector that contains a few unusual values, and I want to explore the effect of different amounts of trimming when computing the mean. In this case, the first argument to `mean()` will be constant, and I want to vary the second argument, `trim`.

```
trims <- c(0, 0.1, 0.2, 0.5)
x <- rcauchy(1000)
```

- The simplest technique is to use an anonymous function to rearrange the argument order:

```
map_dbl(trims, ~ mean(x, trim = .x))
#> [1] -0.3500  0.0434  0.0354  0.0502
```

- Sometimes, if you want to be (too) clever, you can take advantage of R's flexible argument matching rules (as described in Section 5.8.2). For example, in this example you can rewrite `mean(x, trim = 0.1)` as `mean(0.1, x = x)`, so you could write the call to `map_dbl()` as:

```
map_dbl(trims, mean, x = x)
#> [1] -0.3500  0.0434  0.0354  0.0502
```

I don't recommend this technique as it relies on the reader being very familiar with both the argument order to `.f`, and R's argument matching rules.

You'll see one more alternative in Section 8.4.5.

8.2.6 Exercises

1. Use `as_mapper()` to explore how `purrr` generates anonymous functions for the integer, character, and list helpers. What helper allows you to extract attributes? Read the documentation to find out.

2. `map(1:3, ~ runif(2))` is a useful pattern for generating random numbers, but `map(1:3, runif(2))` is not. Why not? Can you explain why it returns the result that it does?
3. Use the appropriate `map()` function to:
 - a) Compute the standard deviation of every column in a numeric data frame.
 - b) Compute the standard deviation of every numeric column in a mixed data frame. (Hint: you'll need to do it in two steps.)
 - c) Compute the number of levels for every factor in a data frame.
4. The following code simulates the performance of a t-test for non-normal data. Extract the p-value from each test, then visualise.

```
trials <- map(1:100, ~ t.test(rpois(10, 10), rpois(7, 10)))
```

5. The following code uses a `map` nested inside another `map` to apply a function to every element of a nested list. Why does it fail, and what do you need to do to make it work?

```
x <- list(
  list(1, c(3, 9)),
  list(c(3, 6), 7, c(4, 7, 6))
)

triple <- function(x) x * 3
map(x, map, .f = triple)
#> Error in .f(.x[[i]], ...):
#>   unused argument (map)
```

6. Use `map()` to fit linear models to the `mtcars` dataset using the formulas stored in this list:

```
formulas <- list(
  mpg ~ disp,
  mpg ~ I(1 / disp),
  mpg ~ disp + wt,
  mpg ~ I(1 / disp) + wt
)
```

7. Fit the model `mpg ~ disp` to each of the bootstrap replicates of `mtcars` in the list below, then extract the R^2 of the model fit (Hint: you can compute the R^2 with `summary()`)

```
bootstrap <- function(df) {
  df[sample(nrow(df), replace = TRUE), , drop = FALSE]
}

bootstraps <- map(1:10, ~ bootstrap(mtcars))
```

8.3 Purrr style

Before we go on to explore more map variants, let's take a quick look at how you tend to use multiple purrr functions to solve a moderately realistic problem: fitting a model to each subgroup and extracting a coefficient of the model. For this toy example, I'm going to break the `mtcars` data set down into groups defined by the number of cylinders, using the base `split` function:

```
by_cyl <- split(mtcars, mtcars$cyl)
```

Now imagine we want to fit a linear model, then extract the second coefficient (i.e. the intercept). The following code shows how you might do that with purrr:

```
by_cyl %>%
  map(~ lm(mpg ~ wt, data = .x)) %>%
  map(coef) %>%
  map_dbl(2)
#>     4      6      8
#> -5.65 -2.78 -2.19
```

(If you haven't seen `%>%`, the pipe, before, it's described in Section 5.3.)

I think this code is easy to read because each line encapsulates a single step, you can easily distinguish the functional from what it does, and the purrr helpers allow us to very concisely describe what to do in each step.

How would you attack this problem with base R? You certainly *could* replace each purrr function with the equivalent base function:

```
by_cyl %>%
  lapply(function(data) lm(mpg ~ wt, data = data)) %>%
  lapply(coef) %>%
  vapply(function(x) x[[2]], double(1))
#>     4      6      8
#> -5.65 -2.78 -2.19
```

But this isn't really base R since we're using the pipe. To tackle purely in base

I think you'd use an intermediate variable, and do more in each step:

```
models <- lapply(by_cyl, function(data) lm(mpg ~ wt, data = data))
vapply(models, function(x) coef(x)[[2]], double(1))
#>     4      6      8
#> -5.65 -2.78 -2.19
```

Or, of course, you could use a for loop:

```
intercepts <- double(length(by_cyl))
for (i in seq_along(by_cyl)) {
  model <- lm(mpg ~ wt, data = by_cyl[[i]])
  intercepts[[i]] <- coef(model)[[2]]
}
intercepts
#> [1] -5.65 -2.78 -2.19
```

It's interesting to note that as you move from purrr to base apply functions to for loops you tend to do more and more in each iteration. In purrr we iterate 3 times (`map()`, `map()`, `map_dbl()`), with apply functions we iterate twice (`lapply()`, `vapply()`), and with a for loop we iterate once. I prefer more, but simpler, steps because I think it makes the code easier to understand and later modify.

8.4 Map variants

There are 23 primary variants of `map()`. So far, you've learned about five (`map()`, `map_lgl()`, `map_int()`, `map_dbl()` and `map_chr()`). That means that you've got 18 (!! more to learn. That sounds like a lot, but fortunately the design of purrr means that you only need to learn five new ideas:

- Output same type as input with `modify()`
- Iterate over two inputs with `map2()`.
- Iterate with an index using `imap()`
- Return nothing with `walk()`.
- Iterate over any number of inputs with `pmap()`.

The map family of functions has orthogonal input and outputs, meaning that we can organise all the family into a matrix, with inputs in the rows and outputs in the columns. Once you've mastered the idea in a row, you can combine it with any column; once you've mastered the idea in a column, you can combine it with any row.

	List	Atomic	Same type	Nothing
One argument	<code>map()</code>	<code>map_1gl()</code> , ...	<code>modify()</code>	<code>walk()</code>
Two arguments	<code>map2()</code>	<code>map2_1gl()</code> , ...	<code>modify2()</code>	<code>walk2()</code>
One argument + index	<code>imap()</code>	<code>imap_1gl()</code> , ...	<code>imodify()</code>	<code>iwalk()</code>
N arguments	<code>pmap()</code>	<code>pmap_1gl()</code> , ...	—	<code>pwalk()</code>

8.4.1 Same type of output as input: `modify()`

Imagine you wanted to double every column in a data frame. You might first try using `map()`, but `map()` always returns a list:

```
df <- data.frame(
  x = 1:3,
  y = 6:4
)

map(df, ~ .x * 2)
#> $x
#> [1] 2 4 6
#>
#> $y
#> [1] 12 10 8
```

If you want to keep the output as a data frame, you can use `modify()`, which always returns the same type of output as the input:

```
modify(df, ~ .x * 2)
#> x y
#> 1 2 12
#> 2 4 10
#> 3 6 8
```

Despite the name, `modify()` doesn't modify in place, it returns a modified copy, so if you wanted to permanently modify `df`, you'd need to assign it:

```
df <- modify(df, ~ .x * 2)
```

As usual, the basic implementation of `modify()` is simple, and in fact it's even simpler than `map()` because we don't need to create a new output vector; we can just progressively replace the input. (The real code is a little complex to handle edge cases more gracefully.)

```
simple_modify <- function(x, f, ...) {
  for (i in seq_along(x)) {
    x[[i]] <- f(x[[i]], ...)
  }
  x
}
```

In Section 8.6.2 you'll learn about a very useful variant of `modify()`, called `modify_if()`. This allows you to (e.g.) only double *numeric* columns of a data frame with `modify_if(df, is.numeric, ~ .x * 2)`.

8.4.2 Two inputs: `map2()` and friends

`map()` is vectorised over a single argument, `.x`. This means it only varies `.x` when calling `.f`, and all other arguments are passed along unchanged, thus making it poorly suited for some problems. For example, how would you find a weighted mean when you have a list of observations and a list of weights? Imagine we have the following data:

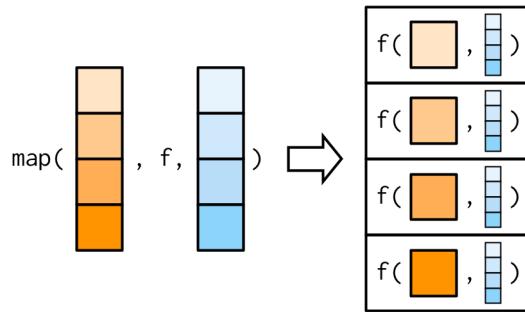
```
xs <- map(1:8, ~ runif(10))
xs[[1]][[1]] <- NA
ws <- map(1:8, ~ rpois(10, 5) + 1)
```

You can use `map_dbl()` to compute the unweighted means:

```
map_dbl(xs, mean)
#> [1] NA 0.463 0.551 0.453 0.564 0.501 0.371 0.443
```

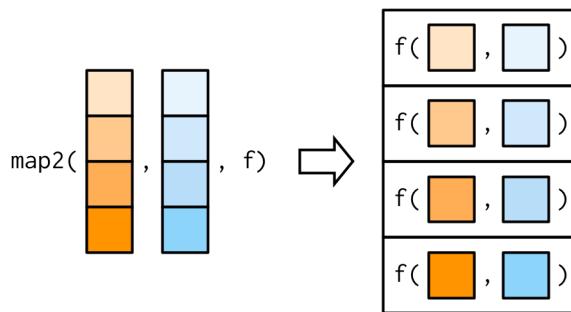
But passing `ws` as an additional argument doesn't work because arguments after `.f` are not transformed:

```
map_dbl(xs, weighted.mean, w = ws)
#> Error in weighted.mean.default(.x[[i]], ...):
#>   'x' and 'w' must have the same length
```



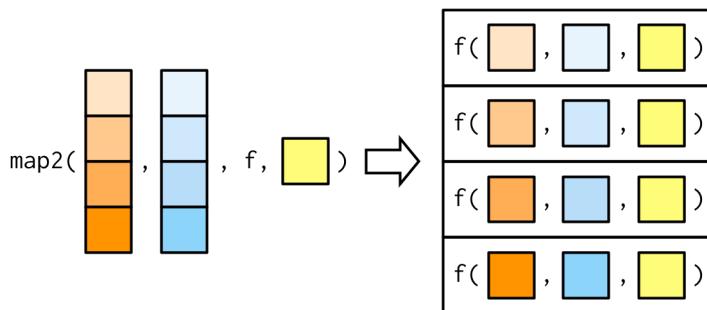
We need a new tool: a `map2()`, which is vectorised over two arguments. This means both `.x` and `.y` are varied in each call to `.f`:

```
map2_dbl(xs, ws, weighted.mean)
#> [1] NA 0.451 0.603 0.452 0.563 0.510 0.342 0.464
```



The arguments to `map2()` are slightly different to the arguments to `map()` as two vectors come before the function, rather than one. Additional arguments still go afterwards:

```
map2_dbl(xs, ws, weighted.mean, na.rm = TRUE)
#> [1] 0.504 0.451 0.603 0.452 0.563 0.510 0.342 0.464
```

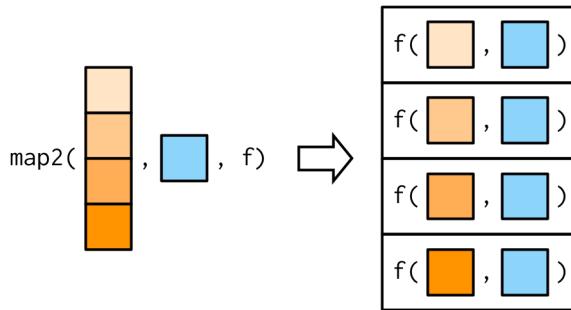


The basic implementation of `map2()` is simple, and quite similar to that of `map()`.

Instead of iterating over one vector, we iterate over two in parallel:

```
simple_map2 <- function(x, y, f, ...) {
  out <- vector("list", length(xs))
  for (i in seq_along(x)) {
    out[[i]] <- f(x[[i]], y[[i]], ...)
  }
  out
}
```

One of the big differences between `map2()` and the simple function above is that `map2()` recycles its inputs to make sure that they're the same length:



In other words, `map2(x, y, f)` will automatically behave like `map(x, f, y)` when needed. This is helpful when writing functions; in scripts you'd generally just use the simpler form directly.

The closest base equivalent to `map2()` is `Map()`, which is discussed in Section 8.4.5.

8.4.3 No outputs: `walk()` and friends

Most functions are called for the value that they return, so it makes sense to capture and store it with a `map()` function. But some functions are called primarily for their side-effects (e.g. `cat()`, `write.csv()`, or `ggsave()`) and it doesn't make sense to capture their results. Take this simple example that displays a welcome message using `cat()`. `cat()` returns `NULL`, so while `map` works (in the sense that it generates the desired welcomes), it also returns `list(NULL, NULL)`.

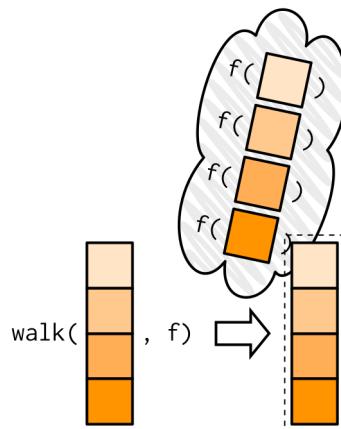
```
welcome <- function(x) {
  cat("Welcome ", x, "\n", sep = "")
}
names <- c("Hadley", "Jenny")
```

```
# As well as generate the welcomes, it also shows
# the return value of cat()
map(names, welcome)
#> Welcome Hadley!
#> Welcome Jenny!
#> [[1]]
#> NULL
#>
#> [[2]]
#> NULL
```

You could avoid this problem by assigning the results of `map()` to a variable that you never use, but that would muddy the intent of the code. Instead, `purrr` provides the `walk` family of functions that ignore the return values of the `.f` and instead return `.x` invisibly⁴.

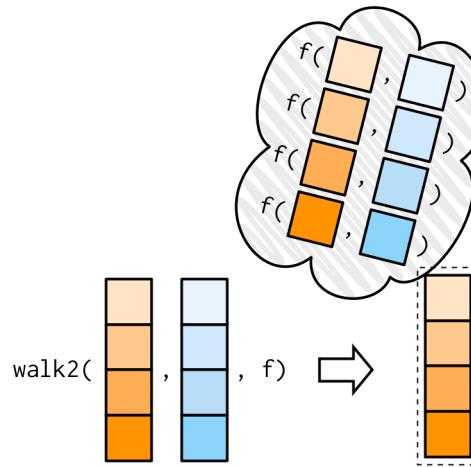
```
walk(names, welcome)
#> Welcome Hadley!
#> Welcome Jenny!
```

My visual depiction of `walk` attempts to capture the important difference from `map()`: the outputs are ephemeral, and the input is returned invisibly.



One of the most useful `walk()` variants is `walk2()` because a very common side-effect is saving something to disk, and when saving something to disk you always have a pair of values: the object and the path that you want to save it to.

⁴In brief, invisible values are only printed if you explicitly request it. This makes them well suited for functions called primarily for their side-effects, as it allows their output to be ignored by default, while still giving an option to capture it. See Section ?? for more details.



For example, imagine you have a list of data frames (which I've created here using `split`), and you'd like to save each one to a separate CSV file. That's easy with `walk2()`:

```
temp <- tempfile()
dir.create(temp)

cyls <- split(mtcars, mtcars$cyl)
paths <- file.path(temp, paste0("cyl-", names(cyls), ".csv"))
walk2(cyls, paths, write.csv)

dir(temp)
#> [1] "cyl-4.csv" "cyl-6.csv" "cyl-8.csv"
```

Here the `walk2()` is equivalent to `write.csv(cyls[[1]], paths[[1]]), write.csv(cyls[[2]], paths[[2]]), write.csv(cyls[[3]], paths[[3]])`.

There is no base equivalent to `walk()`; either wrap the result of `lapply()` in `invisible()` or save it to a variable that is never used.

8.4.4 Iterating over values and indices

There are three basic ways to loop over a vector with a for loop:

- Loop over the elements: `for (x in xs)`
- Loop over the numeric indices: `for (i in seq_along(xs))`
- Loop over the names: `for (nm in names(xs))`

The first form is analogous to the `map()` family. The second and third forms are

equivalent to the `imap()` family which allows you to iterate over the values and the indices of a vector in parallel.

`imap()` is like `map2()` in the sense that your `.f` gets called with two arguments, but here both are derived from the vector. `imap(x, f)` is equivalent to `map2(x, names(x), f)` if `x` has names, and `map2(x, seq_along(x), f)` if it does not.

`imap()` is often useful for constructing labels:

```
imap_chr(iris, ~ paste0("The first value of ", .y, " is ", .x[[1]]))
#>                               Sepal.Length
#> "The first value of Sepal.Length is 5.1"
#>                               Sepal.Width
#> "The first value of Sepal.Width is 3.5"
#>                               Petal.Length
#> "The first value of Petal.Length is 1.4"
#>                               Petal.Width
#> "The first value of Petal.Width is 0.2"
#>                               Species
#> "The first value of Species is setosa"
```

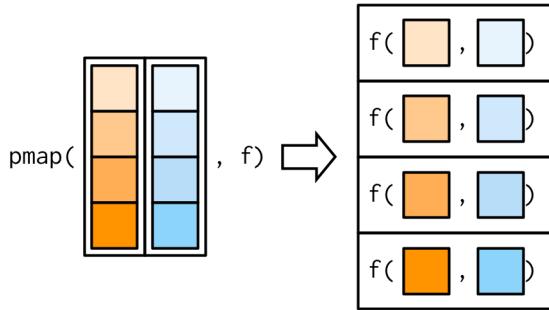
If the vector is unnamed, the second argument will be the index:

```
x <- map(1:6, ~ sample(1000, 10))
imap_chr(x, ~ paste0("The highest value of ", .y, " is ", max(.x)))
#> [1] "The highest value of 1 is 885" "The highest value of 2 is 808"
#> [3] "The highest value of 3 is 942" "The highest value of 4 is 966"
#> [5] "The highest value of 5 is 857" "The highest value of 6 is 671"
```

`imap()` is a useful helper if you want to work with the values in a vector along with their positions.

8.4.5 Any number of inputs: `pmap()` and friends

Since we have `map()` and `map2()`, you might expect `map3()`, `map4()`, `map5()`, ... But where would you stop? Instead of generalising `map2()` to an arbitrary number of arguments, purrr takes a slightly different tack with `pmap()`: you supply it a single list, which contains any number of arguments. In most cases, that will be a list of equal-length vectors, i.e. something very similar to a data frame. In diagrams, I'll emphasise that relationship by drawing the input similar to a data frame.

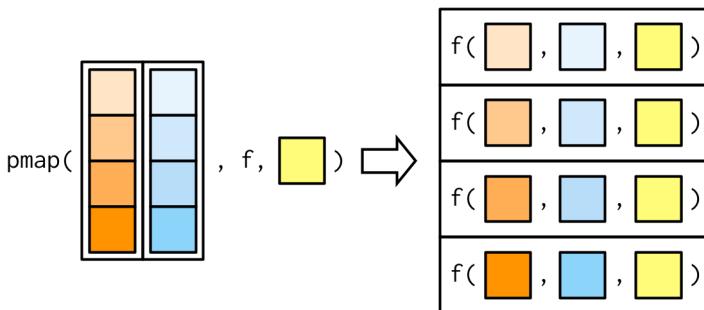


There's a simple equivalence between `map2()` and `pmap()`: `map2(x, y, f)` is the same as `pmap(list(x, y), f)`. The `pmap()` equivalent to the `map2_dbl(xs, ws, weighted.mean)` used above is:

```
pmap_dbl(list(xs, ws), weighted.mean)
#> [1] NA 0.451 0.603 0.452 0.563 0.510 0.342 0.464
```

As before, the varying arguments come before `.f` (although now they must be wrapped in a list), and the constant arguments come afterwards.

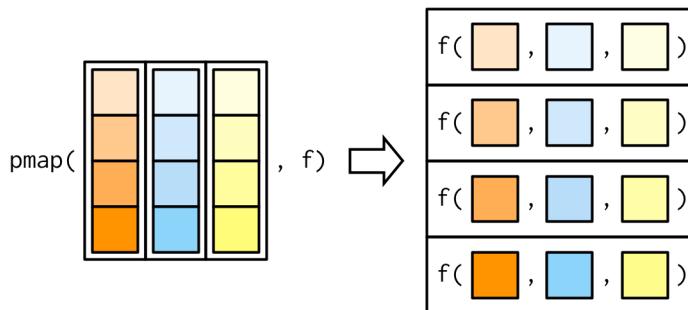
```
pmap_dbl(list(xs, ws), weighted.mean, na.rm = TRUE)
#> [1] 0.504 0.451 0.603 0.452 0.563 0.510 0.342 0.464
```



A big difference between `pmap()` and the other map functions is that `pmap()` gives you much finer control over argument matching because you can name the components of the list. Returning to our example from Section 8.2.5, where we wanted to vary the `trim` argument to `x`, we could instead use `pmap()`:

```
trims <- c(0, 0.1, 0.2, 0.5)
x <- rcauchy(1000)

pmap_dbl(list(trim = trims), mean, x = x)
#> [1] -6.6754 0.0192 0.0228 0.0151
```

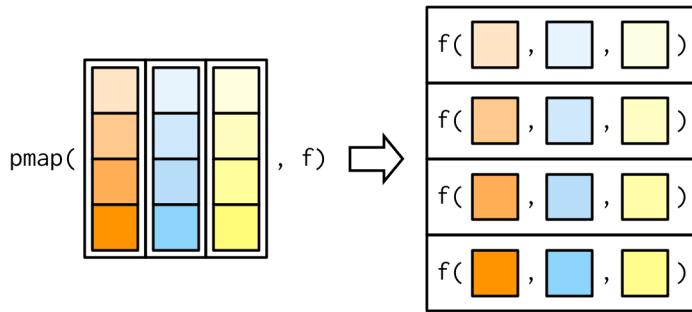


I think it's good practice to name the list to make it very clear how the function will be called.

It's often convenient to call `pmap()` with a data frame. A handy way to create that data frame is with `tibble::tribble()`, which allows you to describe a data frame row-by-row (rather than column-by-column, as usual): thinking about the parameters to a function as a data frame is a very powerful pattern. The following example shows how you might draw random uniform numbers with varying parameters:

```
params <- tibble::tribble(
  ~ n, ~ min, ~ max,
  1L,      0,      1,
  2L,     10,    100,
  3L,    100,   1000
)

pmap(params, runif)
#> [[1]]
#> [1] 0.718
#>
#> [[2]]
#> [1] 19.5 39.9
#>
#> [[3]]
#> [1] 535 476 231
```



Here, the column names are critical: I've carefully chosen to match them to the arguments to `runif()`, so the `pmap(params, runif)` is equivalent to `runif(n = 1L, min = 0, max = 1)`, `runif(n = 2, min = 10, max = 100)`, `runif(n = 3L, min = 100, max = 1000)`. (If you have a data frame in hand, and the names don't match, use `dplyr::rename()` or similar.)

There are two base equivalents to the `pmap()` family: `Map()` and `mapply()`. Both have significant drawbacks:

- `Map()` vectorises over all arguments so you cannot supply arguments that do not vary.
- `mapply()` is the multidimensional version of `sapply()`; conceptually it takes the output of `Map()` and simplifies it if possible. This gives it similar issues to `sapply()`. There is no multi-input equivalent of `vapply()`.

8.4.6 Exercises

1. Explain the results of `modify(mtcars, 1)`.
2. Rewrite the following code to use `iwalk()` instead of `walk2()`. What are the advantages and disadvantages?

```
cyls <- split(mtcars, mtcars$cyl)
paths <- file.path(temp, paste0("cyl-", names(cyls), ".csv"))
walk2(cyls, paths, write.csv)
```

3. Explain how the following code transforms a data frame using functions stored in a list.

```
trans <- list(
  disp = function(x) x * 0.0163871,
  am = function(x) factor(x, labels = c("auto", "manual"))
)
```

```
vars <- names(trans)
mtcars[vars] <- map2(trans, mtcars[vars], function(f, var) f(var))
```

Compare and contrast the `map2()` approach to this `map()` approach:

```
mtcars[vars] <- map(vars, ~ trans[[.x]](mtcars[[.x]]))
```

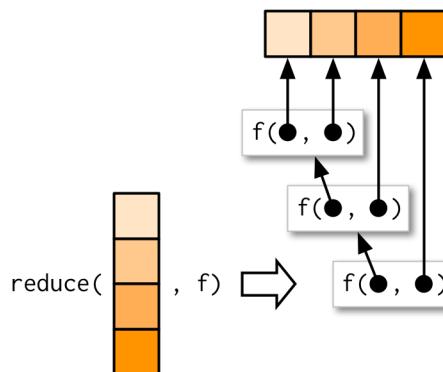
4. What does `write.csv()` return? i.e. what happens if you use it with `map2()` instead of `walk2()`?

8.5 Reduce

After the map family, the next most important family of functions is the reduce family. This family is much smaller, with only two main variants, and is used less commonly, but it's a powerful idea, gives us the opportunity to discuss some useful algebra, and powers the map-reduce framework frequently used for processing very large datasets.

8.5.1 Basics

`reduce()` takes a vector of length n and produces a vector of length one by calling a function with a pair of values at a time: `reduce(1:4, f)` is equivalent to `f(f(f(1, 2), 3), 4)`.



`reduce()` is a useful way to generalise a function that works with two inputs (a **binary** function) to work with any number of inputs. Imagine you have a list of numeric vectors, and you want to find the values that occur in every element:

```
1 <- map(1:4, ~ sample(1:10, 15, replace = T))
str(1)
#> List of 4
#> $ : int [1:15] 7 5 9 7 9 9 5 10 5 5 ...
#> $ : int [1:15] 6 3 6 10 3 4 4 2 9 9 ...
#> $ : int [1:15] 5 3 4 6 1 1 9 9 6 8 ...
#> $ : int [1:15] 4 2 6 6 8 5 10 6 7 1 ...
```

To solve this challenge we need to use `intersect()` repeatedly:

```
out <- 1[[1]]
out <- intersect(out, 1[[2]])
out <- intersect(out, 1[[3]])
out <- intersect(out, 1[[4]])
out
#> [1] 5 1
```

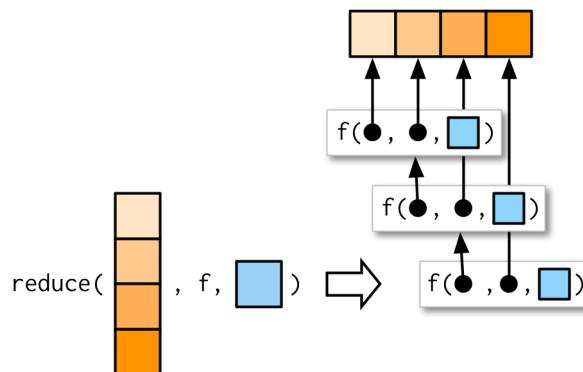
`reduce()` automates this solution for us, so we can write:

```
reduce(1, intersect)
#> [1] 5 1
```

We could apply the same idea if we wanted to list all the elements that appear in at least one entry. All we have to do is switch from `intersect()` to `union()`:

```
reduce(1, union)
#> [1] 7 5 9 10 1 6 3 4 2 8
```

Like the map family, you can also pass additional arguments. `intersect()` and `union()` don't take extra arguments so I can't demonstrate them here, but the principle is straightforward and I drew you a picture.



As usual, the essence of `reduce()` can be reduced to a simple wrapper around a

for loop:

```
simple_reduce <- function(x, f) {
  out <- x[[1]]
  for (i in seq(2, length(x))) {
    out <- f(out, x[[i]])
  }
  out
}
```

The base equivalent is `Reduce()`. Note that the argument order is different: the function comes first, followed by the vector, and there is no way to supply additional arguments.

8.5.2 Accumulate

The first `reduce()` variant, `accumulate()`, is useful for understanding how `reduce` works, because instead of returning just the final result, it returns all the intermediate results as well:

```
accumulate(1, intersect)
#> [[1]]
#> [1] 7 5 9 7 9 9 5 10 5 5 5 10 9 9 1
#>
#> [[2]]
#> [1] 5 9 10 1
#>
#> [[3]]
#> [1] 5 9 1
#>
#> [[4]]
#> [1] 5 1
```

Another useful way to understand `reduce` is to think about `sum()`: `sum(x)` is equivalent to `x[[1]] + x[[2]] + x[[3]] + ...`, i.e. `reduce(x, `+`)`. Then `accumulate(x, `+`)` is the cumulative sum:

```
x <- c(4, 3, 10)
reduce(x, `+`)
#> [1] 17

accumulate(x, `+`)
#> [1] 4 7 17
```

8.5.3 Output types

In the above example using `+`, what should `reduce()` return when `x` is short, i.e. length 1 or 0? Without additional arguments, `reduce()` just returns the input when `x` is length 1:

```
reduce(1, `+`)
#> [1] 1
```

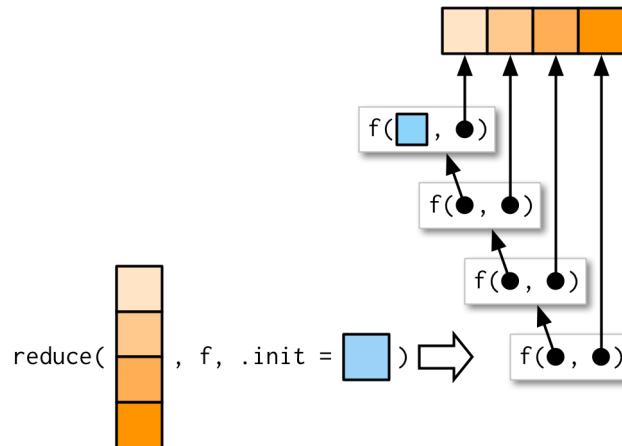
This means that `reduce()` has no way to check that the input is valid:

```
reduce("a", `+`)
#> [1] "a"
```

What if it's length 0? We get an error that suggests we need to use the `.init` argument:

```
reduce(integer(), `+`)
#> Error: `x` is empty, and no `.`init` supplied
```

What should `.init` be here? To figure that out, we need to see what happens when `.init` is supplied:



So if we call `reduce(1, `+`, init)` the result will be $1 + \text{init}$. Now we know that the result should be just 1, so that suggests that `.init` should be 0:

```
reduce(integer(), `+`, .init = 0)
#> [1] 0
```

This also ensures that `reduce()` checks that length 1 inputs are valid for the function that you're calling:

```
reduce("a", `+`, .init = 0)
#> Error in .x + .y:
#>   non-numeric argument to binary operator
```

If you want to get algebraic about it, 0 is called the **identity** of the real numbers under the operation of addition: if you add a 0 to any number, you get the same number back. R applies the same principle to determine what a summary function with a zero length input should return:

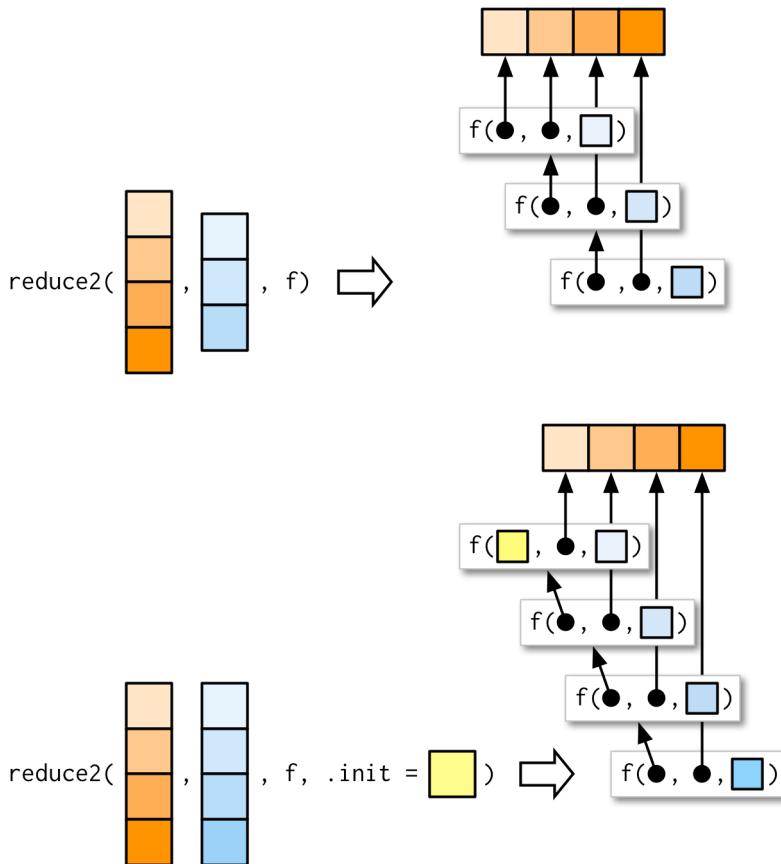
```
sum(integer())  # x + 0 = x
#> [1] 0
prod(integer()) # x * 1 = x
#> [1] 1
min(integer()) # min(x, Inf) = x
#> [1] Inf
max(integer()) # max(x, -Inf) = x
#> [1] -Inf
```

If you're using `reduce()` in a function, you should always supply `.init`. Think carefully about what your function should return when passed a vector of length zero or one, and make sure to test your implementation.

8.5.4 Multiple inputs

Very occassionally you need to pass two arguments to the function that you're reducing. For example, you might have a list of data frames that you want to join together, and the variables that you are joining by vary from element to element. This is a very specialised scenario, so I don't want to spend much time on it, except to know that it exists.

Note that the length of the second argument varies based on whether or not `.init` is supplied: if you have four elements of `x`, `f` will only be called three times. If you supply `init`, `f` will be called four times.



8.5.5 Map-reduce

You might have heard of map-reduce, the idea that powers technology like Hadoop. Now you can see how simple and powerful the underlying idea is: all map-reduce is a map combined with a reduce. The difference for large data is that the data is spread over multiple computers. Each computer performs the map on the data that it has, then it sends the result to back to a coordinator which *reduces* the individual results back to a single result.

8.6 Predicate functionals

A **predicate** is a function that returns a single TRUE or FALSE, like `is.character()`, `is.null()`, or `all()`, and we say a predicate **matches** a vector if it returns TRUE.

8.6.1 Basics

A **predicate functional** applies a predicate to each element of a vector. purrr provides six useful functions which come in three pairs:

- `some(.x, .p)` returns TRUE if *any* element matches; `every(.x, .p)` returns TRUE if *all* elements match.
- `detect(.x, .p)` returns the *value* of the first match; `detect_index(.x, .p)` returns the *location* of the first match.
- `keep(.x, .p)` *keeps* all matching elements; `discard(.x, .p)` *drops* all matching elements.

The following example shows how you might use these functionals with a data frame:

```
df <- data.frame(x = 1:3, y = c("a", "b", "c"))
detect(df, is.factor)
#> [1] a b c
#> Levels: a b c
detect_index(df, is.factor)
#> [1] 2

str(keep(df, is.factor))
#> 'data.frame': 3 obs. of 1 variable:
#> $ y: Factor w/ 3 levels "a","b","c": 1 2 3
str(discard(df, is.factor))
#> 'data.frame': 3 obs. of 1 variable:
#> $ x: int 1 2 3
```

8.6.2 Map variants

`map()` and `modify()` come in variants that also take predicate functions, transforming only the elements of `.x` with `.p` is TRUE.

```
str(map_if(iris, is.numeric, mean))
#> List of 5
#> $ Sepal.Length: num 5.84
#> $ Sepal.Width : num 3.06
#> $ Petal.Length: num 3.76
#> $ Petal.Width : num 1.2
#> $ Species      : Factor w/ 3 levels "setosa","versicolor",...: 1 1 1...
str(modify_if(iris, is.numeric, mean))
```

```
#> 'data.frame': 150 obs. of 5 variables:
#>   $ Sepal.Length: num 5.84 5.84 5.84 5.84 5.84 ...
#>   $ Sepal.Width : num 3.06 3.06 3.06 3.06 3.06 ...
#>   $ Petal.Length: num 3.76 3.76 3.76 3.76 3.76 ...
#>   $ Petal.Width : num 1.2 1.2 1.2 1.2 1.2 ...
#>   $ Species      : Factor w/ 3 levels "setosa","versicolor",...: 1 1 1...
str(map(keep(iris, is.numeric), mean))
#> List of 4
#>   $ Sepal.Length: num 5.84
#>   $ Sepal.Width : num 3.06
#>   $ Petal.Length: num 3.76
#>   $ Petal.Width : num 1.2
```

8.6.3 Exercises

1. Why isn't `is.na()` a predicate function? What base R function is closest to being a predicate version of `is.na()`?
2. What's the relationship between `which()` and `Position()`? What's the relationship between `where()` and `Filter()`?
3. `simple_reduce()` has a problem when `x` is length 0 or length 1. Describe the source of the problem and how you might go about fixing it.

```
simple_reduce <- function(x, f) {
  out <- x[[1]]
  for (i in seq(2, length(x))) {
    out <- f(out, x[[i]])
  }
  out
}
```

4. Implement the `span()` function from Haskell: given a list `x` and a predicate function `f`, `span()` returns the location of the longest sequential run of elements where the predicate is true. (Hint: you might find `rle()` helpful.)
5. Implement `arg_max()`. It should take a function and a vector of inputs, and return the elements of the input where the function returns the highest value. For example, `arg_max(-10:5, function(x) x ^ 2)` should return `-10`. `arg_max(-5:5, function(x) x ^ 2)` should return `c(-5, 5)`. Also implement the matching `arg_min()` function.
6. The function below scales a vector so it falls in the range $[0, 1]$. How would

you apply it to every column of a data frame? How would you apply it to every numeric column in a data frame?

```
scale01 <- function(x) {
  rng <- range(x, na.rm = TRUE)
  (x - rng[1]) / (rng[2] - rng[1])
}
```

8.7 Base functionals

To finish up the chapter, here I provide a survey of important base functionals that are not members of the map, reduce, or predicate families, and hence have no equivalent in purrr. This is not to say that they’re not important, but they have more of a mathematical/statistical flavour, so they are generally less useful in data analysis.

8.7.1 Matrices and arrays

`map()` and friends are specialised to work with 1d vectors. `base::apply()` is specialised to work with 2d and higher vectors, i.e. matrices and arrays. You can think of `apply()` as an operation that summarises a matrix or array by collapsing each row or column to a single value. It has four arguments:

- `X`, the matrix or array to summarise.
- `MARGIN`, an integer vector giving the dimensions to summarise over, 1 = rows, 2 = columns, etc. (The argument name comes from thinking about the “margins” of a joint distribution.)
- `FUN`, a summary function.
- ... other arguments passed on to `FUN`.

A typical example of `apply()` looks like this

```
a <- matrix(1:20, nrow = 5)
apply(a, 1, mean)
#> [1] 8.5 9.5 10.5 11.5 12.5
apply(a, 2, mean)
#> [1] 3 8 13 18
```

You can specify multiple dimensions to `MARGIN`, which is useful for high-d arrays:

```
a <- array(1:24, c(2, 3, 4))
apply(a, 1, mean)
#> [1] 12 13
apply(a, c(1, 2), mean)
#>     [,1] [,2] [,3]
#> [1,]    10    12    14
#> [2,]    11    13    15
```

There are two caveats to using `apply()`:

- Like `base::sapply()`, you have no control over the output type; it will automatically be simplified to a list, matrix, or vector. However, you usually use `apply()` with numeric arrays and a numeric summary function so you are less likely to encounter a problem than with `sapply()`.
- `apply()` is also not idempotent in the sense that if the summary function is the identity operator, the output is not always the same as the input.

```
a1 <- apply(a, 1, identity)
identical(a, a1)
#> [1] FALSE

a2 <- apply(a, 2, identity)
identical(a, a2)
#> [1] FALSE
```

- Never use `apply()` with a data frame. It always coerces it to a matrix, which will lead to undesirable results if your data frame contains anything other than numbers.

```
df <- data.frame(x = 1:3, y = c("a", "b", "c"))
apply(df, 2, mean)
#> Warning in mean.default(newX[, i], ...): argument is not numeric or
#> logical: returning NA

#> Warning in mean.default(newX[, i], ...): argument is not numeric or
#> logical: returning NA
#> x   y
#> NA  NA
```

8.7.2 Mathematical

Functionals are very common in mathematics. The limit, the maximum, the roots (the set of points where $f(x) = 0$), and the definite integral are all functionals: given a function, they return a single number (or vector of numbers). At first glance, these functions don't seem to fit in with the theme of eliminating loops, but if you dig deeper you'll find out that they are all implemented using an algorithm that involves iteration.

Base R provides a useful set:

- `integrate()` finds the area under the curve defined by `f()`
- `uniroot()` finds where `f()` hits zero
- `optimise()` finds the location of the lowest (or highest) value of `f()`

The following example shows how they might be used with a simple function, `sin()`:

```
integrate(sin, 0, pi)
#> 2 with absolute error < 2.2e-14
str(uniroot(sin, pi * c(1 / 2, 3 / 2)))
#> List of 5
#> $ root      : num 3.14
#> $ f.root    : num 1.22e-16
#> $ iter      : int 2
#> $ init.it   : int NA
#> $ estim.prec: num 6.1e-05
str(optimise(sin, c(0, 2 * pi)))
#> List of 2
#> $ minimum   : num 4.71
#> $ objective: num -1
str(optimise(sin, c(0, pi), maximum = TRUE))
#> List of 2
#> $ maximum   : num 1.57
#> $ objective: num 1
```

8.7.3 Exercises

1. How does `apply()` arrange the output? Read the documentation and perform some experiments.
2. What do `eapply()` and `raply()` do? Does `purrr` have equivalents?

3. Challenge: read about the fixed point algorithm (https://mitpress.mit.edu/sites/default/files/sicp/full-text/book/book-Z-H-12.html#%25_idx_1096). Complete the exercises using R.

Chapter 9

Function factories

9.1 Introduction

A **function factory** is a function that makes functions. Here's a very simple example: we use a function factory (`power1()`) to make two child functions (`square()` and `cube()`):

```
power1 <- function(exp) {  
  force(exp)  
  
  function(x) {  
    x ^ exp  
  }  
}  
  
square <- power1(2)  
cube <- power1(3)
```

I'll call `square()` and `cube()` **manufactured functions**, but this is just a term to ease communication with other humans: from R's perspective they are no different to functions created any other way.

```
square(3)  
#> [1] 9  
cube(3)  
#> [1] 27
```

You have already learned about the individual components that make function

factories possible:

- In Section 5.2.1, you learned about R’s “first-class” functions. In R, you bind a function to a name in the same way as you bind any object to a name: with `<-`.
- In Section 6.4.2, you learned that a function captures (encloses) the environment in which it is created.
- In Section 6.4.4, you learned that a function creates a new execution environment every time it is run. This environment is usually ephemeral, but here it becomes the enclosing environment of the manufactured function.

In this chapter, you’ll learn how the non-obvious combination of these three features lead to the function factory. You’ll also see examples of their usage in visualisation and statistics.

Of the three main functional programming tools (functionals, function factories, and function operators), function factories are probably the least useful. Generally, they don’t tend to reduce overall code complexity. Instead, they tend to partition complexity into more easily digested chunks. Function factories are also an important building block for the very useful function operators, which you’ll learn about in Chapter 10.

Outline

- Section 9.2 begins the chapter with an explanation of how function factories work, pulling together ideas from scoping and environments. You’ll also see how function factories can be used to implement a “memory” for functions, allowing data to persist across calls.
- Section 9.3 illustrates the use of function factories with examples from ggplot2. You’ll see two examples of how ggplot2 works with user supplied function factories, and one example of where ggplot2 uses a function factory internally.
- Section 9.4 uses function factories to tackle three challenges from statistics: understanding the Box-Cox transform, solving maximum likelihood problems, and drawing bootstrap resamples.
- Section 9.5 shows how you can combine function factories and functionals to rapidly generate a family of functions from data.

Prerequisites

Make sure you're familiar with the contents of Sections 5.2.1 (first-class functions), 6.4.2 (function environments), and 6.4.4 (execution environments) mentioned above.

Function factories only need base R. We'll use a little rlang to peek inside of them more easily, and we'll use ggplot2 and scales to explore the use of function factories in visualisation.

```
# The development version includes some printing tweaks that we need here
# devtools::install_github("r-lib/rlang")
library(rlang)

library(ggplot2)
library(scales)
```

9.2 Factory fundamentals

The key idea that makes function factories work can be expressed very concisely:

The enclosing environment of the manufactured function is an execution environment of the function factory.

It only takes few words to express these big ideas, but it takes a lot more work to really understand what this means. This section will help you put the pieces together with interactive exploration and some diagrams.

9.2.1 Environments

Let's start by taking a look at `square()` and `cube()`:

```
square
#> function(x) {
#>   x ^ exp
#> }
#> <environment: 0x12bd9d8>

cube
#> function(x) {
#>   x ^ exp
#> }
```

```
#> <bytecode: 0x186b7e0>
#> <environment: 0x1cf1e00>
```

Printing manufactured functions is not revealing because the bodies are identical; it's the contents of the enclosing environment that's important. We can get a little more insight by using `rlang::env_print()`. That shows us that we have two different environments (each of which was originally an execution environment of `power1()`). The environments have the same parent, which is the enclosing environment of `power1()`, the global environment.

```
env_print(square)
#> <environment: 0x12bd9d8>
#>   parent: <environment: global>
#>   bindings:
#>     * exp: <dbl>

env_print(cube)
#> <environment: 0x1cf1e00>
#>   parent: <environment: global>
#>   bindings:
#>     * exp: <dbl>
```

`env_print()` shows us that both environments have a binding to `exp`, but we want to see its value¹. That's easily done with `env_get()`:

```
env_get(square, "exp")
#> Warning: Passing an environment wrapper like a function is deprecated.
#> Please retrieve the environment before calling `env_get()` -
#> This warning is displayed once per session.
#> [1] 2

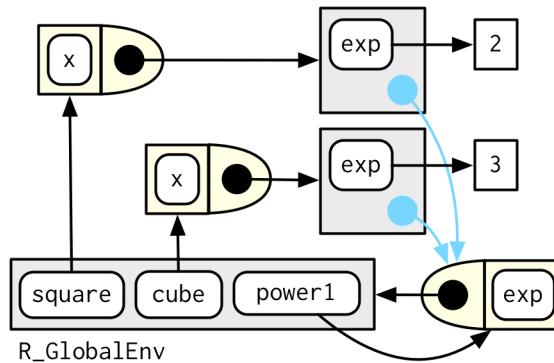
env_get(cube, "exp")
#> [1] 3
```

This is what makes manufactured functions behave differently from one another: names in the enclosing environment are bound to different values.

9.2.2 Diagram conventions

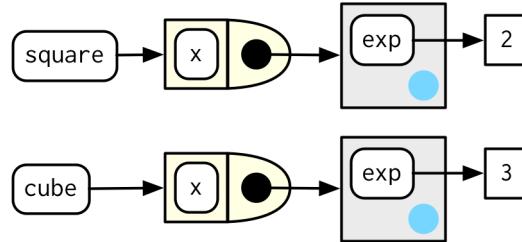
We can also show these relationships in a diagram:

¹A future version of `env_print()` is likely to do better at summarising the contents so you don't need this step.



There's a lot going on this diagram and some of the details aren't that important. We can simplify considerably by using two conventions:

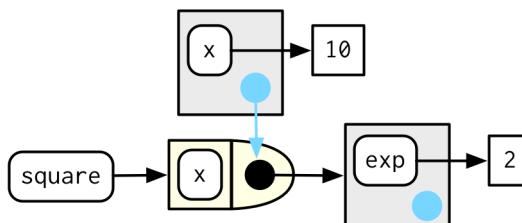
- Any free floating symbol lives in the global environment.
- Any environment without an explicit parent inherits from the global environment.



This view, which focuses on the environments, doesn't show any direct link between `cube()` and `square()`. That's because the link is the through the body of the function, which is identical for both, but is not shown in this diagram.

To finish up, let's look at the execution environment of `square(10)`. When `square()` executes `x ~ exp` it finds `x` in the execution environment and `exp` in its enclosing environment.

```
square(10)
#> [1] 100
```



9.2.3 Stateful functions

Function factories also allow you to maintain state across function invocations, which is generally hard to do because of the fresh start principle described in Section 5.4.3.

There are two things that make this possible:

- The enclosing environment of the manufactured function is unique and constant.
- R has a special assignment operator, `<<-`, which modifies bindings in the enclosing environment.

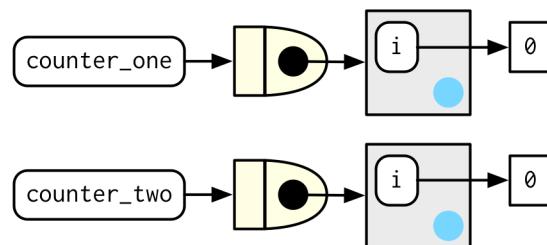
The usual assignment operator, `<-`, always creates a binding in the current environment. The **super assignment operator**, `<<-` rebinds an existing name found in a parent environment.

The following example shows how we can combine these ideas to create a function that records how many times it has been called:

```
new_counter <- function() {
  i <- 0

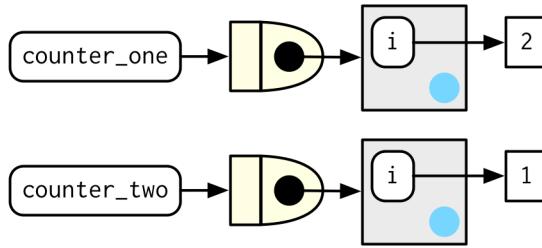
  function() {
    i <<- i + 1
    i
  }
}

counter_one <- new_counter()
counter_two <- new_counter()
```



When the manufactured function is run `i <<- i + 1` will modify `i` in its enclosing environment. Because manufactured functions have independent enclosing environments, they have independent counts:

```
counter_one()
#> [1] 1
counter_one()
#> [1] 2
counter_two()
#> [1] 1
```



Stateful functions are best used in moderation. As soon as your function starts managing the state of multiple variables, it's better to switch to R6, the topic of Chapter 13.

9.2.4 Potential pitfalls

There are two potential pitfalls to be aware of when creating your own function factories: forgetting to evaluate all inputs and accidentally capturing large objects.

Generally, you can rely on lazy evaluation to evaluate function inputs at the right time. However, there's a catch when it comes to function factories: if you don't eagerly evaluate every argument, it's possible to get confusing behaviour, as shown below.

```
power2 <- function(exp) {
  function(x) {
    x  $\wedge$  exp
  }
}

exp2 <- 2
square2 <- power2(exp2)
exp2 <- 3

square2(2)
#> [1] 8
```

This is described in Section 5.5.1, and happens when a binding changes in between calling the factory function and calling the manufactured function. This is likely to only happen rarely, but when it does, it will lead to a real head-scratcher of a bug. Avoid future pain by ensuring every argument is evaluated, using `force()` if the argument is only used by the manufactured function.

With most functions, you can rely on the GC to clean up any large temporary objects created inside a function. However, manufactured functions hold on to the execution environment, so you'll need to explicitly unbind any large temporary objects with `rm()`. Compare the sizes of `g1()` and `g2()` in the example below:

```
f1 <- function(n) {
  x <- runif(n)
  m <- mean(x)
  function() m
}

g1 <- f1(1e6)
lobstr::obj_size(g1)
#> 8,013,656 B

f2 <- function(n) {
  x <- runif(n)
  m <- mean(x)
  rm(x)
  function() m
}

g2 <- f2(1e6)
lobstr::obj_size(g2)
#> 13,496 B
```

9.2.5 Exercises

1. Base R contains two function factories, `approxfun()` and `ecdf()`. Read their documentation and experiment to figure out what the functions do and what they return.
2. Create a function `pick()` that takes an index, `i`, as an argument and returns a function with an argument `x` that subsets `x` with `i`.

```

pick(1)(x)
# should be equivalent to
x[[1]]

lapply(mtcars, pick(5))
# should be equivalent to
lapply(mtcars, function(x) x[[5]])

```

3. Create a function that creates functions that compute the i^{th} central moment (http://en.wikipedia.org/wiki/Central_moment) of a numeric vector. You can test it by running the following code:

```

m1 <- moment(1)
m2 <- moment(2)

x <- runif(100)
stopifnot(all.equal(m1(x), 0))
stopifnot(all.equal(m2(x), var(x) * 99 / 100))

```

4. What happens if you don't use a closure? Make predictions, then verify with the code below.

```

i <- 0
new_counter2 <- function() {
  i <- i + 1
  i
}

```

5. What happens if you use `<-` instead of `<<-`? Make predictions, then verify with the code below.

```

new_counter3 <- function() {
  i <- 0
  function() {
    i <- i + 1
    i
  }
}

```

9.3 Graphical factories

We'll begin our exploration of useful function factories with a few examples from `ggplot2`.

9.3.1 Labelling

One of the goals of the `scales` (<http://scales.r-lib.org>) package is to make it easy to customise the labels on `ggplot2`. It provides many functions to control the fine details of axes and legends. One useful class of functions are the formatter functions² which make it easier to control the appearance of axis breaks. The design of these functions might initially seem a little odd: they all return a function, which you have to call in order to format a number.

```
y <- c(12345, 123456, 1234567)
comma_format()(y)
#> [1] "12,345"     "123,456"     "1,234,567"

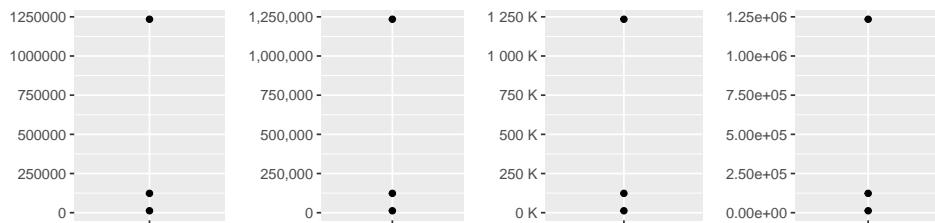
number_format(scale = 1e-3, suffix = " K")(y)
#> [1] "12 K"       "123 K"       "1 235 K"
```

In other words, the primary interface is a function factory. At first glance, this seems to add extra complexity for little gain. But it enables a nice interaction with `ggplot2`'s scales, because they accept functions in the `label` argument:

```
df <- data.frame(x = 1, y = y)
core <- ggplot(df, aes(x, y)) +
  geom_point() +
  scale_x_continuous(breaks = 1, labels = NULL) +
  labs(x = NULL, y = NULL)

core
core + scale_y_continuous(label = comma_format())
core + scale_y_continuous(label = number_format(scale = 1e-3, suffix = " K"))
core + scale_y_continuous(label = scientific_format())
```

²It's an unfortunate accident of history that `scales` uses function suffixes instead of function prefixes. That's because it was written before I understood the autocomplete advantages to using common prefixes instead of common suffixes.



9.3.2 Histogram bins

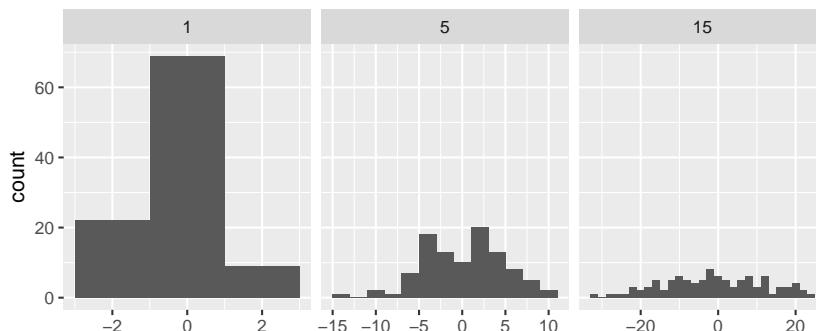
A little known feature of `geom_histogram()` is that the `binwidth` argument can be a function. This is particularly useful because the function is executed once for each group, which means you can have different binwidths in different facets, which is otherwise not possible.

To illustrate this idea, and see where variable binwidth might be useful, I'm going to construct an example where a fixed binwidth isn't great.

```
# construct some sample data with very different numbers in each cell
sd <- c(1, 5, 15)
n <- 100

df <- data.frame(x = rnorm(3 * n, sd = sd), sd = rep(sd, n))

ggplot(df, aes(x)) +
  geom_histogram(binwidth = 2) +
  facet_wrap(~ sd, scales = "free_x") +
  labs(x = NULL)
```



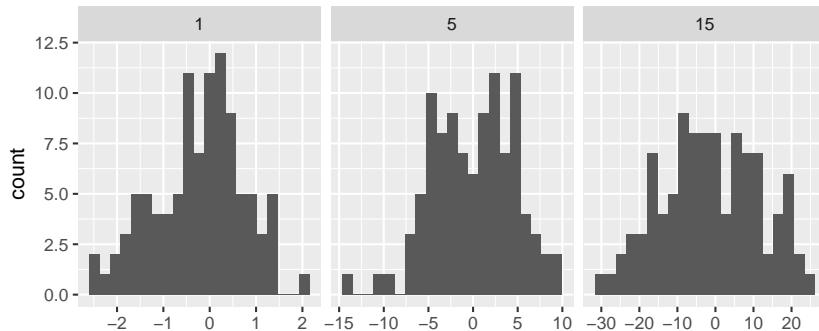
Here each facet has the same number of observations, but the variability is very different. It would be nice if we could request that the binwidths vary so we get approximately the same number of observations in each bin. One way to do that

is with a function factory that inputs the desired number of bins (`n`), and outputs a function that takes a numeric vector and returns a binwidth:

```
binwidth_bins <- function(n) {
  force(n)

  function(x) {
    (max(x) - min(x)) / n
  }
}

ggplot(df, aes(x)) +
  geom_histogram(binwidth = binwidth_bins(20)) +
  facet_wrap(~ sd, scales = "free_x") +
  labs(x = NULL)
```



We could use this same pattern to wrap around the base R functions that automatically find the “optimal”³ binwidth, `nclass.Sturges()`, `nclass.scott()`, and `nclass.FD()`:

```
base_bins <- function(type) {
  fun <- switch(type,
    Sturges = nclass.Sturges,
    scott = nclass.scott,
    FD = nclass.FD,
    stop("Unknown type", call. = FALSE)
  )

  function(x) {
    (max(x) - min(x)) / fun(x)
```

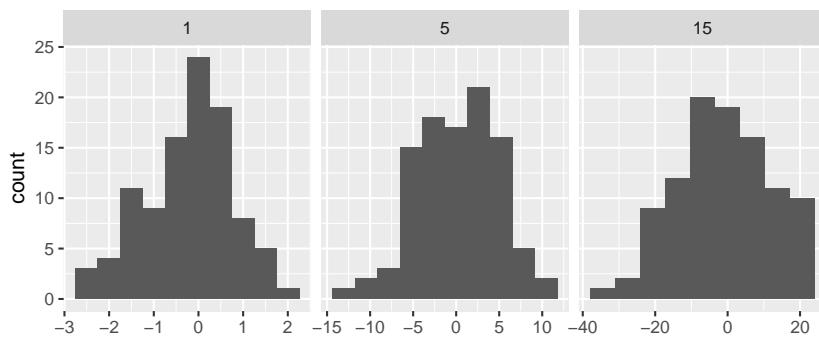
³ggplot2 doesn’t expose these functions directly because I don’t think the defintion of optimality needed to make the problem mathematically tractable is a good match to the actual needs of data exploration.

```

    }
}

ggplot(df, aes(x)) +
  geom_histogram(binwidth = base_bins("FD")) +
  facet_wrap(~ sd, scales = "free_x") +
  labs(x = NULL)

```



9.3.3 ggsave

Finally, I want to show a function factory used internally by `ggplot2`. `ggplot2:::plot_dev()` is used by `ggsave()` to go from a file extension (e.g. `png`, `jpeg` etc) to a graphics device function (e.g. `png()`, `jpeg()`). The challenge here arises because the base graphics devices have some minor inconsistencies which we need to paper over:

- Most have `filename` as first argument but some have `file`.
- The `width` and `height` of raster graphic devices use pixels units by default, but the vector graphics use inches.

A mildly simplified version of `plot_dev()` is shown below:

```

plot_dev <- function(ext, dpi = 96) {
  force(dpi)

  switch(ext,
    eps = ,
    ps = function(filename, ...) {
      grDevices::postscript(
        file = filename, ..., onefile = FALSE,
        horizontal = FALSE, paper = "special"
    }
  )
}

```

```

        )
},
tex =  function(filename, ...) grDevices::pictex(file = filename, ...),
pdf =  function(filename, ...) grDevices::pdf(file = filename, ...),
svg  =  function(filename, ...) svglite::svglite(file = filename, ...),
emf  = ,
wmf  =  function(...) grDevices::win.metafile(...),
png  =  function(...) grDevices::png(..., res = dpi, units = "in"),
jpg  = ,
jpeg =  function(...) grDevices::jpeg(..., res = dpi, units = "in"),
bmp  =  function(...) grDevices::bmp(..., res = dpi, units = "in"),
tiff =  function(...) grDevices::tiff(..., res = dpi, units = "in"),
stop("Unknown graphics extension: ", ext, call. = FALSE)
)
}

plot_dev("pdf")
#> function(filename, ...) grDevices::pdf(file = filename, ...)
#> <bytecode: 0x4f98f30>
#> <environment: 0x49b9148>
plot_dev("png")
#> function(...) grDevices::png(..., res = dpi, units = "in")
#> <bytecode: 0x529d8e0>
#> <environment: 0x572ade0>

```

9.3.4 Exercises

1. Compare and contrast `ggplot2::label_bquote()` with `scales::number_format()`

9.4 Statistical factories

More motivating examples for function factories come from statistics:

- The Box-Cox transformation.
- Bootstrap resampling.
- Maximum likelihood estimation.

All of these examples can be tackled without function factories, but I think function factories are a good fit for these problems and provide elegant solutions.

These examples expect some statistical background, so feel free to skip if they don't make much sense to you.

9.4.1 Box-Cox transformation

The Box-Cox transformation is a flexible transformation often used to transform data towards normality. It has a single parameter, λ , which controls the strength of the transformation. We could express the transformation as a simple two argument function:

```
boxcox1 <- function(x, lambda) {
  stopifnot(length(lambda) != 1)

  if (lambda == 0) {
    log(x)
  } else {
    (x ^ lambda - 1) / lambda
  }
}
```

But re-formulating as a function factory makes it easy to explore its behaviour with `stat_function()`:

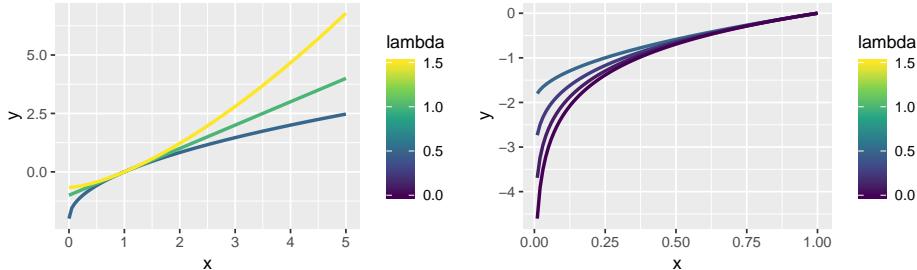
```
boxcox2 <- function(lambda) {
  if (lambda == 0) {
    function(x) log(x)
  } else {
    function(x) (x ^ lambda - 1) / lambda
  }
}

stat_boxcox <- function(lambda) {
  stat_function(aes(colour = lambda), fun = boxcox2(lambda), size = 1)
}

ggplot(data.frame(x = c(0, 5)), aes(x)) +
  lapply(c(0.5, 1, 1.5), stat_boxcox) +
  scale_colour_viridis_c(limits = c(0, 1.5))

# visually, log() does seem to make sense as the limit as lambda -> 0
ggplot(data.frame(x = c(0.01, 1)), aes(x)) +
  lapply(c(0.5, 0.25, 0.1, 0), stat_boxcox) +
```

```
scale_colour_viridis_c(limits = c(0, 1.5))
```



In general, this allows you to use a Box-Cox transformation with any function that accepts a unary transformation function: you don't have to worry about that function providing ... to pass along additional arguments. I also think that the partitioning of `lambda` and `x` into two different function arguments is natural since `lambda` plays quite a different role than `x`.

9.4.2 Bootstrap generators

Function factories are a useful approach for bootstrapping. Instead of thinking about a single bootstrap (you always need more than one!), you can think about a bootstrap **generator**, a function that yields a fresh bootstrap every time it is called:

```
boot_permute <- function(df, var) {
  n <- nrow(df)
  force(var)

  function() {
    df[[var]][sample(n, n, replace = TRUE)]
  }
}

boot_mtcars1 <- boot_permute(mtcars, "mpg")
head(boot_mtcars1())
#> [1] 18.1 22.8 21.5 14.7 21.4 17.3
head(boot_mtcars1())
#> [1] 19.2 19.2 14.3 21.0 13.3 21.4
```

The advantage of a function factory is more clear with a parametric bootstrap where we have to first fit a model. We can do this setup step once, when the factory is called, rather than once every time we generate the bootstrap:

```

boot_model <- function(df, formula) {
  mod <- lm(formula, data = df)
  fitted <- unname(fitted(mod))
  resid <- unname(resid(mod))
  rm(mod)

  function() {
    fitted + sample(resid)
  }
}

boot_mtcars2 <- boot_model(mtcars, mpg ~ wt)
head(boot_mtcars2())
#> [1] 23.1 24.3 23.0 19.1 19.1 16.2
head(boot_mtcars2())
#> [1] 30.2 17.4 31.3 26.1 17.8 16.7

```

I use `rm(mod)` because linear model objects are quite large (they include complete copies of the model matrix and input data) and I want to keep the manufactured function as small as possible.

9.4.3 Maximum likelihood estimation

The goal of maximum likelihood estimation (MLE) is to find the parameter values for a distribution that make the observed data “most likely”. To do MLE, you start with a probability function. For example, take the Poisson distribution. If we know λ , we can compute the probability of getting a vector \mathbf{x} of values (x_1, x_2, \dots, x_n) by multiplying the Poisson probability function as follows:

$$P(\lambda, \mathbf{x}) = \prod_{i=1}^n \frac{\lambda^{x_i} e^{-\lambda}}{x_i!}$$

In statistics, we almost always work with the log of this function. The log is a monotonic transformation which preserves important properties (i.e. the extrema occur in the same place), but has specific advantages:

- The log turns a product into a sum, which is easier to work with.
- Multiplying small numbers yields even smaller numbers, which makes the floating point approximation used by a computer less accurate.

Let’s apply a log transformation to this probability function and simplify it as

much as possible:

$$\begin{aligned}\log(P(\lambda, \mathbf{x})) &= \sum_{i=1}^n \log\left(\frac{\lambda^{x_i} e^{-\lambda}}{x_i!}\right) \\ \log(P(\lambda, \mathbf{x})) &= \sum_{i=1}^n (x_i \log(\lambda) - \lambda - \log(x_i!)) \\ \log(P(\lambda, \mathbf{x})) &= \sum_{i=1}^n x_i \log(\lambda) - \sum_{i=1}^n \lambda - \sum_{i=1}^n \log(x_i!) \\ \log(P(\lambda, \mathbf{x})) &= \log(\lambda) \sum_{i=1}^n x_i - n\lambda - \sum_{i=1}^n \log(x_i!)\end{aligned}$$

We can now turn this function into an R function. The R function is quite elegant because R is vectorised and, because it's a statistical programming language, R comes with built-in functions like the log-factorial (`lfactorial()`).

```
lprob_poisson <- function(lambda, x) {
  n <- length(x)
  (log(lambda) * sum(x)) - (n * lambda) - sum(lfactorial(x))
}
```

Consider this vector of observations:

```
x1 <- c(41, 30, 31, 38, 29, 24, 30, 29, 31, 38)
```

We can use `lprob_poisson()` to compute the (logged) probability of `x1` for different values of `lambda`.

```
lprob_poisson(10, x1)
#> [1] -184
lprob_poisson(20, x1)
#> [1] -61.1
lprob_poisson(30, x1)
#> [1] -31
```

So far we've been thinking of `lambda` as fixed and known and the function told us the probability of getting different values of `x`. But in real-life, we observe `x` and it is `lambda` that is unknown. The likelihood is the probability function seen through this lens: we want to find the `lambda` that makes the observed `x` the “most likely”. That is, given `x`, what value of `lambda` gives us the highest value of `lprob_poisson()`?

In statistics, we highlight this change in perspective by writing $f_x(\lambda)$ instead

of $f(\lambda, \mathbf{x})$. In R, we can use a function factory. We provide \mathbf{x} and generate a function with a single parameter, `lambda`:

```
ll_poisson1 <- function(x) {
  n <- length(x)

  function(lambda) {
    log(lambda) * sum(x) - n * lambda - sum(lfactorial(x))
  }
}
```

One nice thing about this approach is that we can do some precomputation: any term that only involves \mathbf{x} can be computed once in the factory. This is useful because we're going to need to call this function many times to find the best `lambda`.

```
ll_poisson2 <- function(x) {
  n <- length(x)
  sum_x <- sum(x)
  c <- sum(lfactorial(x))

  function(lambda) {
    log(lambda) * sum_x - n * lambda - c
  }
}
```

Now we can use this function to find the value of `lambda` that maximizes the (log) likelihood:

```
ll1 <- ll_poisson2(x1)

ll1(10)
#> [1] -184
ll1(20)
#> [1] -61.1
ll1(30)
#> [1] -31
```

Rather than trial and error, we can automate the process of finding the best value with `optimise()`. It will evaluate `ll1()` many times, using mathematical tricks to narrow in on the largest value as quickly as possible. The results tell us that the highest value is -30.27 which occurs when `lambda = 32.1`:

```
optimise(ll1, c(0, 100), maximum = TRUE)
#> $maximum
```

```
#> [1] 32.1
#>
#> $objective
#> [1] -30.3
```

Now, we could have solved this problem without using a function factory because `optimise()` passes ... on to the function being optimised. That means we could use the log-probability function directly:

```
optimise(lprob_poisson, c(0, 100), x = x1, maximum = TRUE)
#> $maximum
#> [1] 32.1
#>
#> $objective
#> [1] -30.3
```

The advantage of using a function factory here is fairly small, but there are two niceties:

- We can precompute some values in the factory itself, saving computation time in each iteration.
- I think the two-level design better reflects the mathematical structure of the underlying problem.

These advantages get bigger in more complex MLE problems, where you have multiple parameters and multiple data vectors.

9.4.4 Exercises

1. In `boot_model()`, why don't I need to force the evaluation of `df` or `model`?
2. Why might you formulate the Box-Cox transformation like this?

```
boxcox3 <- function(x) {
  function(lambda) {
    if (lambda == 0) {
      log(x)
    } else {
      (x ^ lambda - 1) / lambda
    }
  }
}
```

3. Why don't you need to worry that `boot_permute()` stores a copy of the data inside the function that it generates?
4. How much time does `ll_poisson2()` save compared to `ll_poisson1()`? Use `bench::mark()` to see how much faster the optimisation occurs. How does changing the length of `x` change the results?

9.5 Function factories + functionals

To finish off the chapter, I'll show how you might combine functionals and function factories to turn data into many functions. The following code creates many specially named power functions by iterating over a list of arguments:

```
names <- list(
  square = 2,
  cube = 3,
  root = 1/2,
  cuberoot = 1/3,
  reciprocal = -1
)
funss <- purrr::map(names, power1)

funss$root(64)
#> [1] 8
funss$root
#> function(x) {
#>   x ^ exp
#> }
#> <bytecode: 0x186b7e0>
#> <environment: 0x5b516a0>
```

This idea extends in a straightforward way if your function factory takes two (replace `map()` with `map2()`) or more (replace with `pmap()`) arguments.

9.5.1 Moving a list to the global environment

One downside of the current construction is that you have to prefix every function call with `funss$`. There are three ways to eliminate this additional syntax:

- For a very temporary effect, you can use `with()`:

```
with(funs, root(100))
#> [1] 10
```

I recommend this because it makes it very clear when code is being executed in a special context and what that context is.

- For a longer effect, you can `attach()` the functions to the search path, then `detach()` when you’re done:

```
attach(fun)
#> The following objects are masked _by_ .GlobalEnv:
#>
#>   cube, square
root(100)
#> [1] 10
detach(fun)
```

You’ve probably been told to avoid using `attach()`, and that’s generally good advice. However, the situation is a little different to the usual because we’re attaching a list of functions, not a data frame. It’s less likely that you’ll modify a function than a column in a data frame, so the some of the worst problems with `attach()` don’t apply.

- Finally, you could copy the functions to the global environment with `env_bind()`. This is mostly permanent:

```
```r
rlang::env_bind(globalenv(), !!!fun)
root(100)
#> [1] 10
```

```

You can later unbind those same names, but there’s no guarantee that they haven’t been rebound in the meantime, and you might be deleting an object that someone else created.

```
```r
rlang::env_unbind(globalenv(), names(fun))
```

```

9.5.2 Another approach

You'll learn an alternative approach to the same problem in Section ???. Instead of using a function factory, you could construct the function with quasiquotation. This requires additional knowledge, but generates functions with readable bodies, and avoids accidentally capturing large objects in the enclosing scope. The following code is a quick preview of how we could rewrite `power1()` to use quasiquotation:

```
power3 <- function(exponent) {
  new_function(
    exprs(x = ),
    expr{
      x ^ !!exponent
    },
    caller_env()
  )
}
fun <- purrr::map(names, power3)

fun$root
#> function (x)
#> {
#>   x0.5
#> }
#> <environment: 0x5acf868>
```

As well as 0.5 appearing directly in the body, note that the environment of the function is the global environment, not an execution environment of `power3()`.

9.5.3 Exercises

1. Which of the following commands is equivalent to `with(x, f(z))`?
 - `x$f(x$z).`
 - `f(x$z).`
 - `x$f(z).`
 - `f(z).`
 - It depends.
2. Compare and contrast the effects of `env_bind()` vs. `attach()` for the following code.

```
fun <- list(  
  mean = function(x) mean(x, na.rm = TRUE),  
  sum = function(x) sum(x, na.rm = TRUE)  
)  
  
attach(fun <  
#> The following objects are masked from package:base:  
#>  
#>      mean, sum  
mean <- function(x) stop("Hi!")  
detach(fun <  
  
env_bind(globalenv(), !!!fun <  
mean <- function(x) stop("Hi!")  
env_unbind(globalenv(), names(fun <))
```

Chapter 10

Function operators

10.1 Introduction

In this chapter, you'll learn about function operators (FOs). A function operator is a function that takes one (or more) functions as input and returns a function as output. The following code shows a simple function operator, `chatty()`. It wraps a function, making a new function that prints out its first argument. You might create a function like this because it gives you a window to see how functionals, like `map_int()`, work.

```
chatty <- function(f) {
  force(f)

  function(x, ...) {
    res <- f(x, ...)
    cat("Processing ", x, "\n", sep = "")
    res
  }
}
f <- function(x) x ^ 2
s <- c(3, 2, 1)

purrr::map_dbl(s, chatty(f))
#> Processing 3
#> Processing 2
#> Processing 1
#> [1] 9 4 1
```

Function operators are closely related to function factories; indeed they're just a function factory that takes a function as input. Like factories, there's nothing you can't do without them, but they often allow you to factor out complexity in order to make your code more readable and reusable.

Function operators are typically paired with functionals. If you're using a for-loop, there's rarely a reason to use a FO, as it will make your code more complex for little gain.

If you're familiar with Python, decorators are just another name for function operators.

Outline

- Section 10.2 introduces you to two extremely useful existing FOs, and shows you how to use them to solve real problems.
- Section 10.3 works through a problem amenable to solution with function operators: downloading many web pages.

Prerequisites

Function operators are a type of function factory, so make sure you're familiar with at least Section 5.2 before you go on.

We'll use `purrr` for a couple of functionals that you learned about in Chapter 8, and some function operators that you'll learn about below. We'll also use the `memoise` package for the `memoise()` operator.

```
library(purrr)
library(memoise)
```

10.2 Existing FOs

There are two very useful function operators that will both help you solve common recurring problems, and give you a sense for what FOs can do: `purrr::safely()` and `memoise::memoise()`.

10.2.1 Capturing errors with `purrr::safely()`

One advantage of for-loops is that if one of the iterations fails, you can still access all the results up to the failure:

```
x <- list(
  c(0.512, 0.165, 0.717),
  c(0.064, 0.781, 0.427),
  c(0.890, 0.785, 0.495),
  "oops"
)

out <- rep(NA_real_, length(x))
for (i in seq_along(x)) {
  out[[i]] <- sum(x[[i]])
}
#> Error in sum(x[[i]]):
#>   invalid 'type' (character) of argument
out
#> [1] 1.39 1.27 2.17 NA
```

If you do the same thing with a functional, you get no output, making it hard to figure out where the problem lies:

```
map_dbl(x, sum)
#> Error in sum(..., na.rm = na.rm):
#>   invalid 'type' (character) of argument
```

`purrr::safely()` provides a tool to help with this problem. `safely()` is a function operator that transforms a function to turn errors into data. (You can learn the basic idea that makes it work in Section 7.6.2). Let's start by taking a look at it outside of `map_dbl()`:

```
safe_sum <- safely(sum)
safe_sum
#> function (...)
#> capture_error(.f(...), otherwise, quiet)
#> <bytecode: 0x151e1d8>
#> <environment: 0x151e670>
```

Like all function operators, `safely()` takes a function and returns a wrapped function which we can call as usual:

```
str(safe_sum(x[[1]]))
#> List of 2
```

```
#> $ result: num 1.39
#> $ error : NULL
str(safe_sum(x[[4]]))
#> List of 2
#> $ result: NULL
#> $ error :List of 2
#> ..$ message: chr "invalid 'type' (character) of argument"
#> ..$ call    : language sum(..., na.rm = na.rm)
#> ...- attr(*, "class")= chr [1:3] "simpleError" "error" "condition"
```

You can see that a function transformed by `safely()` always returns a list with two elements, `result` and `error`. If the function runs successfully, `error` is `NULL` and `result` contains the result; if the function fails, `result` is `NULL` and `error` contains the error.

Now lets use `safely()` with a functional:

```
out <- map(x, safely(sum))
str(out)
#> List of 4
#> $ :List of 2
#> ..$ result: num 1.39
#> ..$ error : NULL
#> $ :List of 2
#> ..$ result: num 1.27
#> ..$ error : NULL
#> $ :List of 2
#> ..$ result: num 2.17
#> ..$ error : NULL
#> $ :List of 2
#> ..$ result: NULL
#> ..$ error :List of 2
#> ...$ message: chr "invalid 'type' (character) of argument"
#> ...$ call    : language sum(..., na.rm = na.rm)
#> ...- attr(*, "class")= chr [1:3] "simpleError" "error" "condit..."
```

The output is in a slightly inconvenient form, since we have four lists, each of which is a list containing the `result` and the `error`. We can make the output easier to use with `purrr::transpose()`. This turns it “inside-out” so that we get a list of `results` and a list of `errors`:

```
out <- transpose(map(x, safely(sum)))
str(out)
```

```

#> List of 2
#> $ result:List of 4
#>   ..$ : num 1.39
#>   ..$ : num 1.27
#>   ..$ : num 2.17
#>   ..$ : NULL
#> $ error :List of 4
#>   ..$ : NULL
#>   ..$ : NULL
#>   ..$ : NULL
#>   ..$ :List of 2
#>     ...$ message: chr "invalid 'type' (character) of argument"
#>     ...$ call   : language sum(..., na.rm = na.rm)
#>     ...- attr(*, "class")= chr [1:3] "simpleError" "error" "condit"..

```

Now we can easily find the results that worked, or the inputs that failed:

```

ok <- map_lgl(out$error, is.null)
ok
#> [1] TRUE TRUE TRUE FALSE

x[!ok]
#> [[1]]
#> [1] "oops"

out$result[ok]
#> [[1]]
#> [1] 1.39
#>
#> [[2]]
#> [1] 1.27
#>
#> [[3]]
#> [1] 2.17

```

You can use this same technique in many different situations. For example, imagine you're fitting a generalised linear model (GLM) to a list of data frames. GLMs can sometimes fail because of optimisation problems, but you still want to be able to try to fit all the models, and later look back at those that failed:

```

fit_model <- function(df) {
  glm(y ~ x1 + x2 * x3, data = df)
}

```

```

models <- transpose(map(datasets, safely(fit_model)))
ok <- map_lgl(models$error, is.null)

# which data failed to converge?
datasets[!ok]

# which models were successful?
models[ok]

```

I think this is a great example of the power of combining functionals and function operators: **safely()** lets you succinctly express what you need to solve a common data analysis problem.

`purrr` comes with three other function operators in a similar vein:

- **possibly()**: returns a default value when there's an error.
- **quietly()**: turns output, messages, and warning side-effects into `output`, `message`, and `warning` components of the output.
- **auto_browser()**: automatically executes `browser()` inside the function when there's an error.

See their documentation for more details.

10.2.2 Caching computations with `memoise::memoise()`

Another handy FO is `memoise::memoise()`. It **memoises** a function, meaning that the function will remember previous inputs and return cached results. Memoisation is an example of the classic computer science tradeoff of memory versus speed. A memoised function can run much faster because it stores all of the previous inputs and outputs, using more memory.

Let's explore this idea with a toy function that simulates an expensive operation:

```

slow_function <- function(x) {
  Sys.sleep(1)
  x * 10 * runif(1)
}

system.time(print(slow_function(1)))
#> [1] 0.808
#>    user  system elapsed
#>      0        0        1

```

```
system.time(print(slow_function(1)))
#> [1] 8.34
#>   user  system elapsed
#> 0.00    0.00    1.01
```

When we memoise this function, it's slow when we call it with new arguments. But when we call it with arguments that it's seen before it's instantaneous: it retrieves the previous value of the computation.

```
fast_function <- memoise::memoise(slow_function)
system.time(print(fast_function(1)))
#> [1] 6.01
#>   user  system elapsed
#> 0        0        1

system.time(print(fast_function(1)))
#> [1] 6.01
#>   user  system elapsed
#> 0.016  0.000  0.017
```

A relatively realistic use of memoisation is computing the Fibonacci series. The Fibonacci series is defined recursively: the first two values are defined by convention, $f(0) = 0$, $f(n) = 1$, and then $f(n) = f(n - 1) + f(n - 2)$ (for any positive integer). A naive version is slow because, for example, `fib(10)` computes `fib(9)` and `fib(8)`, and `fib(9)` computes `fib(8)` and `fib(7)`, and so on.

```
fib <- function(n) {
  if (n < 2) return(1)
  fib(n - 2) + fib(n - 1)
}
system.time(fib(23))
#>   user  system elapsed
#> 0.040  0.004  0.043
system.time(fib(24))
#>   user  system elapsed
#> 0.064  0.000  0.067
```

Memoising `fib()` makes the implementation much faster because each value is computed only once:

```
fib2 <- memoise::memoise(function(n) {
  if (n < 2) return(1)
  fib2(n - 2) + fib2(n - 1)
})
```

```
system.time(fib2(23))
#>   user  system elapsed
#> 0.024  0.000  0.025
```

And future calls can rely on previous computations:

```
system.time(fib2(24))
#>   user  system elapsed
#> 0.000  0.000  0.001
```

This is an example of **dynamic programming**, where a complex problem can be broken down into many overlapping subproblems, and remembering the results of a subproblem considerably improves performance.

Think carefully before memoising a function. If the function is not **pure**, i.e. the output does not depend only on the input, you will get misleading and confusing results. I created a subtle bug in devtools because I memoised the results of `available.packages()`, which is rather slow because it has to download a large file from CRAN. The available packages don't change that frequently, but if you have an R process that's been running for a few days, the changes can become important, and because the problem only arose in long-running R processes, the bug was very painful to find.

10.2.3 Exercises

1. Base R provides a function operator in the form of `Vectorize()`. What does it do? When might you use it?
2. Read the source code for `possibly()`. How does it work?
3. Read the source code for `safely()`. How does it work?

10.3 Case study: creating your own FOs

`memoise()` and `safely()` are very useful but also quite complex. In this case study you'll learn how to create your own simpler function operators. Imagine you have a named vector of URLs and you'd like to download each one to disk. That's pretty simple with `walk2()` and `file.download()`:

```
urls <- c(
  "adv-r" = "https://adv-r.hadley.nz",
  "r4ds" = "http://r4ds.had.co.nz/"
```

```

# and many many more
)
path <- paste(tempdir(), names(urls), ".html")

walk2(urls, path, download.file, quiet = TRUE)

```

This approach is fine for a handful of URLs, but as the vector gets longer, it'd be nice to add a couple more features:

- Add a small delay between each request to avoid hammering the server.
- Display a . every few URLs so that we know that the function is still working.

It's relatively easy to add these extra features if we're using a for loop:

```

for(i in seq_along(urls)) {
  Sys.sleep(0.1)
  if (i %% 10 == 0) cat(".")
  download.file(urls[[i]], paths[[i]])
}

```

I think this for loop is suboptimal because it interleaves different concerns: pausing, showing progress, and downloading. This makes the code harder to read, and it makes it harder to reuse the components in new situations. Instead, let's see if we can use function operators to extract out pausing and showing progress and make them reusable.

First, let's write an FO that adds a small delay. I'm going to call it `delay_by()` for reasons that will be more clear shortly, and it has two arguments: the function to wrap, and the amount of delay to add. The actual implementation is quite simple. The main trick is forcing evaluation of all arguments as described in Section 9.2.4, because function operators are a special type of function factory:

```

delay_by <- function(f, amount) {
  force(f)
  force(amount)

  function(...) {
    Sys.sleep(amount)
    f(...)
  }
}
system.time(runif(100))
#>    user  system elapsed

```

```
#>      0      0      0
system.time(delay_by(runif, 0.1)(100))
#>  user  system elapsed
#>  0.000  0.000  0.101
```

And we can use it with the original `walk2()`:

```
walk2(urls, path, delay_by(download.file, 0.1), quiet = TRUE)
```

Creating a function to display the occasional dot is a little harder, because we can no longer rely on the index from the loop. We could pass the index along as another argument, but that breaks encapsulation: a concern of the progress function now becomes a problem that the higher level wrapper needs to handle. Instead, we'll use another function factory trick (from Section 9.2.3), so that the progress wrapper can manage its own internal counter:

```
dot_every <- function(f, n) {
  force(f)
  force(n)

  i <- 1
  function(...) {
    if (i %% n == 0) cat(".")
    i <- i + 1
    f(...)
  }
}
walk(1:100, runif)
walk(1:100, dot_every(runif, 10))
#> .....
```

Now we can express our original for loop as:

```
walk2(
  urls, path,
  dot_every(delay_by(download.file, 0.1), 10),
  quiet = TRUE
)
```

This is starting to get a little hard to read because we are composing many function calls, and the arguments are getting spread out. One way to resolve that is to use the pipe:

```
walk2(
  urls, path,
```

```
download.file %>% dot_every(10) %>% delay_by(0.1),  
  quiet = TRUE  
)
```

The pipe works well here because I've carefully chosen the function names to yield an (almost) readable sentence: take `download.file` then (add) a dot every 10 iterations, then delay by 0.1s. The more clearly you can express the intent of your code through function names, the more easily others (including future you!) can read and understand the code.

10.3.1 Exercises

1. Weigh the pros and cons of `download.file %>% dot_every(10) %>% delay_by(0.1)` vs `download.file %>% delay_by(0.1) %>% dot_every(10)`.
2. Should you memoise `file.download()`? Why/why not?
3. Create a FO that reports whenever a file is created or deleted in the working directory, using `dir()` and `setdiff()`. What other global function effects might you want to track?
4. Write a FO that logs a timestamp and message to a file every time a function is run.
5. Modify `delay_by()` so that instead of delaying by a fixed amount of time, it ensures that a certain amount of time has elapsed since the function was last called. That is, if you called `g <- delay_by(1, f); g(); Sys.sleep(2); g()` there shouldn't be an extra delay.

Part III

Object oriented programming

Introduction

In the following five chapters you'll learn about **object oriented programming** (OOP). OOP is a little more challenging in R than in other languages because:

- There are multiple OOP systems to choose from. In this book, I'll focus on the three that I believe are most important: **S3**, **R6**, and **S4**. S3 and S4 are provided by base R. R6 is provided by the R6 package, and is similar to the “Reference Classes”, or **RC** for short, from base R.
- There is disagreement about the relative importance of the OOP systems. I think S3 is most important, followed by R6, then S4. Others believe that S4 is most important, followed by RC, and that S3 should be avoided. This means that different R communities use different systems.
- S3 and S4 use “generic function OOP” which is rather different from the “encapsulated OOP” used by most languages popular today¹. We'll come back to precisely what those terms mean shortly, but basically, while the underlying ideas of OOP are the same across languages, their expressions are rather different. This means that you can't immediately transfer your existing OOP skills to R.

Generally in R, functional programming is much more important than object oriented programming, because you typically solve complex problems by decomposing them into simple functions, not simple objects. Nevertheless, there are important reasons to learn each of the three systems:

- S3 allows your functions to return rich results with user-friendly display and programmer-friendly internals. S3 is used throughout base R, so it's important to master it if you want to extend base R functions to work with new types of input.
- R6 provides a standardised way to escape R's from copy-on-modify semantics.

¹The exception is Julia, which also uses generic function OOP. Compared to R, Julia's implementation is fully developed and extremely performant.

tics. This is particularly important if you want to model objects that exist independently of R. Today, a common need for R6 is to model data that comes from a web API, and where changes come from inside or outside of R.

- S4 is a rigorous system that forces you to think carefully about program design. It's particularly well-suited for building large systems that evolve over time and will receive contributions from many programmers. This is why it is used by the Bioconductor project, so another reason to learn S4 is in order to contribute to that project.

The goal of this brief introductory chapter is to give you some important vocabulary and some tools to identify OOP systems in the wild. The following four chapters (Base types, S3, R6, and S4) then dive into the details of R's OOP systems.

Note that this book focusses on the mechanics of OOP, not its effective use, and it may be challenging to fully understand if you have done object oriented programming before. You might wonder why I chose not to provide more immediately useful coverage. I have focussed on mechanics here because they need to be well described somewhere (writing these chapters required a considerable amount of reading, exploration, and synthesis on my behalf), and using OOP effectively is sufficiently complex to require book-length treatment; there's simply not enough room in Advanced R to cover it in the depth required.

OOP systems

Different people use OOP terms in different ways, so this section provides a quick overview of important vocabulary. The explanations are necessarily compressed, but we will come back to these ideas multiple times.

The main reason to use OOP is **polymorphism** (literally: many shapes). Polymorphism means that a developer can consider a function's interface separately from its implementation, making it possible to use the same function form for different types of input. This is closely related to the idea of **encapsulation**: the user doesn't need to worry about details of an object because they are encapsulated behind a standard interface.

To be concrete, polymorphism is what allows `summary()` to produce different outputs for numeric and factor variables:

```
diamonds <- ggplot2::diamonds
```

```
summary(diamonds$carat)
#>   Min. 1st Qu. Median   Mean 3rd Qu.   Max.
#> 0.20    0.40    0.70    0.80    1.04    5.01

summary(diamonds$cut)
#>      Fair      Good Very Good Premium      Ideal
#> 1610    4906   12082    13791   21551
```

You could imagine `summary()` containing a series of if-else statements, but that would mean only the original author could add new implementations. An OOP system makes it possible for any developer to extend the interface with implementations for new types of input.

To be more precise, OO systems call the “type” of an object its **class**, and an implementation for a specific class is called a **method**. Roughly speaking, a class defines what an object *is* and methods describe what that object can *do*. The class defines the **fields**, the data possessed by every instance of that class. Classes are organised in a hierarchy so that if a method does not exist for one class, its parent’s method is used, and the child is said to **inherit** behaviour. For example, in R, an ordered factor inherits from a regular factor, and a generalised linear model inherits from a linear model. The process of finding the correct method given a class is called **method dispatch**.

There are two main paradigms of object-oriented programming which differ in how methods and classes are related. In this book, we’ll borrow the terminology of *Extending R* (Chambers 2016) and call these paradigms **encapsulated** and **functional**:

- In **encapsulated** OOP, methods belong to objects or classes, and method calls typically look like `object.method(arg1, arg2)`. This is called encapsulated because the object encapsulates both data (with fields) and behaviour (with methods), and is the paradigm found in most popular languages.
- In **functional** OOP, methods belong to **generic** functions, and method calls look like ordinary function calls: `generic(object, arg2, arg3)`. This is called functional because from the outside it looks like a regular function call, and internally the components are also functions.

With this terminology in hand, we can now talk precisely about the different OO systems available in R.

OOP in R

Base R provides three OOP systems: S3, S4, and reference classes (RC):

- **S3** is R’s first OOP system, and is described in *Statistical Models in S* (Chambers and Hastie 1992). S3 is an informal implementation of functional OOP and relies on common conventions rather than ironclad guarantees. This makes it easy to get started with, providing a low cost way of solving many simple problems.
- **S4** is a formal and rigorous rewrite of S3, and was introduced in *Programming with Data* (Chambers 1998). It requires more upfront work than S3, but in return provides more guarantees and greater encapsulation. S4 is implemented in the base **methods** package, which is always installed with R.

(You might wonder if S1 and S2 exist. They don’t: S3 and S4 were named according to the versions of S that they accompanied. The first two versions of S didn’t have any OOP framework.)

- **RC** implements encapsulated OO. RC objects are a special type of S4 objects that are also **mutable**, i.e., instead of using R’s usual copy-on-modify semantics, they can be modified in place. This makes them harder to reason about, but allows them to solve problems that are difficult to solve in the functional OOP style of S3 and S4.

A number of other OOP systems are provided by CRAN packages:

- **R6** (Chang 2017) implements encapsulated OOP like RC, but resolves some important issues. In this book, you’ll learn about R6 instead of RC, for reasons described in Section 13.5.
- **R.oo** (Bengtsson 2003) provides some formalism on top of S3, and makes it possible to have mutable S3 objects.
- **proto** (Grothendieck, Kates, and Petzoldt 2016) implements another style of OOP based on the idea of **prototypes**, which blur the distinctions between classes and instances of classes (objects). I was briefly enamored with prototype based programming (Wickham 2011) and used it in ggplot2, but now think it’s better to stick with the standard forms.

Apart from R6, which is widely used, these systems are primarily of theoretical interest. They do have their strengths, but few R users know and understand them, so it is hard for others to read and contribute to your code.

sloop

Before we go on I want to introduce the sloop package:

```
# install_github("r-lib/sloop")
library(sloop)
```

The sloop package (think “sail the seas of OOP”) provides a number of helpers that fill in missing pieces in base R. The first of these is `sloop::otype()`. It makes it easy to figure out the OOP system used by a wild-caught object:

```
otype(1:10)
#> [1] "base"

otype(mtcars)
#> [1] "S3"

mle_obj <- stats4::mle(function(x = 1) (x - 2) ^ 2)
otype(mle_obj)
#> [1] "S4"
```

Use this function to figure out which chapter to read to understand how to work with an existing object.

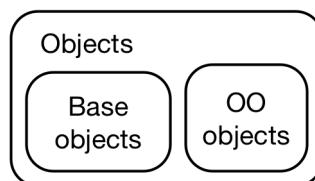
Chapter 11

Base types

11.1 Introduction

To talk about objects and OOP in R we first need to clear up a fundamental confusion about two uses of the word “object”. So far in this book, we’ve used the word in the general sense captured by John Chambers’ pithy quote: “Everything that exists in R is an object”. However, while everything *is* an object, not everything is “object-oriented”. This confusion arises because the base objects come from S, and were developed before anyone thought that S might need an OOP system. The tools and nomenclature evolved organically over many years without a single guiding principle.

Most of the time, the distinction between objects and object-oriented objects is not important. But here we need to get into the nitty gritty details so we’ll use the terms **base objects** and **OO objects** to distinguish them.



Outline

- Section 11.2 shows you how to identify base and OO objects.

- Section 11.3 gives a complete set of the base types that all objects are built up from.

11.2 Base vs OO objects

To tell the difference between a base and OO object, use `is.object()` or `sloop::otype()`:

```
# A base object:
is.object(1:10)
#> [1] FALSE
sloop::otype(1:10)
#> [1] "base"

# An OO object
is.object(mtcars)
#> [1] TRUE
sloop::otype(mtcars)
#> [1] "S3"
```

Technically, the difference between base and OO objects is that OO objects have a “class” attribute:

```
attr(1:10, "class")
#> NULL

attr(mtcars, "class")
#> [1] "data.frame"
```

You may already be familiar with the `class()` function. This function is safe to apply to S3 and S4 objects, but it returns misleading results when applied to base objects. It’s safer to use `sloop::s3_class()`, which returns the implicit class that the S3 and S4 systems will use to pick methods. You’ll learn more about `s3_class()` in Section 12.7.1.

```
x <- matrix(1:4, nrow = 2)
class(x)
#> [1] "matrix"
sloop::s3_class(x)
#> [1] "matrix"  "integer" "numeric"
```

11.3 Base types

While only OO objects have a `class` attribute, every object has a **base type**:

```
typeof(1:10)
#> [1] "integer"

typeof(mtcars)
#> [1] "list"
```

Base types do not form an OOP system because functions that behave differently for different base types are primarily written in C code that uses switch statements. This means that only R-core can create new types, and creating a new type is a lot of work because every switch statement needs to be modified to handle a new case. As a consequence, new base types are rarely added. The most recent change, in 2011, added two exotic types that you never see in R itself, but are needed for diagnosing memory problems. Prior to that, the last type added was a special base type for S4 objects added in 2005.

In total, there are 25 different base types. They are listed below, loosely grouped according to where they’re discussed in this book. These types are most important in C code, so you’ll often see them called by their C type names. I’ve included those in parentheses.

- Vectors, Chapter 3, include types `NULL` (`NULLSXP`), `logical` (`LGLSXP`), `integer` (`INTSXP`), `double` (`REALSXP`), `complex` (`CPLSXP`), `character` (`STRSXP`), `list` (`VECSXP`), and `raw` (`RAWSXP`).

```
typeof(NULL)
#> [1] "NULL"

typeof(1L)
#> [1] "integer"

typeof(1i)
#> [1] "complex"
```

- Functions, Chapter 5, include types `closure` (regular R functions, `CLOSXP`), `special` (internal functions, `SPECIALSXP`), and `builtin` (primitive functions, `BUILTINSXP`).

```
typeof(mean)
#> [1] "closure"

typeof(`[`)
#> [1] "special"

typeof(sum)
```

```
#> [1] "builtin"
```

Internal and primitive functions are described in Section 5.2.3.

- Environments, Chapter 6, have type `environment` (ENVSXP).

```
typeof(globalenv())
#> [1] "environment"
```

- The `S4` type (S4SXP), Chapter 14, is used for S4 classes that don't inherit from an existing base type.

```
mle_obj <- stats4::mle(function(x = 1) (x - 2) ^ 2)
typeof(mle_obj)
#> [1] "S4"
```

- Language components, Chapter 16, include `symbol` (aka name, SYMSXP), `language` (usually called calls, LANGSXP), and `pairlist` (used for function arguments, LISTSXP) types.

```
typeof(quote(a))
#> [1] "symbol"
typeof(quote(a + 1))
#> [1] "language"
typeof(formals(mean))
#> [1] "pairlist"
```

`expression` (EXPRSXP) is a special purpose type that's only returned by `parse()` and `expression()`. Expressions are generally not needed in user code.

- The remaining types are esoteric and rarely seen in R. They are important primarily for C code: `externalptr` (EXTPTRSXP), `weakref` (WEAKREFSXP), `bytecode` (BCODESXP), `promise` (PROMSXP), ... (DOTSXP), and `any` (ANYSXP).

You may have heard of `mode()` and `storage.mode()`. Do not use these functions: they exist only to provide type names that are compatible with S.

11.3.1 Numeric type

Be careful when talking about the “numeric” type, because R uses “numeric” to mean three slightly different things:

1. In some places numeric is used as an alias for the “double” type. For example `as.numeric()` is identical to `as.double()`, and `numeric()` is identical to `double()`.

(R also occasionally uses “real” instead of double; `NA_real_` is the one place that you’re likely to encounter this in practice.)

2. In the S3 and S4 systems, numeric is used as a shorthand for either integer or double type, and is used when picking methods:

```
sloop::s3_class(1)
#> [1] "double"  "numeric"
sloop::s3_class(1L)
#> [1] "integer" "numeric"
```

3. `is.numeric()` tests for objects that *behave* like numbers. For example, factors have type “integer” but don’t behave like numbers (i.e. it doesn’t make sense to take the mean of factor).

```
typeof(factor("x"))
#> [1] "integer"
is.numeric(factor("x"))
#> [1] FALSE
```

In this book, I consistently use numeric to mean an object of type integer or double.

Chapter 12

S3

12.1 Introduction

S3 is R’s first and simplest OO system. S3 is informal and ad hoc, but there is a certain elegance in its minimalism: you can’t take away any part of it and still have a useful OO system. For these reasons, you should use it, unless you have a compelling reason to do otherwise. S3 is the only OO system used in the base and stats packages, and it’s the most commonly used system in CRAN packages.

S3 is very flexible, which means it allows you to do things that are quite ill-advised. If you’re coming from a strict environment like Java this will seem pretty frightening, but it gives R programmers a tremendous amount of freedom. It may be very difficult to prevent someone from doing something you don’t want them to do, but your users will never be held back because there is something you haven’t implemented yet. Since S3 has few built-in constraints, the key to its successful use is applying the constraints yourself. This chapter will therefore teach you the conventions you should (almost) always adhere to.

The goal of this chapter is to show you how the S3 system works, not how to use it effectively to create new classes and generics. I’d recommend coupling the theoretical knowledge from this chapter with the practical knowledge encoded in the `vctrs` package (<https://vctrs.r-lib.org>).

Outline

- Section 12.2 gives a rapid overview of all the main components of S3: classes, generics, and methods. You’ll also learn about `sloop::s3_dispatch()`, which we’ll use throughout the chapter to explore how S3 works.
- Section 12.3 goes into the details of creating a new S3 class, including the three functions that should accompany most classes: a constructor, a helper, and a validator.
- Section 12.4 describes how S3 generics and methods work, including the basics of method dispatch.
- Section 12.5 discusses the four main styles of S3 objects: vector, record, data frame, and scalar.
- Section 12.6 demonstrates how inheritance works in S3, and shows you what you need to make a class “subclassable”.
- Section 12.7 concludes the chapter with a discussion of the finer details of method dispatch including base types, internal generics, group generics, and double dispatch.

Prerequisites

S3 classes are implemented using attributes, so make sure you’re familiar with the details described in Section 3.3. We’ll use existing base S3 vectors for examples and exploration, so make sure that you’re familiar with the factor, Date, difftime, POSIXct, and POSIXlt classes described in Section 3.4.

We’ll use the `sloop` package for interactive helpers, and the `vctrs` package for some niceties for creating new S3 classes.

```
# install_github("r-lib/sloop")
# install_github("r-lib/vctrs")

library(sloop)
```

12.2 Basics

An S3 object is a base type with at least a “class” attribute (other attributes may be used to store other data). For example, take the factor. Its base type is

the integer vector, it has a class attribute of “factor”, and a levels attribute that stores the possible levels:

```
f <- factor(c("a", "b", "c"))

typeof(f)
#> [1] "integer"
attributes(f)
#> $levels
#> [1] "a" "b" "c"
#>
#> $class
#> [1] "factor"
```

You can get the “underlying” base type by `unclass()`ing it, which strips the class attribute, causing it to lose its special behaviour:

```
unclass(f)
#> [1] 1 2 3
#> attr("levels")
#> [1] "a" "b" "c"
```

An S3 object behaves differently from its underlying base type whenever it’s passed to a **generic** (short for generic function). The easiest way to tell if a function is a generic is to use `sloop::ftype()` and look for “generic” in the output:

```
ftype(print)
#> [1] "S3"      "generic"
ftype(str)
#> [1] "S3"      "generic"
ftype(unclass)
#> [1] "primitive"
```

A generic function defines an interface, which uses a different implementation depending on the class of an argument (almost always the first argument). Many base R functions are generic, including the important `print()`:

```
print(f)
#> [1] a b c
#> Levels: a b c

# stripping class reverts to integer behaviour
print(unclass(f))
```

```
#> [1] 1 2 3
#> attr("levels")
#> [1] "a" "b" "c"
```

Beware that `str()` is generic, and some S3 classes use that generic to hide the internal details. For example, the `POSIXlt` class used to represent date-time data is actually built on top of a list, a fact which is hidden by its `str()` method:

```
time <- strftime(c("2017-01-01", "2020-05-04 03:21"), "%Y-%m-%d")
str(time)
#> POSIXlt[1:2], format: "2017-01-01" "2020-05-04"

str(unclass(time))
#> List of 9
#> $ sec  : num [1:2] 0 0
#> $ min  : int [1:2] 0 0
#> $ hour : int [1:2] 0 0
#> $ mday : int [1:2] 1 4
#> $ mon  : int [1:2] 0 4
#> $ year : int [1:2] 117 120
#> $ wday : int [1:2] 0 1
#> $ yday : int [1:2] 0 124
#> $ isdst: int [1:2] 0 0
#> - attr(*, "tzone")= chr "UTC"
```

The generic is a middleman: its job is to define the interface (i.e. the arguments) then find the right implementation for the job. The implementation for a specific class is called a **method**, and the generic finds that method by performing **method dispatch**.

You can use `s3_dispatch()` to see the process of method dispatch:

```
s3_dispatch(print(f))
#> => print.factor
#> * print.default
```

We'll come back to the details of dispatch in Section 12.4.1, for now note that S3 methods are functions with a special naming scheme, `generic.class()`. For example, the `factor` method for the `print()` generic is called `print.factor()`. You should never call the method directly, but instead rely on the generic to find it for you.

Generally, you can identify a method by the presence of `.` in the function name, but there are a number of important functions in base R that were written before

S3, and hence use `.` to join words. If you’re unsure, check with `sloop::ftype()`:

```
ftype(t.test)
#> [1] "S3"      "generic"
ftype(t.data.frame)
#> [1] "S3"      "method"
```

Unlike most functions, you can’t see the source code for most S3 methods¹ just by typing their names. That’s because S3 methods are not usually exported: they live only inside the package, and are not available from the global environment. Instead, you can use `sloop::s3_get_method()`, which will work regardless of where the method lives:

```
weighted.mean.Date
#> Error in eval(expr, envir, enclos):
#>   object 'weighted.mean.Date' not found

s3_get_method(weighted.mean.Date)
#> function (x, w, ...)
#> structure(weighted.mean(unclass(x), w, ...), class = "Date")
#> <bytecode: 0x74d59e8>
#> <environment: namespace:stats>
```

12.2.1 Exercises

1. Describe the difference between `t.test()` and `t.data.frame()`? When is each function called?
2. Make a list of commonly used base R functions that contain `.` in their name but are not S3 methods.
3. What does the `as.data.frame.data.frame()` method do? Why is it confusing? How could you avoid this confusion in your own code?
4. Describe the difference in behaviour in these two calls.

```
set.seed(1014)
some_days <- as.Date("2017-01-31") + sample(10, 5)

mean(some_days)
#> [1] "2017-02-05"
```

¹The exceptions are methods found in the base package, like `t.data.frame`, and methods that you’ve created.

```
mean(unclass(some_days))
#> [1] 17202
```

5. What class of object does the following code return? What base type is it built on? What attributes does it use?

```
x <- ecdf(rpois(100, 10))
x
#> Empirical CDF
#> Call: ecdf(rpois(100, 10))
#> x[1:18] = 2, 3, 4, ..., 2e+01, 2e+01
```

6. What class of object does the following code return? What base type is it built on? What attributes does it use?

```
x <- table(rpois(100, 5))
x
#>
#> 1 2 3 4 5 6 7 8 9 10
#> 8 5 18 14 12 19 12 3 5 4
```

12.3 Classes

If you have done object oriented programming in other languages, you may be surprised to learn that S3 has no formal definition of a class: to make an object an instance of a class, you simply set the **class attribute**. You can do that during creation with `structure()`, or after the fact with `class<-()`:

```
# Create and assign class in one step
x <- structure(list(), class = "my_class")

# Create, then set class
x <- list()
class(x) <- "my_class"
```

You can determine the class of an S3 object with `class(x)`, and see if an object is an instance of a class using `inherits(x, "classname")`.

```
class(x)
#> [1] "my_class"
inherits(x, "my_class")
#> [1] TRUE
```

```
inherits(x, "your_class")
#> [1] FALSE
```

The class name can be any string, but I recommend using only letters and `_`. Avoid `.` because (as mentioned earlier) it can be confused with the `.` separator between a generic name and a class name. When using a class in a package, I recommend including the package name in the class name. That ensures you won't accidental clash with a class defined by another package.

S3 has no checks for correctness which means you can change the class of existing objects:

```
# Create a linear model
mod <- lm(log(mpg) ~ log(disp), data = mtcars)
class(mod)
#> [1] "lm"
print(mod)
#>
#> Call:
#> lm(formula = log(mpg) ~ log(disp), data = mtcars)
#>
#> Coefficients:
#> (Intercept)    log(disp)
#>       5.381      -0.459

# Turn it into a date (?!)
class(mod) <- "Date"

# Unsurprisingly this doesn't work very well
print(mod)
#> Error in as.POSIXlt.Date(x):
#>   (list) object cannot be coerced to type 'double'
```

If you've used other OO languages, this might make you feel queasy, but in practice this flexibility causes few problems. R doesn't stop you from shooting yourself in the foot, but as long as you don't aim the gun at your toes and pull the trigger, you won't have a problem.

To avoid foot-bullet intersections when creating your own class, I recommend that you usually provide three functions:

- A low-level **constructor**, `new_myclass()`, that efficiently creates new objects with the correct structure.

- A **validator**, `validate_myclass()`, that performs more expensive checks to ensure that the object has correct values.
- A user-friendly **helper**, `myclass()`, that provides a convenient way for others to create objects of your class.

You don't need a validator for very simple classes, and you can skip the helper if the class is for internal use only, but you should always provide a constructor.

12.3.1 Constructors

S3 doesn't provide a formal definition of a class, so it has no built-in way to ensure that all objects of a given class have the same structure (i.e. the same base type and the same attributes with the same types). Instead, you must enforce a consistent structure yourself by using a **constructor**.

The constructor should follow three principles:

- Be called `new_myclass()`.
- Have one argument for the base object, and one for each attribute.
- Check the type of the base object and the types of each attribute.

I'll illustrate these ideas by creating constructors for base classes² that you're already familiar with. To start, let's make a constructor for the simplest S3 class: `Date`. A `Date` is just a double with a "Date" class attribute, and no additional attributes. This makes for a very simple constructor:

```
new_Date <- function(x = double()) {
  stopifnot(is.double(x))
  structure(x, class = "Date")
}

new_Date(c(-1, 0, 1))
#> [1] "1969-12-31" "1970-01-01" "1970-01-02"
```

The purpose of constructors is to help you, the developer. That means you can keep them simple, and you don't need to optimise error messages for public consumption. If you expect users to also create objects, you should create a friendly helper function, called `class_name()`, which I'll describe shortly.

A slightly more complicated constructor is that for `difftime`, which is used to represent time differences. It is again built on a double, but has a `units` attribute

²Recent versions of R have `.Date()`, `.difftime()`, `.POSIXct()`, and `.POSIXlt()` constructors but they are internal, not well documented, and do not follow the principles that I recommend.

that must take one of a small set of values:

```
new_difftime <- function(x = double(), units = "secs") {
  stopifnot(is.double(x))
  units <- match.arg(units, c("secs", "mins", "hours", "days", "weeks"))

  structure(x,
    class = "difftime",
    units = units
  )
}

new_difftime(c(1, 10, 3600), "secs")
#> Time differences in secs
#> [1] 1 10 3600
new_difftime(52, "weeks")
#> Time difference of 52 weeks
```

The constructor is a developer function: it will be called in many places, by an experienced user. That means it's ok to trade a little safety in return for performance, and you should avoid potentially time-consuming checks in the constructor.

12.3.2 Validators

More complicated classes require more complicated checks for validity. Take factors, for example. A constructor only checks that types are correct, making it possible to create malformed factors:

```
new_factor <- function(x = integer(), levels = character()) {
  stopifnot(is.integer(x))
  stopifnot(is.character(levels))

  structure(
    x,
    levels = levels,
    class = "factor"
  )
}

new_factor(1:5, "a")
#> Error in as.character.factor(x):
```

```
#>   malformed factor
new_factor(0:1, "a")
#> Error in as.character.factor(x):
#>   malformed factor
```

Rather than encumbering the constructor with complicated checks, it's better to put them in a separate function. Doing so allows you to cheaply create new objects when you know that the values are correct, and easily re-use the checks in other places.

```
validate_factor <- function(x) {
  values <- unclass(x)
  levels <- attr(x, "levels")

  if (!all(!is.na(values) & values > 0)) {
    stop(
      "All `x` values must be non-missing and greater than zero",
      call. = FALSE
    )
  }

  if (length(levels) < max(values)) {
    stop(
      "There must at least as many `levels` as possible values in `x`",
      call. = FALSE
    )
  }

  x
}

validate_factor(new_factor(1:5, "a"))
#> Error: There must at least as many `levels` as possible values in `x`
validate_factor(new_factor(0:1, "a"))
#> Error: All `x` values must be non-missing and greater than zero
```

This validator function is called primarily for its side-effects (throwing an error if the object is invalid) so you'd expect it to invisibly return its primary input (as described in Section [??invisible](#)). However, it's useful for validation methods to return visibly, as we'll see next.

12.3.3 Helpers

If you want users to construct objects from your class, you should also provide a helper method that makes their life as easy as possible. A helper should always:

- Have the same name as the class, e.g. `myclass()`.
- Finish by calling the constructor, and the validator, if it exists.
- Create carefully crafted error messages tailored towards an end-user.
- Have a thoughtfully crafted user interface with carefully chosen default values and useful conversions.

The last bullet is the trickiest, and it's hard to give general advice. However, there are three common patterns:

- Sometimes all the helper needs to do is coerce its inputs to the desired type. For example, `new_difftime()` is very strict, and violates the usual convention that you can use an integer vector wherever you can use a double vector:

```
new_difftime(1:10)
#> Error in new_difftime(1:10):
#>   is.double(x) is not TRUE
```

It's not the job of the constructor to be flexible, so here we create a helper that just coerces the input to a double.

```
difftime <- function(x = double(), units = "secs") {
  x <- as.double(x)
  new_difftime(x, units = units)
}

difftime(1:10)
#> Time differences in secs
#> [1] 1 2 3 4 5 6 7 8 9 10
```

- Often, the most natural representation of a complex object is a string. For example, it's very convenient to specify factors with a character vector. The code below shows a simple version of `factor()`: it takes a character vector, and guesses that the levels should be the unique values. This is not always correct (since some levels might not be seen in the data), but it's a useful default.

```
factor <- function(x = character(), levels = unique(x)) {
  ind <- match(x, levels)
```

```

  validate_factor(new_factor(ind, levels))
}

factor(c("a", "a", "b"))
#> [1] a a b
#> Levels: a b

```

- Some complex objects are most naturally specified by multiple simple components. For example, I think it's natural to construct a date-time by supplying the individual components (year, month, day etc). That leads me to this `POSIXct()` helper that resembles the existing `ISOdatetime()` function³:

```

POSIXct <- function(year = integer(),
                     month = integer(),
                     day = integer(),
                     hour = 0L,
                     minute = 0L,
                     sec = 0,
                     tzzone = "") {
  ISOdatetime(year, month, day, hour, minute, sec, tz = tzzone)
}

POSIXct(2020, 1, 1, tzzone = "America/New_York")
#> [1] "2020-01-01 EST"

```

For more complicated classes, you should feel free to go beyond these patterns to make life as easy as possible for your users.

12.3.4 Exercises

1. Write a constructor for `data.frame` objects. What base type is a data frame built on? What attributes does it use? What are the restrictions placed on the individual elements? What about the names?
2. Enhance my `factor()` helper to have better behaviour when one or more `values` is not found in `levels`. What does `base::factor()` do in this situation?

³Note that this helper is not efficient: behind the scenes `ISOdatetime()` works by pasting the components into a string and then using `strptime()`. A more efficient equivalent is available in `lubridate::make_datetime()`.

3. Carefully read the source code of `factor()`. What does it do that my constructor does not?
4. Factors have an optional “contrasts” attribute. Read the help for `C()`, and briefly describe the purpose of the attribute. What type should it have? Rewrite the `new_factor()` constructor to include this attribute.
5. Read the documentation for `utils::as.roman()`. How would you write a constructor for this class? Does it need a validator? What might a helper do?

12.4 Generics and methods

The job of an S3 generic is to perform method dispatch, i.e. find the specific implementation for a class. Method dispatch is performed by `UseMethod()`, which every generic calls⁴. `UseMethod()` takes two arguments: the name of the generic function (required), and the argument to use for method dispatch (optional). If you omit the second argument, it will dispatch based on the first argument, which is almost always what is desired.

Most generics are very simple, and consist of only a call to `UseMethod()`. Take `mean()` for example:

```
mean
#> function (x, ...)
#> UseMethod("mean")
#> <bytecode: 0x3d152c0>
#> <environment: namespace:base>
```

Creating your own generic is similarly simple:

```
my_new_generic <- function(x) {
  UseMethod("my_new_generic")
}
```

(If you wonder why we have to repeat `my_new_generic` twice, think back to Section 5.2.1.)

Note that you don’t pass any of the arguments of the generic to `UseMethod()`; it uses deep magic to pass to the method automatically. The precise process is complicated and frequently surprising, so you should avoid doing any computa-

⁴The exception is internal generics, which are implemented in C, and are the topic of Section 12.7.2.

tion in a generic. To learn the full details, carefully read the “technical details” section in `?UseMethod`.

12.4.1 Method dispatch

How does `UseMethod()` work? It basically creates a vector of method names, `paste0("generic", ".", c(class(x), "default"))`, and then looks for each potential method in turn. We can see this in action with `sloop::s3_dispatch()`. You give it a call to an S3 generic, and it lists all the possible methods. For example, what method is called when you print a `Date` object?

```
x <- Sys.Date()
s3_dispatch(print(x))
#> => print.Date
#> * print.default
```

The output here is simple:

- `=>` indicates the method that is called, here `print.Date()`
- `*` indicates a method that is defined, but not called, here `print.default()`.

The “default” class is a special **pseudo-class**. This is not a real class, but is included to make it possible to define a standard fallback that is found whenever a class-specific method is not available.

The essence of method dispatch is quite simple, but as the chapter proceeds you’ll see it get progressively more complicated to encompass inheritance, base types, internal generics, and group generics. The code below shows a couple of more complicated cases which we’ll come back to in Sections 13.2.4 and 12.7.

```
x <- matrix(1:10, nrow = 2)
s3_dispatch(mean(x))
#>     mean.matrix
#>     mean.integer
#>     mean.numeric
#> => mean.default

s3_dispatch(sum(Sys.time()))
#>     sum.POSIXct
#>     sum.POSIXt
#>     sum.default
#> => Summary.POSIXct
#>     Summary.POSIXt
```

```
#>     Summary.default
#> -> sum (internal)
```

12.4.2 Finding methods

`sloop::s3_dispatch()` lets you find the specific method used for a single call. What if you want to find all methods defined for a generic or associated with a class? That's the job of `sloop::s3_methods_generic()` and `sloop::s3_methods_class()`:

```
s3_methods_generic("mean")
#> # A tibble: 6 x 4
#>   generic class  visible source
#>   <chr>   <chr>  <lgcl>  <chr>
#> 1 mean    Date    TRUE    base
#> 2 mean    default TRUE    base
#> 3 mean    difftime TRUE   base
#> 4 mean    POSIXct  TRUE   base
#> 5 mean    POSIXlt  TRUE   base
#> 6 mean    quosure  FALSE   registered S3method

s3_methods_class("ordered")
#> # A tibble: 4 x 4
#>   generic      class  visible source
#>   <chr>        <chr>  <lgcl>  <chr>
#> 1 as.data.frame ordered TRUE    base
#> 2 Ops          ordered TRUE    base
#> 3 relevel     ordered FALSE   registered S3method
#> 4 Summary     ordered TRUE    base
```

12.4.3 Creating methods

There are two wrinkles to be aware of when you create a new method:

- First, you should only ever write a method if you own the generic or the class. R will allow you to define a method even if you don't, but it is exceedingly bad manners. Instead, work with the author of either the generic or the class to add the method in their code.
- A method must have the same arguments as its generic. This is enforced in packages by R `CMD check`, but it's good practice even if you're not creating

a package.

There is one exception to this rule: if the generic has ..., the method can contain a superset of the arguments. This allows methods to take arbitrary additional arguments. The downside of using ..., however, is that any misspelled arguments will be silently swallowed⁵, as mentioned in Section 5.6.

12.4.4 Exercises

1. Read the source code for `t()` and `t.test()` and confirm that `t.test()` is an S3 generic and not an S3 method. What happens if you create an object with class `test` and call `t()` with it? Why?

```
x <- structure(1:10, class = "test")
t(x)
```

2. What generics does the `table` class have methods for?
3. What generics does the `ecdf` class have methods for?
4. Which base generic has the greatest number of defined methods?
5. Carefully read the documentation for `UseMethod()` and explain why the following code returns the results that it does. What two usual rules of function evaluation does `UseMethod()` violate?

```
g <- function(x) {
  x <- 10
  y <- 10
  UseMethod("g")
}
g.default <- function(x) c(x = x, y = y)

x <- 1
y <- 1
g(x)
#>  x  y
#>  1 10
```

6. What are the arguments to `[`? Why is this a hard question to answer?

⁵See <https://github.com/hadley/ellipsis> for an experimental way of warning when methods fail to use all the argument in ..., providing a potential resolution of this issue.

12.5 Object styles

So far I've focussed on "vector style" classes like `Date` and `factor`. These have the key property that `length(x)` represents the number of observations in the vector. There are three variants that do not have this property:

- "Record style" objects use a list of equal-length vectors to represent individual components of the object. The best example of this is `POSIXlt`, which underneath the hood is a list of 11 date-time components like year, month, and day. Record style classes override `length()` and subsetting methods to conceal this implementation detail.

```
x <- as.POSIXlt(ISOdatetime(2020, 1, 1, 0, 0, 1:3))
x
#> [1] "2020-01-01 00:00:01 UTC" "2020-01-01 00:00:02 UTC"
#> [3] "2020-01-01 00:00:03 UTC"

length(x)
#> [1] 3
length(unclass(x))
#> [1] 9

x[[1]] # the first date time
#> [1] "2020-01-01 00:00:01 UTC"
unclass(x)[[1]] # the first component, the number of seconds
#> [1] 1 2 3
```

- Data frames are similar to record style objects in that both use lists of equal length vectors. However, data frames are conceptually two dimensional, and the individual components are readily exposed to the user. The number of observations is the number of rows, not the length:

```
x <- data.frame(x = 1:100, y = 1:100)
length(x)
#> [1] 2
nrow(x)
#> [1] 100
```

- Scalar objects typically use a list to represent a single "thing". For example, an `lm` object is a list of length 12 but it represents one model.

```
mod <- lm(mpg ~ wt, data = mtcars)
length(mod)
#> [1] 12
```

Scalar objects can also be built on top of functions, calls, and environments⁶. This is less generally useful, but you can see applications in `stats::ecdf()`, `R6` (Chapter 13), and `rlang::quo()` (Chapter 17).

Unfortunately, describing the appropriate use of each of these object styles is beyond the scope of this book. However, you can learn more from the documentation of the `vctrs` package (<https://vctrs.r-lib.org>); the package also provides constructors and helper that make implementation of the different styles easier.

12.5.1 Exercises

1. Categorise the objects returned by `lm()`, `factor()`, `table()`, `as.Date()`, `as.POSIXct()`, `ecdf()`, `ordered()`, `I()` into the styles described above.
2. What would a constructor function for `lm` objects, `new_lm()`, look like? Use `?lm` and experimentation to figure out the required fields and their types.

12.6 Inheritance

S3 classes can share behaviour through a mechanism called **inheritance**. Inheritance is powered by three ideas:

- The class can be a character *vector*. For example, the `ordered` and `POSIXct` classes have two components in their class:

```
class(ordered("x"))
#> [1] "ordered" "factor"
class(Sys.time())
#> [1] "POSIXct" "POSIXt"
```

- If a method is not found for the class in the first element of the vector, R looks for a method for the second class (and so on):

```
s3_dispatch(print(ordered("x")))
#>     print.ordered
#> => print.factor
#>   * print.default
s3_dispatch(print(Sys.time()))
#> => print.POSIXct
#>     print.POSIXt
#>   * print.default
```

⁶You can also build an object on top of a pairlist, but I have yet to find a good reason to do so.

- A method can delegate work by calling `NextMethod()`. We'll come back to that very shortly; for now, note that `s3_dispatch()` reports delegation with `->`.

```
s3_dispatch(ordered("x") [1])
#>     [.ordered
#> => [.factor
#>     [.default
#> -> [ (internal)
s3_dispatch(Sys.time() [1])
#> => [.POSIXct
#>     [.POSIXt
#>     [.default
#> -> [ (internal)
```

Before we continue we need a bit of vocabulary to describe the relationship between the classes that appear together in a class vector. We'll say that `ordered` is a **subclass** of `factor` because it always appears before it in the class vector, and, conversely, we'll say `factor` is a **superclass** of `ordered`.

S3 imposes no restrictions on the relationship between sub- and superclasses but your life will be easier if you impose some yourself. I recommend that you adhere to two simple principles when creating a subclass:

- The base type of the subclass should be that same as the superclass.
- The attributes of the subclass should be a superset of the attributes of the superclass.

Note that `POSIXt` does not adhere to these principles because `POSIXct` has type `double`, and `POSIXlt` has type `list`. This means that `POSIXt` is not a superclass, and illustrates that it's quite possible to use the S3 inheritance system to implement other styles of code sharing (here `POSIXt` plays a role more like an interface), but you'll need to figure out safe conventions yourself.

12.6.1 `NextMethod()`

`NextMethod()` is the hardest part of inheritance to understand, so we'll start with a concrete example for the most common use case: `[`. We'll start by creating a simple toy class: a `secret` class that hides its output when printed:

```
new_secret <- function(x = double()) {
  stopifnot(is.double(x))
```

```

  structure(x, class = "secret")
}

print.secret <- function(x, ...) {
  print(strrep("x", nchar(x)))
  invisible(x)
}

x <- new_secret(c(15, 1, 456))
x
#> [1] "xx"  "x"   "xxx"

```

This works, but the default `[` method doesn't preserve the class:

```

s3_dispatch(x[1])
#>   [.secret
#>   [.default
#> => [ (internal)
x[1]
#> [1] 15

```

To fix this, we need to provide a `[.secret` method. How could we implement this method? The naive approach won't work because we'll get stuck in an infinite loop:

```

`[.secret` <- function(x, i) {
  new_secret(x[i])
}

```

Instead, we need some way to call the the underlying `[` code, i.e. the implementation that would get called if we didn't have a `[.secret` method. One approach would be to `unclass()` the object:

```

`[.secret` <- function(x, i) {
  x <- unclass(x)
  new_secret(x[i])
}
x[1]
#> [1] "xx"

```

This works, but is inefficient because it creates a copy of `x`. A better approach is to use `NextMethod()`, which concisely solves the problem delegating to the method that would've have been called if `[.secret` didn't exist:

```
`.secret` <- function(x, i) {
  new_secret(NextMethod())
}
x[1]
#> [1] "xx"
```

We can see what's going on with `sloop::s3_dispatch()`:

```
s3_dispatch(x[1])
#> => [.secret
#>     [.default
#> -> [ (internal)
```

The `=>` indicates that `[.secret` is called, but that `NextMethod()` delegates work to the underlying internal `[` method, as shown by the `->`.

As with `UseMethod()`, the precise semantics of `NextMethod()` are complex. In particular, it tracks the list of potential next methods with a special variable, which means that modifying the object that's being dispatched upon will have no impact on which method gets called next.

12.6.2 Allowing subclassing

When you create a class, you need to decide if you want to allow subclasses, because it requires some changes to the constructor and careful thought in your methods.

To allow subclasses, the parent constructor needs to have `...` and `class` arguments:

```
new_secret <- function(x, ..., class = character()) {
  stopifnot(is.double(x))

  structure(
    x,
    ...,
    class = c(class, "secret")
  )
}
```

Then the subclass constructor can just call to the parent class constructor with additional arguments as needed. For example, imagine we want to create a `supersecret` class which also hides the number of characters:

```

new_supersecret <- function(x) {
  new_secret(x, class = "supersecret")
}

print.supersecret <- function(x, ...) {
  print(rep("xxxxx", length(x)))
  invisible(x)
}

x2 <- new_supersecret(c(15, 1, 456))
x2
#> [1] "xxxxx" "xxxxx" "xxxxx"

```

To allow inheritance, you also need to think carefully about your methods, as you can no longer use the constructor. If you do, the method will always return the same class, regardless of the input. This forces whoever makes a subclass to do a lot of extra work.

Concretely, this means we need to revise the `[.secret` method. Currently it always returns a `secret()`, even when given a `supersecret`:

```

`[.secret` <- function(x, ...) {
  new_secret(NextMethod())
}

x2[1:3]
#> [1] "xx"  "x"   "xxx"

```

We want to make sure that `[.secret` returns the same class as `x` even if it's a subclass. As far as I can tell, there is no way to solve this problem using base R alone. Instead, you'll need to use the `vctrs` package, which provides a solution in the form of the `vctrs::vec_restore()` generic. This generic takes two inputs: an object which has lost subclass information, and a template object to use for restoration.

Typically `vec_restore()` methods are quite simple: you just call the constructor with appropriate arguments:

```

vec_restore.secret <- function(x, to) new_secret(x)
vec_restore.supersecret <- function(x, to) new_supersecret(x)

```

(If your class has attributes, you'll need to pass them from `to` into the constructor.)

Now we can use `vec_restore()` in the `[.secret` method:

```
`.secret` <- function(x, ...) {
  vctrs::vec_restore(NextMethod(), x)
}
x2[1:3]
#> [1] "xxxxx" "xxxxx" "xxxxx"
```

(I only fully understood this issue quite recently, so at time of writing it is not used in the tidyverse. Hopefully by the time you're reading this, it will have rolled out, making it much easier to (e.g.) subclass tibbles.)

If you build your class using the tools provided by the `vctrs` package, `[` will gain this behaviour automatically. You will only need to provide your own `[` method if you use attributes that depend on the data or want non-standard subsetting behaviour. See `?vctrs::new_vctr` for details.

12.6.3 Exercises

1. How does `[.Date` support subclasses? How does it fail to support subclasses?
2. R has two classes for representing date time data, `POSIXct` and `POSIXlt`, which both inherit from `POSIXt`. Which generics have different behaviours for the two classes? Which generics share the same behaviour?
3. What do you expect this code to return? What does it actually return? Why?

```
generic2 <- function(x) UseMethod("generic2")
generic2.a1 <- function(x) "a1"
generic2.a2 <- function(x) "a2"
generic2.b <- function(x) {
  class(x) <- "a1"
  NextMethod()
}

generic2(structure(list(), class = c("b", "a2")))
```

12.7 Dispatch details

This chapter concludes with a few additional details about method dispatch. It is safe to skip these details if you're new to S3.

12.7.1 S3 and base types

What happens when you call an S3 generic with a base object, i.e. an object with no class? You might think it would dispatch on what `class()` returns:

```
class(matrix(1:5))
#> [1] "matrix"
```

But unfortunately dispatch actually occurs on the **implicit class**, which has three components:

- “array” or “matrix” (if the object has dimensions).
- `typeof()` (with a few minor tweaks).
- If it’s “integer” or “double”, “numeric”.

There is no base function that will compute the implicit class, but you can use `sloop::s3_class()`

```
s3_class(matrix(1:5))
#> [1] "matrix"  "integer" "numeric"
```

This is used by `s3_dispatch()`:

```
s3_dispatch(print(matrix(1:5)))
#>   print.matrix
#>   print.integer
#>   print.numeric
#> => print.default
```

Note that this means that the `class()` of an object does not uniquely determine its dispatch:

```
x1 <- 1:5
class(x1)
#> [1] "integer"
s3_dispatch(mean(x1))
#>   mean.integer
#>   mean.numeric
#> => mean.default

x2 <- structure(x1, class = "integer")
class(x2)
#> [1] "integer"
s3_dispatch(mean(x2))
#>   mean.integer
#> => mean.default
```

12.7.2 Internal generics

Some base functions, like `[`, `sum()`, and `cbind()`, are called **internal generics** because they don't call `UseMethod()` but instead call the C functions `DispatchGroup()` or `DispatchOrEval()`. `s3_dispatch()` shows internal generics by including the name of the generic followed by `(internal)`:

```
s3_dispatch(Sys.time() [1])
#> => [.POSIXct
#>     [.POSIXt
#>     [.default
#> -> [ (internal)]
```

For performance reasons, internal generics do not dispatch to methods unless the class attribute has been set, which means that internal generics do not use the implicit class. Again, if you're ever confused about method dispatch, you can rely on `s3_dispatch()`.

12.7.3 Group generics

Group generics are the most complicated part of S3 method dispatch because they involve both `NextMethod()` and internal generics. Like internal generics, they only exist in base R, and you cannot define your own group generic.

There are four group generics:

- **Math**: `abs()`, `sign()`, `sqrt()`, `floor()`, `cos()`, `sin()`, `log()`, and more (see `?Math` for the complete list).
- **Ops**: `+`, `-`, `*`, `/`, `^`, `%%`, `%%/%`, `&`, `|`, `!`, `==`, `!=`, `<`, `<=`, `>`, `>=`, and `>>`.
- **Summary**: `all()`, `any()`, `sum()`, `prod()`, `min()`, `max()`, and `range()`.
- **Complex**: `Arg()`, `Conj()`, `Im()`, `Mod()`, `Re()`.

Defining a single group generic for your class overrides the default behaviour for all of the members of the group. Methods for group generics are looked for only if the methods for the specific generic do not exist:

```
s3_dispatch(sum(Sys.time()))
#>     sum.POSIXct
#>     sum.POSIXt
#>     sum.default
```

```
#> => Summary.POSIXct
#>   Summary.POSIXt
#>   Summary.default
#> -> sum (internal)
```

Most group generics involve a call to `NextMethod()`. For example, take `difftime()` objects. If you look at the method dispatch for `abs()`, you'll see there's a `Math` group generic defined.

```
y <- as.difftime(10, units = "mins")
s3_dispatch(abs(y))
#>   abs.difftime
#>   abs.default
#> => Math.difftime
#>   Math.default
#> -> abs (internal)
```

`Math.difftime` basically looks like this:

```
Math.difftime <- function(x, ...) {
  new_difftime(NextMethod(), units = attr(x, "units"))
}
```

It dispatches to the next method, here the internal default, to perform the actual computation, then restore the class and attributes. (To better support subclasses of `difftime` this would need to call `vec_restore()`, as described in Section 12.6.2.)

Note that inside a group generic function a special variable `.Generic` provides the actual generic function called. This can be useful when producing error messages, and can sometimes be useful if you need to manually re-call the generic with different arguments.

12.7.4 Double dispatch

Generics in the “Ops” group, which includes the two-argument arithmetic and boolean operators like `-` and `&`, implement a special type of method dispatch. They dispatch on the type of *both* of the arguments, which is called **double dispatch**. This is necessary to preserve the commutative property of many operators, i.e. `a + b` should equal `b + a`. Take the following simple example:

```
date <- as.Date("2017-01-01")
integer <- 1L
```

```
date + integer
#> [1] "2017-01-02"
integer + date
#> [1] "2017-01-02"
```

If `+` dispatched only on the first argument, it would return different values for the two cases. To overcome this problem, generics in the Ops group use a slightly different strategy from usual. Rather than doing a single method dispatch, they do two, one for each input. There are three possible outcomes of this lookup:

- The methods are the same, so it doesn't matter which method is used.
- The methods are different, and R falls back to the internal method with a warning.
- One method is internal, in which case R calls the other method.

This approach is error prone so if you want to implement robust double dispatch for algebraic operators, I recommend using the `vctrs` package. See `?vctrs::vec_arith` for details.

12.7.5 Exercises

1. Explain the differences in dispatch below:

```
length.integer <- function(x) 10

x1 <- 1:5
class(x1)
#> [1] "integer"
s3_dispatch(length(x1))
#> * length.integer
#>   length.numeric
#>   length.default
#> => length (internal)

x2 <- structure(x1, class = "integer")
class(x2)
#> [1] "integer"
s3_dispatch(length(x2))
#> => length.integer
#>   length.default
#> * length (internal)
```

2. What classes have a method for the `Math` group generic in base R? Read the source code. How do the methods work?
3. `Math.difftime()` is more complicated than I described. Why?

Chapter 13

R6

13.1 Introduction

This chapter describes the R6 OOP system. R6 has two special properties:

- It uses the encapsulated OOP paradigm, which means that methods belong to objects, not generics, and you call them like `object$method()`.
- R6 objects are **mutable**, which means that they are modified in place, and hence have reference semantics.

If you've learned OOP in another programming language, it's likely that R6 will feel very natural, and you'll be inclined to prefer it over S3. Resist the temptation to follow the path of least resistance: in most cases R6 will lead you to non-idiomatic R code. We'll come back to this theme in Section 15.3.

R6 is very similar to a base OOP system called **reference classes**, or RC for short. I describe why I teach R6 and not RC in Section 13.5.

Outline

- Section 13.2 introduces `R6::R6class()`, the one function that you need to know to create R6 classes. You'll learn about the constructor method, `$new()`, which allows you to create R6 objects, as well as other important methods like `$initialize()` and `$print()`.
- Section 13.3 discusses the access mechanisms of R6: private and active fields. Together, these allow you to hide data from the user, or expose private data for reading but not writing.

- Section 13.4 explores the consequences of R6’s reference semantics. You’ll learn about the use of finalizers to automatically clean up any operations performed in the initializer, and a common gotcha if you use an R6 object as a field in another R6 object.
- Section 13.5 describes why I cover R6, rather than the base RC system.

Prerequisites

Because R6 is not built into base R, you’ll need to install and load the R6 package to use it:

```
# install.packages("R6")
library(R6)
```

R6 objects have reference semantics which means that they are modified in-place, not copied-on-modify. If you’re not familiar with these terms, brush up your vocab by reading Section 2.5.

13.2 Classes and methods

R6 only needs a single function call to create both the class and its methods: `R6::R6Class()`. This is the only function from the package that you’ll ever use!¹

The following example shows the two most important arguments to `R6Class()`:

- The first argument is the `classname`. It’s not strictly needed, but it improves error messages and makes it possible to use R6 objects with S3 generics. By convention, R6 classes have `UpperCamelCase` names.
- The second argument, `public`, supplies a list of methods (functions) and fields (anything else) that make up the public interface of the object. By convention, methods and fields use `snake_case`. Methods can access the methods and fields of the current object via `self$`.²

```
Accumulator <- R6Class("Accumulator", list(
  sum = 0,
  add = function(x = 1) {
    self$sum <- self$sum + x
  }
))
```

¹That means if you’re creating R6 in a package, you only need to make sure it’s listed in the `Imports` field of the `DESCRIPTION`. There’s no need to import the package into the `NAMESPACE`.

²Unlike in `this` in python, the `self` variable is automatically provided by R6, and does not form part of the method signature.

```

    invisible(self)
  })
)

```

You should always assign the result of `R6Class()` into a variable with the same name as the class, because `R6Class()` returns an R6 object that defines the class:

```

Accumulator
#> <Accumulator> object generator
#>   Public:
#>     sum: 0
#>     add: function (x = 1)
#>     clone: function (deep = FALSE)
#>     Parent env: <environment: R_GlobalEnv>
#>     Locked objects: TRUE
#>     Locked class: FALSE
#>     Portable: TRUE

```

You construct a new object from the class by calling the `new()` method. In R6, methods belong to objects, so you use `$` to access `new()`:

```
x <- Accumulator$new()
```

You can then call methods and access fields with `$`:

```

x$add(4)
x$sum
#> [1] 4

```

In this class, the fields and methods are public, which means that you can get or set the value of any field. Later, we'll see how to use private fields and methods to prevent casual access to the internals of your class.

To make it clear when we're talking about fields and methods as opposed to variables and functions, I'll prefix their names with `$`. For example, the `Accumulate` class has field `$sum` and method `$add()`.

13.2.1 Method chaining

`$add()` is called primarily for its side-effect of updating `$sum`.

```

Accumulator <- R6Class("Accumulator", list(
  sum = 0,
  add = function(x = 1) {

```

```

    self$sum <- self$sum + x
    invisible(self)
  })
)

```

Side-effect R6 methods should always return `self` invisibly. This returns the “current” object and makes it possible to chain together multiple method calls:

```

x$add(10)$add(10)$sum
#> [1] 24

```

For, readability, you might put one method call on each line:

```

x$add(10)$add(10)$sum
#> [1] 44

```

This technique is called **method chaining** and is commonly used in languages like Python and JavaScript. Method chaining is deeply related to the pipe, and we’ll discuss the pros and cons of each approach in Section 15.3.3.

13.2.2 Important methods

There are two important methods that should be defined for most classes: `$initialize()` and `$print()`. They’re not required, but providing them will make your class easier to use.

`$initialize()` overrides the default behaviour of `$new()`. For example, the following code defines an `Person` class with fields `$name` and `$age`. To ensure that that `$name` is always a single string, and `$age` is always a single number, I placed checks in `$initialize()`.

```

Person <- R6Class("Person", list(
  name = NULL,
  age = NA,
  initialize = function(name, age = NA) {
    stopifnot(is.character(name), length(name) == 1)
    stopifnot(is.numeric(age), length(age) == 1)

    self$name <- name
    self$age <- age
  }
))

```

```

  }
))

hadley <- Person$new("Hadley", age = "thirty-eight")
#> Error in .subset2(public_bind_env, "initialize")(...):
#>   is.numeric(age) is not TRUE

hadley <- Person$new("Hadley", age = 38)

```

If you have more expensive validation requirements, implement them in a separate `$validate()` and only call when needed.

Defining `$print()` allows you to override the default printing behaviour. As with any R6 method called for its side effects, `$print()` should return `invisible(self)`.

```

Person <- R6Class("Person", list(
  name = NULL,
  age = NA,
  initialize = function(name, age = NA) {
    self$name <- name
    self$age <- age
  },
  print = function(...) {
    cat("Person: \n")
    cat("  Name: ", self$name, "\n", sep = "")
    cat("  Age:  ", self$age, "\n", sep = "")
    invisible(self)
  }
))

hadley2 <- Person$new("Hadley")
hadley2
#> Person:
#>   Name: Hadley
#>   Age:  NA

```

This code illustrates an important aspect of R6. Because methods are bound to individual objects, the previously created `hadley` object does not get this new method:

```

hadley
#> <Person>

```

```
#>   Public:
#>     age: 38
#>     clone: function (deep = FALSE)
#>     initialize: function (name, age = NA)
#>     name: Hadley

hadley$print
#> NULL
```

From the perspective of R6, there is no relationship between `hadley` and `hadley2`; they just coincidentally share the same class name. This doesn't cause problems when using already developed R6 objects but can make interactive experimentation confusing. If you're changing the code and can't figure out why the results of method calls aren't any different, make sure you've re-constructed R6 objects with the new class.

13.2.3 Adding methods after creation

Instead of continuously creating new classes, it's also possible to modify the fields and methods of an existing class. This is useful when exploring interactively, or when you have a class with many functions that you'd like to break up into pieces. Add new elements to an existing class with `$set()`, supplying the visibility (more on in Section 13.3), the name, and the component.

```
Accumulator <- R6Class("Accumulator")
Accumulator$set("public", "sum", 0)
Accumulator$set("public", "add", function(x = 1) {
  self$sum <- self$sum + x
})
```

As above, new methods and fields are only available to new objects; they are not retrospectively added to existing objects.

13.2.4 Inheritance

To inherit behaviour from an existing class, provide the class object to the `inherit` argument:

```
AccumulatorChatty <- R6Class("AccumulatorChatty",
  inherit = Accumulator,
  public = list(
    add = function(x = 1) {
```

```

    cat("Adding ", x, "\n", sep = "")
    super$add(x = x)
  }
)
)

x2 <- AccumulatorChatty$new()
x2$add(10)$add(1)$sum
#> Adding 10
#> Adding 1
#> [1] 11

```

Note that `$add()` overrides the implementation in the superclass, but we can delegate to the superclass implementation through `super$`. (This is analogous to `NextMethod()` in S3, as discussed in Section 12.6.) Any methods which are not overridden will use the implementation in the parent class.

13.2.5 Introspection

Every R6 object has an S3 class that reflects its hierarchy of R6 classes. This means that the easiest way to determine the class (and all classes it inherits from) is to use `class()`:

```

class(hadley2)
#> [1] "Person" "R6"

```

The S3 hierarchy includes the base “R6” class. This provides common behaviour, including a `print.R6()` method which calls `$print()`, as described above.

You can list all methods and fields with `names()`:

```

names(hadley2)
#> [1] ".__enclos_env__" "name"           "clone"
#> [4] "initialize"      "age"            "print"

```

We defined `$name`, `$age`, `$print`, and `$initialize`. As suggested by the name `.__enclos_env__` is an internal implementation detail that you shouldn’t touch; we’ll come back to `$clone()` in Section 13.4.

13.2.6 Exercises

1. Create a bank account R6 class that stores a balance and allows you to deposit and withdraw money. Create a subclass that throws an error if you attempt to go into overdraft. Create another subclass that allows you to go into overdraft, but charges you a fee.
2. Create an R6 class that represents a shuffled deck of cards. You should be able to draw cards from the deck with `$draw(n)`, and return all cards to the deck and reshuffle with `$reshuffle()`. Use the following code to make a vector of cards.

```
suit <- c(" ", " ", " ", " ")
value <- c("A", 2:10, "J", "Q", "K")
cards <- paste0(rep(value, 4), suit)
```

3. Why can't you model a bank account or a deck of cards with an S3 class?
4. Create an R6 class that allows you to get and set the current timezone. You can access the current timezone with `Sys.timezone()` and set it with `Sys.setenv(TZ = "newtimezone")`. When setting the time zone, make sure the new time zone is in the list provided by `OlsonNames()`.
5. Create an R6 class that manages the current working directory. It should have `$get()` and `$set()` methods.
6. Why can't you model the time zone or current working directory with an S3 class?
7. What base type are R6 objects built on top of? What attributes do they have?

13.3 Controlling access

`R6Class()` has two other arguments that work similarly to `public`:

- `private` allows you to create fields and methods that are only available from within the class, not outside of it.
- `active` allows you to use accessor functions to define dynamic, or active, fields.

These are described in the following sections.

13.3.1 Privacy

With R6 you can define **private** fields and methods, elements that can only be accessed from within the class, not from the outside³. There are two things that you need to know to take advantage of private elements:

- The **private** argument to `R6Class` works in the same way as the `public` argument: you give it a named list of methods (functions) and fields (everything else).
- Fields and methods defined in `private` are available within the methods using `private$` instead of `self$`. You cannot access private fields or methods outside of the class.

To make this concrete, we could make `$age` and `$name` fields of the `Person` class private. With this definition of `Person` we can only set `$age` and `$name` during object creation, and we cannot access their values from outside of the class.

```
Person <- R6Class("Person",
  public = list(
    initialize = function(name, age = NA) {
      private$name <- name
      private$age <- age
    },
    print = function(...) {
      cat("Person: \n")
      cat("  Name: ", private$name, "\n", sep = "")
      cat("  Age:  ", private$age, "\n", sep = "")
    }
  ),
  private = list(
    age = NA,
    name = NULL
  )
)

hadley3 <- Person$new("Hadley")
hadley3
#> Person:
#>   Name: Hadley
#>   Age: NA
```

³Because R is such a flexible language, it's technically still possible to access private values, but you'll have to try much harder, spelunking in to the details of R6's implementation.

```
hadley3$name
#> NULL
```

The distinction between public and private fields is important when you create complex networks of classes, and you want to make it as clear as possible what it's ok for others to access. Anything that's private can be more easily refactored because you know others aren't relying on it. Private methods tend to be less important in R compared to other programming languages because the object hierarchies in R tend to be simpler.

13.3.2 Active fields

Active fields allow you to define components that look like fields from the outside, but are defined with functions, like methods. Active fields are implemented using **active bindings** (see Section 6.2.7 for details). Each active binding is a function that takes a single argument: `value`. If the argument is `missing()`, the value is being retrieved; otherwise it's being modified.

For example, you could make an active field `random` that returns a different value every time you access it:

```
Rando <- R6:::R6Class("Rando", active = list(
  random = function(value) {
    if (missing(value)) {
      runif(1)
    } else {
      stop("Can't set `random`", call. = FALSE)
    }
  })
x <- Rando$new()
x$random
#> [1] 0.0808
x$random
#> [1] 0.834
x$random
#> [1] 0.601
```

Active fields are particularly useful in conjunction with private fields, because they make it possible to implement components that look like fields from the outside but provide additional checks. For example, we can use them to make a read-only `age` field, and to ensure that `name` is a length 1 character vector.

```
Person <- R6Class("Person",
  private = list(
    .age = NA,
    .name = NULL
  ),
  active = list(
    age = function(value) {
      if (missing(value)) {
        private$.age
      } else {
        stop("`$age` is read only", call. = FALSE)
      }
    },
    name = function(value) {
      if (missing(value)) {
        private$.name
      } else {
        stopifnot(is.character(value), length(value) == 1)
        private$.name <- value
        self
      }
    }
  ),
  public = list(
    initialize = function(name, age = NA) {
      private$.name <- name
      private$.age <- age
    }
  )
)

hadley4 <- Person$new("Hadley", age = 38)
hadley4$name
#> [1] "Hadley"
hadley4$name <- 10
#> Error in (function (value) :
#>   is.character(value) is not TRUE
hadley4$age <- 20
#> Error: `$age` is read only
```

13.3.3 Exercises

1. Create a bank account class that prevents you from directly setting the account balance, but you can still withdraw from and deposit to. Throw an error if you attempt to go into overdraft.
2. Create a class with a write-only `$password` field. It should have `$check_password(password)` method that returns TRUE or FALSE, but there should be no way to view the complete password.
3. Extend the `Rando` class with another active binding that allows you to access the previous random value. Ensure that active binding is the only way to access the value.
4. Can subclasses access private fields/methods from their parent? Perform an experiment to find out.

13.4 Reference semantics

One of the big differences between R6 and most other objects is that they have reference semantics. The primary consequence of reference semantics is that objects are not copied when modified:

```
y1 <- Accumulator$new()
y2 <- y1

y1$add(10)
c(y1 = y1$sum, y2 = y2$sum)
#> y1 y2
#> 10 10
```

Instead, if you want a copy, you'll need to explicitly `$clone()` the object:

```
y1 <- Accumulator$new()
y2 <- y1$clone()

y1$add(10)
c(y1 = y1$sum, y2 = y2$sum)
#> y1 y2
#> 10 0
```

(Note that `$clone()` does not recursively clone nested R6 objects. If you want that, you'll need to use `$clone(deep = TRUE)`.)

There are three other less obvious consequences:

- It is harder to reason about code that uses R6 objects because you need to understand more context.
- It makes sense to think about when an R6 object is deleted, and you can write a `$finalize()` to complement the `$initialize()`.
- If one of the fields is an R6 object, you must create it inside `$initialize()`, not `R6Class()`.

These consequences are described in more detail below.

13.4.1 Reasoning

Generally, reference semantics makes code harder to reason about. Take this very simple example:

```
x <- list(a = 1)
y <- list(b = 2)

z <- f(x, y)
```

For the vast majority of functions, you know that the final line only modifies `z`.

Take a similar example that uses an imaginary `List` reference class:

```
x <- List$new(a = 1)
y <- List$new(b = 2)

z <- f(x, y)
```

The final line is much harder to reason about: if `f()` calls methods of `x` or `y`, it might modify them as well as `z`. This is the biggest potential downside of R6 and you should take care to avoid it by writing functions that either return a value, or modify their R6 inputs, but not both. That said, doing both can lead to substantially simpler code in some cases, and we'll discuss this further in Section 15.3.2.

13.4.2 Finalizer

One useful property of reference semantics is that it makes sense to think about when an R6 object is **finalized**, i.e. when it's deleted. This doesn't make sense for most objects because copy-on-modify semantics mean that there may be many

transient versions of an object, as alluded to in Section 2.6. For example, the following creates two factor objects: the second is created when the levels are modified, leaving the first to be destroyed by the garbage collector.

```
x <- factor(c("a", "b", "c"))
levels(x) <- c("c", "b", "a")
```

Since R6 objects are not copied-on-modify they are only deleted once, and it makes sense to think about `$finalize()` as a complement to `$initialize()`. Finalizers usually play a similar role to `on.exit()` (as described in Section 5.7.4), cleaning up any resources created by the initializer. For example, the following class wraps up a temporary file, automatically deleting it when the class is finalized.

```
TemporaryFile <- R6Class("TemporaryFile", list(
  path = NULL,
  initialize = function() {
    self$path <- tempfile()
  },
  finalize = function() {
    message("Cleaning up ", self$path)
    unlink(self$path)
  }
))
```

The finalize method will be run when the object is deleted (or more precisely, by the first garbage collection after the object has been unbound from all names) or when R exits. This means that the finalizer can be called effectively anywhere in your R code, and therefore it's almost impossible to reason about finalizer code that touches shared data structures. Avoid these potential problems by only using the finalizer to clean up private resources allocated by initializer.

```
tf <- TemporaryFile$new()
rm(tf)
#> Cleaning up /tmp/Rtmpk73JdI/file155f31d8424bd
```

13.4.3 R6 fields

A final consequence of reference semantics can crop up where you don't expect it. If you use a R6 class as the default value of a field, it will be shared across all instances of the object! Take the following code: we want to create a temporary database every time we call `TemporaryDatabase$new()`, but the current code always uses the same path.

```

TemporaryDatabase <- R6Class("TemporaryDatabase", list(
  con = NULL,
  file = TemporaryFile$new(),
  initialize = function() {
    self$con <- DBI::dbConnect(RSQLite::SQLite(), path = file$path)
  },
  finalize = function() {
    DBI::dbDisconnect(self$con)
  }
))

db_a <- TemporaryDatabase$new()
db_b <- TemporaryDatabase$new()

db_a$file$path == db_b$file$path
#> [1] TRUE

```

(If you’re familiar with Python, this is very similar to the “mutable default argument” problem.)

The problem arises because `TemporaryFile$new()` is called only once when the `TemporaryDatabase` class is defined. To fix the problem, we need to make sure it’s called every time that `TemporaryDatabase$new()` is called, i.e. we need to put it in `$initialize()`:

```

TemporaryDatabase <- R6Class("TemporaryDatabase", list(
  con = NULL,
  file = NULL,
  initialize = function() {
    self$file <- TemporaryFile$new()
    self$con <- DBI::dbConnect(RSQLite::SQLite(), path = file$path)
  },
  finalize = function() {
    DBI::dbDisconnect(self$con)
  }
))

db_a <- TemporaryDatabase$new()
db_b <- TemporaryDatabase$new()

db_a$file$path == db_b$file$path
#> [1] FALSE

```

13.4.4 Exercises

1. Create a class that allows you to write a line to a specified file. You should open a connection to the file in `$initialize()`, append a line using `cat()` in `$append_line()`, and close the connection in `$finalize()`.

13.5 Why R6?

R6 is very similar to a built-in OO system called **reference classes**, or RC for short. I prefer R6 to RC because:

- R6 is much simpler. Both R6 and RC are built on top of environments, but while R6 uses S3, RC uses S4. This means to fully understand RC, you need to understand how the more complicated S4 works.
- R6 has comprehensive online documentation at <https://r6.r-lib.org>.
- R6 has a simpler mechanism for cross-package subclassing, which just works without you having to think about it. For RC, read the details in the “External Methods; Inter-Package Superclasses” section of `?setRefClass`.
- RC mingles variables and fields in the same stack of environments so that you get `(field)` and set `(field <- value)` fields like regular values. R6 puts fields in a separate environment so you get `(self$field)` and set `(self$field <- value)` with a prefix. The R6 approach is more verbose but I like it because it is more explicit.
- R6 is much faster than RC. Generally, the speed of method dispatch is not important outside of microbenchmarks. However, RC is quite slow, and switching from RC to R6 led to a substantial performance improvement in the shiny package. For more details, see `vignette("Performance", "R6")`.
- RC is tied to R. That means if any bugs are fixed, you can only take advantage of the fixes by requiring a newer version of R. This makes it difficult for packages (like those in the tidyverse) that need to work across many R versions.
- Finally, because the ideas that underlie R6 and RC are similar, it will only require a small amount of additional effort to learn RC if you need to.

Chapter 14

S4

14.1 Introduction

S4 provides a formal approach to functional OOP. The underlying ideas are similar to S3 (the topic of Chapter 12), but implementation is much stricter and makes use of specialised functions for creating classes (`setClass()`), generics (`setGeneric()`), and methods (`setMethod()`). Additionally, S4 provides both multiple inheritance (i.e. a class can have multiple parents) and multiple dispatch (i.e. method dispatch can use the class of multiple arguments).

An important new component of S4 is the **slot**, a named component of the object that is accessed using the specialised subsetting operator `@` (pronounced at). The set of slots, and their classes, forms an important part of the definition of an S4 class.

Like the other OO chapters, the focus here will be on S4 works, not how to deploy it most effectively.

Learning more

There are two main challenges when learning S4:

- There is no one reference that will answer all your questions about S4.
- R's built-in documentation sometimes clashes with community best practices.

As you move towards more advanced usage, you will need to piece together needed

information by carefully reading the documentation, asking questions on StackOverflow, and performing experiments. Some recommendations:

- The Bioconductor community is a long-term user of S4 and have produced much of best material about its effective use. Start with S4 classes and methods (<https://bioconductor.org/help/course-materials/2017/Zurich/S4-classes-and-methods.html>) taught by Martin Morgan and Hervé Pagès, or check for a newer version at Bioconductor course materials (<https://bioconductor.org/help/course-materials/>).

Martin Morgan is a member of R-core and the project lead of Bioconductor. He's a world expert on the practical use of S4, and I recommend reading anything he has written about it, starting with the questions he has answered on stackoverflow (<http://stackoverflow.com/search?tab=votes&q=user%3a547331%20%5bs4%5d%20is%3aanswe>).

- John Chambers is the author of the S4 system, and provides an overview of its motivation and historical context in “Object-oriented programming, functional programming and R” (Chambers 2014). For a fuller exploration of S4, see his book “Software for Data Analysis” (Chambers 2008).

Outline

- Section 14.2 gives a quick overview of the main components of S4: classes, generics, and methods.
- Section 14.3 dives into the details of S4 classes, including prototypes, constructors, helpers, and validators.
- Section 14.4 shows you how to create new S4 generics, and how to supply those generics with methods. You'll also learn about accessor functions which are designed to allow users to safely inspect and modify object slots.
- Section 14.5 dives into the full details of method dispatch in S4. The basic idea is simple, the it rapidly gets more complex once multiple inheritance and multiple dispatch are combined.
- Section 14.6 discusses the interaction between S4 and S3, showing you how to use them together.

Prerequisites

All functions related to S4 live in the `methods` package. This package is always available when you're running R interactively, but may not be available when

running R in batch mode, i.e. from `Rscript`¹. For this reason, it's a good idea to call `library(methods)` whenever you use S4. This also signals to the reader that you'll be using the S4 object system.

```
library(methods)
```

14.2 Basics

We'll start with a quick overview of the main components of S4. You define a S4 class by calling `setClass()` with the class name and a definition of its slots, the names and classes of the class data:

```
setClass("Person",
  slots = c(
    name = "character",
    age = "numeric"
  )
)
```

Once the class is defined, you can construct new objects from it by calling `new()` with the name of the class and a value for each slot:

```
john <- new("Person", name = "John Smith", age = NA_real_)
```

Given an S4 object you can see its class with `is()` and access slots with `@` (equivalent to `$`) and `slot()` (equivalent to `[[]`):

```
is(john)
#> [1] "Person"
john@name
#> [1] "John Smith"
slot(john, "age")
#> [1] NA
```

Generally, you should only use `@` in your methods. If you're working with someone else's class, look for `accessor` functions that allow you to safely set and get slot values. As the developer of a class, you should also provide your own accessor functions. Accessors are typically S4 generics allowing multiple classes to share the same external interface.

Here we'll create a setter and getter for the `age` slot by first creating generics with `setGeneric()`:

¹This is a historical quirk introduced because the `methods` package used to take a long time to load and `Rscript` is optimised for fast command line invocation.

```
setGeneric("age", function(x) standardGeneric("age"))
setGeneric("age<-", function(x, value) standardGeneric("age<-"))
```

And then defining methods with `setMethod()`:

```
setMethod("age", "Person", function(x) x@age)
setMethod("age<-", "Person", function(x, value) {
  x@age <- value
  x
})

age(john) <- 50
age(john)
#> [1] 50
```

If you're using an S4 class defined in a package, you can get help on it with `class?Person`. To get help for a method, put `?` in front of a call (e.g. `?age(john)`) and `?` will use the class of the arguments to figure out which help file you need.

Finally, you can use sloop functions to identify S4 objects and generics found in the wild:

```
sloop::otype(john)
#> [1] "S4"
sloop::ftype(age)
#> [1] "S4"      "generic"
```

14.2.1 Exercises

1. `lubridate::period()` returns an S4 class. What slots does it have? What class is each slot? What accessors does it provide?
2. What other ways can you find help for a method? Read `??"?"` and summarise the details.

14.3 Classes

To define an S4 class, call `setClass()` with three arguments:

- The class **name**. By convention, S4 class names use `UpperCamelCase`.

- A named character vector that describes the names and classes of the **slots** (fields). For example, a person might be represented by a character name and a numeric age: `c(name = "character", age = "numeric")`. The pseudo-class **ANY** allows a slot to accept objects of any type.
- A **prototype**, a list of default values for each slot. Technically, the prototype is optional², but you should always provide it.

The code below illustrates the three arguments by creating a **Person** class with character **name** and numeric **age** slots.

```
setClass("Person",
  slots = c(
    name = "character",
    age = "numeric"
  ),
  prototype = list(
    name = NA_character_,
    age = NA_real_
  )
)

me <- new("Person", name = "Hadley")
str(me)
#> Formal class 'Person' [package ".GlobalEnv"] with 2 slots
#> ..@ name: chr "Hadley"
#> ..@ age : num NA
```

14.3.1 Inheritance

There is one other important argument to `setClass()`: **contains**. This specifies a class (or classes) to inherit slots and behaviour from. For example, we can create an **Employee** class that inherits from the **Person** class, adding an extra slot describes their **boss**.

```
setClass("Employee",
  contains = "Person",
  slots = c(
    boss = "Person"
  ),
  prototype = list()
```

²Note that `?setClass` recommends that you avoid the the `prototype` argument, but this is generally considered to be bad advice.

```

    boss = new("Person")
  )
)

str(new("Employee"))
#> Formal class 'Employee' [package ".GlobalEnv"] with 3 slots
#>   ..@ boss:Formal class 'Person' [package ".GlobalEnv"] with 2 slots
#>   ... . . . @ name: chr NA
#>   ... . . . @ age : num NA
#>   ..@ name: chr NA
#>   ..@ age : num NA

```

`setClass()` has 9 other arguments but they are either deprecated or not recommended.

14.3.2 Introspection

To determine what classes an object inherits from, use `is()`:

```

is(new("Person"))
#> [1] "Person"
is(new("Employee"))
#> [1] "Employee" "Person"

```

To test if an object inherits from a specific class, use the second argument of `is()`:

```

is(john, "person")
#> [1] FALSE

```

14.3.3 Redefinition

In most programming languages, class definition occurs at compile-time and object construction occurs later, at run-time. In R, however, both definition and construction occur at run time. When you call `setClass()`, you are registering a class definition in a (hidden) global variable. As with all state-modifying functions you need to use `setClass()` with care. It's possible to create invalid objects if you redefine a class after already having instantiated an object:

```

setClass("A", slots = c(x = "numeric"))
a <- new("A", x = 10)

```

```
setClass("A", slots = c(a_different_slot = "numeric"))
a
#> An object of class "A"
#> Slot "a_different_slot":
#> Error in slot(object, what):
#>   no slot of name "a_different_slot" for this object of class "A"
```

This can cause confusion during interactive creation of new classes. (R6 classes have the same problem, as described in Section 13.2.2.)

14.3.4 Helper

`new()` is a low-level constructor suitable for use by you, the developer. User-facing classes should always be paired with a user-friendly helper. A helper should always:

- Have the same name as the class, e.g. `myclass()`.
- Have a thoughtfully crafted user interface with carefully chosen default values and useful conversions.
- Create carefully crafted error messages tailored towards an end-user.
- Finish by calling by calling `methods::new()`.

The `Person` class is so simple so a helper is almost superfluous, but we can use it to clearly define the contract: `age` is optional but `name` is required. We'll also coerce `age` to a double so the helper also works when passed an integer.

```
Person <- function(name, age = NA) {
  age <- as.double(age)

  new("Person", name = name, age = age)
}

Person("Hadley")
#> An object of class "Person"
#> Slot "name":
#> [1] "Hadley"
#>
#> Slot "age":
#> [1] NA
```

14.3.5 Validator

The constructor automatically checks that the slots have correct classes:

```
Person(mtcars)
#> Error in validObject(.Object):
#>   Error in validObject(.Object): invalid class "Person" object:
#>   invalid object for slot "name" in class "Person": got class
#>   "data.frame", should be or extend class "character"
```

You will need to implement more complicated checks (i.e. checks that involve lengths, or multiple slots) yourself. For example, we might want to make it clear that the Person class is a vector class, and can store data about multiple people. That's not currently clear because `@name` and `@age` can be different lengths:

```
Person("Hadley", age = c(30, 37))
#> An object of class "Person"
#> Slot "name":
#> [1] "Hadley"
#>
#> Slot "age":
#> [1] 30 37
```

To enforce these additional constraints we write a validator with `setValidity()`. It takes class and a function that returns `TRUE` if the input is valid, and otherwise returns a character vector describing the problem(s):

```
setValidity("Person", function(object) {
  if (length(object$name) != length(object$age)) {
    "@name and @age must be same length"
  } else {
    TRUE
  }
})
```

Now we can no longer create an invalid object:

```
Person("Hadley", age = c(30, 37))
#> Error in validObject(.Object):
#>   invalid class "Person" object: @name and @age must be same length
```

Note that the validity method is only called automatically by `new()`, so you can still create an invalid object by modifying it:

```
alex <- Person("Alex", age = 30)
alex@age <- 1:10
```

You can explicitly check the validity yourself by calling `validObject()`:

```
validObject(alex)
#> Error in validObject(alex):
#>   invalid class "Person" object: @name and @age must be same length
```

In Section 14.4.4, we'll use `validObject()` to create accessors can not create invalid objects.

14.3.6 Exercises

1. Extend the `Person` class with fields to match `utils::person()`. Think about what slots you will need, what class each slot should have, and what you'll need to check in your validity method.
2. What happens if you define a new S4 class that doesn't have any slots?
(Hint: read about virtual classes in `?setClass`.)
3. Imagine you were going to reimplement factors, dates, and data frames in S4. Sketch out the `setClass()` calls that you would use to define the classes. Think about appropriate `slots` and `prototype`.

14.4 Generics and methods

The job of a generic is to perform method dispatch, i.e. find the specific implementation for the combination of classes passed to the generic. Here you'll learn how to define S4 generics and methods, then in the next section we'll explore precisely how S4 method dispatch works.

To create a new S4 generic, call `setGeneric()` with a function that calls `standardGeneric()`:

```
setGeneric("myGeneric", function(x) standardGeneric("myGeneric"))
```

By convention, new S4 generics should use `lowerCamelCase`.

It is bad practice to use `{}` in the generic as it triggers a special case that is more expensive, and generally best avoided.

```
# Don't do this!
setGeneric("myGeneric", function(x) {
  standardGeneric("myGeneric")
})
```

14.4.1 Signature

Like `setClass()`, `setGeneric()` has many other arguments. There is only one that you need to know about: `signature`. This allows you to control the arguments that are used for method dispatch. If `signature` is not supplied, all arguments (apart from `...`) are used. It is occasionally useful to remove arguments from dispatch. This allows you to require that methods provide arguments like `verbose = TRUE` or `quiet = FALSE`, but they don't take part in dispatch.

```
setGeneric("myGeneric",
  function(x, ..., verbose = TRUE) standardGeneric("myGeneric"),
  signature = "x"
)
```

14.4.2 Methods

A generic isn't useful without some methods, and in S4 you define methods with `setMethod()`. There are three important arguments: the name of the generic, the name of the class, and the method itself.

```
setMethod("myGeneric", "Person", function(x) {
  # method implementation
})
```

More formally, the second argument to `setMethod()` is called the `signature`. In S4, unlike S3, the signature can include multiple arguments. This makes method dispatch in S4 substantially more complicated, but avoids having to implement double-dispatch as specially. We'll talk more about multiple dispatch in the next section. `setMethod()` has other arguments, but you should never use them.

To list all the methods that belong to a generic, or that are associated with a class, use `methods("generic")` or `methods(class = "class")`; to find the implementation of a specific method, use `selectMethod("generic", "class")`.

14.4.3 Show method

The most commonly defined S4 method controls printing is `show()`, which controls how the object appears when it is printed. To define a method for an existing generic, you must first determine the arguments. You can get those from the documentation or by looking at the `args()` of the generic:

```
args(getGeneric("show"))
#> function (object)
#> NULL
```

Our show method needs to have a single argument `object`:

```
setMethod("show", "Person", function(object) {
  cat(is(object)[[1]], "\n",
      "  Name: ", object@name, "\n",
      "  Age:  ", object@age, "\n",
      sep = ""
)
john
#> Person
#>   Name: John Smith
#>   Age:  50
```

14.4.4 Accessors

Slots should be considered an internal implementation detail: they can change without warning and user code should avoid accessing them directly. Instead, all user-accessible slots should be accompanied by a pair of **accessors**. If the slot is unique to the class, this can just be a function:

```
person_name <- function(x) x@name
```

Typically, however, you'll define a generic so that multiple classes can use the same interface:

```
setGeneric("name", function(x) standardGeneric("name"))
setMethod("name", "Person", function(x) x@name)

name(john)
#> [1] "John Smith"
```

If the slot is also writeable, you should provide a setter function. You should

always `validObject()` in the setter to prevent the user from creating invalid objects.

```
setGeneric("name<-", function(x, value) standardGeneric("name<-"))
setMethod("name<-", "Person", function(x, value) {
  x@name <- value
  validObject(x)
  x
})

name(john) <- "Jon Smythe"
name(john)
#> [1] "Jon Smythe"

name(john) <- letters
#> Error in validObject(x):
#>   invalid class "Person" object: @name and @age must be same length
```

(If the `name<-` notation is unfamiliar, review Section 5.8.)

14.4.5 Exercises

1. Add `age()` accessors for the `Person` class.
2. In the definition of the generic, why is it necessary to repeat the name of the generic twice?
3. Why does the `show()` method defined in Section 14.4.3 use `is(object)[[1]]`.
(Hint: try printing the `employee` subclass.)
4. What happens if you define a method with different argument names to the generic?

14.5 Method dispatch

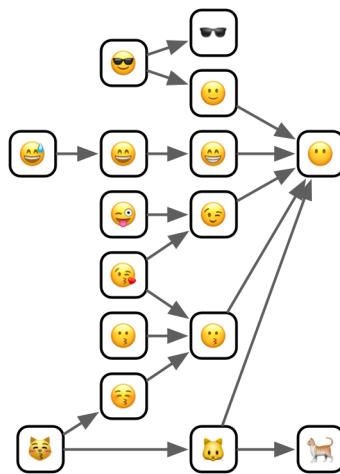
S4 dispatch is complicated because S4 has two important features:

- Multiple inheritance, i.e. a class can have multiple parents,
- Multiple dispatch, i.e. a generic can use multiple arguments to pick a method.

These features make S4 very powerful, but can also make it hard to understand which method will get selected for a given combination of inputs. In practice,

keep method dispatch as simple as possible by avoiding multiple inheritance, and reserving multiple dispatch only for where it is absolutely necessary.

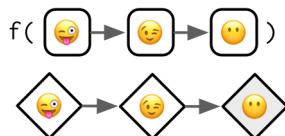
But it's important to describe the full details, so here we'll start simple with single inheritance and single dispatch, and work our way up to the more complicated cases. To illustrate the ideas without getting bogged down in the details, we'll use an imaginary **class graph** based on emoji:



Emoji give us very compact class names that evoke the relationships between the classes. It should be straightforward to remember that 😊 inherits from 😃 which inherits from 😊, and that 😎 inherits from both 😂 and 😃.

14.5.1 Single dispatch

Let's start with the simplest case: a generic function that dispatches on a single class with a single parent. The method dispatch here is simple so it's a good place to define the graphical conventions we'll use for the more complex cases.



There are two parts to this diagram:

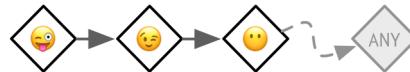
- The top part, $f(\dots)$, defines the scope of the diagram. Here we have a generic with one argument, that has a class hierarchy that is three levels deep.

- The bottom part is the **method graph** and displays all the possible methods that could be defined. Methods that exist, i.e. that have been defined with `setMethod()`, have a grey background.

To find the method that gets called, you start with the most specific class of the actual arguments, then follow the arrows until you find a method that exists. For example, if you called the function with an object of class 😊 you would follow the arrow right to find the method defined for the more general 😊 class. If no method is found, method dispatch has failed and an error is thrown. In practice, this means that you should always define methods for the terminal nodes, i.e. those on the far right.

There are two **pseudo-classes** that you can define methods for. These are called pseudo-classes because they don't actually exist, but allow you to define useful behaviours. The first pseudo-class is **ANY** which matches any class [^s3-default]. For technical reasons that we'll get to later, the link to the **ANY** method is longer than the links between the other classes:

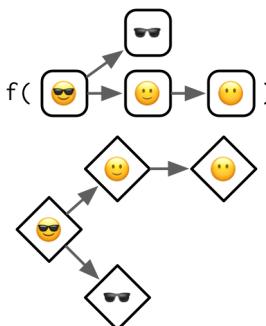
[^s3-default] The S4 **ANY** pseudoclass plays the same role as the S3 **default** pseudo-class.



The second pseudo-class is **MISSING**. If you define a method for this pseudo-class, it will match whenever the argument is missing. It's not useful for single dispatch, but is important for functions like `+` and `-` that use double dispatch and behave differently depending on whether they have one or two arguments.

14.5.2 Multiple inheritance

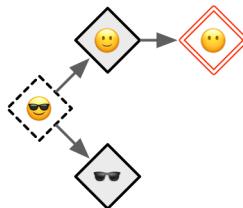
Things get more complicated when the class has multiple parents.



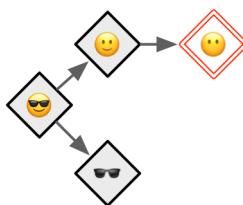
The basic process remains the same: you start from the actual class supplied to the generic, then follow the arrows until you find a defined method. The wrinkle is that now there are multiple arrows to follow, so you might find multiple methods. If that happens, you pick the method that is closest, i.e. requires travelling the fewest arrows.

NB: while the method graph is a powerful metaphor for understanding method dispatch, implementing it in this way would be rather inefficient, so the actual approach that S4 uses is somewhat different. You can read the details in [?Methods_Details](#)

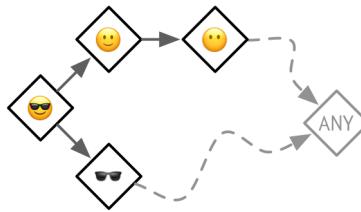
What happens if methods are the same distance? For example, imagine we've defined methods for `vv` and `😊`, and we call the generic with `😎`. Note that no method can be found for the `😊` class, which I'll highlight with a red double outline.



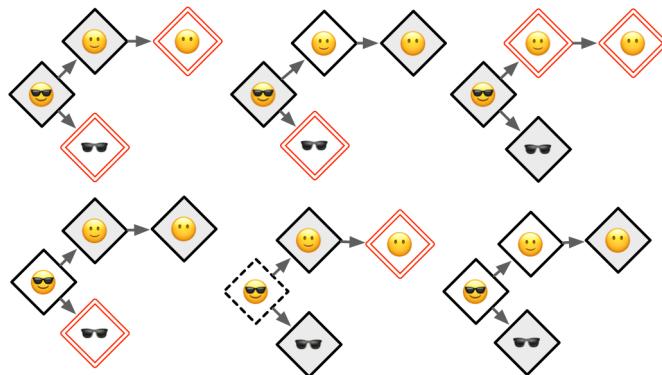
This is called an **ambiguous** method, and in diagrams I'll illustrate it with a thick dotted border. When this happens in R, you'll get a warning, and the method for the class that comes earlier in the alphabet will be picked (this is effectively random and should not be relied upon). When you discover ambiguity you should always resolve it by providing a more precise method:



The fallback `ANY` method still exists but the rules are little more complex. As indicated by the wavy dotted lines, the `ANY` method is always considered further away than a method for a real class. This means that it will never contribute to ambiguity.

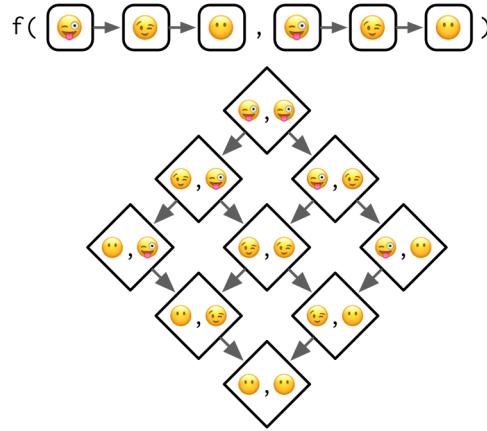


With multiple inheritances it is hard to simultaneously prevent ambiguity, ensure that every terminal method has an implementation, and minimise the number of defined methods (in order to benefit from OOP). For example, of the six ways to define only two methods for this call, only one is free from problems. For this reason, I recommend using multiple inheritance with extreme care: you will need to carefully think about the method graph and plan accordingly.



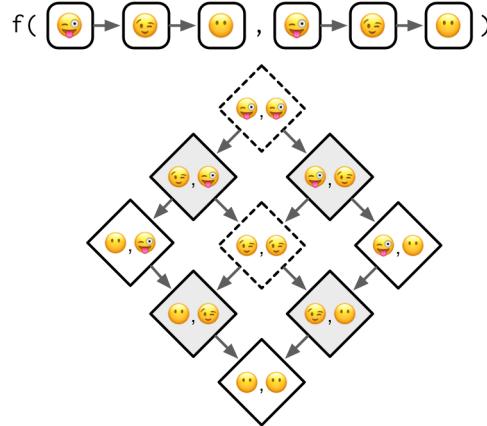
14.5.3 Multiple dispatch

Once you understand multiple inheritance, understanding multiple dispatch is straightforward. You follow multiple arrows in the same way as previously, but now each method is specified by two classes (separated by a comma).



I'm not going to show examples of dispatching on more than two arguments, but you can follow the basic principles to generate your own method graphs.

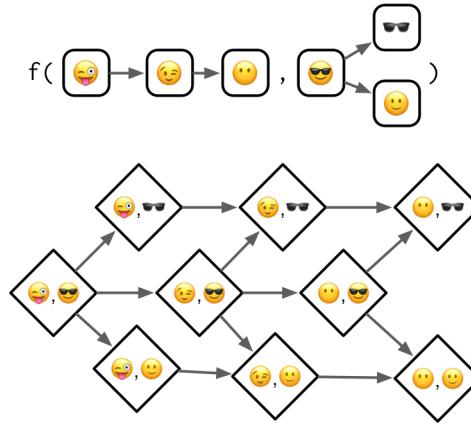
The main difference between multiple inheritance and multiple dispatch is that there are many more arrows to follow. The following diagram shows four defined methods which produce two ambiguous cases:



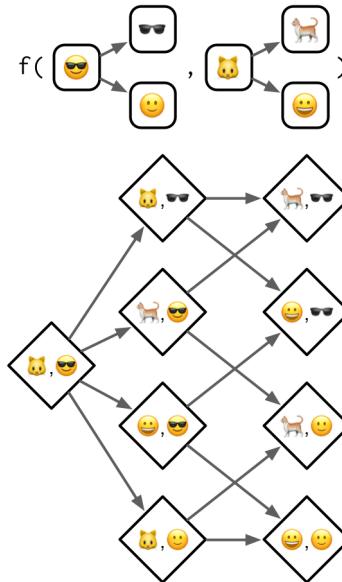
Multiple dispatch tends to be less tricky to work with than multiple inheritance because there are usually fewer terminal class combinations. In this example, there's only one. That means, at a minimum, you can define a single method and have default behaviour for all inputs.

14.5.4 Multiple dispatch and multiple inheritance

Of course you can combine multiple dispatch with multiple inheritance:



A still more complicated case dispatches on two classes, both of which have multiple inheritance:



As the method graph gets more and more complicated it gets harder and harder to predict which method will get called given a combination of inputs, and it gets harder and harder to make sure that you haven't introduced ambiguity. If you have to draw diagrams to figure out what method is actually going to be called, it's a strong indication that you should go back and simplify your design.

14.5.5 Exercises

1. Draw the method graph for $f(\text{医治}, \text{感冒})$.
2. Draw the method graph for $f(\text{微笑}, \text{哭泣}, \text{睡觉})$.
3. Take the last example which shows multiple dispatch over two classes that use multiple inheritance. What happens if you define a method for all terminal classes? Why does method dispatch not save us much work here?

14.6 S4 and S3

When writing S4 code, you'll often need to interact with existing S3 classes and generics. This section describes how S4 classes, methods, and generics interact with existing code.

14.6.1 Classes

In `slots` and `contains` you can use S4 classes, S3 classes, or the implicit class (Section 12.7.1) of a base type. To use an S3 class, you must first register it with `setOldClass()`. You call this function once for each S3 class, giving it the class attribute. For example, the following definitions are already provided by base R:

```
setOldClass("data.frame")
setOldClass(c("ordered", "factor"))
setOldClass(c("glm", "lm"))
```

However, it's generally better to be more specific and provide a full S4 definition with `slots` and a `prototype`:

```
setClass("factor",
  contains = "integer",
  slots = c(
    levels = "character"
  ),
  prototype = structure(
    integer(),
    levels = character()
  )
)
setOldClass("factor", S4Class = "factor")
```

Generally, these definitions should be provided by the creator of the S3 class. If you’re trying to build an S4 class on top of an S3 class provided by a package, you should request that the package maintainer add this call to their package, rather than adding it to your own code.

If an S4 object inherits from an S3 class or a base type, it will have a special virtual slot called `.Data`. This contains the underlying base type or S3 object:

```
RangedNumeric <- setClass(
  "RangedNumeric",
  contains = "numeric",
  slots = c(min = "numeric", max = "numeric"),
  prototype = structure(numeric(), min = NA_real_, max = NA_real_)
)
rn <- RangedNumeric(1:10, min = 1, max = 10)
rn@min
#> [1] 1
rn@.Data
#> [1] 1 2 3 4 5 6 7 8 9 10
```

It is possible to define S3 methods for S4 generics, and S4 methods for S3 generics (provided you’ve called `setOldClass()`). However, it’s more complicated than it might appear at first glance, so make sure you thoroughly read [?Methods_for_S3](#).

14.6.2 Generics

As well as creating a new generic from scratch, it’s also possible to convert an existing S3 generic to an S4 generic:

```
setGeneric("mean")
```

In this case, the existing function becomes the default (ANY) method:

```
selectMethod("mean", "ANY")
#> Method Definition (Class "derivedDefaultMethod"):
#>
#> function (x, ...)
#> UseMethod("mean")
#> <bytecode: 0x303e8f0>
#> <environment: namespace:base>
#>
#> Signatures:
#>      x
```

```
#> target "ANY"  
#> defined "ANY"
```

Note that `setMethod()` will automatically call `setGeneric()` if the first argument isn't already a generic, enabling you to turn any existing function into an S4 generic. It is ok to convert an existing S3 generic to S4, but you should avoid converting regular functions to S4 generics in packages because requires careful coordination if done by multiple packages.

14.6.3 Exercises

1. What would a full `setOldClass()` definition look like for an ordered factor?
(i.e. add `slots` and `prototype` the definition above)
2. Define a `length` method for the `Person` class.

Chapter 15

Trade-offs

15.1 Introduction

You now know about the three most important OOP toolkits available in R. Now that you understand their basic operation and the principles that underlie them, we can start to compare and contrast the systems in order to understand their strengths and weaknesses. This will help you pick the system that is most likely to solve new problems.

Overall, when picking an OO system, I recommend that you default to S3. S3 is simple, and widely used throughout base R and CRAN. While it's far from perfect, its idiosyncracies are well understood and there are known approaches to overcome most shortcomings. If you have an existing background in programming you are likely to lean towards R6, because it will feel familiar. I think you should resist this tendency for two reasons. Firstly, if you use R6 it's very easy to create a non-idiomatic API that will feel very odd to native R users, and will have surprising pain points because of the reference semantics. Secondly, if you stick to R6, you'll lose out on learning a new way of thinking about OOP that gives you a new set of tools for solving problems.

Outline

This chapter is divided into two parts. S4 vs S3 compares S3 and S4. In brief, S4 is more formal and tends to require more upfront planning. That makes it more suitable for big projects developed by teams, not individuals. R6 vs S3 compares S3 and R6. This section is quite long because these two systems are

fundamentally different and there are a number of tradeoffs that you need to consider.

15.2 S4 vs S3

Once you've mastered S3, S4 is not too difficult to pick up: the underlying ideas are the same, S4 is just more formal, more strict, and more verbose. The strictness and formality of S4 make it well suited for large teams. Since more structure is provided by the system itself, there is less need for convention, and new contributors don't need as much training. S4 tends to require more upfront design than S3, and this investment is more likely to pay off on larger projects where greater resources are available.

One large team effort where S4 is used to good effect is Bioconductor. Bioconductor is similar to CRAN: it's a way of sharing packages amongst a wider audience. Bioconductor is smaller than CRAN (~1,300 vs ~10,000 packages, July 2017) and the packages tend to be more tightly integrated because of the shared domain and because Bioconductor has a stricter review process. Bioconductor packages are not required to use S4, but most will because the key data structures (e.g. `SummarizedExperiment`, `IRanges`, `DNAStringSet`) are built using S4.

S4 is also a good fit for complex systems of interrelated objects, and it's possible to minimise code duplication through careful implementation of methods. The best example of such a system is the `Matrix` package (Bates and Maechler 2018). It is designed to efficiently store and compute with many different types of sparse and dense matrices. As of version 1.2.14, it defines 102 classes, 21 generic functions, and 1993 methods, and to give you some idea of the complexity, a small subset of the class graph is shown in Figure 15.1.

This domain is a good fit for S4 because there are often computational shortcuts for specific combinations of sparse matrices. S4 makes it easy to provide a general method that works for all inputs, and then provide more specialised methods where the inputs allow a more efficient implementation. This requires careful planning to avoid method dispatch ambiguity, but the planning pays off with higher performance.

The biggest challenge to using S4 is the combination of increased complexity and absence of a single source of documentation. S4 is a complex system and it can be challenging to use effectively in practice. This wouldn't be such a problem if S4 documentation wasn't scattered through R documentation, books, and websites. S4 needs a book length treatment, but that book does not (yet) exist. (The documentation for S3 is no better, but the lack is less painful because S3 is much

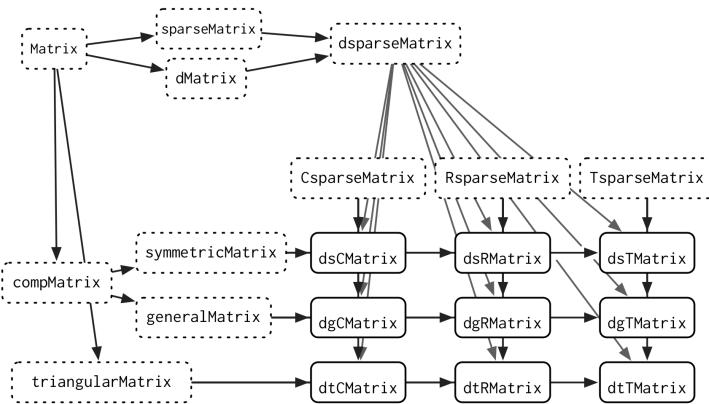


Figure 15.1: A small subset of the Matrix class graph showing the inheritance of sparse matrices. Each concrete class inherits from two virtual parents: one that describes how the data is stored (C = column oriented, R = row oriented, T = tagged) and one that describes any restriction on the matrix (s = symmetric, t = triangle, g = general)

simpler.)

15.3 R6 vs S3

R6 is a profoundly different OO system from S3 and S4 because it is built on encapsulated objects, rather than generic functions. Additionally R6 objects have reference semantics, which means that they can be modified in place. These two big differences have a number of non-obvious consequences which we'll explore here:

- A generic is a regular function so lives in the global namespace. An R6 method belongs to an object so lives in a local namespace. This influences how we think about naming.
- R6's reference semantics allow methods to simultaneously return a value and modify an object. This solves a painful problem called "threading state".
- You invoke an R6 method using `$`, which is an infix operator. If you set up your methods correctly you can use chains of method calls as an alternative to the pipe.

These are general trade-offs between functional and encapsulated OOP, so they

also serve as a discussion of system design in R vs Python.

15.3.1 Namespacing

One non-obvious difference between S3 and R6 is the “space” in which methods are found:

- Generic functions are global: all packages share the same namespace.
- Encapsulated methods are local: methods are bound to a single object.

The advantage of a global namespace is that multiple packages can use the same verbs for working with different types of objects. Generic functions provide a uniform API that makes it easier to perform typical actions with a new object because there are strong naming conventions. This works well for data analysis because you often want to do the same thing to different types of objects. In particular, this is one reason that R’s modelling system is so useful: regardless of where the model has been implemented you always work with it using the same set of tools (`summary()`, `predict()`, ...).

The disadvantage of a global namespace is that it forces you to think more deeply about naming. You want to avoid multiple generics with the same name in different packages because it requires the user to type `::` frequently. This can be hard because function names are usually English verbs, and verbs often have multiple meanings. Take `plot()` for example:

```
plot(data)      # plot some data
plot(bank_heist) # plot a crime
plot(land)      # create a new plot of land
plot(movie)     # extract plot of a movie
```

Generally, you should avoid methods that are homonyms of the original generic, and instead define a new generic.

This problem doesn’t occur with R6 methods because they are scoped to the object. The following code is fine, because there is no implication that the `plot` method of two different R6 objects has the same meaning:

```
data$plot()
bank_heist$plot()
land$plot()
movie$plot()
```

These considerations also apply to the arguments to the generic. S3 generics must have the same core arguments, which mean they generally have non-specific

names like `x` or `.data`. S3 generics generally need `...` to pass on additional arguments to methods, but this has the downside that misspelled argument names will not create an error. In comparison, R6 methods can vary more widely and use more specific and evocative argument names.

A secondary advantage of local namespacing is that creating an R6 method is very cheap. Most encapsulated OO languages encourage you to create many small methods, each doing one thing well with an evocative name. Creating a new S3 method is more expensive, because you may also have to create a generic, and think about the naming issues described above. That means that the advice to create many small methods does not apply to S3. It's still a good idea to break your code down into small, easily understood chunks, but they should generally just be regular functions, not methods.

15.3.2 Threading state

One challenge of programming with S3 is when you want to both return a value and modify the object. This violates our guideline that a function should either be called for its return value or for its side effects, but is necessary in a handful of cases.

For example, imagine you want to create a `stack` of objects. A stack has two main methods:

- `push()` adds a new object to the top of the stack.
- `pop()` returns the top most value, and removes it from the stack.

The implementation of the constructor and the `push()` method is straightforward. A stack contains a list of items, and pushing an object to the stack simply appends to this list.

```
new_stack <- function(items = list()) {
  structure(list(items = items), class = "stack")
}

push <- function(x, y) {
  x$items <- c(x$items, list(y))
  x
}
```

(Note that I haven't created a real method for `push()` because making it generic would just make this example more complicated for no real benefit.)

Implementing `pop()` is more challenging because it has to both return a value

(the object at the top of the stack), and have a side-effect (remove that object from that top). Since we can't modify the input object in S3 we need to return two things: the value, and the updated object.

```
pop <- function(x) {
  n <- length(x$items)

  item <- x$items[[n]]
  x$items <- x$items[-n]

  list(item = item, x = x)
}
```

This leads to rather awkward usage:

```
s <- new_stack()
s <- push(s, 10)
s <- push(s, 20)

out <- pop(s)
out$item
#> [1] 20
s <- out$x
s
#> $items
#> $items[[1]]
#> [1] 10
#>
#>
#> attr("class")
#> [1] "stack"
```

This problem is known as **threading state** or **accumulator programming**, because no matter how deeply the `pop()` is called, you have to thread the modified stack object all the way back to where it lives.

One way that other FP languages deal with this challenge is to provide a **multiple assign** (or destructuring bind) operator that allows you to assign multiple values in a single step. The `zeallot` package (Teetor 2018) provides multi-assign for R with `%<-%`. This makes the code more elegant, but doesn't solve the key problem:

```
library(zeallot)

c(value, s) %<-% pop(s)
```

```
value
#> [1] 10
```

An R6 implementation of a stack is simpler because `$pop()` can modify the object in place, and return only the top-most value:

```
Stack <- R6::R6Class("Stack", list(
  items = list(),
  push = function(x) {
    self$items <- c(self$items, x)
    invisible(self)
  },
  pop = function() {
    item <- self$items[[self$length()]]
    self$items <- self$items[-self$length()]
    item
  },
  length = function() {
    length(self$items)
  }
))
```

This leads to more natural code:

```
s <- Stack$new()
s$push(10)
s$push(20)
s$pop()
#> [1] 20
```

I encountered a real-life example of threading state in ggplot2 scales. Scales are complex because they need to combine data across every facet and every layer. I originally used S3 classes, but it required passing scale data to and from many functions. Switching to R6 made the code substantially simpler. However, it also introduced some problems because I forgot to call to `$clone()` when modifying a plot. This allowed independent plots to share the same scale data, creating a subtle bug that was hard to track down.

15.3.3 Method chaining

The pipe, `%>%`, is useful because it provides an infix operator that makes it easy to compose functions from left-to-right. Interestingly, the pipe is not so important for R6 objects because they already use an infix operator: `$`. This allows the

user to chain together multiple method calls in a single expression, a technique known as **method chaining**:

```
s <- Stack$new()
s$  
  push(10)$
  push(20)$
  pop()
#> [1] 20
```

This technique is commonly used in other programming languages, like Python and JavaScript, and is made possible with one convention: any R6 method that is primarily called for its side-effects (usually modifying the object) should return `invisible(self)`.

The primary advantage of method chaining is that you can get useful autocomplete; the primary disadvantage is that only the creator of the class can add new methods (and there's no way to use multiple dispatch).

Part IV

Metaprogramming

Introduction

One of the most intriguing things about R is its capability for **metaprogramming**: the idea that code is itself data, and can be inspected and modified programmatically. This is a powerful idea and deeply influences much R code. At a simple level this tooling allows you to write `library(purrr)` instead of `library("purrr")` and enables `plot(x, sin(x))` to label the axes with `x` and `sin(x)`. At a deeper level it allows `y ~ x1 + x2` to represent a model that predicts the value of `y` from `x1` and `x2`. It allows `subset(df, x == y)` to be translated to `df[df$x == df$y, , drop = FALSE]`, and for `dplyr::filter(db, is.na(x))` to generate the SQL `WHERE x IS NULL` when `db` is a remote database table.

Closely related to metaprogramming is **non-standard evalution**, or NSE for short. This a term that's commonly used to describe the behaviour of R functions, but there are two problems with the term that lead me to avoid it. Firstly, NSE is actually a property of an argument (or arguments) of a function, so talking about NSE functions is a little sloppy. Secondly, it's confusing to define something by what it is not (standard), so in this book I'll teach you more precise vocabulary.

In particular, this book focusses on tidy evaluation, or tidy eval for short. Tidy eval which is made up of three major ideas: quasiquotation, quosures, and data masks. This book focusses on the theoetical side of tidy evaluation, so you can fully understand how it works from the ground up. If you are looking for a practical introduction, I recommend the “tidy evaluation book”, <https://tidyeval.tidyverse.org>¹.

Metaprogramming is the hardest topic in this book because it brings together many formerly unrelated topics and forces you grapple with issues that you haven't thought about before. Don't be surprised if you're frustrated or confused at first; this is a natural part of the process that happens to everyone!

¹The tidy evaluation book is a work-in-progress at the time I wrote this chapter, but will hopefully be finished by the time you read it!

15.4 Big ideas

But before you dive into details, I wanted to give you an overview of the most important ideas and vocabulary of metaprogramming::

- Code is data; captured code is called an expression.
- Code has a tree-like structure called an abstract syntax tree.
- Expressions can be generated by code.
- Evaluation executes an expression in an environment.
- Evaluation can be customised by modifying or overriding the environment.
- Data masks blur environments and data frames.
- A quosure captures an expression with its environment.

Below, I'll use tools primarily from the `rlang` package, as it allows you to focus on the big ideas, rather than implementation quirks that arise from R's history. This approach seems backward to some, but it's analogous to learning how to drive an automatic transmission before a manual transmission so you can focus on the big picture before learning the details.

```
library(rlang)
```

15.4.1 Code is data

The first big idea is that code is data: you can capture code and compute on it like any other type of data. To compute on code, you first need some way to capture it. The first function that captures code is `rlang::expr()`. You can think of it returning exactly what you pass in:

```
expr(mean(x, na.rm = TRUE))
#> mean(x, na.rm = TRUE)
expr(10 + 100 + 1000)
#> 10 + 100 + 1000
```

More formally, captured code is called an **expression**. An expression isn't a single type of object, but is a collective term for any of four types (call, symbol, constant, or pairlist), which you'll learn more about in Chapter 16.

`expr()` lets you capture code that you've typed. You need a different tool to capture code passed to a function because `expr()` doesn't work:

```
capture_it <- function(x) {
  expr(x)
}
```

```
capture_it(a + b + c)
#> x
```

Here you need to use a function specifically designed to capture user input in a function argument: `enexpr()`.

```
capture_it <- function(x) {
  enexpr(x)
}
capture_it(a + b + c)
#> a + b + c
```

Once you have captured an expression, you can inspect and modify it. Complex expressions behave much like lists. That means you can modify them using `[[` and `$`:

```
f <- expr(f(x = 1, y = 2))

# Add a new argument
f$z <- 3
f
#> f(x = 1, y = 2, z = 3)

# Or remove an argument:
f[[2]] <- NULL
f
#> f(y = 2, z = 3)
```

Note that the first element of the call is the function to be called, which means the first argument is in the second position. You'll learn about the full details in Section 16.3.3.

15.4.2 Code is a tree

To do more complex manipulation with code, you need to fully understand its structure. Behind the scenes, almost every programming language represents code as a tree, often called the **abstract syntax tree**, or AST for short. R is unusual in that you can actually inspect and manipulate this tree.

A very convenient tool for understanding the tree-like structure is `lobstr::ast()`. Given some code, will display the underlying tree structure. Function calls form the branches of the tree, and are shown by rectangles. The leaves of the tree are symbols (like `a`) and constants (like "b").

```
lobstr::ast(f(a, "b"))
#> f
#> a
#> "b"
```

Nested function calls create more deeply branching trees:

```
lobstr::ast(f1(f2(a, b), f3(1, f4(2))))
#> f1
#> f2
#> a
#> b
#> f3
#> 1
#> f4
#> 2
```

Because all function forms in can be written in prefix form (Section 5.8.2), every R expression can be displayed in this way:

```
lobstr::ast(1 + 2 * 3)
#> `+`
#> 1
#> `*`
#> 2
#> 3
```

Displaying the code tree in this way provides useful tools for exploring R’s grammar, the topic of Section 16.4.

15.4.3 Code can generate code

As well as seeing the tree from code typed by a human, you can also use code to create new trees. There are two main tools: `call2()` and unquoting.

`rlang::call2()` constructs a function call from its components: the function to call, and the arguments to call it with.

```
call2("f", 1, 2, 3)
#> f(1, 2, 3)
call2("+", 1, call2("*", 2, 3))
#> 1 + 2 * 3
```

This is often convenient to program with, but is a bit clunkly for interactive use.

An alternative technique is to build complex code trees by combining simpler code trees with a template. `expr()` and `enexpr()` have built-in support for this idea via `!!` (pronounced bang-bang), the **unquote operator**.

The precise details are the topic of Chapter 17, but basically `!!x` inserts the code tree stored in `x`. This makes it easy to build complex trees from simple fragments:

```
xx <- expr(x + x)
yy <- expr(y + y)

expr (!!xx / !!yy)
#> (x + x)/(y + y)
```

Notice that the output preserves the operator precedence so we get `(x + x) / (y + y)` not `x + x / y + y` (i.e. `x + (x / y) + y`). This is important to note, particularly if you've been thinking "wouldn't this be easier to do by pasting strings?".

Unquoting gets even more useful when you wrap it up into a function, first using `enexpr()` to capture the user's expression, then `expr()` and `!!` to create a new expression using a template. The example below shows you might generate an expression that computes the coefficient of variation:

```
cv <- function(var) {
  var <- enexpr(var)
  expr(mean (!!var) / sd (!!var))
}

cv(x)
#> mean(x)/sd(x)
cv(x + y)
#> mean(x + y)/sd(x + y)
```

Importantly, this works even when given weird variable names:

```
cv(``)
#> mean(``)/sd(``)
```

Dealing with non-syntactic variable names is another good reason to `paste()` when generating R code. You might think this is an esoteric concern, but not worrying about it when generating SQL code in web applications lead to SQL injection attacks that have collectively cost billions of dollars.

These techniques become yet more powerful when combined with functional programming. You'll explore these ideas in detail in Section ?? but the teaser belows

shows how you might generate a complex model specification from simple inputs.

```
library(purrr)
#>
#> Attaching package: 'purrr'
#> The following objects are masked from 'package:rlang':
#>
#>     %>%, %/%, as_function, flatten, flatten_chr,
#>     flatten_dbl, flatten_int, flatten_lgl, invoke,
#>     list_along, modify, prepend, rep_along, splice

poly <- function(n) {
  i <- as.double(seq(2, n))
  xs <- c(1, expr(x), map(i, function(i) expr(I(x^!i))))
  terms <- reduce(xs, call2, .fn = "+")
  expr(y ~ !!terms)
}
poly(5)
#> y ~ 1 + x + I(x^2) + I(x^3) + I(x^4) + I(x^5)
```

15.4.4 Evaluation executes an expression in an environment

Inspecting and modifying code gives you one set of powerful tools. You get another set of powerful tools when you **evaluate**, i.e. execute, an expression. Evaluating an expression requires an environment. This tells R what the symbols (found in the leaves of tree) mean. You'll learn the details of evaluation in Chapter 18.

The primary tool for evaluating expressions is `base:::eval()`, which takes an expression and an environment:

```
eval(expr(x + y), env(x = 1, y = 10))
#> [1] 11
eval(expr(x + y), env(x = 2, y = 100))
#> [1] 102
```

If you omit the environment, it will use the current environment. Here that's the global environment:

```
x <- 10
y <- 100
eval(expr(x + y))
#> [1] 110
```

One of the big advantages of evaluating code manually is that you can tweak the execution environment. There are two main reasons to do this:

- To temporarily override functions to implement a domain specific language.
- To add a data mask so you can refer to variables in a data frame as if they are variables in an environment.

15.4.5 You can override functions to make a DSL

It's fairly straightforward to understand customising the environment with different variable values. It's less obvious that you can also rebind functions to do different things. This is a big idea that we'll come back to in Chapter ??, but I wanted to show a small example here.

The example below evaluates code in a special environment where the basic algebraic operators (+, -, *, /) have been overridden to work with string instead of numbers:

```
string_math <- function(x) {
  e <- env(
    caller_env(),
    `+` = function(x, y) paste0(x, y),
    `*` = function(x, y) strrep(x, y),
    ` -` = function(x, y) sub(paste0(y, "$"), "", x),
    `/` = function(x, y) substr(x, 1, nchar(x) / y)
  )

  eval(enexpr(x), e)
}

name <- "Hadley"
string_math("Hi" - "i" + "ello" + name)
#> [1] "Hello Hadley"
string_math("x-" * 3 + "y")
#> [1] "x-x-x-y"
```

dplyr takes this idea to the extreme, running code in an environment that generates SQL for execution in a remote database:

```
library(dplyr)

con <- DBI::dbConnect(RSQLite::SQLite(), filename = ":memory:")
mtcars_db <- copy_to(con, mtcars)
```

```

mtcars_db %>%
  filter(cyl > 2) %>%
  select(mpg:hp) %>%
  head(10) %>%
  show_query()
#> <SQL>
#> SELECT `mpg`, `cyl`, `disp`, `hp`
#> FROM `mtcars`
#> WHERE (`cyl` > 2.0)
#> LIMIT 10

DBI::dbDisconnect(con)

```

15.4.6 Data masks blur the line between data frames and environments

Rebinding functions is an extremely powerful technique, but it tends to require a lot of investment. A more immediately practical application is modifying evaluation to look for variables in a data frame instead of an environment. This idea powers the base `subset()` and `transform()` functions, as well as many tidyverse functions like `ggplot2::aes()` and `dplyr::mutate()`. It's possible to use `eval()` for this, but there are a few potential pitfalls, so we'll use `rlang::eval_tidy()` instead.

As well as expression and environment, `eval_tidy()` also takes a **data mask**, which is typically a data frame:

```

df <- data.frame(x = 1:5, y = sample(5))
eval_tidy(expr(x + y), df)
#> [1] 2 6 5 9 8

```

Evaluating with a data mask is a useful technique for interactive analysis because it allows you to write `x + y` rather than `df$x + df$y`. However, that convenience comes at a cost: ambiguity. In Section 18.5.2 you'll learn how to deal with ambiguity using special `.data` and `.env` pronouns.

We can wrap this pattern up into a function by using `enexpr()`. This gives us a function very similar to `base::with()`:

```

with2 <- function(df, expr) {
  eval_tidy(enexpr(expr), df)
}

```

```
with2(df, x + y)
#> [1] 2 6 5 9 8
```

Unfortunately, however, this function has a subtle bug, and we need a new data structure to deal with it.

15.4.7 Quosures capture an expression with its environment

To make the problem more obvious, I'm going to modify `with2()`:

```
with2 <- function(df, expr) {
  a <- 1000
  eval_tidy(enexpr(expr), df)
}
```

(The problem occurs without this modification but it's a subtler and creates error messages that are harder to understand.)

We can see the problem if we attempt to use `with2()` mingling a variable from the data frame, and a variable called `a` in the current environment:

```
df <- data.frame(x = 1:3)
a <- 10
with2(df, x + a)
#> [1] 1001 1002 1003
```

That's because we really want to evaluate the captured expression in the environment where it was written (where `a` is 10), not the environment inside of `with2()` (where `a` is 1000).

Fortunately we can solve this problem by using a new data structure: the **quosure** which bundles an expression with an environment. `eval_tidy()` knows how to work with quosures so all we need to do is switch out `enexpr()` for `enquo()`:

```
with2 <- function(df, expr) {
  a <- 1000
  eval_tidy(enquo(expr), df)
}

with2(df, x + a)
#> [1] 11 12 13
```

Whenever you use a data mask, you must always use `enquo()` instead of `enexpr()`. This is the topic of Chapter 18.

Overview

In the following chapters, you’ll learn about the three pieces that underpin metaprogramming:

- In **Expressions**, Chapter 16, you’ll learn that all R code forms a tree. You’ll learn how to visualise that tree, how the rules of R’s grammar convert linear sequences of characters into a tree, and how to use recursive functions to work with code trees.
- In **Quasiquotation**, Chapter 17, you’ll learn to use tools from `rlang` to capture (“quote”) unevaluated function arguments. You’ll also learn about quasiquotation, which provides a set of techniques for “unquoting” input that makes it possible to easily generate new trees from code fragments.
- In **Evaluation**, Chapter 18, you’ll learn about the inverse of quotation: evaluation. Here you’ll learn about an important data structure, the **quosure**, which ensures correct evaluation by capturing both the code to evaluate, and the environment in which to evaluate it. This chapter will show you how to put all the pieces together to understand how NSE in base R works, and how to write your own functions that work like `subset()`.
- Finally, in **Translating R code**, Chapter 19, you’ll see how to combine first-class environments, lexical scoping, and metaprogramming to translate R code into other languages, namely HTML and LaTeX.

Each chapter follows the same basic structure. You’ll get the lay of the land in introduction, then see a motivating example. Next you’ll learn the big ideas using functions from the `rlang` package (Henry and Wickham 2018), and then we’ll circle back to talk about how those ideas are expressed in base R.

Chapter 16

Expressions

16.1 Introduction

To compute on the language, we first need to understand its structure. That requires some new vocabulary, some new tools, and some new ways of thinking about R code. The first thing you'll need to understand is the distinction between an operation and its result. Take the following code, which takes a variable `x`, multiplies it by 10, and saves the result to a new variable called `y`. It doesn't work because we haven't defined a variable called `x`:

```
y <- x * 10
#> Error in eval(expr, envir, enclos):
#>   object 'x' not found
```

It would be nice if we could capture the intent of the code, without executing it. In other words, how can we separate our description of the action from the action itself? One way is to use `rlang::expr()`:

```
z <- rlang::expr(y <- x * 10)
z
#> y <- x * 10
```

`expr()` returns an expression, an object that captures the structure of the code without evaluating it (i.e. running it). If you have an expression, you can evaluate it with `base::eval()`:

```
x <- 4
eval(z)
y
```

```
#> [1] 40
```

The focus of this chapter is the data structures that underlie expressions. Mastering this knowledge will allow you to inspect and modify captured code. We'll come back to `expr()` in Section ??, and to `eval()` in Section 18.2.

Outline

Prerequisites

Make sure you've read the metaprogramming overview in Chapter IV to get a broad overview of the motivation and the basic vocabulary. You'll also need the `rlang` package to capture and compute on expressions, and the `lobstr` package to visualise them.

```
library(rlang)

# devtools::install_github("r-lib/lobstr")
library(lobstr)
```

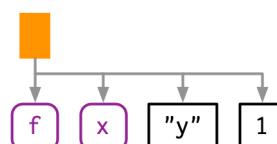
16.2 Abstract syntax trees

Expressions are also called **abstract syntax trees** (ASTs) because the structure of code is hierarchical and can be naturally represented as a tree. Understanding this tree structure is crucial for inspecting and modifying expressions (i.e. metaprogramming).

16.2.1 Drawing

So we'll start by introducing some conventions for drawing ASTs, starting with a simple call that shows the main components: `f(x, "y", 1)`. I'll draw trees in two ways:

- By “hand” (with omnigraffle):



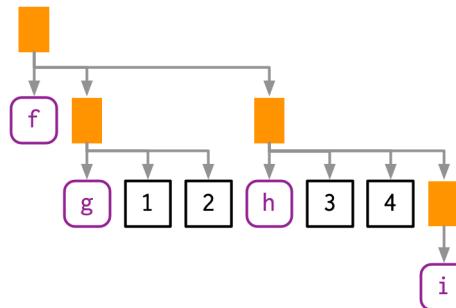
- With `lobstr::ast()`¹:

```
lobstr::ast(f(x, "y", 1))
#> f
#> x
#> "y"
#> 1
```

Both approaches share conventions as much as possible:

- The leaves of the tree are either symbols, like `f` and `x`, or constants, like `1` or `"y"`. Symbols are drawn in purple and have rounded corners. Constants have black borders and square corners. Strings and symbols are easily confused, so strings are always surrounded in quotes.
- The branches of the tree are function calls, represented by call objects and drawn as orange squares. The first child (`f`) is the function that gets called; the second and subsequent children (`x`, `"y"`, and `1`) are the arguments to that function.

The above example only contained one function call, making for a very shallow tree. Most expressions will contain considerably more calls, creating trees with multiple levels of hierarchy. For example, consider `f(g(1, 2), h(3, 4, i()))`:



```
lobstr::ast(f(g(1, 2), h(3, 4, i())))
#> f
#> g
#> 1
#> 2
#> h
#> 3
#> 4
```

¹For more complex code, you can also use RStudio's tree viewer which doesn't obey quite the same graphical conventions, but allows you to interactively explore the AST. Try it out with `View(expr(f(x, "y", 1)))`.

```
#>     i
```

You can read the hand-drawn diagrams from left-to-right (ignoring vertical position), and the lobstr-drawn diagrams from top-to-bottom (ignoring horizontal position). The depth within the tree is determined by the nesting of function calls. This also determines evaluation order, as evaluation generally proceeds from deepest-to-shallowest (but this is not guaranteed because of lazy evaluation, Section 5.5). Also note the appearance of `i()`, a function call with no arguments; it's a branch with a single (symbol) leaf.

16.2.2 Non-code components

You might have wondered why these are *abstract* syntax trees. They are abstract because they only capture important structural details of the code, not whitespace or comments:

```
ast(
  f(x,  y)  # important!
)
#>  f
#>  x
#>  y
```

There's one important situation where whitespace does affect the AST:

```
lobstr::ast(y <- x)
#> `<-`
#>  y
#>  x
lobstr::ast(y < -x)
#> `<`
#>  y
#>  `-`
#>  x
```

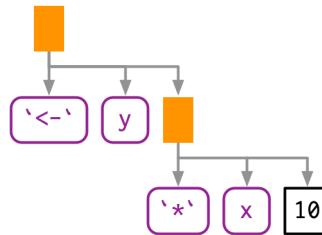
16.2.3 Infix calls

Every call in R can be written in tree form, even if it doesn't look like it at first glance. Take `y <- x * 10` again: what are the functions that are being called? It is not as easy to spot as `f(x, 1)` because this expression contains two infix calls: `<-` and `*`.

However, as discussed in Section 5.8.1, any call can be rewritten in prefix form. That means that these two lines of code are equivalent:

```
y <- x * 10
`<-`(y, `*`(x, 10))
```

And they both have this AST²:



```
lobstr::ast(y <- x * 10)
#> `<-`
#> y
#> `*`
#> x
#> 10
```

There really is no difference between the ASTs, and if you generate an expression with prefix calls, R will still print them in infix form:

```
expr(`<-`(y, `*`(x, 10)))
#> y <- x * 10
```

The order in which infix operators are applied is governed by a set of rules called operator precedence. In Section 16.4.1 we'll use `lobstr::ast()` to explore R's rules.

16.2.4 Exercises

1. Reconstruct the code represented by the trees below:

```
#> f
#> g
#> h
#> `+`
#> `+`
```

²The names of non-prefix functions are non-syntactic so I show them with ```, as in Section 2.2.1.

```
#> 1
#> 2
#> 3
#> `*`
#> `(` 
#> `+` 
#> x
#> y
#> z
```

2. Draw the following trees by hand then check your answers with `lobstr::ast()`.

```
f(g(h(i(1, 2, 3))))
f(1, g(2, h(3, i())))
f(g(1, 2), h(3, i(4, 5)))
```

3. How are function factories (Chapter 9) show in the AST? What makes the ASTs of the expressions below special?

```
lobstr::ast(f(x)(y))
#> f
#> x
#> y
lobstr::ast(f(1)(2)(3)(4))
#> f
#> 1
#> 2
#> 3
#> 4
```

4. What's happening with the ASTs below? (Hint: carefully read ?"~")

```
lobstr::ast(`x` + `y`)
#> `+` 
#> x
#> y
lobstr::ast(x ** y)
#> `^` 
#> x
#> y
lobstr::ast(1 -> x)
#> `->` 
#> x
```

```
#> 1
```

5. What is special about the AST below? (Hint: re-read Section ??)

```
lobstr::ast(function(x, y) x + y)
#> `function`
#> x = ``
#> y = ``
#> `+`
#> x
#> y
#> <inline srcref>
```

6. What does the call tree of an `if` statement with multiple `else if` conditions look like? Why?

16.3 Expressions

Collectively, the data structures present in the AST are called expressions. More precisely, an **expression** is any member of the set of base types created by parsing code: constant scalars, symbols, call objects. These are the data structures used to represent captured code from `expr()`, and so `is_expression(expr(...))` is always true³. In the subsequent sections, we'll come back to define each of these types precisely, and show you how to create, inspect, and modify them.

There are couple of data structures that we'll come back to later. Pairlists are used in one place, but behave identically to lists; we'll discuss them in Section 16.6.1. There also a special symbol used to represent missing arguments, we'll come back to that in Section 16.6.2.

NB: In base R documentation “expression” is used to mean two things. As well as the definition above, expression is also used to refer to the type of object returned by `expression()` and `parse()`, which are basically lists of expressions as defined above. In this book I'll call these **expression vectors**, and I'll come back to them in Section 16.6.3.

16.3.1 Constants

Constants are the simplest component of the AST, and use data structures that you learned about in Chapter ???. More precisely, a **constant** is either `NULL` or

³It is *possible* to insert any other base type into an expression, but this is unusual and only needed in rare circumstances. We'll come back to the idea in Section 17.4.7.

a length-1 atomic vector⁴ like `TRUE`, `1L`, `2.5` or `"x"`. You can test for a constant with `rlang::is_syntactic_literal()`.

⁵ See Section ??scalars) for the conventions for creating these scalars.

Constants are “self-quoting” in the sense that the expression used to represent a constant is the constant itself:

```
identical(expr(TRUE), TRUE)
#> [1] TRUE
identical(expr(1), 1)
#> [1] TRUE
identical(expr(2L), 2L)
#> [1] TRUE
identical(expr("x"), "x")
#> [1] TRUE
```

16.3.2 Symbols

A **symbol** represents the name of an object like `x`, `mtcars`, or `mean`. In base R, symbol and name are used interchangeably (i.e. `is.name()` is identical to `is.symbol()`), but in this book I used symbol consistently because “name” has many other non-technical meanings. You can test for a symbol with `is.symbol()`.

You can create a symbol in two ways: by capturing code that references an object with `expr()`, or turning a string into a symbol with `sym()`:

```
expr(x)
#> x
sym("x")
#> x
```

You can turn a symbol back into a string with `as.character()` or `as_string()`. `as_string()` has the advantage of clearly signalling that you’ll get a character vector of length 1.

```
as_string(expr(x))
#> [1] "x"
```

⁴Technically, the R language does not possess scalars, and everything that looks like a scalar is actually a vector of length one. This however, is mainly a theoretical distinction, and blurring the distinction between scalar and length-1 vector is unlikely to harm your code.

⁵Technically, the R language does not possess scalars, and everything that looks like a scalar is actually a vector of length one. This however, is mainly a theoretical distinction, and blurring the distinction between scalar and length-1 vector is unlikely to harm your code.

You can recognise a symbol because it's printed without quotes, and `str()` tells you that it's a symbol:

```
str(expr(x))
#> symbol x
```

The symbol type is not vectorised, i.e. a symbol is always length 1. If you want multiple symbols, you'll need to put them in a list, using (e.g.) `rlang::syms()`.

16.3.3 Calls

A **call object** represents a captured function call. Call objects are vectors: the first component is name of the function to call (usually represented as a symbol), and the remaining elements are the arguments for that call. Call objects create branches in the AST, because calls can be nested inside other calls.

You can identify a call object when printed because it looks just like a function call. Unfortunately `typeof()` and `str()` print “language”⁶ for call objects, but `is_call()` returns `TRUE`:

```
lobstr::ast(read.table("important.csv", row.names = FALSE))
#> read.table
#> "important.csv"
#> row.names = FALSE
x <- expr(read.table("important.csv", row.names = FALSE))

typeof(x)
#> [1] "language"
is.call(x)
#> [1] TRUE
```

16.3.3.1 Subsetting

Calls generally behave like lists, i.e. you can use standard subsetting tools. The first element of the call object is the function to call, which is usually a symbol[⁷symbol-exception]:

```
x[[1]]
#> read.table
is_symbol(x[[1]])
#> [1] TRUE
```

⁶Avoid `is.language()` which returns `TRUE` for symbols, calls, and expression vectors.

The primary exception[^function-factories] to this rule occurs when you use `::` to call a function in a specific package. In that case the first element will be another call:

```
lobstr::ast(base::read.csv("important.csv"))
#>   `::`
#>   base
#>   read.csv
#>   "important.csv"
```

[^function-factories] This is a general example of calls to a function factory, a function that returns a function, the topic of Chapter 9.

The remainder of the elements are the arguments:

```
as.list(x[-1])
#> [[1]]
#> [1] "important.csv"
#>
#> $row.names
#> [1] FALSE
```

You can extract individual arguments with `[[` or `$` (if named):

```
x[[2]]
#> [1] "important.csv"
x$row
#> [1] FALSE
```

You can determine the number of arguments in call object by subtracting 1 from the length:

```
length(x) - 1
#> [1] 2
```

Extracting specific arguments from calls is challenging because of R’s flexible rules for argument matching: it could potentially be in any location, with the full name, with an abbreviated name, or with no name. To work around this problem, you can use `rlang::call_standardise()` which standardises all arguments to use the full name:

```
rlang::call_standardise(x)
#> read.table(file = "important.csv", row.names = FALSE)
```

(Note that if the function uses `...` it’s not possible to standardise all arguments.)

Calls can be modified in the same way as lists:

```
x$header <- TRUE
x
#> read.table("important.csv", row.names = FALSE, header = TRUE)
```

16.3.3.2 Function position

The first element of the call object is the **function position**. This contains the function that will be called when the object is evaluated, and is usually a symbol⁷:

```
lobstr::ast(foo())
#> foo
```

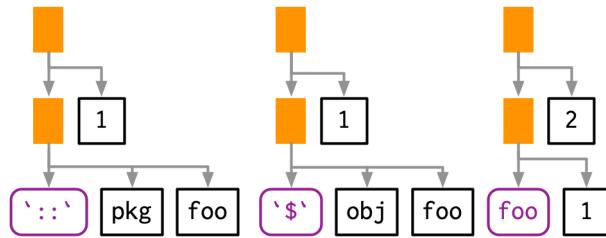
Note that while R allows you to surround the name of the function with quotes, the parser still converts this to a symbol:

```
lobstr::ast("foo"())
#> foo
```

However, sometimes the function doesn't exist in the current environment and you need to do some computation to retrieve it. For example, the function is in another package, is a method of an R6 object, or it's created by a function factory. In this case, the function position will be occupied by another call:

```
lobstr::ast(pkg::foo(1))
#> `::` 
#> pkg
#> foo
#> 1
lobstr::ast(obj$foo(1))
#> `$` 
#> obj
#> foo
#> 1
lobstr::ast(foo(1)(2))
#> foo
#> 1
#> 2
```

⁷Peculiarly, it can also be a number, as in the expression `3()`. But this call will always fail to evaluate because a number is not a function.



16.3.3.3 Constructing

You can construct a call object from its components by using `rlang::call2()`. The first argument is the name of function to call (either as a string, a symbol, or another call). The remaining arguments will be passed along to the call:

```
call2("mean", x = expr(x), na.rm = TRUE)
#> mean(x = x, na.rm = TRUE)
call2(expr(base::mean), x = expr(x), na.rm = TRUE)
#> base::mean(x = x, na.rm = TRUE)
```

Note that infix calls created in this way still print as usual.

```
call2("<-", expr(x), 10)
#> x <- 10
```

Using `call2()` to create complex expressions is a bit clunky. You'll learn another technique in Chapter 17.

16.3.4 Vocabulary

| | str | typeof |
|-------------------|------------------|----------------------------------|
| Scalar constant | logi/int/num/chr | logical/integer/double/character |
| Symbol | symbol | symbol |
| Call object | language | language |
| Pairlist | Dotted pair list | pairlist |
| Expression vector | expression() | expression |

| | base | rlang |
|-----------------|-------------|------------------------|
| Scalar constant | — | is_syntactic_literal() |
| Symbol | is.symbol() | is_symbol() |
| Call object | is.call() | is_call() |

| | base | rlang |
|-------------------|------------------------------|----------------------------|
| Pairlist | <code>is.pairlist()</code> | <code>is_pairlist()</code> |
| Expression vector | <code>is.expression()</code> | — |

16.3.5 Exercises

1. Which two of the six types of atomic vector can't appear in an expression? Why? Why can't you create an expression that contains an atomic vector of length greater than one?
2. What happens when you subset a call object to remove the first element? e.g. `expr(read.csv("foo.csv", header = TRUE))[-1]`. Why?
3. Describe the differences between the following call objects.

```
x <- 1:10

call2(median, x, na.rm = TRUE)
call2(expr(median), x, na.rm = TRUE)
call2(median, expr(x), na.rm = TRUE)
call2(expr(median), expr(x), na.rm = TRUE)
```

4. `rlang::call_standardise()` doesn't work so well for the following calls. Why? What makes `mean()` special?

```
call_standardise(quote(mean(1:10, na.rm = TRUE)))
#> mean(x = 1:10, na.rm = TRUE)
call_standardise(quote(mean(n = T, 1:10)))
#> mean(x = 1:10, n = T)
call_standardise(quote(mean(x = 1:10, , TRUE)))
#> mean(x = 1:10, , TRUE)
```

5. Why does this code not make sense?

```
x <- expr(foo(x = 1))
names(x) <- c("x", "")
```

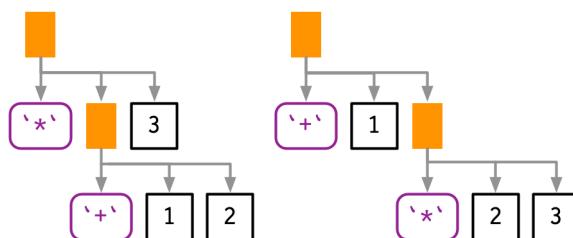
6. Construct the expression `if(x > 1) "a" else "b"` using multiple calls to `call2()`. How does the code structure reflect the structure of the AST?

16.4 Parsing and grammar

We've talked a lot about expressions and the AST, but not how expressions are created from code that you type. The process by which a computer language takes a string like (like "x + y") and constructs an expression is called **parsing**, and it is governed by a set of rules known as a **grammar**. In this section, we'll use `lobstr::ast()` to explore some of the details of R's grammar, and then see how you can transform back and forth between expressions and strings.

16.4.1 Operator precedence

Infix functions introduce ambiguity in a way that prefix functions do not⁸. The parser has to resolve two sources of ambiguity when parsing infix operators. First, what does $1 + 2 * 3$ yield? Do you get 9 (i.e. $(1 + 2) * 3$), or 7 (i.e. $1 + (2 * 3)$)? In other words, which of the two possible parse trees below does R use?



Programming languages use conventions called **operator precedence** to resolve this ambiguity. We can use `ast()` to see what R does:

```
lobstr::ast(1 + 2 * 3)
#> `+`
#> 1
#> `*`
#> 2
#> 3
```

Predicting the precedence of arithmetic operations is usually easy because it's drilled into you in school and is consistent across the vast majority of programming languages. Predicting the precedence of other operators is harder. There's one particularly surprising case in R: `!` has a much lower precedence (i.e. it binds

⁸This ambiguity does not arise without infix operators, which can be considered an advantage of purely prefix and postfix languages. It's interesting to compare a simple arithmetic operation in Lisp (prefix) and Forth (postfix). In Lisp you'd write `(* (+ 1 2) 3)`; this avoids ambiguity by requiring parentheses everywhere. In Forth, you'd write `1 2 + 3 *`; this doesn't require any parentheses, but does require more thought when reading.

less tightly) than you might expect. This allows you to write useful operations like:

```
lobstr::ast(!x %in% y)
#> `!`
#> `%in%` 
#> x
#> y
```

R has over 30 infix operators divided into 18 precedence groups. While the details are described in `?Syntax`, very few people have memorised the complete ordering. Indeed, if there's any confusion, use parentheses!

```
lobstr::ast((1 + 2) * 3)
#> `*` 
#> `(` 
#> `+` 
#> 1
#> 2
#> 3
```

Note the appearance of the parentheses in the AST as a call to the `(` function.

16.4.2 Associativity

Another source of ambiguity is introduced by repeated usage of the same infix function. For example, is `1 + 2 + 3` equivalent to `(1 + 2) + 3` or to `1 + (2 + 3)`? This normally doesn't matter because `x + (y + z) == (x + y) + z`, i.e. addition is associative, but is needed because some S3 classes define `+` in a non-associative way. For example, `ggplot2` overloads `+` to build up a complex plot from simple pieces; this is non-associative because earlier layers are drawn underneath later layers (i.e. `geom_point() + geom_smooth()` does not yield the same plot as `geom_smooth() + geom_point()`).

In R, most operators are **left-associative**, i.e. the operations on the left are evaluated first:

```
lobstr::ast(1 + 2 + 3)
#> `+` 
#> `+` 
#> 1
#> 2
#> 3
```

There are two exceptions: exponentiation and assignment.

```
lobstr::ast(2^2^3)
#> `^` `^` `2` `^` `2` `3`
lobstr::ast(x <- y <- z)
#> `<-` `<-` `x` `<-` `y` `<-` `z`
```

16.4.3 Parsing and deparsing

Most of the time you type code into the console, and R takes care of turning the characters you've typed into an AST. But occasionally you have code stored in a string, and you want to parse it yourself. You can do so using `rlang::parse_expr()`:

```
x1 <- "y <- x + 10"
lobstr::ast(!x1)
#> "y <- x + 10"

x2 <- rlang::parse_expr(x1)
x2
#> y <- x + 10
lobstr::ast(!x2)
#> `<-` `y` `<-` `x` `+` `10`
```

`parse_expr()` always returns a single expression. If you have multiple expression separated by ; or \n, you'll need to use `rlang::parse_exprs()`. It returns a list of expressions:

```
x3 <- "a <- 1; a + 1"
rlang::parse_exprs(x3)
#> [[1]]
```

```
#> a <- 1
#>
#> [[2]]
#> a + 1
```

If you find yourself working with strings containing code very frequently, you should reconsider your process. Read the Chapter 17 and consider if you can instead more safely generate expressions using quasiquotation.

The base equivalent to `parse_exprs()` is `parse()`. It is a little harder to use because it's specialised for parsing R code stored in files. You need supply your string to the `text` argument. It returns an expression vector, discussed in Section `??`, which I recommend turning into a list:

```
as.list(parse(text = x1))
#> [[1]]
#> y <- x + 10
```

The inverse of parsing is **deparsing**: given an expression, you want the string that would generate it. This happens automatically when you print an expression, and you can get the string yourself with `rlang::expr_text()`:

```
z <- expr(y <- x + 10)
expr_text(z)
#> [1] "y <- x + 10"
```

Parsing and deparsing are not perfectly symmetric because parsing generates an *abstract* syntax tree. This means we lose backticks around ordinary names, comments, and whitespace:

```
cat(expr_text(expr({
  # This is a comment
  x <- `x` + 1
})))
#> {
#>   x <- x + 1
#> }
```

Be careful when using the base R equivalent, `deparse()`: it returns a character vector with one element for each line. Whenever you use it, remember that the length of the output might be greater than one, and plan accordingly.

16.4.4 Exercises

1. R uses parentheses in two slightly different ways as illustrated by these two calls:

```
f((1))
`(`(1 + 1)
```

Compare and contrast the two uses by referencing the AST.

2. = can also be used in two ways. Construct a simple example that shows both uses.
3. Does -2^2 yield 4 or -4? Why?
4. What does `!1 + !1` return? Why?
5. Why does `x1 <- x2 <- x3 <- 0` work? Describe the two reasons.
6. Compare the ASTs of `x + y %+% z` and `x ^ y %+% z`. What have you learned about the precedence of custom infix functions?
7. What happens if you call `parse_expr()` with a string that generates multiple expressions? e.g. `parse_expr("x + 1; y + 1")`
8. What happens if you attempt to parse an invalid expression? e.g. `"a +"` or `"f()"`.
9. `deparse()` produces vectors when the input is long. For example, the following call produces a vector of length two:

```
expr <- expr(g(a + b + c + d + e + f + g + h + i + j + k + l + m +
n + o + p + q + r + s + t + u + v + w + x + y + z))

deparse(expr)
```

What does `expr_text()` do instead?

10. `pairwise.t.test()` assumes that `deparse()` always returns a length one character vector. Can you construct an input that violates this expectation? What happens?

16.5 Walking the AST with recursive functions

To conclude the chapter I'm going to pull together everything that you've learned about ASTs and use that knowledge to solve more complicated problems. The

inspiration comes from the base codetools package, which provides two interesting functions:

- `findGlobals()` locates all global variables used by a function. This can be useful if you want to check that your function doesn't inadvertently rely on variables defined in their parent environment.
- `checkUsage()` checks for a range of common problems including unused local variables, unused parameters, and the use of partial argument matching.

Getting all of the details of these functions correct is fiddly, so we won't fully develop the ideas. Instead we'll focus on the big underlying idea: recursion on the AST. Recursive functions are a natural fit to tree-like data structures because a recursive function is made up of two parts that correspond to the two parts of the tree:

- The **recursive case** handles the nodes in the tree. Typically, you'll do something to each child of node, usually calling the recursive function again, and then combine the results back together again. For expressions, you'll need to handle calls and pairlists (function arguments).
- The **base case** handles the leaves of the tree. The base cases ensure that the function eventually terminates, by solving the simplest cases directly. For expressions, you need to handle symbols and constants in the base case.

To make this pattern easier to see, we'll need two helper functions. First we define `expr_type()` which will return "constant" for constant, "symbol" for symbols, "call", for calls, "pairlist" for pairlists, and the "type" of anything else:

```
expr_type <- function(x) {  
  if (rlang::is_syntactic_literal(x)) {  
    "constant"  
  } else if (is.symbol(x)) {  
    "symbol"  
  } else if (is.call(x)) {  
    "call"  
  } else if (is.pairlist(x)) {  
    "pairlist"  
  } else {  
    typeof(x)  
  }  
}  
  
expr_type(expr("a"))
```

```
#> [1] "constant"
expr_type(expr(f(1, 2)))
#> [1] "call"
```

We'll couple this with a wrapper around the `switch` function:

```
switch_expr <- function(x, ...) {
  switch(expr_type(x),
    ...,
    stop("Don't know how to handle type ", typeof(x), call. = FALSE)
  )
}
```

With these two functions in hand, the basic template for any function that walks the AST is as follows:

```
recurse_call <- function(x) {
  switch_expr(x,
    # Base cases
    symbol = ,
    constant = ,

    # Recursive cases
    call = ,
    pairlist =
  )
}
```

Typically, solving the base case is easy, so we'll do that first, then check the results. The recursive cases are a little more tricky. Typically you'll think about the structure of final output and then find the correct `purrr` function to produce it. To that end, make sure you're familiar with Functionals before continuing.

16.5.1 Finding F and T

We'll start simple with a function that determines whether a function uses the logical abbreviations T and F: it will return `TRUE` if it finds a logical abbreviation, and `FALSE` otherwise. Using T and F is generally considered to be poor coding practice, and is something that `R CMD check` will warn about.

Let's first compare the AST for T vs. `TRUE`:

```
ast(TRUE)
#> TRUE
ast(T)
#> T
```

TRUE is parsed as a logical vector of length one, while T is parsed as a name. This tells us how to write our base cases for the recursive function: a constant is never a logical abbreviation, and a symbol is an abbreviation if it's "F" or "T":

```
logical_abbr_rec <- function(x) {
  switch_expr(x,
    constant = FALSE,
    symbol = as_string(x) %in% c("F", "T"))
}

logical_abbr_rec(expr(TRUE))
#> [1] FALSE
logical_abbr_rec(expr(T))
#> [1] TRUE
```

I've written `logical_abbr_rec()` function assuming that the input will be an expression as this will make the recursive operation simpler. However, when writing a recursive function it's common to write a wrapper that provides defaults or makes the function a little easier to use. Here we'll typically make a wrapper that quotes its input (we'll learn more about that in the next chapter), so we don't need to use `expr()` every time.

```
logical_abbr <- function(x) {
  logical_abbr_rec(enexpr(x))
}

logical_abbr(T)
#> [1] TRUE
logical_abbr(FALSE)
#> [1] FALSE
```

Next we need to implement the recursive cases. Here it's simple because we want to do the same thing for calls and for pairlists: recursively apply the function to each subcomponent, and return TRUE if any subcomponent contains a logical abbreviation. This is made easy by `purrr::some()`, which iterates over a list and returns TRUE if the predicate function is true for any element.

```
logical_abbr_rec <- function(x) {
  switch_expr(x,
  # Base cases
  constant = FALSE,
  symbol = as_string(x) %in% c("F", "T"),

  # Recursive cases
  call = ,
  pairlist = purrr::some(x, logical_abbr_rec)
)
}

logical_abbr(mean(x, na.rm = T))
#> [1] TRUE
logical_abbr(function(x, na.rm = T) FALSE)
#> [1] TRUE
```

16.5.2 Finding all variables created by assignment

`logical_abbr()` is very simple: it only returns a single TRUE or FALSE. The next task, listing all variables created by assignment, is a little more complicated. We'll start simply, and then make the function progressively more rigorous.

We start by looking at the AST for assignment:

```
ast(x <- 10)
#> `<-`
#> x
#> 10
```

Assignment is a call object where the first element is the symbol `<-`, the second is the name of variable, and the third is the value to be assigned.

Next, we need to decide what data structure we're going to use for the results. Here I think it will be easiest if we return a character vector. If we return symbols, we'll need to use a `list()` and that makes things a little more complicated.

With that in hand we can start by implementing the base cases and providing a helpful wrapper around the recursive function. The base cases here are really simple!

```
find_assign_rec <- function(x) {
  switch_expr(x,
```

```

constant = ,
symbol = character()
)
}
find_assign <- function(x) find_assign_rec(enexpr(x))

find_assign("x")
#> character(0)
find_assign(x)
#> character(0)

```

Next we implement the recursive cases. This is made easier by a function that should exist in purrr, but currently doesn't. `flat_map_chr()` expects `.f` to return a character vector of arbitrary length, and flattens all results into a single character vector.

```

flat_map_chr <- function(.x, .f, ...) {
  purrr::flatten_chr(purrr::map(.x, .f, ...))
}

flat_map_chr(letters[1:3], ~ rep(., sample(3, 1)))
#> [1] "a" "b" "b" "b" "c" "c"

```

The recursive case for pairlists is simple: we iterate over every element of the pairlist (i.e. each function argument) and combine the results. The case for calls is a little bit more complex - if this is a call to `<-` then we should return the second element of the call:

```

find_assign_rec <- function(x) {
  switch_expr(x,
    # Base cases
    constant = ,
    symbol = character(),

    # Recursive cases
    pairlist = flat_map_chr(as.list(x), find_assign_rec),
    call = {
      if (is_call(x, "<-")) {
        as_string(x[[2]])
      } else {
        flat_map_chr(as.list(x), find_assign_rec)
      }
    }
  )
}

```

```

    )
}

find_assign(a <- 1)
#> [1] "a"
find_assign({
  a <- 1
  {
    b <- 2
  }
})
#> [1] "a" "b"

```

Now we need to make our function more robust by coming up with examples intended to break it. What happens when we assign to the same variable multiple times?

```

find_assign({
  a <- 1
  a <- 2
})
#> [1] "a" "a"

```

It's easiest to fix this at the level of the wrapper function:

```

find_assign <- function(x) unique(find_assign_rec(enexpr(x)))

find_assign({
  a <- 1
  a <- 2
})
#> [1] "a"

```

What happens if we have nested calls to `<-`? Currently we only return the first. That's because when `<-` occurs we immediately terminate recursion.

```

find_assign({
  a <- b <- c <- 1
})
#> [1] "a"

```

Instead we need to take a more rigorous approach. I think it's best to keep the recursive function focused on the tree structure, so I'm going to extract out `find_assign_call()` into a separate function.

```

find_assign_call <- function(x) {
  if (is_call(x, "<-") && is_symbol(x[[2]])) {
    lhs <- as_string(x[[2]])
    children <- as.list(x)[-1]
  } else {
    lhs <- character()
    children <- as.list(x)
  }

  c(lhs, flat_map_chr(children, find_assign_rec))
}

find_assign_rec <- function(x) {
  switch_expr(x,
    # Base cases
    constant = ,
    symbol = character(),

    # Recursive cases
    pairlist = flat_map_chr(x, find_assign_rec),
    call = find_assign_call(x)
  )
}

find_assign(a <- b <- c <- 1)
#> [1] "a" "b" "c"
find_assign(system.time(x <- print(y <- 5)))
#> [1] "x" "y"

```

While the complete version of this function is quite complicated, it's important to remember we wrote it by working our way up by writing simple component parts.

16.5.3 Exercises

1. `logical_abbr()` returns TRUE for `T(1, 2, 3)`. How could you modify `logical_abbr_rec()` so that it ignores function calls that use T or F?
2. `logical_abbr()` works with expressions. It currently fails when you give it a function. Why not? How could you modify `logical_abbr()` to make it work? What components of a function will you need to recurse over?

```
logical_abbr(function(x = TRUE) {
  g(x + T)
})
```

3. Modify `find_assignment` to also detect assignment using replacement functions, i.e. `names(x) <- y`.
4. Write a function that extracts all calls to a specified function.

16.6 Specialised data structures

There are two data structures and one special symbol that we need to cover for the sake of completeness. They are not usually important in practice.

16.6.1 Pairlists

Pairlists are a remnant of R’s past and have been replaced by lists almost everywhere. The only place you are likely to see pairlists in R⁹ is when working with calls to the “function” function, as the formal arguments to a function are stored in a pairlist:

```
f <- expr(function(x, y = 10) x + y)

args <- f[[2]]
args
#> $x
#>
#>
#> $y
#> [1] 10
typeof(args)
#> [1] "pairlist"
```

Fortunately, whenever you encounter a pairlist, you can treat it just like a regular list:

```
pl <- pairlist(x = 1, y = 2)
length(pl)
#> [1] 2
```

⁹If you’re working in C, you’ll encounter pairlists more often. For example, call objects are also implemented using pairlists.

```
pl$x
#> [1] 1
```

Behind the scenes pairlists are implemented using a different data structure, a linked list instead of an array. That makes subsetting a pairlist much slower than subsetting a list, but this has little practical impact.

16.6.2 Missing arguments

There's one special symbol that needs a little extra discussion: the empty symbol, which is used to represent missing arguments (not missing values!). You only need to care about the missing symbol if you're programmatically creating functions with missing arguments; we'll come back to that in Section 17.4.3. You can make an empty symbol with `missing_arg()` (or `expr()`):

```
missing_arg()
typeof(missing_arg())
#> [1] "symbol"
```

An empty symbol doesn't print anything, so check if you have one with `rlang::is_missing()`:

```
is_missing(missing_arg())
#> [1] TRUE
```

And you'll find them in the wild in function formals:

```
f <- expr(function(x, y = 10) x + y)
args <- f[[2]]
is_missing(args[[1]])
#> [1] TRUE
```

The empty symbol has a peculiar property: if you bind it to a variable, then access that variable, you will get an error:

```
m <- missing_arg()
m
#> Error in eval(expr, envir, enclos):
#>   argument "m" is missing, with no default
```

This is the same error you get when referring to a missing argument inside a function, and indeed this is the magic that powers missing arguments.

If you need to preserve the missingness of a variable, `rlang::maybe_missing()` is often helpful. It allows you to refer to a potentially missing variable without

triggering the error.

16.6.3 Expression vectors

Finally, we need to briefly discuss the expression vector. Expression vectors are produced by only two base functions: `expression()` and `parse()`:

```
exp1 <- parse(text = c(
  x <- 4
  x
))
exp2 <- expression(x <- 4, x)

typeof(exp1)
#> [1] "expression"
typeof(exp2)
#> [1] "expression"

exp1
#> expression(x <- 4, x)
exp2
#> expression(x <- 4, x)
```

Like calls and pairlists, expression vectors behave like a list:

```
length(exp1)
#> [1] 2
exp1[[1]]
#> x <- 4
```

Conceptually, an expression vector is just a list of expressions. The only difference is that calling `eval()` on an expression evaluates each individual expression. I don't believe this advantage merits introducing a new data structure, so instead of expression vectors I just use lists of expressions.

Chapter 17

Quasiquotation

17.1 Introduction

Now that you understand the tree structure of R code, it’s time to come back to one of the fundamental ideas that make `expr()` and `ast()` work: quasiquotation. **Quasiquotation** is made up of two parts:

- **Quotation** is the act of capturing an unevaluated expression.
- **Unquotation** is the ability to selectively evaluate parts of an otherwise quoted expression.

The combination of these two ideas makes it easy create functions that combine code written by the function author with code written by the function user, and helps to solve a wide variety of challenging problems.

Quasiquotation is one of the three components of tidy evaluation. You’ll learn about the other two components (quosures and the data mask) in Chapter [??](#). By itself, quasiquotation is mostly useful for programming, particularly for generating code; when combined with the other techniques, tidy evalation is a powerful tool for data analysis.

Outline

- Section 17.2 motivates the development of quasiquotation with a function, `cement()`, that works like `paste()` but automatically “quotes” its arguments so that you don’t have to.

- Section 17.3 gives you the tools to quote expressions, whether they come from you or the user, or whether you use `rlang` or base R tools.
- Section 17.4 introduces the biggest difference between `rlang` quoting functions and base quoting function: unquoting with `!!` and `!!!`.
- Section 17.5 discusses the three main “non-quoting” techniques that base R functions use to disable quoting behaviour.
- Section 17.6 explores another place that you can use `!!!`, functions that take `...`. It also introduces the special `:=` operator, which allows you to dynamically change argument names.
- Section 17.7 shows a few practical uses of quoting to solve problems that naturally require some code generation.

Prerequisites

Make sure you’ve read the metaprogramming overview in Chapter IV to get a broad overview of the motivation and the basic vocabulary, and that you’re familiar with the tree structure of expressions as described in Section 16.

Code-wise, we’ll mostly be using the tools from `rlang`, but at the end of the chapter you’ll also see some powerful applications in conjunction with `purrr`.

```
library(rlang)
library(purrr)
```

Related work

Quoting functions have deep connections to Lisp **macros**. But macros are usually run at compile-time, which doesn’t exist in R, and they always input and output ASTs. See Lumley (2001) for one approach to implementing them in R. Quoting functions are more closely related to Lisp **fexprs** (<http://en.wikipedia.org/wiki/Fexpr>), functions where all arguments are quoted by default. These terms are useful to know when looking for related techniques in other programming languages.

17.2 Motivation

We’ll start with a simple and concrete example that helps motivate the need for unquoting, and hence quasiquote. Imagine you’re creating a lot of strings by

joining together words:

```
paste("Good", "morning", "Hadley")
#> [1] "Good morning Hadley"
paste("Good", "afternoon", "Alice")
#> [1] "Good afternoon Alice"
```

You are sick and tired of writing all those quotes, and instead you just want to use bare words. To that end, you've written the following function:

```
cement <- function(...) {
  args <- ensyms(...)
  paste(purrr::map(args, as_string), collapse = " ")
}

cement(Good, morning, Hadley)
#> [1] "Good morning Hadley"
cement(Good, afternoon, Alice)
#> [1] "Good afternoon Alice"
```

(You'll learn what `ensyms()` does shortly; for now just look at the results.)

Formally, this function *quotes* the arguments in You can think of it as automatically putting quotation marks around each argument. That's not precisely true as the intermediate objects it generates are expressions, not strings, but it's a useful approximation, and meaning at the root of the term "quote".

This function is nice because we no longer need to type quotation marks. The problem, however, comes when we want to use variables. It's easy to use variables with `paste()`: just don't surround them with quotation marks.

```
name <- "Hadley"
time <- "morning"

paste("Good", time, name)
#> [1] "Good morning Hadley"
```

Obviously this doesn't work with `cement()` because every input is automatically quoted:

```
cement(Good, time, name)
#> [1] "Good time name"
```

We need some way to explicitly *unquote* the input, to tell `cement()` to remove the automatic quote marks. Here we need `time` and `name` to be treated differently to `Good`. Quasiquotation gives us a standard tool to do so: `!!`, called "unquote",

and pronounced bang-bang. `!!` tells a quoting function to drop the implicit quotes:

```
cement(Good, !!time, !!name)
#> [1] "Good morning Hadley"
```

It's useful to compare `cement()` and `paste()` directly. `paste()` evaluates its arguments, so we need to quote where needed; `cement()` quotes its arguments, so we need to unquote where needed.

```
paste("Good", time, name)
cement(Good, !!time, !!name)
```

17.2.1 Vocabulary

The distinction between quoted and evaluated arguments is important:

- An **evaluated** argument obeys R's usual evaluation rules.
- A **quoted** argument is captured by the function and something unusual will happen.

`paste()` evaluates all its arguments; `cement()` quotes all its arguments.

If you're ever unsure about whether an argument is quoted or evaluated, try executing the code outside of the function. If it doesn't work (or does something profoundly different), then that argument is quoted. For example, you can use this technique to determine that the first argument to `library()` is quoted:

```
# works
library(MASS)

# fails
MASS
#> Error in eval(expr, envir, enclos):
#>   object 'MASS' not found
```

Talking about whether an argument is quoted or evaluated is a more precise way of stating whether or not a function uses non-standard evaluation (NSE). I will sometimes use “quoting function” as short-hand for a “function that quotes one or more arguments”, but generally, I'll refer to quoted arguments since that is the level at which the difference applies.

17.2.2 History

The idea of quasiquotation is an old one. It was first developed by a philosopher, Willard van Orman Quine¹, in the early 1940s. It's needed in philosophy² because it helps when precisely delineating the use and mention of words, i.e. between the object and the words we use to refer to that object.

Quasiquotation was first used in a programming language, LISP, in the mid-1970s (Bawden 1999). LISP has one quoting function ` , and uses , for unquoting. Most languages with a LISP heritage behave similarly. For example, racket (` and @), clojure (` and ~), and julia (: and @) all have quasiquotation tools that differ only slightly from LISP. These languages have a single quoting function and you must call it explicitly.

In R, however, many functions quote one or more inputs. This introduces ambiguity (because you need to read the documentation to determine if an argument is quoted or not), but allows for concise and elegant data exploration code. In base R, only one function supports quasiquotation: `bquote()`, written in 2003 by Thomas Lumley. But `bquote()` is not used anywhere in base R, and has had relatively little impact on how R code is written. There are three challenges to effective use of `bquote()`:

- It is only easily used with your code; it is hard to apply it to arbitrary code supplied by a user.
- It does not provide an unquote-splice operator that allows you to unquote multiple expressions stored in a list.
- It lacks the ability to handle code accompanied by an environment, which is crucial for functions that evaluate code in the context of a data frame, like `subset()` and friends.

Figuring out how to fix the first and second challenges lead to my `lazyeval` package (2014-2015). Identifying and remedying the third challenge (the topic of Chapter 18 lead to the tidy evaluation framework taught in this book and implemented in the `rlang` package by Lionel Henry, during 2017. Despite the newness of tidy eval, I teach it here because it is a rich and powerful theory that, once you master it, makes many hard problems much easier.

¹You might be familiar with the name Quine from “quines”, computer programs that return a copy of their own source when run.

²A fun connection between philosophy and R is in <https://johnmacfarlane.net/142/substitutional-quantifiers.pdf>; this article is written by philosophy professor John MacFarlane, the author of pandoc, which powers RMarkdown.

17.2.3 Exercises

1. For each function in the following base R code, identify which arguments are quoted and which are evaluated.

```
library(MASS)

mtcars2 <- subset(mtcars, cyl == 4)

with(mtcars2, sum(vs))
sum(mtcars2$am)

rm(mtcars2)
```

2. For each function in the following tidyverse code, identify which arguments are quoted and which are evaluated.

```
library(dplyr)
library(ggplot2)

by_cyl <- mtcars %>%
  group_by(cyl) %>%
  summarise(mean = mean(mpg))

ggplot(by_cyl, aes(cyl, mean)) + geom_point()
```

17.3 Quoting

The first part of quasiquotation is quotation: capturing an expression without evaluating it. There are two components to this: capturing an expression supplied directly, and capturing an expression supplied indirectly in a lazily-evaluated function argument. We'll discuss two sets of tools for these two ways of capturing: those provided by `rlang`, and those provided by base R.

17.3.1 Capturing expressions

There are four important quoting functions. For interactive exploration, the most important quoting function is `expr()`. It captures its argument exactly as provided:

```
expr(x + y)
#> x + y
expr(1 / 2 / 3)
#> 1/2/3
```

(Remember that white space and comments are not part of the expression, so will not be captured by a quoting function.)

`expr()` is great for interactive exploration, because it captures what you, the developer, typed. It's not so useful inside a function:

```
f1 <- function(x) expr(x)
f1(a + b + c)
#> x
```

We need another function to solve this problem: `enexpr()`. This captures what the caller supplied to the function by looking at the internal promise object that powers lazy evaluation (Section 5.5.2).

```
f2 <- function(x) enexpr(x)
f2(a + b + c)
#> a + b + c
```

To capture multiple arguments (e.g. all arguments in `...`), use `enexprs()`.

```
f <- function(...) enexprs(...)
f(x = 1, y = 10 * z)
#> $x
#> [1] 1
#>
#> $y
#> 10 * z
```

Finally, `exprs()` is useful interactively to make a list of expressions:

```
exprs(x = x ^ 2, y = y ^ 3, z = z ^ 4)
#> $x
#> x^2
#>
#> $y
#> y^3
#>
#> $z
#> z^4
# shorthand for
```

```
# list(x = expr(x ^ 2), y = expr(y ^ 3), z = expr(z ^ 4))
```

In short, use `enexpr()` and `enexprs()` to capture the expressions supplied as arguments *by the user*. Use `expr()` and `exprs()` to capture expressions that *you* supply.

17.3.2 Capturing symbols

Sometimes you only want to allow the user to specify a variable name, not an arbitrary expression. In this case, you can use `ensym()` or `ensyms()`. These are variants of `enexpr()` and `enexprs()` that check the captured expression is either symbol or a string (which is converted to symbol³).

```
f <- function(...) ensyms(...)
f(x)
#> [[1]]
#> x
f("x")
#> [[1]]
#> x
```

`ensym()` and `ensyms()` throw an error if given anything else.

17.3.3 With base R

The base equivalent of `expr()` is `quote()`:

```
quote(x + y)
#> x + y
quote(1 / 2 / 3)
#> 1/2/3
```

It is identical to `expr()` except that it does not support unquoting (which we'll talk about very soon). This makes it is a quoting function, not a quasiquoting function.

The base function closest to `enexpr()` is `substitute()`:

```
f3 <- function(x) substitute(x)
f3(x + y + z)
#> x + y + z
```

³This is for compatibility with base R, which allows you to provide a string instead of a symbol in many places: `"x" <- 1`, `"foo"(x, y)`, `c("x" = 1)`.

Substitution

You'll most often see `substitute()` used to capture unevaluated arguments. However, as well as quoting, `substitute()` also does "substitution": if you give it an expression, rather than a symbol, it will substitute in the values of symbols defined in the current environment.

```
f4 <- function(x) substitute(x * 2)
f4(a + b + c)
#> (a + b + c) * 2
```

I think this makes code hard to understand, because, taken out of context, you can't tell if the goal of `substitute(x + y)` is to replace `x`, or `y`, or both. If you do want to use `substitute()` for substitution, I recommend that you use the 2nd argument to make your goal clear:

```
substitute(x * y * z, list(x = 10, y = quote(a + b)))
#> 10 * (a + b) * z
```

The base equivalent to `exprs()` is `alist()`:

```
alist(x = 1, y = x + 2)
#> $x
#> [1] 1
#>
#> $y
#> x + 2
```

There the equivalent to `enexprs()` is an undocumented feature of `substitute()`⁴: you can pretend `...` is a function to capture all arguments in `....`:

```
f <- function(...) as.list(substitute(...()))
f(x = 1, y = 10 * z)
#> $x
#> [1] 1
#>
#> $y
#> 10 * z
```

There are two other important base quoting functions that we'll cover elsewhere:

- `bquote()` provides a limited form of quasiquotation, and is discussed in Section 17.5.
- `~`, the formula, is a quoting function that also captures the environment. It's

⁴Discovered by Peter Meilstrup and described in R-devel on 2018-08-13 (<http://r.789695.n4.nabble.com/substitute-on-arguments-in-ellipsis-quot-dot-dot-dot-quot-td4751658.html>).

the inspiration for quosures, the topic of the next chapter, and is discussed in Section 18.3.4.

17.3.4 Summary

When quoting (i.e. capturing code), there are two important distinctions:

- Is it supplied by the developer of the code or the user of the code? i.e. is it fixed or varying, supplied in the body of the function or via an argument?
- Do you want to capture a single expression or multiple expressions?

This leads to a 2 x 2 table of function for rlang and base R:

- rlang:

| | Developer | User |
|------|----------------------|------------------------|
| One | <code>expr()</code> | <code>enexpr()</code> |
| Many | <code>exprs()</code> | <code>enexprs()</code> |

- base R:

| | Developer | User |
|------|----------------------|--|
| One | <code>quote()</code> | <code>substitute()</code> |
| Many | <code>alist()</code> | <code>eval(substitute(alist()))</code> |

17.3.5 Exercises

1. What does the following command return? What information is lost? Why?

```
expr({
  x +
  y # comment
})
```

2. How is `expr()` implemented?
3. Compare and contrast the following two functions. Can you predict the output before running them?

```
f1 <- function(x, y) {
  exprs(x = x, y = y)
}
```

```
f2 <- function(x, y) {
  enexprs(x = x, y = y)
}
f1(a + b, c + d)
f2(a + b, c + d)
```

4. What happens if you try to use `enexpr()` with an expression (i.e. `enexpr(x + y)`)? What happens if `enexpr()` is passed a missing argument?
5. How are `exprs(a)` and `exprs(a =)` different? Think about both the input and the output.
6. What are other differences between `exprs()` and `alist()`? Read the documentation for the named arguments of `exprs()` to find out.
7. The documentation for `substitute()` says:

Substitution takes place by examining each component of the parse tree as follows:

- If it is not a bound symbol in `env`, it is unchanged.
- If it is a promise object (i.e., a formal argument to a function) the expression slot of the promise replaces the symbol.
- If it is an ordinary variable, its value is substituted;
- Unless `env` is `.GlobalEnv` in which case the symbol is left unchanged.

Create four examples that illustrate each of the different cases.

17.4 Unquoting

So far, you've only seen relatively small advantages of the rlang quoting functions over the base R quoting functions: they have a more consistent naming scheme. The big difference is that rlang quoting functions are actually **quasiquoting** functions, because they support unquoting with `!!` (called “unquote”, and pronounced bang-bang).

Unquoting allows you to selectively execute, or evaluate, parts of the expression that would otherwise be quoted, and it effectively allows you to merge together ASTs using a template AST. Since base functions don't use unquoting, they instead use a variety of other techniques, which you'll learnn about in Section 17.5.

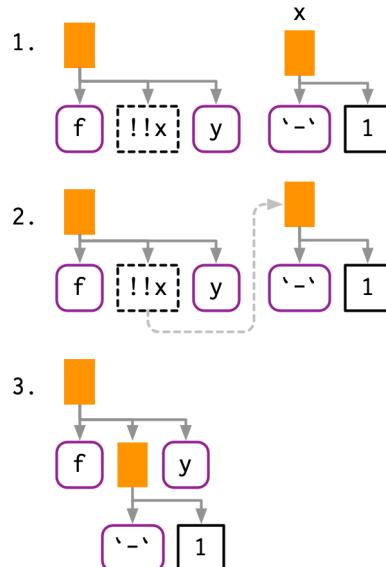
Unquoting is one inverse of quoting. It allows you to selectively evaluate code inside `expr()`, so that `expr(!!x)` is equivalent to `x`. In Chapter 18, you'll learn about another inverse, evaluation. Evaluation happens outside `expr()`, so that `eval(expr(x))` is equivalent to `x`.

17.4.1 Unquoting one argument

Use `!!` to unquote a single argument in a function call. `!!` takes a single expression, evaluates it, and inlines the result in to the AST.

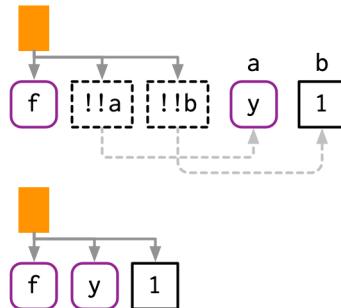
```
x <- expr(a + b + c)
expr(f(!!x, y))
#> f(a + b + c, y)
```

I think this is easiest to understand with a diagram. `!!` introduces a placeholder in the AST, shown with dotted borders. Here the placeholder `x` is replaced by an AST, illustrated by a dotted connection.



As well as call objects, `!!` also works with symbols and constants:

```
a <- sym("y")
b <- 1
expr(f (!!a, !!b))
#> f(y, 1)
```



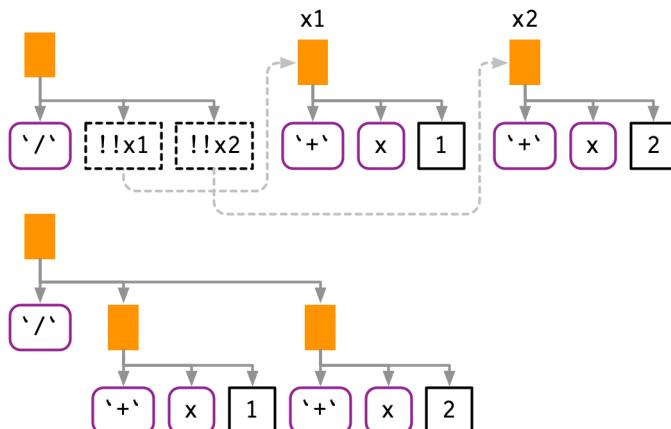
Note that the right-hand side of `!!` can be a function call. `!!` will evaluate the call and insert the results in the AST:

```
mean_rm <- function(var) {
  var <- ensym(var)
  expr(mean (!!var, na.rm = TRUE))
}
expr (!!mean_rm(x) + !!mean_rm(y))
#> mean(x, na.rm = TRUE) + mean(y, na.rm = TRUE)
```

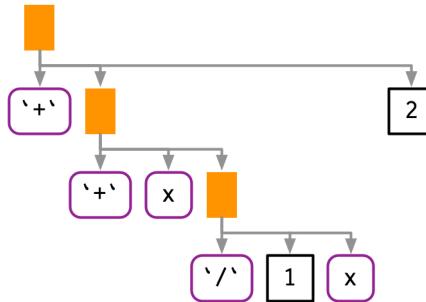
Note that `!!` preserves operator precedence because it works with expressions.

```
x1 <- expr(x + 1)
x2 <- expr(x + 2)

expr (!!x1 / !!x2)
#> (x + 1)/(x + 2)
```



If we simply pasted the text of the expressions together, we'd end up with `x + 1 / x + 2`, which has a very different AST:



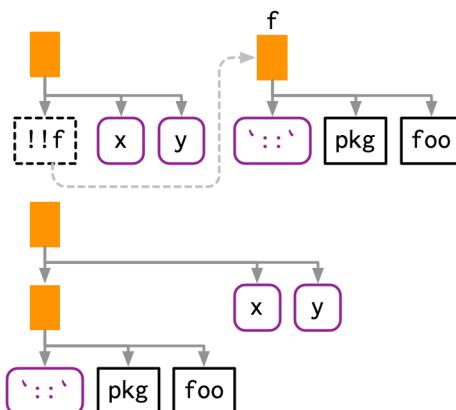
17.4.2 Unquoting a function

`!!` is most commonly used to replace the arguments to a function, but you can also use it to replace the function itself. The only challenge here is operator precedence: `expr(!!f(x, y))` unquotes the result of `f(x, y)`, so you need an extra pair of parentheses.

```
f <- expr(foo)
expr((!!f)(x, y, z))
#> foo(x, y, z)
```

This also works when `f` is itself a call:

```
f <- expr(pkg::foo)
expr((!!f)(x, y, z))
#> pkg::foo(x, y, z)
```



Because of the large number of parentheses involved, it can be more clear to use `rlang::call2()`:

```
f <- expr(pkg::foo)
call2(f, expr(x), expr(y))
#> pkg::foo(x, y)
```

17.4.3 Unquoting a missing argument

Very occasionally it is useful to unquote a missing argument (Section 16.6.2), but the naive approach doesn't work:

```
arg <- missing_arg()
expr(foo(!!arg, !!arg))
#> Error in enexpr(expr):
#>   argument "arg" is missing, with no default
```

You can work around this with the `maybe_missing()` helper:

```
expr(foo(!!maybe_missing(arg), !!maybe_missing(arg)))
#> foo(, )
```

17.4.4 Unquoting in special forms

There are a few special forms where unquoting is a syntax error:

```
expr(df$!!x)
#> Error: unexpected '!!' in "expr(df$!"
```

Here you need to use the prefix form:

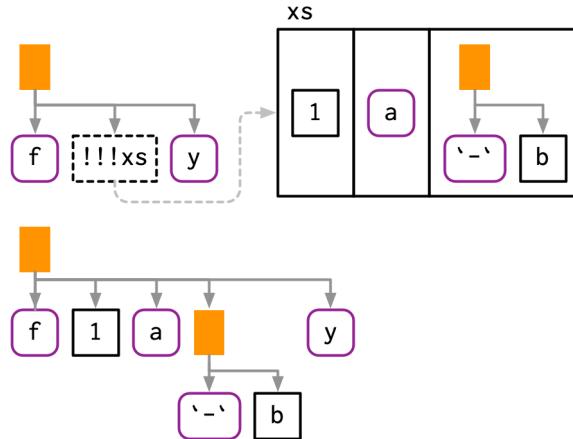
```
x <- expr(x)
expr(`$`(df, !!x))
#> df$x
```

17.4.5 Unquoting many arguments

`!!` is a one-to-one replacement. `!!!` (called “unquote-splice”, and pronounced bang-bang-bang) is a one-to-many replacement. It takes a list of expressions and inserts them at the location of the `!!!`:

```
xs <- exprs(1, a, -b)
expr(f(!!!xs, y))
#> f(1, a, -b, y)
```

```
# Or with names
ys <- set_names(xs, c("a", "b", "c"))
expr(f(!!!ys, d = 4))
#> f(a = 1, b = a, c = -b, d = 4)
```



`!!!` can be used in any rlang function that takes ... regardless of whether or not ... is quoted or evaluated. We'll come back to this in Section 17.6; for now note that this can be useful in `call2()`.

```
call2("f", !!!xs, expr(y))
#> f(1, a, -b, y)
```

17.4.6 The polite fiction of `!!`

So far we have acted as if `!!` and `!!!` are regular prefix operators like `+`, `-`, and `!`. They're not. From R's perspective, `!!` and `!!!` are simply the repeated application of `!`:

```
!!TRUE
#> [1] TRUE
!!!TRUE
#> [1] FALSE
```

`!!` and `!!!` behave specially inside all quoting functions powered by rlang, where they behave like real operators with precedence equivalent to unary `+` and `-`. This requires considerable work inside rlang, but means that you can write `!!x + !!y` instead of `(!!x) + (!!y)`.

The biggest downside⁵ to using a fake operator is that you might get silent errors when misusing `!!` outside of quasiquoting functions. Most of the time this is not an issue because `!!` is typically used to unquote expressions or quosures. Since expressions are not supported by the negation operator, you will get an argument type error in this case:

```
x <- quote(variable)
!!x
#> Error in !x:
#>   invalid argument type
```

But you can get silently incorrect results when working with numeric values:

```
df <- data.frame(x = 1:5)
y <- 100
with(df, x + !!y)
#> [1] 2 3 4 5 6
```

Given these drawbacks, you might wonder why we introduced new syntax instead of using regular function calls. Indeed, early versions of tidy eval used function calls like `UQ()` and `UQS()`, however they're not really function calls, and pretending they leads to a misleading mental mode. We chose `!!` and `!!!` as the least-worst solution:

- They are visually strong and don't look like existing syntax. When you see `!!x` or `!!!x` it's clear that something unusual is happening.
- They overrides a rarely used piece of syntax, as double negation is not a common pattern in R⁶. If you need it, you can just add parentheses `!(!x)`.

17.4.7 Non-standard ASTs

With unquoting, it's easy to create non-standard ASTs, i.e. ASTs that contain components that are not expressions. (It is also possible to create non-standard ASTs by directly manipulating the underlying objects, but it's harder to do so accidentally.) These are valid, and occasionally useful, but their correct use is

⁵Prior to R 3.5.1, there was another major downside: the R deparser treated `!!x` as `!(!x)`. This is why in old versions of R you might see extra parentheses when printing expressions. The good news is that these parentheses are not real and can be safely ignored most of the time. The bad news is that they will become real if you reparse that printed output to R code. These roundtripped functions will not work as expected since `!(!x)` does not unquote.

⁶Unlike, say, javascript, where `!!x` is a commonly used shortcut to convert an integer into a logical.

beyond the scope of this book. It's important to learn about them, however, because they can be deparsed, and hence printed, in misleading ways.

For example, if you inline more complex objects, their attributes are not printed. This can lead to confusing output:

```
x1 <- expr(class(!!data.frame(x = 10)))
x1
#> class(list(x = 10))
eval(x1)
#> [1] "data.frame"
```

You have two main tools to reduce this confusion: `rlang::expr_print()` and `lobstr::ast()`:

```
expr_print(x1)
#> class(<data.frame>)
lobstr::ast(!!x1)
#>  class
#>  <inline data.frame>
```

Another confusing case arises if you inline an integer sequence:

```
x2 <- expr(f(!!c(1L, 2L, 3L, 4L, 5L)))
x2
#> f(1:5)
expr_print(x2)
#> f(<int: 1L, 2L, 3L, 4L, 5L>)
lobstr::ast(!!x2)
#>  f
#>  <inline integer>
```

It's also possible to create regular ASTs that can not be generated from code because of operator precedence. In this case, R will print parentheses that do not exist in the AST:

```
x3 <- expr(1 + !!expr(2 + 3))
x3
#> 1 + (2 + 3)

lobstr::ast(!!x3)
#>  `+`
#>  1
#>  `+`
#>  2
```

#> 3

17.4.8 Exercises

- Given the following components:

```
xy <- expr(x + y)
xz <- expr(x + z)
yz <- expr(y + z)
abc <- exprs(a, b, c)
```

Use quasiquotation to construct the following calls:

```
(x + y) / (y + z)
-(x + z) ^ (y + z)
(x + y) + (y + z) - (x + y)
atan2(x + y, y + z)
sum(x + y, x + y, y + z)
sum(a, b, c)
mean(c(a, b, c), na.rm = TRUE)
foo(a = x + y, b = y + z)
```

- Explain why both `!0 + !0` and `!1 + !1` return `FALSE` while `!0 + !1` returns `TRUE`.
- Base functions `match.fun()`, `page()`, and `ls()` all try to automatically determine whether you want standard or non-standard evaluation. Each uses a different approach. Figure out the essence of each approach by reading the source code, then compare and contrast the techniques.
- The following two calls print the same, but are actually different:

```
(a <- expr(mean(1:10)))
#> mean(1:10)
(b <- expr(mean(!!(1:10))))
#> mean(1:10)
identical(a, b)
#> [1] FALSE
```

What's the difference? Which one is more natural?

17.5 Non-quoting in base R

Base R has one function that implements quasiquotation: `bquote()`. It uses `.()` for unquoting:

```
xyz <- bquote((x + y + z))
bquote(-.(xyz) / 2)
#> -(x + y + z)/2
```

However, `bquote()` isn't used in any other function in base R. Instead functions that quote an argument use some other technique to allow indirect specification. Rather than using use unquoting all base R approaches selectively turn quoting off, so I call them **non-quoting** techniques.

There are four basic forms seen in base R:

- A pair of quoting and non-quoting functions. For example, `$` has two arguments, and the second argument is quoted. This is easier to see if you write in prefix form: `mtcars$cyl` is equivalent to ``$`(mtcars, cyl)`. If you want to refer to a variable indirectly, you use `[[`, as it takes the name of a variable as a string.

```
x <- list(var = 1, y = 2)
var <- "y"

x$var
#> [1] 1
x[[var]]
#> [1] 2
```

There are three other quoting functions closely related to `$`: `subset()`, `transform()`, and `with()`. These are seen as wrappers around `$` only suitable for interactive use so they all have the same non-quoting alternative: `[`

`<-/assign()` and `::/getExportedValue()` work similarly to `$/[`.

- A pair of quoting and non-quoting arguments. For example, `rm()` allows you to provide bare variable names in `...`, or a character vector of variable names in `list`:

```
x <- 1
rm(x)

y <- 2
```

```
vars <- c("y", "vars")
rm(list = vars)
```

`data()` and `save()` work similarly.

- An argument that controls whether a different argument is quoting or non-quoting. For example, in `library()`, the `character.only` argument controls the quoting behaviour of the first argument, `package`:

```
library(MASS)

pkg <- "MASS"
library(pkg, character.only = TRUE)
```

`demo()`, `detach()`, `example()`, and `require()` work similarly.

- Quoting if evaluation fails. For example, the first argument to `help()` is non-quoting if it evaluates to a string; if evaluation fails, the first argument is quoted.

```
# Shows help for var
help(var)

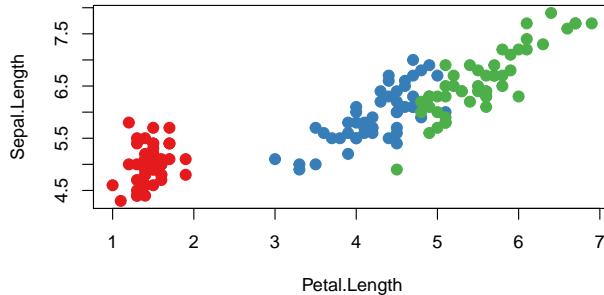
var <- "mean"
# Shows help for mean
help(var)

var <- 10
# Shows help for var
help(var)
```

`ls()`, `page()`, and `match.fun()` work similarly.

Another important class of quoting functions are the base modelling and plotting functions, which follow the so-called standard non-standard evaluation rules: <http://developer.r-project.org/nonstandard-eval.pdf>. For example, `lm()` quotes the `weight` and `subset` arguments, and when used with a formula argument, the plotting function quotes the aesthetic arguments (`col`, `cex`, etc):

```
palette(RColorBrewer::brewer.pal(3, "Set1"))
plot(
  data = iris,
  Sepal.Length ~ Petal.Length, col = Species,
  pch = 20, cex = 2
)
```



These functions have no built-in options for indirect specification, but you'll learn how to simulate unquoting in Section ??.

17.6 Dot-dot-dot (...)

!!! is useful because it's not uncommon to have a list of expressions that you want to insert into a call. It turns out that this pattern is common elsewhere. Take the following two motivating problems:

- What do you do if the elements you want to put in ... are already stored in a list? For example, imagine you have a list of data frames that you want to rbind() together:

```
dfs <- list(
  a = data.frame(x = 1, y = 2),
  b = data.frame(x = 3, y = 4)
)
```

You could solve this specific case with rbind(dfs\$a, df\$b), but how do you generalise that solution to a list of arbitrary length?

- What do you do if you want to supply the argument name indirectly? For example, imagine you want to create a single column data frame where the name of the column is specified in a variable:

```
var <- "x"
val <- c(4, 3, 9)
```

In this case, you could create a data frame and then change names (i.e. setNames(data.frame(val), var)), but this feels inelegant. How can we do better?

One way to think about these problems is to draw explicit parallels to quasiquotation:

- Row-binding multiple data frames is like unquote-splicing: we want to inline individual elements of the list into the call:

```
 dplyr::bind_rows(!!!dfs)
#>   x y
#> 1 1 2
#> 2 3 4
```

When used in this context, the behaviour of `!!!` is known as splicing in Ruby, Go, PHP, and Julia. It is closely related to `*args` (star-args) and `**kwargs` (star-star-kwargs) in Python, which are sometimes called argument unpacking.

- The second problem is like unquoting the left-hand side of `=`: rather than interpreting `var` literally, we want to use the value stored in the variable called `var`:

```
 tibble::tibble(!!var := val)
#> Warning: `list_len()` is soft-deprecated as of rlang 0.2.0.
#> Please use `new_list()` instead
#> This warning is displayed once per session.
#> # A tibble: 3 x 1
#>       x
#>   <dbl>
#> 1     4
#> 2     3
#> 3     9
```

Note the use of `:=` (pronounced colon-equals) rather than `=`. Unfortunately we need this new operation because R's grammar does not allow expressions as argument names:

```
 tibble::tibble(!!var = value)
#> Error: unexpected '=' in "tibble::tibble(!!var ="
```

`:=` is like a vestigial organ: it's recognised by R's parser, but it doesn't have any code associated with it. It looks like an `=` but allows expressions on either side, making it a more flexible alternative to `=`. It is used in `data.table` for similar reasons.

Base R takes a different approach, which we'll come back to Section @ref{do-call}.

We say functions that support these tools, without quoting arguments, have `tidy`

dots⁷. To gain tidy dots behaviour in your own function, all you need to do is use `list2()`.

17.6.1 Examples

One place we could use `list2()` is to create a wrapper around `attributes()` that allows us to flexibly set attributes:

```
set_attr <- function(.x, ...) {
  attr <- rlang::list2(...)
  attributes(.x) <- attr
  .x
}

attrs <- list(x = 1, y = 2)
attr_name <- "z"

1:10 %>%
  set_attr(w = 0, !!! attrs, !!attr_name := 3) %>%
  str()
#>  int [1:10] 1 2 3 4 5 6 7 8 9 10
#>  - attr(*, "w")= num 0
#>  - attr(*, "x")= num 1
#>  - attr(*, "y")= num 2
#>  - attr(*, "z")= num 3
```

17.6.2 `exec()`

What if you want to use this technique with a function that doesn't have tidy dots? One option is to use `rlang::exec()` which makes it easy to call functions with some arguments supplied directly (in ...) and others indirectly (in a list):

```
# Directly
exec("mean", x = 1:10, na.rm = TRUE, trim = 0.1)
#> [1] 5.5

# Indirectly
args <- list(x = 1:10, na.rm = TRUE, trim = 0.1)
exec("mean", !!!args)
```

⁷This is admittedly not the most creative of names, but it clearly suggests it's something that has been added to R after the fact.

```
#> [1] 5.5

# Mixed
params <- list(na.rm = TRUE, trim = 0.1)
exec("mean", x = 1:10, !!!params)
#> [1] 5.5
```

And also makes it possible to supply argument names indirectly:

```
arg_name <- "na.rm"
arg_val <- TRUE
exec("mean", 1:10, !!arg_name := arg_val)
#> [1] 5.5
```

And finally, it's useful if you have a vector of function names or a list of functions that you want to call with the same arguments:

```
x <- c(runif(10), NA)
fun <- c("mean", "median", "sd")

purrr:::map_dbl(fun, exec, x, na.rm = TRUE)
#> [1] 0.444 0.482 0.298
```

`exec()` is closely related to `call2()`; where `call2()` returns an expression, `exec()` evaluates it.

17.6.3 dots_list()

`list2()` provides one other handy feature: by default it will ignore any empty arguments at the end. This is useful in functions like `tibble::tibble()` because it means that you can easily change the order of variables without worrying about the final comma:

```
# Can easily move x to first entry:
tibble::tibble(
  y = 1:5,
  z = 3:-1,
  x = 5:1,
)

# Need to remove comma from z and add comma to x
data.frame(
  y = 1:5,
```

```

z = 3:-1,
x = 5:1
)

```

`list2()` is a wrapper around `rlang::dots_list()` with defaults set to the most commonly used settings. You can get more control by calling `dots_list()` directly:

- `.ignore_empty` allows you to control exactly which arguments are ignored. The default ignores a single trailing argument to get the behaviour described above, but you can choose to ignore all missing arguments, or no missing arguments.
- `.homonyms` controls what happens if multiple arguments use the same name:

```

str(dots_list(x = 1, x = 2))
#> List of 2
#> $ x: num 1
#> $ x: num 2
str(dots_list(x = 1, x = 2, .homonyms = "first"))
#> List of 1
#> $ x: num 1
str(dots_list(x = 1, x = 2, .homonyms = "last"))
#> List of 1
#> $ x: num 2
str(dots_list(x = 1, x = 2, .homonyms = "error"))
#> Error: Arguments can't have the same name.
#> We found multiple arguments named `x` at positions 1 and 2

```

- If there are empty arguments that are not ignored, `.preserve_empty` controls what to do with them. The default throws an error; setting `.preserve_empty = TRUE` instead returns missing symbols. This is useful if you’re using `dots_list()` to generate function calls.

17.6.4 With base R

Base R provides a swiss-army knife to solve these problems: `do.call()`. `do.call()` has two main arguments. The first argument, `what`, gives a function to call. The second argument, `args`, is a list of arguments to pass to that function, and so `do.call("f", list(x, y, z))` is equivalent to `f(x, y, z)`.

- `do.call()` gives a straightforward solution to `rbind()`ing together many

data frames:

```
do.call("rbind", dfs)
#>   x y
#> a 1 2
#> b 3 4
```

- With a little more work, we can use `do.call()` to solve the second problem. We first create a list of arguments, then name that, then use `do.call()`:

```
args <- list(val)
names(args) <- var

do.call("data.frame", args)
#>   x
#> 1 4
#> 2 3
#> 3 9
```

Some base functions (including `interaction()`, `expand.grid()`, `options()`, and `par()`) use a trick to avoid `do.call()`: if the first component of `...` is a list, they'll take its components instead of looking at the other elements of `....`. The implementation looks something like this:

```
f <- function(...) {
  dots <- list(...)
  if (length(dots) == 1 && is.list(dots[[1]])) {
    dots <- dots[[1]]
  }

  # Do something
  ...
}
```

Another approach to avoiding `do.call()` is found in the `RCurl:::getURL()` function written by Duncan Temple Lang. `getURL()` takes both `...` and `.opts` which are concatenated together. This looks something like this:

```
f <- function(..., .dots) {
  dots <- c(list(...), .dots)
  # Do something
}
```

At the time I discovered it, I found this technique particularly compelling so you can see it used throughout the tidyverse. Now, however, I prefer the approach

described next.

17.6.5 Exercises

1. One way to implement `exec()` below. Describe how it works. What are the key ideas?

```
exec <- function(f, ..., .env = caller_env()) {
  args <- list2(...)
  do.call(f, args, envir = .env)
}
```

2. Carefully read the source code for `interaction()`, `expand.grid()`, and `par()`. Compare and contrast the techniques they use for switching between dots and list behaviour.
3. Explain the problem with this definition of `set_attr()`

```
set_attr <- function(x, ...) {
  attr <- rlang::list2(...)
  attributes(x) <- attr
  x
}
set_attr(1:10, x = 10)
#> Error in attributes(x) <- attr:
#>   attributes must be named
```

17.7 Case studies

To make the ideas of quasiquotation concrete, this section contains a few smaller case studies that show how you can use it to solve real problems. Some of the case studies also use `purrr`: I find the combination of quasiquotation and functional programming to be particularly elegant.

Most users of quasiquotation will not involve `expr()` or `exprs()` but will instead involve a function that calls `enexpr()` or `enexprs()`. You should be able to tell if a function uses quasiquotation because the documentation will mention it, and consequently if you use `enexpr()` in a documented function, make sure to mention quasiquotation.

This technique allows you to write functions that wrap around quasiquotation functions with a simple pattern: quote with `enexpr()` then unquote with `!!`:

```
cv <- function(x) {
  x <- enexpr(x)
  expr(sd (!!x) / mean (!!x))
}

cv(x + y)
#> sd(x + y)/mean(x + y)
```

17.7.1 `lobstr::ast()`

Quasiquotation allows us to solve an annoying problem with `lobstr::ast()`: what happens if we've already captured the expression?

```
z <- expr(foo(x, y))
lobstr::ast(z)
#> z
```

Because `ast()` supports quasiquotation, we can use `!!`:

```
lobstr::ast (!!z)
#> foo
#> x
#> y
```

17.7.2 Map-reduce to generate code

Quasiquotation gives us powerful tools for generating code, particularly when combined with `purrr::map()` and `purrr::reduce()`. For example, assume you have a linear model specified by the following coefficients:

```
intercept <- 10
coefs <- c(x1 = 5, x2 = -4)
```

And you want to convert it into an expression like $10 + (5 * x1) + (-4 * x2)$. The first thing we need to do is turn the character names vector into a list of symbols. `rlang::syms()` is designed precisely for this case:

```
coef_sym <- syms(names(coefs))
coef_sym
#> [[1]]
#> x1
#>
```

```
#> [[2]]
#> x2
```

Next we need to combine each variable name with its coefficient. We can do this by combining `rlang::expr()` with `purrr::map2()`:

```
summands <- map2(coef_sym, coefs, ~ expr (!! .x * !! .y))
summands
#> [[1]]
#> (x1 * 5)
#>
#> [[2]]
#> (x2 * -4)
```

In this case, the intercept is also a part of the sum, although it doesn't involve a multiplication. We can just add it to the start of the `summands` vector:

```
summands <- c(intercept, summands)
summands
#> [[1]]
#> [1] 10
#>
#> [[2]]
#> (x1 * 5)
#>
#> [[3]]
#> (x2 * -4)
```

Finally, we need to reduce the individual terms into a single sum by adding the pieces together:

```
eq <- reduce(summands, ~ expr (!! .x + !! .y))
eq
#> 10 + (x1 * 5) + (x2 * -4)
```

We could make this even more general by allowing the user to supply the name of the coefficient, and instead of assuming many different variables, index into a single one.

```
var <- expr(y)
coef_sym <- map(seq_along(coefs), ~ expr (!! var)[[!! .x]]))
coef_sym
#> [[1]]
#> y[[1L]]
```

```
#>
#> [[2]]
#> y[[2L]]
```

And finish by wrapping this up into a function:

```
linear <- function(var, val) {
  var <- ensym(var)
  coef_name <- map(seq_along(val[-1]), ~ expr (!!var)[[!!x]]))

  summands <- map2(coefs, coef_name, ~ expr (!!x * !!y))
  summands <- c(val[[1]], summands)

  reduce(summands, ~ expr (!!x + !!y))
}

linear(x, c(10, 5, -4))
#> 10 + (5 * x[[1L]]) + (-4 * x[[2L]])
```

Note the use of `ensym()`. We want the user to supply the name of a single variable, not a more complex expression.

We could even make this into a function-generating function:

```
linear_fun <- function(var, val) {
  var <- ensym(var)

  new_function(
    set_names(list(missing_arg()), var),
    linear (!!var, val),
    caller_env()
  )
}

linear_fun(x, c(10, 5, -4))
#> function (x)
#> 10 + (5 * x[[1L]]) + (-4 * x[[2L]])
```

17.7.3 Slicing an array

An occassionally useful tool missing from base R is the ability to extract a slice of an array given a dimension and an index. For example, we'd like to write `slice(x, 2, 1)` to extract the first slice along the second dimension, which you

can write as `x[, 1,]`. This is a moderately challenging problem because it requires working with missing arguments.

We'll need to generate a call with multiple missing arguments. Fortunately that's easy with `rep()` and `missing_arg()`. Once we have those arguments, we can unquote-splice them into a call:

```
indices <- rep(list(missing_arg()), 3)
expr(x[!!!indices])
#> x[, , ]
```

Then we use subset-assignment to insert the index in the desired position:

```
indices[[2]] <- 1
expr(x[!!!indices])
#> x[, 1, ]
```

We then wrap this into a function, using a couple of `stopifnot()`s to make the interface clear:

```
slice <- function(x, along, index) {
  stopifnot(length(along) == 1)
  stopifnot(length(index) == 1)

  nd <- length(dim(x))
  indices <- rep(list(missing_arg()), nd)
  indices[[along]] <- index

  expr(x[!!!indices])
}
```

```
x <- array(sample(30), c(5, 2, 3))
slice(x, 1, 3)
#> x[3, , ]
slice(x, 2, 2)
#> x[, 2, ]
slice(x, 3, 1)
#> x[, , 1]
```

A real `slice()` would evaluate the generated call, but here I think it's more illuminating to see the code that's generated, as that's the hard part of the challenge.

17.7.4 Creating functions

Another powerful application of quotation is creating functions “by hand”, using `rlang::new_function()`. It’s a function that create a function from its three components (Section ??) arguments, body, and (optionally) environment:

```
new_function(
  exprs(x = , y = ),
  expr({x + y})
)
#> function (x, y)
#> {
#>   x + y
#> }
```

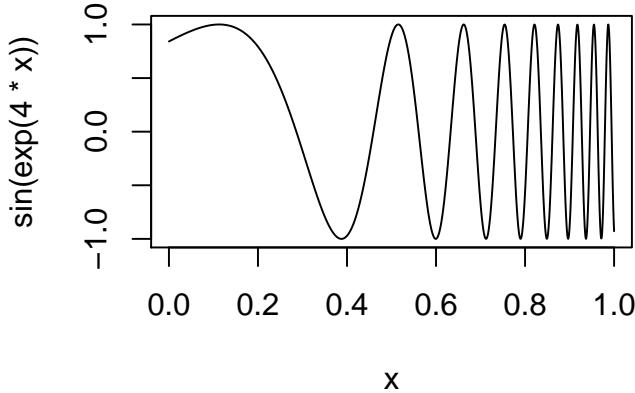
One use of `new_function()` is as an alternative to function factories with scalar or symbol arguments. For example, we could write a function that generates functions that raise a function to the power of a number.

```
power <- function(exponent) {
  new_function(
    exprs(x = ),
    expr({
      x ^ !!exponent
    }),
    caller_env()
  )
}
power(0.5)
#> function (x)
#> {
#>   x^0.5
#> }
```

(Note that `power()` is not a quoting function. It inlines the *value* of `exponent`, not the expression that generates it.)

Another application of `new_function()` for functions that work like `graphics::curve()`. `curve()` allows you to plot a mathematical expression, without creating a function:

```
curve(sin(exp(4 * x)), n = 1000)
```



Here `x` is a pronoun: it doesn't represent a single concrete value, but is instead a placeholder that varies over the range of the plot. One way to implement `curve()` is to turn that expression into a function with a single argument, `x`, then call that function:

```
curve2 <- function(expr, xlim = c(0, 1), n = 100) {
  expr <- enexpr(expr)
  f <- new_function(exprs(x = ), expr)

  x <- seq(xlim[1], xlim[2], length = n)
  y <- f(x)

  plot(x, y, type = "l", ylab = expr_text(expr))
}
curve2(sin(exp(4 * x)), n = 1000)
```

Functions, like `curve()`, that use an expression containing a pronoun are known as **anaphoric** functions⁸.

17.7.5 Exercises

1. In the linear-model example, we could replace the `expr()` in `reduce(summands, ~ expr(!!.x + !!.y))` with `call2(): reduce(summands, call2, "+")`. Compare and contrast the two approaches. Which do you think is easier to read?

⁸Anaphoric comes from the linguistics term “anaphora”, an expression that is context dependent. Anaphoric functions are found in Arc (<http://www.arcfn.com/doc/anaphoric.html>) (a LISP like language), Perl (http://www.perlmonks.org/index.pl?node_id=666047), and Clojure (<http://amalloy.hubpages.com/hub/Unhygienic-anaphoric-Clojure-macros-for-fun-and-profit>).

2. Re-implement the Box-Cox transform defined below using unquoting and `new_function()`:

```
bc <- function(lambda) {  
  if (lambda == 0) {  
    function(x) log(x)  
  } else {  
    function(x) (x ^ lambda - 1) / lambda  
  }  
}
```

3. Re-implement the simple `compose()` defined below using quasiquotation and `new_function()`:

```
compose <- function(f, g) {  
  function(...) f(g(...))  
}
```


Chapter 18

Evaluation

18.1 Introduction

The user-facing inverse of quotation is unquotation: it gives the *user* the ability to selectively evaluate parts of an otherwise quoted argument. The developer-facing complement of quotation is evaluation: this gives the *developer* the ability to evaluate quoted expressions in custom environments to achieve specific goals.

This chapter begins with a discussion of evaluation in its purest. You’ll learn how `rlang::eval_bare()` evaluates an expression in an environment, and then how it can be used to implement a number of important base R functions. Next, we’ll circle back to `base::eval()` and friends to see how these ideas are expressed in base R.

Once you have the basics under your belt, you’ll learn extensions to evaluation that are needed for robustness. There are two big new ideas:

- The quosure: a data structure that captures an expression along with its associated environment, as found in function arguments.
- The data mask, which makes it easier to evaluate an expression in the context of a data frame. This introduces potential evaluation ambiguity which we’ll then resolve with data pronouns.

Together, quasiquotation, quosures, and data masks form what we call **tidy evaluation**, or tidy eval for short. Tidy eval provides a principled approach to non-standard evaluation that makes it possible to use such functions both interactively and embedded with other functions. Tidy evaluation is the most important practical implication of all this theory so we’ll spend a little time exploring the

implications. The chapter finishes off with a discussion of the closest related approaches in base R, and how you can program around their drawbacks.

Outline

Prerequisites

You'll need to be familiar with the content of Chapter 16 and Chapter ??, as well as the environment data structure (Section 6.2) and the caller environments (Section 6.5).

We'll continue to use rlang and purrr.

```
library(rlang)
library(purrr)
#>
#> Attaching package: 'purrr'
#> The following objects are masked from 'package:rlang':
#>
#>     %%, %/%, as_function, flatten, flatten_chr,
#>     flatten_dbl, flatten_int, flatten_lgl, invoke,
#>     list_along, modify, prepend, rep_along, splice
```

18.2 Evaluation basics

In the previous chapter, we briefly mentioned `eval()`. Here, however, we're going to start with `rlang::eval_bare()` as it's the purest evocation of the idea of evaluation. It has two arguments: `expr` and `env`. The first argument, `expr`, is the object to evaluate, which is typically either a symbol or an expression¹. None of the evaluation functions quote their inputs, so you'll usually use them with `expr()` or similar:

```
x <- 10
eval_bare(expr(x))
#> [1] 10

y <- 2
eval_bare(expr(x + y))
#> [1] 12
```

¹All object yield themselves when evaluated; i.e. `eval_bare(x)` yields `x` except when `x` is a symbol or expression.

The second argument, `env`, gives the environment in which the expression should be evaluated, i.e. where should the values of `x`, `y`, and `+` be looked for? By default, this is the current environment, i.e. the calling environment of `eval_bare()`, but you can override it if you want:

```
eval_bare(expr(x + y), env(x = 1000))
#> [1] 1002
```

Because R looks up functions in the same way as variables, we can also override the meaning of functions. This is a very useful technique if you want to translate R code into something else, as you'll learn about Chapter 19.

```
eval_bare(
  expr(x + y),
  env(`+` = function(x, y) paste0(x, " + ", y))
)
#> [1] "10 + 2"
```

Note that the first argument to `eval_bare()` (and to `base::eval()`) is evaluated, not quoted. This can lead to confusing results if you forget to quote the input:

```
eval_bare(x + y)
#> [1] 12
eval_bare(x + y, env(x = 1000))
#> [1] 12
```

Now that you've seen the basics, let's explore some applications. We'll focus primarily on base R functions that you might have used before; now you can learn how they work. To focus on the underlying principles, we'll extract out their essence implemented using `rlang`. Once you've seen some applications, we'll circle back and talk more about `base::eval()`.

18.2.1 Application: `local()`

Sometimes you want to perform a chunk of calculation that creates some intermediate variables. The intermediate variables have no long-term use and could be quite large, so you'd rather not keep them around. One approach is to clean up after yourself using `rm()`; another approach is to wrap the code in a function, and just call it once. A more elegant approach is to use `local()`:

```
# Clean up variables created earlier
rm(x, y)

foo <- local({
```

```

x <- 10
y <- 200
x + y
})

foo
#> [1] 210
x
#> Error in eval(expr, envir, enclos):
#>   object 'x' not found
y
#> Error in eval(expr, envir, enclos):
#>   object 'y' not found

```

The essence of `local()` is quite simple. We capture the input expression, and create a new environment in which to evaluate it. This is a new environment (so `assign` doesn't affect the existing environment) with the caller environment as parent (so that `expr` can still access variables in that environment). This effectively emulates running `expr` as if it was inside a function (i.e. it's lexically scoped, Section 5.4).

```

local2 <- function(expr) {
  env <- child_env(caller_env())
  eval_bare(enexpr(expr), env)
}

foo <- local2({
  x <- 10
  y <- 200
  x + y
})

foo
#> [1] 210
x
#> Error in eval(expr, envir, enclos):
#>   object 'x' not found
y
#> Error in eval(expr, envir, enclos):
#>   object 'y' not found

```

Understanding how `base::local()` works is harder, as it uses `eval()` and

`substitute()` together in rather complicated ways. Figuring out exactly what's going on is good practice if you really want to understand the subtleties of `substitute()` and the base `eval()` functions, so is included in the exercises below.

18.2.2 Application: `source()`

We can create a simple version of `source()` by combining `eval_bare()` with `parse_expr()` from Section 16.4.3. We read in the file from disk, use `parse_expr()` to parse the string into a list of expressions, and then use `eval_bare()` to evaluate each element in turn. This version evaluates the code in the caller environment, and invisibly returns the result of the last expression in the file just like `base::source()`.

```
source2 <- function(path, env = caller_env()) {
  file <- paste(readLines(path, warn = FALSE), collapse = "\n")
  exprs <- parse_exprs(file)

  res <- NULL
  for (i in seq_along(exprs)) {
    res <- eval_bare(exprs[[i]], env)
  }

  invisible(res)
}
```

The real `source()` is considerably more complicated because it can echo input and output, and has many other settings that control its behaviour.

18.2.3 Gotcha: `function()`

There's one small gotcha that you should be aware of if you're using `eval_bare()` and `expr()` to generate functions:

```
x <- 10
y <- 20
f <- eval_bare(expr(function(x, y) !!x + !!y))
f
#> function(x, y) !!x + !!y
```

This function doesn't look like it will work, but it does:

```
f()
#> [1] 30
```

This is because, if available, functions print their `srcref` attribute (Section 5.2.2), and because the `srcref` is a base R feature it's unaware of quasiquotation. To work around this problem, either use `new_function()`, Section 17.7.4, or remove the `srcref` attribute:

```
attr(f, "srcref") <- NULL
f
#> function (x, y)
#> 10 + 20
```

18.2.4 Base R

The closest base equivalent to `eval_bare()` is the two-argument form of `eval()`: `eval(expr, envir)`:

```
eval(expr(x + y), env(x = 1000, y = 1))
#> [1] 1001
```

`eval()` has a third argument, `enclos`, which provides support for data masks, the topic of Section [??](#). `eval()` is paired with two helper functions:

- `evalq(x, env)` quotes its first argument, and is hence a shortcut for `eval(quote(x), env)`.
- `eval.parent(expr, n)` is a shortcut for `eval(expr, env = parent.frame(n))`.

In most cases, there is no reason to prefer `rlang::eval_bare()` over `eval()`; I just used it here because it has a more minimal interface.

Expression vectors

`base::eval()` has special behaviour for expression *vectors*, evaluating each component in turn. This makes for a very compact implementation of `source2()` because `base::parse()` also returns an expression object:

```
source3 <- function(file, env = parent.frame()) {
  lines <- parse(file)
  res <- eval(lines, envir = env)
  invisible(res)
}
```

While `source3()` is considerably more concise than `source2()`, this one use is the strongest argument for expression objects. Overall we don't believe this benefit

outweighs the cost of introducing a new data structure, and hence this book avoids expression vectors as much as possible.

18.2.5 Exercises

1. Carefully read the documentation for `source()`. What environment does it use by default? What if you supply `local = TRUE`? How do you provide a custom argument?
2. Predict the results of the following lines of code:

```
eval(quote(eval(quote(eval(quote(2 + 2))))))
eval(eval(quote(eval(quote(eval(quote(2 + 2)))))))
quote(eval(quote(eval(quote(eval(quote(2 + 2)))))))
```

3. Write an equivalent to `get()` using `sym()` and `eval_bare()`. Write an equivalent to `assign()` using `sym()`, `expr()`, and `eval_bare()`. (Don't worry about the multiple ways of choosing an environment that `get()` and `assign()` support; assume that the user supplies it explicitly.)

```
# name is a string
get2 <- function(name, env) {}
assign2 <- function(name, value, env) {}
```

4. Modify `source2()` so it returns the result of *every* expression, not just the last one. Can you eliminate the for loop?
5. We can make `base::local()` slightly easier to understand by spreading out over multiple lines:

```
local3 <- function(expr, envir = new.env()) {
  call <- substitute(eval(quote(expr), envir))
  eval(call, envir = parent.frame())
}
```

Explain how `local()` works in words. (Hint: you might want to `print(call)` to help understand what `substitute()` is doing, and read the documentation to remind yourself what environment `new.env()` will inherit from.)

18.3 Quosures

Almost every use of `eval()` involves both an expression and environment. This coupling is so important we need a data structure that can hold both pieces. Base R² does not have such a structure so `rlang` fills the gap with the `quosure`, an object that contains an expression and an environment. The name is a portmanteau of quoting and closure, because a quosure both quotes the expression and encloses the environment. Quosures reify the internal promise object (Section [??](#)) into something that you can program with.

In this section, you'll learn how to create and manipulate quosures, and a little about how they are implemented.

18.3.1 Creating

There are three ways to create quosures:

- Use `enquo()` and `enquos()` to capture user-supplied expressions, as shown above. The vast majority of quosures should be created this way.

```
foo <- function(x) enquo(x)
foo(a + b)
#> <quosure>
#> expr: `a + b
#> env: global
```

- `quo()` and `quos()` exist to match to `expr()` and `exprs()`, but they are included only for the sake of completeness and are needed very rarely.

```
quo(x + y + z)
#> <quosure>
#> expr: `x + y + z
#> env: global
```

- `new_quosure()` create a quosures from its components: an expression and an environment. This is rarely needed in practice, but is useful for learning about the system so used a lot in this chapter.

```
new_quosure(expr(x + y), env(x = 1, y = 10))
#> <quosure>
```

²That's a bit of simplification because technically a formula combines an expression and environment. However, formulas are tightly coupled to modelling so a new data structure makes sense.

```
#> expr: ^x + y
#> env: 0x49999e8
```

18.3.2 Evaluating

Quosures are paired with a new evaluation function: `eval_tidy()` that takes an expression and environment bundled together into a quosure. It is straightforward to use:

```
q1 <- new_quosure(expr(x + y), env(x = 1, y = 10))
eval_tidy(q1)
#> [1] 11
```

For this simple case, `eval_tidy(q1)` is basically a shortcut for `eval_bare(get_expr(q1), get_env(q2))`. However, it has two important features that you'll learn about later in the chapter: it supports nested quosures and pronouns.

18.3.3 Dots {quosure-dots}

Quosures are typically just a convenience: they make code cleaner because you only have one object to pass around, instead of two. They are, however, essential when it comes to working with ... because it's possible for each argument passed to ... to have a different environment associated with it. In the following example note that both quosures have the same expression, `x`, but a different environment:

```
f <- function(...) {
  x <- 1
  g(..., f = x)
}

g <- function(...) {
  enquos(...)
}

x <- 0
qs <- f(global = x)
qs
#> <listof<quosures>>
#>
#> $global
#> <quosure>
#> expr: ^x
```

```
#> env: global
#>
#> $f
#> <quosure>
#> expr: ~x
#> env: 0x52432b8
```

That means that when you evaluate them, you get the correct results:

```
map(qs, eval_tidy)
#> $global
#> [1] 0
#>
#> $f
#> [1] 1
```

Correctly evaluating the elements of dots was one of the original motivation for the development of quosures.

18.3.4 Under the hood

Quosures were inspired by R's formulas, because formulas capture an expression and an environment:

```
f <- ~runif(3)
str(f)
#> Class 'formula' language ~runif(3)
#> . . - attr(*, ".Environment")=<environment: R_GlobalEnv>
```

An early version of tidy evaluation used formulas instead of quosures, as an attractive feature of `~` is that it provides quoting with a single keystroke. Unfortunately, however, there is no clean way to make `~` a quasiquoting function.

Quosures are, however, a subclass of formulas:

```
q4 <- new_quosure(expr(x + y + z))
class(q4)
#> [1] "quosure" "formula"
```

This makes them a call to `~`:

```
is_call(q4)
#> [1] TRUE
```

```
q4[[1]]
#> `~`
q4[[2]]
#> x + y + z
```

With an attribute that stores the environment:

```
attr(q4, ".environment")
#> NULL
```

If you need to extract the expression or environment, don't rely on these implementation details. Instead use the `quo_get_` helpers:

```
quo_get_env(q4)
#> <environment: R_GlobalEnv>
quo_get_expr(q4)
#> x + y + z
```

18.3.5 Nested quosures

It's possible to use quasiquotation to embed a quosure in an expression. This is an advanced tool, and most of the time you don't need to think about it because it just works, but I talk about it here so you can spot nested quosures in the wild and not be confused. Take this example, which inlines two quosures into an expression:

```
q2 <- new_quosure(expr(x), env(x = 1))
q3 <- new_quosure(expr(x), env(x = 10))

x <- expr (!!q2 + !!q3)
```

It evaluates correctly with `eval_tidy()`:

```
eval_tidy(x)
#> [1] 11
```

Even though when you print it, you only see the `xs` (and here their formula heritage leaks through):

```
x
#> (~x) + ~x
```

You can get a better display with `rlang::expr_print()` (Section 17.4.7):

```
expr_print(x)
#> (x) + (x)
```

When you use `expr_print()` in the console, quosures are coloured according to their environment, making it easier to spot when symbols are bound to different variables.

18.3.6 Exercises

1. Predict what evaluating each of the following quosures will return.

```
q1 <- new_quosure(expr(x), env(x = 1))
q1
#> <quosure>
#> expr: x
#> env: 0x48db258

q2 <- new_quosure(expr(x + !!q1), env(x = 10))
q2
#> <quosure>
#> expr: x + (x)
#> env: 0x4a98450

q3 <- new_quosure(expr(x + !!q2), env(x = 100))
q3
#> <quosure>
#> expr: x + (x + (x))
#> env: 0x4d80310
```

2. Write an `enenv()` function that captures the environment associated with an argument.

18.4 Data masks

So far, you've learned about quosures and `eval_tidy()`. In this section, you'll learn about the **data mask**, a data frame where the evaluated code will look first for variable definitions. The data mask is the key idea that powers base functions like `with()`, `subset()` and `transform()`, and is used throughout the tidyverse in packages like `dplyr` and `ggplot2`.

18.4.1 Basics

The data mask allows you to mingle variables from an environment and data frame in a single expression. You supply the data mask as the second argument to `eval_tidy()`:

```
q1 <- new_quosure(expr(x * y), env(x = 100))
df <- data.frame(y = 1:10)

eval_tidy(q1, df)
#> [1] 100 200 300 400 500 600 700 800 900 1000
```

This code is a little hard to follow because there's so much syntax as we're creating every object from scratch. It's easier to see what's going on if we make a little wrapper. I call this `with2()` because it's equivalent to `base::with()`.

```
with2 <- function(data, expr) {
  expr <- enquo(expr)
  eval_tidy(expr, data)
}
```

We can now rewrite the code above as below:

```
x <- 100
with2(df, x * y)
#> [1] 100 200 300 400 500 600 700 800 900 1000
```

`base::eval()` has similar functionality, although it doesn't call it a data mask. Instead you can supply a data frame to the `envir` argument and an environment to the `enclos` argument. That gives the following implementation of `with()`:

```
with3 <- function(data, expr) {
  expr <- substitute(expr)
  eval(expr, data, caller_env())
}
```

18.4.2 Pronouns

The data mask introduces ambiguity. For example, in the following code you can't know whether `x` will come from the data mask or the environment, unless you know what variables are found in `df`.

```
with2(df, x)
```

That makes code harder to reason about (because you need to know more context), and can introduce bugs. To resolve that issue, the data mask provides two pronouns: `.data` and `.env`.

- `.data$x` always refers to `x` in the data mask, or dies trying.
- `.env$x` always refers to `x` in the environment, or dies trying.

```
x <- 1
df <- data.frame(x = 2)

with2(df, .data$x)
#> [1] 2
with2(df, .env$x)
#> [1] 1
```

You can also subset using `[[`. Otherwise the pronouns are special objects and you shouldn't expect them to behave like data frames or environments. In particular, they throw error if the object isn't found:

```
with2(df, .data$y)
#> Error: Column `y` not found in `^.data`
```

Pronouns are particularly important when using tidy evaluation, and we'll come back to them in Section 18.5.2.

18.4.3 Application: `subset()`

We'll explore tidy evaluation in the context of `base::subset()`, because it's a simple yet powerful function that encapsulates one of the central ideas that makes R so elegant for data analysis. If you haven't used it before, `subset()`, like `dplyr::filter()`, provides a convenient way of selecting rows of a data frame. You give it some data, along with an expression that is evaluated in the context of that data. This considerably reduces the number of times you need to type the name of the data frame:

```
sample_df <- data.frame(a = 1:5, b = 5:1, c = c(5, 3, 1, 4, 1))

# Shorthand for sample_df[sample_df$a >= 4, ]
subset(sample_df, a >= 4)
#>   a b c
#> 4 4 2 4
#> 5 5 1 1

# Shorthand for sample_df[sample_df$b == sample_df$c, ]
```

```
subset(sample_df, b == c)
#> a b c
#> 1 1 5 5
#> 5 5 1 1
```

The core of our version of `subset()`, `subset2()`, is quite simple. It takes two arguments: a data frame, `data`, and an expression, `rows`. We evaluate `rows` using `df` as a data mask, then use the results to subset the data frame with `[`. I've included a very simple check to ensure the result is a logical vector; real code would do more to create an informative error.

```
subset2 <- function(data, rows) {
  rows <- enquo(rows)

  rows_val <- eval_tidy(rows, data)
  stopifnot(is.logical(rows_val))

  data[rows_val, , drop = FALSE]
}

subset2(sample_df, b == c)
#> a b c
#> 1 1 5 5
#> 5 5 1 1
```

18.4.4 Application: transform

A more complicated situation is `base:::transform()` which allows you to add new variables to data frame, evaluating their expressions in the context of the existing variables:

```
df <- data.frame(x = c(2, 3, 1), y = runif(3))
transform(df, x = -x, y2 = 2 * y)
#> x y y2
#> 1 -2 0.0808 0.162
#> 2 -3 0.8343 1.669
#> 3 -1 0.6008 1.202
```

Implementing `transform2()` is again quite straightforward. We capture the unevaluated `...` with `enquos(...)`, and then evaluate each expression using a for loop. Real code would need to do more error checking, ensure that each input is named, and evaluates to a vector the same length as `data`.

```

transform2 <- function(.data, ..., .na.last = TRUE) {
  dots <- enquos(...)

  for (i in seq_along(dots)) {
    name <- names(dots)[[i]]
    dot <- dots[[i]]

    .data[[name]] <- eval_tidy(dot, data = .data)
  }

  .data
}

transform2(df, x2 = x * 2, y = -y)
#>   x      y x2
#> 1 2 -0.0808  4
#> 2 3 -0.8343  6
#> 3 1 -0.6008  2

```

Note that I named the first argument `.data`. This avoids problems if the user tried to create a variable called `data`; this is the same reasoning that leads to `map()` having `.x` and `.f` arguments (Section 8.2.4).

18.4.5 Application: `select()`

Typically, the data mask will be a data frame. But it's sometimes useful to provide a list filled with more exotic contents. This is basically how the `select` argument `base::subset()` works. It allows you to refer to variables as if they were numbers:

```

df <- data.frame(a = 1, b = 2, c = 3, d = 4, e = 5)
subset(df, select = b:d)
#>   b c d
#> 1 2 3 4

```

The key idea is to create a named list where each component gives the position of the corresponding variable:

```

vars <- as.list(set_names(seq_along(df), names(df)))
str(vars)
#> List of 5
#> $ a: int 1

```

```
#> $ b: int 2
#> $ c: int 3
#> $ d: int 4
#> $ e: int 5
```

Then it's a straight application of `enquo()` and `eval_tidy()`:

```
select2 <- function(data, ...) {
  dots <- enquos(...)

  vars <- as.list(set_names(seq_along(data), names(data)))
  cols <- unlist(map(dots, eval_tidy, data = vars))

  df[, cols, drop = FALSE]
}

select2(df, b:d)
#> b c d
#> 1 2 3 4
```

`dplyr::select()` takes this idea and runs with it, providing a number of helpers that allow you to select variables based on their names (e.g. `starts_with("x")`, `ends_with("_a")`).

18.4.6 Exercises

1. What the difference between using a for loop and a map function in `transform2()`? Consider `transform2(df, x = x * 2, x = x * 2)`.
2. Here's an alternative implementation of `subset2()`:

```
subset3 <- function(data, rows) {
  rows <- enquo(rows)
  eval_tidy(expr(data[!!rows, , drop = FALSE]), data = data)
}

df <- data.frame(x = 1:3)
subset3(df, x == 1)
```

Compare and contrast `subset3()` to `subset2()`. What are its advantages and disadvantages.

3. The following function implements the basics of `dplyr::arrange()`. Annotate each line with a comment explaining what it does. Can you

explain why `!na.last` is strictly correct, but omitting the `!!` is unlikely to cause problems?

```
arrange2 <- function(.df, ..., .na.last = TRUE) {
  args <- enquos(...)

  order_call <- expr(order(!!args, na.last = !!.na.last))

  ord <- eval_tidy(order_call, .df)
  stopifnot(length(ord) == nrow(.df))

  .df[ord, , drop = FALSE]
}
```

18.5 Using tidy evaluation

While it's useful to understand how `eval_tidy()` works, most of the time you won't call it directly. Instead, you'll usually use it indirectly by calling a function that uses `eval_tidy()`. Tidy evaluation is infectious: the root always involves a call to `eval_tidy()` but that may be several levels away.

In this section we'll explore how tidy evalution facilitates this division of responsibility, and you'll learn how to create safe and useful wrapper functions.

18.5.1 Quoting and unquoting

Imagine we have written a function that bootstraps a function:

```
bootstrap <- function(df, n) {
  idx <- sample(nrow(df), n, replace = TRUE)
  df[idx, , drop = FALSE]
}
```

And we want to create a new function that allows us to bootstrap and subset in a single step. Our naive approach doesn't work:

```
bootset <- function(df, cond, n = nrow(df)) {
  df2 <- subset2(df, cond)
  bootstrap(df2, n)
}

df <- data.frame(x = c(1, 1, 1, 2, 2), y = 1:5)
```

```
bootset(df, x == 1)
#>     x y
#> 1  1 1
#> 1.1 1 1
#> 3  1 3
#> 3.1 1 3
#> 2  1 2
```

`bootset()` doesn't quote any arguments so `cond` is evaluated normally (not in a data mask), and we get an error when it tries to find a binding for `x`. To fix this problem we need to quote `cond`, and then unquote it when we pass it on to `subset2()`:

```
bootset <- function(df, cond, n = nrow(df)) {
  cond <- enquo(cond)

  df2 <- subset2(df, !!cond)
  bootstrap(df2, n)
}

bootset(df, x == 1)
#>     x y
#> 3  1 3
#> 3.1 1 3
#> 3.2 1 3
#> 1  1 1
#> 1.1 1 1
```

This is a very common pattern; whenever you call a quoting function with arguments from the user, you need to quote them yourself and then unquote.

18.5.2 Handling ambiguity

In the case above, we needed to think about tidy eval because of quasiquotation. We also need to think tidy evaluation even when the wrapper doesn't need to quote any arguments. Take this wrapper around `subset2()`:

```
threshold_x <- function(df, val) {
  subset2(df, x >= val)
}
```

This function can silently return an incorrect result in two situations:

- When `x` exists in the calling environment, but not in `df`:

```
x <- 10
no_x <- data.frame(y = 1:3)
threshold_x(no_x, 2)
#>     y
#> 1 1
#> 2 2
#> 3 3
```

- When `val` exists in `df`:

```
has_val <- data.frame(x = 1:3, val = 9:11)
threshold_x(has_val, 2)
#> [1] x   val
#> <0 rows> (or 0-length row.names)
```

These failure modes arise because tidy evaluation is ambiguous: each variable can be found in **either** the data mask **or** the environment. To make this function safe we need to remove the ambiguity using the `.data` and `.env` pronouns:

```
threshold_x <- function(df, val) {
  subset2(df, .data$x >= .env$val)
}

x <- 10
threshold_x(no_x, 2)
#> Error: Column `x` not found in `data`!
threshold_x(has_val, 2)
#>   x val
#> 2 2 10
#> 3 3 11
```

Generally, whenever you use the `.env` pronoun, you can use unquoting instead:

```
threshold_x <- function(df, val) {
  subset2(df, .data$x >= !!val)
}
```

There are subtle differences in when `val` is evaluated. If you unquote, `val` will be early evaluated by `enquo()`; if you use a pronoun, `val` will be lazily evaluated by `eval_tidy()`. These differences are usually unimportant, so pick the form that looks most natural.

18.5.3 Quoting and ambiguity

To finish our discussion let's consider the case where we have both quoting and potential ambiguity. I'll generalise `threshold_x()` slightly so that the user can pick the variable used for thresholding. I

```
threshold_var <- function(df, var, val) {
  var <- as_string(ensym(var))
  subset2(df, .data[[var]] >= !!val)
}

df <- data.frame(x = 1:10)
threshold_var(df, x, 8)
#>     x
#> 8   8
#> 9   9
#> 10  10
```

Note that it is not always the responsibility of the function author to avoid ambiguity. Imagine we generalise further to allow thresholding based on any expression:

```
threshold_expr <- function(df, expr, val) {
  expr <- enquo(expr)
  subset2(df, !!expr >= !!val)
}
```

It's not possible to evaluate `expr` only the data mask, because the data mask doesn't include any functions like `+` or `==`. Here, it's the user's responsibility to avoid ambiguity. As a general rule of thumb, as a function author it's your responsibility to avoid ambiguity with any expressions that you create; it's the user's responsibility to avoid ambiguity in expressions that they create.

18.5.4 Exercises

1. I've included an alternative implementation of `threshold_var()` below. What makes it different to the approach I used above? What makes it harder?

```
threshold_var <- function(df, var, val) {
  var <- ensym(var)
  subset2(df, `$(.data, !!var) >= !!val)
}
```

18.6 Base evaluation

Now that you understand tidy evaluation, it's time to come back to the alternative approaches taken by base R, a family of approaches collectively known as non-standard evaluation (NSE). Here I'll explore the two most common techniques in base R:

- `substitute()` and evaluation in the caller environment, as used by `subset()`. I'll use this technique to motivate why this technique is not programming friendly, as warned about in the `subset()` documentation.
- `match.call()`, call manipulation, and evaluation in the caller environment, as used by `write.csv()` and `lm()`. I'll use this technique to motivate how quasiquotation and (regular) evaluation can help you write wrappers around NSE functions.

18.6.1 `substitute()`

The most common form of NSE in base R is `substitute() + eval()`. The following code shows how you might write the core of `subset()` in this style, using `substitute()` and `eval()` rather than `enquo()` and `eval_tidy()`. I repeat the code introduced in Section 18.4.3 so you can compare easily. The main difference is the evaluation environment: in `subset_base()` the expression is evaluated in the caller environment; in `subset_tidy()`, it's evaluated in the environment where it was defined.

```
subset_base <- function(data, rows) {
  rows <- substitute(rows)

  rows_val <- eval(rows, data, caller_env())
  stopifnot(is.logical(rows_val))

  data[rows_val, , drop = FALSE]
}

subset_tidy <- function(data, rows) {
  rows <- enquo(rows)

  rows_val <- eval_tidy(rows, data)
  stopifnot(is.logical(rows_val))

  data[rows_val, , drop = FALSE]
```

```
}
```

18.6.1.1 Programming with `subset()`

The documentation of `subset()` includes the following warning:

This is a convenience function intended for use interactively. For programming it is better to use the standard subsetting functions like `[`, and in particular the non-standard evaluation of argument `subset` can have unanticipated consequences.

There are main three problems:

- `base::subset()` always evaluates `rows` in the calling environment, but if `...` has been used, then the expression might need to be evaluated elsewhere:

```
f1 <- function(df, ...) {
  xval <- 3
  subset_base(df, ...)
}

my_df <- data.frame(x = 1:3, y = 3:1)
xval <- 1
f1(my_df, x == xval)
#>   x y
#> 3 3 1
```

This may seems like an esoteric concern, but it means that `subset_base()` cannot reliably work with functionals like `map()` or `lapply()`:

```
local({
  y <- 2
  dfs <- list(data.frame(x = 1:3), data.frame(x = 4:6))
  lapply(dfs, subset_base, x == y)
})
#> [[1]]
#> [1] x
#> <0 rows> (or 0-length row.names)
#>
#> [[2]]
#> [1] x
#> <0 rows> (or 0-length row.names)
```

- Calling `subset()` from another function requires some care: you have to use `substitute()` to capture a call to `subset()` complete expression, and then evaluate. Because `substitute()` doesn't use a syntactic marker for unquoting, it's a little hard to predict exactly what `substitute()` does. Here I print the generated call to make it a little easier.

```
f2 <- function(df1, expr) {
  call <- substitute(subset_base(df1, expr))
  expr_print(call)
  eval(call, caller_env())
}

my_df <- data.frame(x = 1:3, y = 3:1)
f2(my_df, x == 1)
#> subset_base(my_df, x == 1)
#>   x y
#> 1 1 3
```

- `eval()` doesn't provide any pronouns so there's no way to require part of the expression to come from the data. As far as I can tell, there's no way to make the following function safe except by manually checking for the presence of `z` variable in `df`.

```
f3 <- function(df) {
  call <- substitute(subset_base(df, z > 0))
  expr_print(call)
  eval(call, caller_env())
}

z <- -1
f3(my_df)
#> subset_base(my_df, z > 0)
#> [1] x y
#> <0 rows> (or 0-length row.names)
```

18.6.1.2 What about [?

Given that tidy evaluation is quite complex, why not simply use `[` as `?subset` recommends? Primarily, it seems unappealing to have functions that can only be interactively, and never inside another function. Even the simple `subset()` function provides two useful features compared to `[`:

- It sets `drop = FALSE` by default, so it's guaranteed to return a data frame.

- It drops rows where the condition evaluates to `NA`.

That means `subset(df, x == y)` is not equivalent to `df[x == y,]` as you might expect. Instead, it is equivalent to `df[x == y & !is.na(x == y), , drop = FALSE]`: that's a lot more typing! Real-life alternatives to `subset()`, like `dplyr::filter()`, do even more. For example, `dplyr::filter()` can translate R expressions to SQL so that they can be executed in a database. This makes programming with `filter()` relatively more important (because it does more behind the scenes that you want to take advantage of).

It would be possible to pair `subset_base()` with a programmable version, say `subset_prog()` below. I think this is unappealing because now need twice as many functions.

```
subset_prog <- function(data, rows, env = caller_env()) {
  rows_val <- eval(rows, data, env)
  stopifnot(is.logical(rows_val))
  data[rows_val, , drop = FALSE]
}
```

18.6.2 `match.call()`

Another common form of NSE is to capture the complete call with `match.call()`, modify it, and then evaluate. `match.call()` doesn't have an equivalent in tidy evaluation, but it rather than capturing a single argument like `substitute()` it captures the complete call:

```
g <- function(x, y, z) {
  match.call()
}
g(1, 2, z = 3)
#> g(x = 1, y = 2, z = 3)
```

One prominent user of `match.call()` is `write.csv()`, which basically works by transforming the call into a call to `write.table()` with the appropriate arguments set. The following code shows the heart of `write.csv()`:

```
write.csv <- function(...) {
  call <- match.call(write.table, expand.dots = TRUE)

  call[[1]] <- quote(write.table)
  call$sep <- ","
  call$dec <- "."
```

```
  eval(call, parent.frame())
}
```

I don't think this technique is a good idea because you can achieve the same result without NSE:

```
write.csv <- function(...) {
  write.table(..., sep = ",", dec = ".")
}
```

Nevertheless, it's important to understand this technique because it's commonly used in the modelling functions. The modelling functions also prominently print the captured call, which poses some special challenges, as you'll see next.

18.6.2.1 Wrapping modelling functions

To begin, consider the simplest possible wrapper around `lm()`:

```
lm2 <- function(formula, data) {
  lm(formula, data)
}
```

This wrapper works, but is suboptimal because `lm()` captures its call, and displays it when printing.

```
lm2(mpg ~ disp, mtcars)
#>
#> Call:
#> lm(formula = formula, data = data)
#>
#> Coefficients:
#> (Intercept)          disp
#>     29.5999      -0.0412
```

This is important because this call is the chief way that you see the model specification when printing the model. To overcome this problem, we need to capture the arguments, create the call to `lm()` using unquoting, then evaluate that call. To make it easier to see what's going on, I'll also print the expression we generate. This will become more useful as the calls get more complicated.

```
lm3 <- function(formula, data, env = caller_env()) {
  formula <- enexpr(formula)
  data <- enexpr(data)
```

```

lm_call <- expr(lm (!!formula, data = !!data))
expr_print(lm_call)
eval(lm_call, env)
}

lm3(mpg ~ disp, mtcars)
#> lm(mpg ~ disp, data = mtcars)
#>
#> Call:
#> lm(formula = mpg ~ disp, data = mtcars)
#>
#> Coefficients:
#> (Intercept)      disp
#> 29.5999      -0.0412

```

There are three pieces that you'll use whenever wrapping a base NSE function in this way:

- You capture the unevaluated arguments using `enexpr()`, and capture the caller environment using `caller_env()`. You have to accept that the function will not work correctly if the arguments are not defined in the caller environment.
- You generate a new expression using `expr()` and unquoting.
- You evaluate that expression in the caller environment. This is not guaranteed to be correct, but providing the `env` argument at least provides a hook that wrapper functions can use.

Note that the user of `enexpr()` has a nice side-effect: we can use unquoting to generate formulas dynamically:

```

resp <- expr(mpg)
disp1 <- expr(vs)
disp2 <- expr(wt)
lm3 (!!resp ~ !!disp1 + !!disp2, mtcars)
#> lm(mpg ~ vs + wt, data = mtcars)
#>
#> Call:
#> lm(formula = mpg ~ vs + wt, data = mtcars)
#>
#> Coefficients:
#> (Intercept)      vs          wt
#> 33.00          3.15        -4.44

```

18.6.2.2 The evaluation environment

What if you want to mingle objects supplied by the user with objects that you create in the function? For example, imagine you want to make an auto-bootstrapping version of `lm()`. You might write it like this:

```
boot_lm0 <- function(formula, data, env = caller_env()) {
  formula <- enexpr(formula)
  boot_data <- bootstrap(data, n = nrow(data))

  lm_call <- expr(lm(!!formula, data = boot_data))
  expr_print(lm_call)
  eval(lm_call, env)
}

df <- data.frame(x = 1:10, y = 5 + 3 * (1:10) + rnorm(10))
boot_lm0(y ~ x, data = df)
#> lm(y ~ x, data = boot_data)
#> Error in is.data.frame(data):
#>   object 'boot_data' not found
```

Why doesn't this code work? We're evaluating `lm_call` in the caller environment, but `boot_data` exists in the execution environment. We could instead evaluate in the execution environment of `boot_lm0()`, but there's no guarantee that `formula` could be evaluated in that environment.

There are two basic ways to overcome this challenge:

1. Unquote the data frame into the call. This means that no lookup has to occur, but has all the problems of inlining expressions. For modelling functions this means that the captured call is suboptimal:

```
boot_lm1 <- function(formula, data, env = caller_env()) {
  formula <- enexpr(formula)
  boot_data <- bootstrap(data, n = nrow(data))

  lm_call <- expr(lm(!!formula, data = !!boot_data))
  expr_print(lm_call)
  eval(lm_call, env)
}

boot_lm1(y ~ x, data = df)$call
#> lm(y ~ x, data = <data.frame>)
#> lm(formula = y ~ x, data = list(x = c(7L, 1L, 8L, 8L, 10L, 10L,
#> 4L, 5L, 4L, 2L), y = c(26.6480432853289, 7.53337955186315, 29.075803955))
```

```
#> 29.0758039597908, 34.2464592942242, 34.2464592942242, 18.9694248434104,
#> 20.4631747068887, 18.9694248434104, 10.1428095974415)))
```

2. Alternatively you can create a new environment that inherits from the caller, and you can bind variables that you've created inside the function to that environment.

```
boot_lm2 <- function(formula, data, env = caller_env()) {
  formula <- enexpr(formula)
  boot_data <- bootstrap(data, n = nrow(data))

  lm_env <- env(env, boot_data = boot_data)
  lm_call <- expr(lm(!!formula, data = boot_data))
  expr_print(lm_call)
  eval(lm_call, lm_env)
}

boot_lm2(y ~ x, data = df)
#> lm(y ~ x, data = boot_data)
#>
#> Call:
#> lm(formula = y ~ x, data = boot_data)
#>
#> Coefficients:
#> (Intercept)          x
#>       4.14          3.12
```

This is more work, but gives the cleanest specification.

18.6.3 Exercises

1. Why does this function fail?

```
lm3a <- function(formula, data) {
  formula <- enexpr(formula)

  lm_call <- expr(lm(!!formula, data = data))
  eval(lm_call, caller_env())
}

lm3(mpg ~ disp, mtcars)$call
#> lm(mpg ~ disp, data = mtcars)
#> lm(formula = mpg ~ disp, data = mtcars)
```

- When model building, typically the response and data are relatively constant while you rapidly experiment with different predictors. Write a small wrapper that allows you to reduce duplication in this situation.

```
pred_mpg <- function(resp, ...) {  
  
}  
pred_mpg(~ disp)  
pred_mpg(~ I(1 / disp))  
pred_mpg(~ disp * cyl)
```

- Another way to way to write `boot_lm()` would be to include the bootstrapping expression (`data[sample(nrow(data), replace = TRUE), , drop = FALSE]`) in the `data` argument. Implement that approach. What are the advantages? What are the disadvantages?
- To make these functions somewhat more robust, instead of always using the `caller_env()` we could capture a quosure, and then use its environment. However, if there are multiple arguments, they might be associated with different environments. Write a function that takes a list of quosures, and returns the common environment, if they have one, or otherwise throws an error.
- Write a function that takes a data frame and a list of formulas, fitting a linear model with each formula, generating a useful model call.
- Create a formula generation function that allows you to optionally supply a transformation function (e.g. `log()`) to the response or the predictors.

Chapter 19

Translating R code

19.1 Introduction

The combination of first-class environments, lexical scoping, and metaprogramming gives us a powerful toolkit for translating R code into other languages. One fully-fledged example of this idea is dbplyr, which powers the database backends for dplyr, allowing you to express data manipulation in R and automatically translate it into SQL. You can see the key idea in `translate_sql()` which takes R code and returns the equivalent SQL:

```
library(dbplyr)
translate_sql(x ^ 2)
#> <SQL> POWER("x", 2.0)
translate_sql(x < 5 & !is.na(x))
#> <SQL> "x" < 5.0 AND NOT((("x") IS NULL))
translate_sql(!first %in% c("John", "Roger", "Robert"))
#> <SQL> NOT("first" IN ('John', 'Roger', 'Robert'))
translate_sql(select == 7)
#> <SQL> "select" = 7.0
```

Translating R to SQL is complex because of the many idiosyncrasies of the different SQL dialects. So here I'll develop two simple, but useful, domain specific languages (DSL): one to generate HTML, and the other to generate mathematical equations LaTeX. If you're interested in learning more about domain specific languages in general, I highly recommend *Domain Specific Languages* (Fowler 2010). It discusses many options for creating a DSL and provides many examples of different languages.

Outline

- Section 19.2 creates a DSL for generating HTML, using quasiquotation and purrr to generate a function for each HTML tag, then tidy evaluation to easily access them.
- Section 19.3 transforms mathematically R code into its latex equivalent using a combination of tidy evaluation and expression walking.

Prerequisites

This chapter together pulls together many techniques discussed elsewhere in the book. In particular, you'll need to understand environments, expressions, tidy evaluation, and a little functional programming and S3. We'll use rlang for its metaprogramming tools, and purrr for its mapping functions.

```
library(rlang)
library(purrr)
#>
#> Attaching package: 'purrr'
#> The following objects are masked from 'package:rlang':
#>
#>     %%, %/%, as_function, flatten, flatten_chr,
#>     flatten_dbl, flatten_int, flatten_lgl, invoke,
#>     list_along, modify, prepend, rep_along, splice
```

19.2 HTML

HTML (hypertext markup language) is the language that underlies the majority of the web. It's a special case of SGML (standard generalised markup language), and it's similar but not identical to XML (extensible markup language). HTML looks like this:

```
<body>
  <h1 id='first'>A heading</h1>
  <p>Some text &lt;b>some bold text.</b></p>
  <img src='myimg.png' width='100' height='100' />
</body>
```

Even if you've never looked at HTML before, you can still see that the key component of its coding structure is tags: `<tag></tag>`. Tags can be nested

within other tags and intermingled with text. There are over 100 HTML tags, but in this chapter we'll focus on just a handful:

- `<body>` is the top-level tag that contains all content.
- `<h1>` defines a top level heading.
- `<p>` defines a paragraph.
- `` emboldens text.
- `` embeds an image.

Tags can also have named **attributes** which look like `<tag name1='value1' name2='value2'></tag>`. Two important attributes used with just about every tag are `id` and `class`. These are used in conjunction with CSS (cascading style sheets) in order to control the visual appearance of the page.

Void tags, like ``, don't have any content, and are written ``, not ``. Since they have no content, attributes are more important, and `img` has three that are used with almost every image: `src` (where the image lives), `width`, and `height`.

Because `<` and `>` have special meanings in HTML, you can't write them directly. Instead you have to use the HTML **escapes**: `>` and `<`. And, since those escapes use `&`, if you want a literal ampersand you have to escape it with `&`.

19.2.1 Goal

Our goal is to make it easy to generate HTML from R. To give a concrete example, we want to generate the following HTML:

```
<body>
  <h1 id='first'>A heading</h1>
  <p>Some text &lt;code>&amp;lt;></code></p>
  <img src='myimg.png' width='100' height='100' />
</body>
```

And we want the structure of the R code to match the structure of the HTML as closely as possible. To that end, we will work our way up to the following DSL:

```
with_html(
  body(
    h1("A heading", id = "first"),
    p("Some text &lt;code>&amp;lt;></code></p>"),
    img(src = "myimg.png", width = 100, height = 100)
  )
)
```

This DSL has the following three properties:

- The nesting of function calls matches the nesting of tags.
- Unnamed arguments become the content of the tag, and named arguments become their attributes.
- & and other special characters are automatically escaped.

19.2.2 Escaping

Escaping is so fundamental to translation that it'll be our first topic. There are two related challenges:

- In user input, we need to automatically escape &, < and >.
- At the same time we need to make sure that the &, < and > we generate are not double-escaped (i.e. to &amp;, &lt; and &gt;).

The easiest way to do this is to create an S3 class that distinguishes between regular text (that needs escaping) and HTML (that doesn't).

```
html <- function(x) structure(x, class = "advr_html")
cat_line <- function(...) cat(..., "\n", sep = "")

print.advr_html <- function(x, ...) {
  out <- paste0("<HTML> ", x)
  cat_line(paste(strwrap(out), collapse = "\n"))
}
```

We then write an escape generic. It has two important methods:

- `escape.character()` takes a regular character vector and returns an HTML vector with special characters (&, <, >) escaped.
- `escape.advr_html()` which leaves already escaped HTML as is.

```
escape <- function(x) UseMethod("escape")

escape.character <- function(x) {
  x <- gsub("&", "&amp;", x)
  x <- gsub("<", "&lt;", x)
  x <- gsub(">", "&gt;", x)

  html(x)
}
```

```
escape.advr_html <- function(x) x
```

Now we check that it works

```
escape("This is some text.")
#> <HTML> This is some text.

escape("x > 1 & y < 2")
#> <HTML> x &gt; 1 & y &lt; 2

# Double escaping is not a problem
escape(escape("This is some text. 1 > 2"))
#> <HTML> This is some text. 1 &gt; 2

# And text we know is HTML doesn't get escaped.
escape(html("<hr />"))
#> <HTML> <hr />
```

Conveniently, this also allows a user to opt-out of our escaping if they know the content is already escaped.

19.2.3 Basic tag functions

Next, we'll write a one tag function by hand, then figure out how to generalise it so we can generate a function for every tag with code.

Let's start with `<p>`. HTML tags can have both attributes (e.g., `id` or `class`) and children (like `` or `<i>`). We need some way of separating these in the function call. Given that attributes are named values and children are not, it seems natural to separate using named arguments from unnamed ones. For example, a call to `p()` might look like:

```
p("Some text. ", b(i("some bold italic text")), class = "mypara")
```

We could list all the possible attributes of the `<p>` tag in the function definition. But that's hard not only because there are many attributes, but also because it's possible to use custom attributes (<http://html5doctor.com/html5-custom-data-attributes/>). Instead, we'll use `...` and separate the components based on whether or not they are named. With this in mind, we create a helper function that wraps around `rlang::list2()` (so we can use `!!` and `!!!`) and returns named and unnamed components separately:

```
dots_partition <- function(...) {
  dots <- list2(...)
```

```

is_named <- names(dots) != ""
list(
  named = dots[is_named],
  unnamed = dots[!is_named]
)
}

str(dots_partition(a = 1, 2, b = 3, 4))
#> List of 2
#> $ named  :List of 2
#>   ..$ a: num 1
#>   ..$ b: num 3
#> $ unnamed:List of 2
#>   ..$ : num 2
#>   ..$ : num 4

```

We can now create our `p()` function. Notice that there's one new function here: `html_attributes()`. It takes a named list and returns the HTML attribute specification as a string. It's a little complicated (in part, because it deals with some idiosyncracies of HTML that I haven't mentioned here), but it's not that important and doesn't introduce any new programming ideas, so I won't discuss it here. You can find the source online (<https://github.com/hadley/adv-r/blob/master/dsl-html-attributes.r>) if you want to work through it yourself.

```

source("dsl-html-attributes.r")
p <- function(...) {
  dots <- dots_partition(...)
  attrs <- html_attributes(dots$named)
  children <- map_chr(dots$unnamed, escape)

  html(paste0(
    "<p", attrs, ">",
    paste(children, collapse = ""),
    "</p>"
  ))
}

p("Some text")
#> <HTML> <p></p>
p("Some text", id = "myid")
#> <HTML> <p id='myid'>Some text</p>

```

```
p("Some text", class = "important", `data-value` = 10)
#> <HTML> <p class='important' data-value='10'>Some text</p>
```

19.2.4 Tag functions

It's straightforward to adapt `p()` to other tags: we just need to replace "`p`" with the name of the tag. One elegant way to do that is to create a function with `rlang::new_function()`, using unquoting and `paste0()` to generate the starting and ending tags.

```
tag <- function(tag) {
  new_function(
    exprs(... = ),
    expr({
      dots <- dots_partition(...)
      attrs <- html_attributes(dots$named)
      children <- map_chr(dots$unnamed, escape)

      html(paste0(
        !!paste0("<", tag), attrs, ">",
        paste(children, collapse = ""),
        !!paste0("</", tag, ">"))
    )))
  },
  caller_env()
)
}

tag("b")
#> function (...)

#> {
#>   dots <- dots_partition(...)
#>   attrs <- html_attributes(dots$named)
#>   children <- map_chr(dots$unnamed, escape)
#>   html(paste0("<b", attrs, ">", paste(children, collapse = ""),
#>             "</b>"))
#> }
```

Now we can run our earlier example:

```
p <- tag("p")
b <- tag("b")
i <- tag("i")
```

```

p("Some text. ", b(i("some bold italic text")), class = "mypara")
#> <HTML> <p class='mypara'>Some text. <b><i>some bold italic
#> text</i></b></p>

```

Before we generate functions for every possible HTML tag, we need to create a variant that handles void tags. `void_tag()` is quite similar to `tag()`, but it throws an error if there are any unnamed tags, and the tag itself looks a little different.

```

void_tag <- function(tag) {
  new_function(
    exprs(... = ),
    expr({
      dots <- dots_partition(...)
      if (length(dots$unnamed) > 0) {
        stop(!!paste0("<", tag, "> must not have unnamed arguments"), call. = TRUE)
      }
      attrs <- html_attributes(dots$named)

      html(paste0(!!paste0("<", tag), attrs, " />"))
    }),
    caller_env()
  )
}

img <- void_tag("img")
img
#> function (...)
#> {
#>   dots <- dots_partition(...)
#>   if (length(dots$unnamed) > 0) {
#>     stop("<img> must not have unnamed arguments", call. = FALSE)
#>   }
#>   attrs <- html_attributes(dots$named)
#>   html(paste0("<img", attrs, " />"))
#> }
img(src = "myimage.png", width = 100, height = 100)
#> <HTML> <img src='myimage.png' width='100' height='100' />

```

19.2.5 Processing all tags

Next we need to generate these functions for every tag. We'll start with a list of all HTML tags:

```
tags <- c("a", "abbr", "address", "article", "aside", "audio",
  "b", "bdi", "bdo", "blockquote", "body", "button", "canvas",
  "caption", "cite", "code", "colgroup", "data", "datalist",
  "dd", "del", "details", "dfn", "div", "dl", "dt", "em",
  "eventsource", "fieldset", "figcaption", "figure", "footer",
  "form", "h1", "h2", "h3", "h4", "h5", "h6", "head", "header",
  "hgroup", "html", "i", "iframe", "ins", "kbd", "label",
  "legend", "li", "mark", "map", "menu", "meter", "nav",
  "noscript", "object", "ol", "optgroup", "option", "output",
  "p", "pre", "progress", "q", "ruby", "rp", "rt", "s", "samp",
  "script", "section", "select", "small", "span", "strong",
  "style", "sub", "summary", "sup", "table", "tbody", "td",
  "textarea", "tfoot", "th", "thead", "time", "title", "tr",
  "u", "ul", "var", "video"
)
void_tags <- c("area", "base", "br", "col", "command", "embed",
  "hr", "img", "input", "keygen", "link", "meta", "param",
  "source", "track", "wbr"
)
```

If you look at this list carefully, you'll see there are quite a few tags that have the same name as base R functions (`body`, `col`, `q`, `source`, `sub`, `summary`, `table`). This means we don't want to make all the functions available by default, in either the global environment or in a package. Instead, we'll put them in a list and then provide a helper to make it easy to use them when desired. First, we make a named list containing all the tag functions:

```
html_tags <- c(
  tags %>% set_names() %>% map(tag),
  void_tags %>% set_names() %>% map(void_tag)
)
```

This gives us an explicit (but verbose) way to call create HTML:

```
html_tags$p(
  "Some text. ",
  html_tags$b(html_tags$i("some bold italic text")),
  class = "mypara"
```

```

)
#> <HTML> <p class='mypara'>Some text. <b><i>some bold italic
#> text</i></b></p>

```

We can then finish off our HTML DSL with a function that allows us to evaluate code in the context of that list. Here we slightly abuse the data mask, passing it a list of functions rather than a data frame. This is quick hack to mingle the execution environment of `code` with the functions in `html_tags`.

```

with_html <- function(code) {
  code <- enquo(code)
  eval_tidy(code, html_tags)
}

```

This gives us a succinct API which allows us to write HTML when we need it but doesn't clutter up the namespace when we don't.

```

with_html(
  body(
    h1("A heading", id = "first"),
    p("Some text &", b("some bold text.")),
    img(src = "myimg.png", width = 100, height = 100)
  )
)
#> <HTML> <body><h1 id='first'>A heading</h1><p>Some text
#> &#amp;lt;b>some bold text.</b></p><img src='myimg.png'
#> width='100' height='100' /></body>

```

If you want to access the R function overridden by an HTML tag with the same name inside `with_html()`, you can use the full `package::function` specification.

19.2.6 Exercises

1. The escaping rules for `<script>` tags are different because they contain javascript, not HTML. Instead of escaping angle brackets or ampersands, you need to escape `</script>` so that the tag isn't closed too early. For example, `script("'<>/script>'")`, shouldn't generate this:

```

<script>'</script>'</script>

```

But

```

<script>'<\\>/script>'</script>

```

Adapt the code above to follow these rules.

2. The use of `...` for all functions has some big downsides. There's no input validation and there will be little information in the documentation or autocomplete about how they are used in the function. Create a new function that, when given a named list of tags and their attribute names (like below), creates tag functions with named arguments.

```
list(
  a = c("href"),
  img = c("src", "width", "height")
)
```

All tags should get `class` and `id` attributes.

3. Currently the HTML doesn't look terribly pretty, and it's hard to see the structure. How could you adapt `tag()` to do indenting and formatting? (You may need to do some research into block vs inline tags.)
4. Reason about the following code that calls `with_html()` referencing objects from the environment. Will it work or fail? Why? Run the code to verify your predictions.

```
greeting <- "Hello!"
with_html(p(greeting))

p <- function() "p"
address <- "123 anywhere street"
with_html(p(address))
```

19.3 LaTeX

The next DSL will convert R expressions into their LaTeX math equivalents. (This is a bit like `?plotmath`, but for text instead of plots.) LaTeX is the lingua franca of mathematicians and statisticians: it's common to use LaTeX notation whenever you want to express an equation in text, like in email. Since many reports are produced using both R and LaTeX, it might be useful to be able to automatically convert mathematical expressions from one language to the other.

Because we need to convert both functions and names, this mathematical DSL will be more complicated than the HTML DSL. We'll also need to create a “default” conversion, so that symbols that we don't know about get a standard conversion. This means that we can no longer use just evaluation: we also need

to walk the abstract syntax tree (AST).

19.3.1 LaTeX mathematics

Before we begin, let's quickly cover how formulas are expressed in LaTeX. The full spectrum of LaTeX mathematical notation is complex. Fortunately, they are well documented (<http://en.wikibooks.org/wiki/LaTeX/Mathematics>), and the most common commands have a fairly simple structure:

- Most simple mathematical equations are written in the same way you'd type them in R: `x * y`, `z ^ 5`. Subscripts are written using `_` (e.g., `x_1`).
- Special characters start with a `\`: `\pi` = π , `\pm` = \pm , and so on. There are a huge number of symbols available in LaTeX. Googling for `latex math symbols` will return many lists (<http://www.sunilpatel.co.uk/latex-type/latex-math-symbols/>). There's even a service (<http://detexify.kirelabs.org/classify.html>) that will look up the symbol you sketch in the browser.
- More complicated functions look like `\name{arg1}{arg2}`. For example, to write a fraction you'd use `\frac{a}{b}`. To write a square root, you'd use `\sqrt{a}`.
- To group elements together use `{}`: i.e., `x ^ a + b` vs. `x ^ {a + b}`.
- In good math typesetting, a distinction is made between variables and functions. But without extra information, LaTeX doesn't know whether `f(a * b)` represents calling the function `f` with input `a * b`, or is shorthand for `f * (a * b)`. If `f` is a function, you can tell LaTeX to typeset it using an upright font with `\text{f}(a * b)`.

19.3.2 Goal

Our goal is to use these rules to automatically convert an R expression to its appropriate LaTeX representation. We'll tackle this in four stages:

- Convert known symbols: `pi` -> `\pi`
- Leave other symbols unchanged: `x` -> `x`, `y` -> `y`
- Convert known functions to their special forms: `sqrt(frac(a, b))` -> `\sqrt{\frac{a}{b}}`
- Wrap unknown functions with `\text{f}`: `f(a)` -> `\text{f}(a)`

We'll code this translation in the opposite direction of what we did with the HTML DSL. We'll start with infrastructure, because that makes it easy to experiment with our DSL, and then work our way back down to generate the desired output.

19.3.3 `to_math()`

To begin, we need a wrapper function that will convert R expressions into LaTeX math expressions. This will work similarly to `to_html()`: capturing the unevaluated expression and evaluate it in a special environment. There are two main differences:

- The evaluation environment is no longer constant, as it has to vary depending the input. This is necessary to handle unknown symbols and functions.
- We never evaluate in the argument environment because we're translating every function to a `latex` expression. The user will need to explicit use `!!` in order to evaluate normally.

This gives us:

```
to_math <- function(x) {
  expr <- enexpr(x)
  out <- eval_bare(expr, latex_env(expr))

  latex(out)
}

latex <- function(x) structure(x, class = "advr_latex")
print.advr_latex <- function(x) {
  cat_line("<LATEX> ", x)
}
```

Next we'll build up `latex_env()`, starting simple and getting progressively more complex.

19.3.4 Known symbols

Our first step is to create an environment that will convert the special LaTeX symbols used for Greek character, e.g., `pi` to `\pi`. We'll use the trick from Section 18.4.3, binding symbol `pi` to value "`\pi`".

```

greek <- c(
  "alpha", "theta", "tau", "beta", "vartheta", "pi", "upsilon",
  "gamma", "varpi", "phi", "delta", "kappa", "rho",
  "varphi", "epsilon", "lambda", "varrho", "chi", "varepsilon",
  "mu", "sigma", "psi", "zeta", "nu", "varsigma", "omega", "eta",
  "xi", "Gamma", "Lambda", "Sigma", "Psi", "Delta", "Xi",
  "Upsilon", "Omega", "Theta", "Pi", "Phi")
greek_list <- set_names(paste0("\\", greek), greek)
greek_env <- as_environment(greek_list)

```

We can then check it:

```

latex_env <- function(expr) {
  greek_env
}

to_math(pi)
#> <LATEX> \pi
to_math(beta)
#> <LATEX> \beta

```

Looks good so far!

19.3.5 Unknown symbols

If a symbol isn't Greek, we want to leave it as is. This is tricky because we don't know in advance what symbols will be used, and we can't possibly generate them all. Instead, we'll use the approach described in Section @ref(#ast-funs): walking the AST and to find all symbols. This gives us `all_names_rec()` and helper `all_names()`:

```

all_names_rec <- function(x) {
  switch_expr(x,
    constant = character(),
    symbol = as.character(x),
    pairlist = ,
    call = flat_map_chr(as.list(x[-1]), all_names)
  )
}

all_names <- function(x) {
  unique(all_names_rec(x))
}

```

```

}

all_names(expr(x + y + f(a, b, c, 10)))
#> [1] "x" "y" "a" "b" "c"

```

We now want to take that list of symbols and convert it to an environment so that each symbol is mapped to its corresponding string representation (e.g., so `eval(quote(x), env)` yields "x"). We again use the pattern of converting a named character vector to a list, then converting the list to an environment.

```

latex_env <- function(expr) {
  names <- all_names(expr)
  symbol_env <- as_environment(set_names(names))

  symbol_env
}

to_math(x)
#> <LATEX> x
to_math(longvariablename)
#> <LATEX> longvariablename
to_math(pi)
#> <LATEX> pi

```

This works, but we need to combine it with the Greek symbols environment. Since we want to give preference to Greek over defaults (e.g., `to_math(pi)` should give "\pi", not "pi"), `symbol_env` needs to be the parent of `greek_env`. To do that, we need to make a copy of `greek_env` with a new parent. This gives us a function that can convert both known (Greek) and unknown symbols.

```

latex_env <- function(expr) {
  # Unknown symbols
  names <- all_names(expr)
  symbol_env <- as_environment(set_names(names))

  # Known symbols
  env_clone(greek_env, parent = symbol_env)
}

to_math(x)
#> <LATEX> x
to_math(longvariablename)
#> <LATEX> longvariablename

```

```
to_math(pi)
#> <LATEX> \pi
```

19.3.6 Known functions

Next we'll add functions to our DSL. We'll start with a couple of helpers that make it easy to add new unary and binary operators. These functions are very simple: they only assemble strings.

```
unary_op <- function(left, right) {
  new_function(
    exprs(e1 = ),
    expr(
      paste0(!left, e1, !right)
    ),
    caller_env()
  )
}

binary_op <- function(sep) {
  new_function(
    exprs(e1 = , e2 = ),
    expr(
      paste0(e1, !sep, e2)
    ),
    caller_env()
  )
}

unary_op("\sqrt{", "}")
#> function (e1)
#> paste0("\sqrt{", e1, "}")
binary_op("+")
#> function (e1, e2)
#> paste0(e1, "+", e2)
```

Using these helpers, we can map a few illustrative examples of converting R to LaTeX. Note that with R's lexical scoping rules helping us, we can easily provide new meanings for standard functions like `+`, `-`, and `*`, and even `(` and `{`.

```

# Binary operators
f_env <- child_env(
  .parent = empty_env(),
  `+` = binary_op(" + "),
  `--` = binary_op(" - "),
  `*` = binary_op(" * "),
  `/` = binary_op(" / "),
  `^` = binary_op("^"),
  `[_` = binary_op("_"),

# Grouping
`{` = unary_op("\left{ ", " \right}"),
`(` = unary_op("\left( ", " \right)"),
paste = paste,

# Other math functions
sqrt = unary_op("\sqrt{", "}" ),
sin = unary_op("\sin(", ")" ),
log = unary_op("\log(", ")" ),
abs = unary_op("\left| ", " \right| "),
frac = function(a, b) {
  paste0("\frac{", a, "}{", b, "}")
},

# Labelling
hat = unary_op("\hat{", "}" ),
tilde = unary_op("\tilde{", "}" )
)

```

We again modify `latex_env()` to include this environment. It should be the last environment R looks for names in. This ensures that `sin(sin)` will work.

```

latex_env <- function(expr) {
  # Known functions
  f_env

  # Default symbols
  names <- all_names(expr)
  symbol_env <- as_environment(set_names(names), parent = f_env)

  # Known symbols
  greek_env <- env_clone(greek_env, parent = symbol_env)

```

```

greek_env
}

to_math(sin(x + pi))
#> <LATEX> \sin(x + \pi)
to_math(log(x_i ^ 2))
#> <LATEX> \log(x_i^2)
to_math(sin(sin))
#> <LATEX> \sin(\sin)

```

19.3.7 Unknown functions

Finally, we'll add a default for functions that we don't yet know about. Like the unknown names, we can't know in advance what these will be, so we again walk the AST to find them:

```

all_calls_rec <- function(x) {
  switch_expr(x,
    constant = ,
    symbol = character(),
    call = {
      fname <- as.character(x[[1]])
      children <- flat_map_chr(as.list(x[-1]), all_calls)
      c(fname, children)
    },
    pairlist = flat_map_chr(as.list(x[1]), all_calls)
  )
}

all_calls <- function(x) {
  unique(all_calls_rec(x))
}

all_calls(expr(f(g + b, c, d(a))))
#> [1] "f" "+" "d"

```

And we need a closure that will generate the functions for each unknown call.

```

unknown_op <- function(op) {
  new_function(
    exprs(... = ),
    expr({

```

```

  contents <- paste(..., collapse = ", ")
  paste0(!!paste0("\\"mathrm{", op, "}"()), contents, ")")
}
)
}
unknown_op("foo")
#> function (...)
#> {
#>   contents <- paste(..., collapse = ", ")
#>   paste0("\\"mathrm{foo}"(), contents, ")")
#> }
#> <environment: 0x105ee60>

```

And again we update `latex_env()`:

```

latex_env <- function(expr) {
  calls <- all_calls(expr)
  call_list <- map(set_names(calls), unknown_op)
  call_env <- as_environment(call_list)

  # Known functions
  f_env <- env_clone(f_env, call_env)

  # Default symbols
  names <- all_names(expr)
  symbol_env <- as_environment(set_names(names), parent = f_env)

  # Known symbols
  greek_env <- env_clone(greek_env, parent = symbol_env)
  greek_env
}

```

This completes our original requirements:

```

to_math(sin(pi) + f(a))
#> <LATEX> \sin(\pi) + \mathrm{f}(a)

```

You could certainly take this idea further and translate types of mathematical expression, but you should not need any additional metaprogramming tools.

19.3.8 Exercises

1. Add escaping. The special symbols that should be escaped by adding a backslash in front of them are `\`, `$`, and `%`. Just as with HTML, you'll need to make sure you don't end up double-escaping. So you'll need to create a small S3 class and then use that in function operators. That will also allow you to embed arbitrary LaTeX if needed.
2. Complete the DSL to support all the functions that `plotmath` supports.

Part V

Techniques

Chapter 20

Debugging

20.1 Introduction

What happens when something goes wrong with your R code? What do you do? What tools do you have to address the problem? This chapter will teach you how to fix unanticipated problems (debugging), show you how functions can communicate problems and how you can take action based on those communications (condition handling), and teach you how to avoid common problems before they occur (defensive programming).

Debugging is the art and science of fixing unexpected problems in your code. In this section you'll learn the tools and techniques that help you get to the root cause of an error. You'll learn general strategies for debugging, useful R functions like `traceback()` and `browser()`, and interactive tools in RStudio.

The chapter concludes with a discussion of “defensive” programming: ways to avoid common errors before they occur. In the short run you'll spend more time writing code, but in the long run you'll save time because error messages will be more informative and will let you narrow in on the root cause more quickly. The basic principle of defensive programming is to “fail fast”, to raise an error as soon as something goes wrong. In R, this takes three particular forms: checking that inputs are correct, avoiding non-standard evaluation, and avoiding functions that can return different types of output.

Outline

1. Debugging techniques outlines a general approach for finding and resolving bugs.
2. Debugging tools introduces you to the R functions and RStudio features that help you locate exactly where an error occurred.
3. Defensive programming introduces you to some important techniques for defensive programming, techniques that help prevent bugs from occurring in the first place.

20.2 Techniques

“Finding your bug is a process of confirming the many things that you believe are true — until you find one which is not true.”

—Norm Matloff

Debugging code is challenging. Many bugs are subtle and hard to find. Indeed, if a bug was obvious, you probably would’ve been able to avoid it in the first place. While it’s true that with a good technique, you can productively debug a problem with just `print()`, there are times when additional help would be welcome. In this section, we’ll discuss some useful tools, which R and RStudio provide, and outline a general procedure for debugging.

While the procedure below is by no means foolproof, it will hopefully help you to organise your thoughts when debugging. There are four steps:

1. Realise that you have a bug

If you’re reading this chapter, you’ve probably already completed this step. It is a surprisingly important one: you can’t fix a bug until you know it exists. This is one reason why automated test suites are important when producing high-quality code. Unfortunately, automated testing is outside the scope of this book, but you can read more about it at <http://r-pkgs.had.co.nz/tests.html>.

2. Make it repeatable

Once you’ve determined you have a bug, you need to be able to reproduce it on command. Without this, it becomes extremely difficult to isolate its cause and to confirm that you’ve successfully fixed it.

Generally, you will start with a big block of code that you know causes the error and then slowly whittle it down to get to the smallest possible snippet that still causes the error. Binary search is particularly useful for this. To do a binary search, you repeatedly remove half of the code until you find the bug. This is fast because, with each step, you reduce the amount of code to look through by half.

If it takes a long time to generate the bug, it's also worthwhile to figure out how to generate it faster. The quicker you can do this, the quicker you can figure out the cause.

As you work on creating a minimal example, you'll also discover similar inputs that don't trigger the bug. Make note of them: they will be helpful when diagnosing the cause of the bug.

If you're using automated testing, this is also a good time to create an automated test case. If your existing test coverage is low, take the opportunity to add some nearby tests to ensure that existing good behaviour is preserved. This reduces the chances of creating a new bug.

3. Figure out where it is

If you're lucky, one of the tools in the following section will help you to quickly identify the line of code that's causing the bug. Usually, however, you'll have to think a bit more about the problem. It's a great idea to adopt the scientific method. Generate hypotheses, design experiments to test them, and record your results. This may seem like a lot of work, but a systematic approach will end up saving you time. I often waste a lot of time relying on my intuition to solve a bug ("oh, it must be an off-by-one error, so I'll just subtract 1 here"), when I would have been better off taking a systematic approach.

4. Fix it and test it

Once you've found the bug, you need to figure out how to fix it and to check that the fix actually worked. Again, it's very useful to have automated tests in place. Not only does this help to ensure that you've actually fixed the bug, it also helps to ensure you haven't introduced any new bugs in the process. In the absence of automated tests, make sure to carefully record the correct output, and check against the inputs that previously failed.

20.3 Tools

To implement a strategy of debugging, you'll need tools. In this section, you'll learn about the tools provided by R and the RStudio IDE. RStudio's integrated debugging support makes life easier by exposing existing R tools in a user friendly way. I'll show you both the R and RStudio ways so that you can work with whatever environment you use. You may also want to refer to the official RStudio debugging documentation (<https://support.rstudio.com/hc/en-us/articles/205612627-Debugging-with-RStudio>) which always reflects the tools in the latest version of RStudio.

There are three key debugging tools:

- RStudio's error inspector and `traceback()` which list the sequence of calls that lead to the error.
- RStudio's “Rerun with Debug” tool and `options(error = browser)` which open an interactive session where the error occurred.
- RStudio's breakpoints and `browser()` which open an interactive session at an arbitrary location in the code.

I'll explain each tool in more detail below.

You shouldn't need to use these tools when writing new functions. If you find yourself using them frequently with new code, you may want to reconsider your approach. Instead of trying to write one big function all at once, work interactively on small pieces. If you start small, you can quickly identify why something doesn't work. But if you start large, you may end up struggling to identify the source of the problem.

20.3.1 Determining the sequence of calls

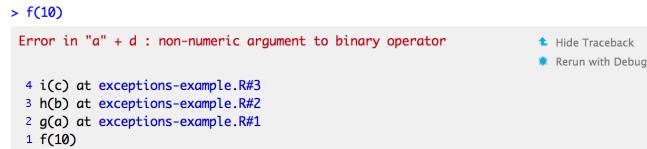
The first tool is the **call stack**, the sequence of calls that lead up to an error. Here's a simple example: you can see that `f()` calls `g()` calls `h()` calls `i()` which adds together a number and a string creating an error:

```
f <- function(a) g(a)
g <- function(b) h(b)
h <- function(c) i(c)
i <- function(d) "a" + d
f(10)
```

When we run this code in RStudio we see:



Two options appear to the right of the error message: “Show Traceback” and “Rerun with Debug”. If you click “Show traceback” you see:



If you’re not using RStudio, you can use `traceback()` to get the same information:

```
traceback()
# 4: i(c) at exceptions-example.R#3
# 3: h(b) at exceptions-example.R#2
# 2: g(a) at exceptions-example.R#1
# 1: f(10)
```

Read the call stack from bottom to top: the initial call is `f()`, which calls `g()`, then `h()`, then `i()`, which triggers the error. If you’re calling code that you `source()`d into R, the traceback will also display the location of the function, in the form `filename.r#linenumber`. These are clickable in RStudio, and will take you to the corresponding line of code in the editor.

Sometimes this is enough information to let you track down the error and fix it. However, it’s usually not. `traceback()` shows you where the error occurred, but not why. The next useful tool is the interactive debugger, which allows you to pause execution of a function and interactively explore its state.

20.3.2 Browsing on error

The easiest way to enter the interactive debugger is through RStudio’s “Rerun with Debug” tool. This reruns the command that created the error, pausing execution where the error occurred. You’re now in an interactive state inside the function, and you can interact with any object defined there. You’ll see the corresponding code in the editor (with the statement that will be run next highlighted), objects in the current environment in the “Environment” pane, the call stack in a “Traceback” pane, and you can run arbitrary R code in the console.

As well as any regular R function, there are a few special commands you can

use in debug mode. You can access them either with the RStudio toolbar () or with the keyboard:

- Next, **n**: executes the next step in the function. Be careful if you have a variable named **n**; to print it you'll need to do `print(n)`.
- Step into,  or **s**: works like next, but if the next step is a function, it will step into that function so you can work through each line.
- Finish,  or **f**: finishes execution of the current loop or function.
- Continue, **c**: leaves interactive debugging and continues regular execution of the function. This is useful if you've fixed the bad state and want to check that the function proceeds correctly.
- Stop, **Q**: stops debugging, terminates the function, and returns to the global workspace. Use this once you've figured out where the problem is, and you're ready to fix it and reload the code.

There are two other slightly less useful commands that aren't available in the toolbar:

- Enter: repeats the previous command. I find this too easy to activate accidentally, so I turn it off using `options(browserNLdisabled = TRUE)`.
- **where**: prints stack trace of active calls (the interactive equivalent of `traceback`).

To enter this style of debugging outside of RStudio, you can use the `error` option which specifies a function to run when an error occurs. The function most similar to RStudio's debug is `browser()`: this will start an interactive console in the environment where the error occurred. Use `options(error = browser)` to turn it on, re-run the previous command, then use `options(error = NULL)` to return to the default error behaviour. You could automate this with the `browseOnce()` function as defined below:

```
browseOnce <- function() {
  old <- getOption("error")
  function() {
    options(error = old)
    browser()
  }
}
options(error = browseOnce())
```

```
f <- function() stop("!")
# Enters browser
f()
# Runs normally
f()
```

(You'll learn more about functions that return functions in Functional programming.)

There are two other useful functions that you can use with the `error` option:

- `recover` is a step up from `browser`, as it allows you to enter the environment of any of the calls in the call stack. This is useful because often the root cause of the error is a number of calls back.
- `dump.frames` is an equivalent to `recover` for non-interactive code. It creates a `last.dump.rda` file in the current working directory. Then, in a later interactive R session, you load that file, and use `debugger()` to enter an interactive debugger with the same interface as `recover()`. This allows interactive debugging of batch code.

```
# In batch R process ----
dump_and_quit <- function() {
  # Save debugging info to file last.dump.rda
  dump.frames(to.file = TRUE)
  # Quit R with error status
  q(status = 1)
}
options(error = dump_and_quit)

# In a later interactive session ----
load("last.dump.rda")
debugger()
```

To reset error behaviour to the default, use `options(error = NULL)`. Then errors will print a message and abort function execution.

20.3.3 Browsing arbitrary code

As well as entering an interactive console on error, you can enter it at an arbitrary code location by using either an RStudio breakpoint or `browser()`. You can set a breakpoint in RStudio by clicking to the left of the line number, or pressing `Shift + F9`. Equivalently, add `browser()` where you want execution to pause.

Breakpoints behave similarly to `browser()` but they are easier to set (one click instead of nine key presses), and you don't run the risk of accidentally including a `browser()` statement in your source code. There are two small downsides to breakpoints:

- There are a few unusual situations in which breakpoints will not work: read breakpoint troubleshooting (<http://www.rstudio.com/ide/docs/debugging/breakpoint-troubleshooting>) for more details.
- RStudio currently does not support conditional breakpoints, whereas you can always put `browser()` inside an `if` statement.

As well as adding `browser()` yourself, there are two other functions that will add it to code:

- `debug()` inserts a `browser` statement in the first line of the specified function. `undebug()` removes it. Alternatively, you can use `debugonce()` to browse only on the next run.
- `utils::setBreakpoint()` works similarly, but instead of taking a function name, it takes a file name and line number and finds the appropriate function for you.

These two functions are both special cases of `trace()`, which inserts arbitrary code at any position in an existing function. `trace()` is occasionally useful when you're debugging code that you don't have the source for. To remove tracing from a function, use `untrace()`. You can only perform one trace per function, but that one trace can call multiple functions.

20.3.4 The call stack: `traceback()`, `where`, and `recover()`

Unfortunately, the call stacks printed by `traceback()`, `browser()` + `where`, and `recover()` are not consistent. The following table shows how the call stacks from a simple nested set of calls are displayed by the three tools.

<code>traceback()</code>	<code>where</code>	<code>recover()</code>
4: <code>stop("Error")</code>	<code>where 1: stop("Error")</code>	1: <code>f()</code>
3: <code>h(x)</code>	<code>where 2: h(x)</code>	2: <code>g(x)</code>
2: <code>g(x)</code>	<code>where 3: g(x)</code>	3: <code>h(x)</code>
1: <code>f()</code>	<code>where 4: f()</code>	

Note that numbering is different between `traceback()` and `where`, and that `recover()` displays calls in the opposite order, and omits the call to `stop()`.

RStudio displays calls in the same order as `traceback()` but omits the numbers.

20.3.5 Other types of failure

There are other ways for a function to fail apart from throwing an error or returning an incorrect result.

- A function may generate an unexpected warning. The easiest way to track down warnings is to convert them into errors with `options(warn = 2)` and use the regular debugging tools. When you do this you'll see some extra calls in the call stack, like `doWithOneRestart()`, `withOneRestart()`, `withRestarts()`, and `.signalSimpleWarning()`. Ignore these: they are internal functions used to turn warnings into errors.
- A function may generate an unexpected message. There's no built-in tool to help solve this problem, but it's possible to create one:

```
message2error <- function(code) {
  withCallingHandlers(code, message = function(e) stop(e))
}

f <- function() g()
g <- function() message("Hi!")
f()
# Hi!
message2error(f())
# Error in message("Hi!"): Hi!
traceback()
# 11: stop(e) at #2
# 10: (function (e)
#     stop(e))(list(message = "Hi!\n", call = message("Hi!")))
# 9: signalCondition(cond)
# 8: doWithOneRestart(return(expr), restart)
# 7: withOneRestart(expr, restarts[[1L]])
# 6: withRestarts({
#     signalCondition(cond)
#     defaultHandler(cond)
#   }, muffleMessage = function() NULL)
# 5: message("Hi!") at #1
# 4: g() at #1
# 3: f() at #2
# 2: withCallingHandlers(code, message = function(e) stop(e)) at #2
```

```
# 1: message2error(f())
```

As with warnings, you’ll need to ignore some of the calls on the traceback (i.e., the first two and the last six).

- A function might never return. This is particularly hard to debug automatically, but sometimes terminating the function and looking at the call stack is informative. Otherwise, use the basic debugging strategies described above.
- The worst scenario is that your code might crash R completely, leaving you with no way to interactively debug your code. This indicates a bug in the underlying C code. This is hard to debug. Sometimes an interactive debugger, like `gdb`, can be useful, but describing how to use it is beyond the scope of this book.

If the crash is caused by base R code, post a reproducible example to R-help. If it’s in a package, contact the package maintainer. If it’s your own C or C++ code, you’ll need to use numerous `print()` statements to narrow down the location of the bug, and then you’ll need to use many more print statements to figure out which data structure doesn’t have the properties that you expect.

Chapter 21

Performance

R is not a fast language. This is not an accident. R was purposely designed to make data analysis and statistics easier for you to do. It was not designed to make life easier for your computer. While R is slow compared to other programming languages, for most purposes, it's fast enough.

The goal of this part of the book is to give you a deeper understanding of R's performance characteristics. In this chapter, you'll learn about some of the trade-offs that R has made, valuing flexibility over performance. The following four chapters will give you the skills to improve the speed of your code when you need to:

- In Profiling, you'll learn how to systematically make your code faster. First you figure what's slow, and then you apply some general techniques to make the slow parts faster.
- For really high-performance code, you can move outside of R and use another programming language. Rcpp will teach you the absolute minimum you need to know about C++ so you can write fast code using the Rcpp package.
- To really understand the performance of built-in base functions, you'll need to learn a little bit about R's C API. In R's C interface, you'll learn a little about R's C internals.

Let's get started by learning more about why R is slow.

21.1 Why is R slow?

To understand R’s performance, it helps to think about R as both a language and as an implementation of that language. The R-language is abstract: it defines what R code means and how it should work. The implementation is concrete: it reads R code and computes a result. The most popular implementation is the one from r-project.org (<http://r-project.org>). I’ll call that implementation GNU-R to distinguish it from R-language, and from the other implementations I’ll discuss later in the chapter.

The distinction between R-language and GNU-R is a bit murky because the R-language is not formally defined. While there is the R language definition (<http://cran.r-project.org/doc/manuals/R-lang.html>), it is informal and incomplete. The R-language is mostly defined in terms of how GNU-R works. This is in contrast to other languages, like C++ (<http://isocpp.org/std/the-standard>) and JavaScript (<http://www.ecma-international.org/publications/standards/Ecma-262.htm>), that make a clear distinction between language and implementation by laying out formal specifications that describe in minute detail how every aspect of the language should work. Nevertheless, the distinction between R-language and GNU-R is still useful: poor performance due to the language is hard to fix without breaking existing code; fixing poor performance due to the implementation is easier.

In Language performance, I discuss some of the ways in which the design of the R-language imposes fundamental constraints on R’s speed. In Implementation performance, I discuss why GNU-R is currently far from the theoretical maximum, and why improvements in performance happen so slowly. While it’s hard to know exactly how much faster a better implementation could be, a $>10x$ improvement in speed seems achievable. In alternative implementations, I discuss some of the promising new implementations of R, and describe one important technique they use to make R code run faster.

Beyond performance limitations due to design and implementation, it has to be said that a lot of R code is slow simply because it’s poorly written. Few R users have any formal training in programming or software development. Fewer still write R code for a living. Most people use R to understand data: it’s more important to get an answer quickly than to develop a system that will work in a wide variety of situations. This means that it’s relatively easy to make most R code much faster, as we’ll see in the following chapters.

Before we examine some of the slower parts of the R-language and GNU-R, we need to learn a little about benchmarking so that we can give our intuitions about

performance a concrete foundation.

21.2 Microbenchmarking

A microbenchmark is a measurement of the performance of a very small piece of code, something that might take microseconds (μs) or nanoseconds (ns) to run. I'm going to use microbenchmarks to demonstrate the performance of very low-level pieces of R code, which help develop your intuition for how R works. This intuition, by-and-large, is not useful for increasing the speed of real code. The observed differences in microbenchmarks will typically be dominated by higher-order effects in real code; a deep understanding of subatomic physics is not very helpful when baking. Don't change the way you code because of these microbenchmarks. Instead wait until you've read the practical advice in the following chapters.

The best tool for microbenchmarking in R is the `microbenchmark` (<http://cran.r-project.org/web/packages/microbenchmark/>) package. It provides very precise timings, making it possible to compare operations that only take a tiny amount of time. For example, the following code compares the speed of two ways of computing a square root.

```
library(microbenchmark)

x <- runif(100)
microbenchmark(
  sqrt(x),
  x ^ 0.5
)
#> Unit: nanoseconds
#>      expr    min     lq   mean median     uq    max neval
#>  sqrt(x) 899 1,220 1430 1,330 1,510 5,350   100
#>  x^0.5 9,440 9,780 10651 9,960 10,200 51,500   100
```

By default, `microbenchmark()` runs each expression 100 times (controlled by the `times` parameter). In the process, it also randomises the order of the expressions. It summarises the results with a minimum (`min`), lower quartile (`lq`), median, upper quartile (`uq`), and maximum (`max`). Focus on the median, and use the upper and lower quartiles (`lq` and `uq`) to get a feel for the variability. In this example, you can see that using the special purpose `sqrt()` function is faster than the general exponentiation operator.

As with all microbenchmarks, pay careful attention to the units: here, each

computation takes about 1,000 ns, 1,000 billionths of a second. To help calibrate the impact of a microbenchmark on run time, it's useful to think about how many times a function needs to run before it takes a second. If a microbenchmark takes:

- 1 ms, then one thousand calls takes a second
- 1 μ s, then one million calls takes a second
- 1 ns, then one billion calls takes a second

The `sqrt()` function takes about 1,000 ns, or 1 μ s, to compute the square root of 100 numbers. That means if you repeated the operation a million times, it would take 1 s. So changing the way you compute the square root is unlikely to significantly affect real code.

21.2.1 Exercises

1. Instead of using `microbenchmark()`, you could use the built-in function `system.time()`. But `system.time()` is much less precise, so you'll need to repeat each operation many times with a loop, and then divide to find the average time of each operation, as in the code below.

```
n <- 1e6
system.time(for (i in 1:n) sqrt(x)) / n
system.time(for (i in 1:n) x ^ 0.5) / n
```

How do the estimates from `system.time()` compare to those from `microbenchmark()`? Why are they different?

2. Here are two other ways to compute the square root of a vector. Which do you think will be fastest? Which will be slowest? Use microbenchmarking to test your answers.

```
x ^ (1 / 2)
exp(log(x) / 2)
```

3. Use microbenchmarking to rank the basic arithmetic operators (+, -, *, /, and $^$) in terms of their speed. Visualise the results. Compare the speed of arithmetic on integers vs. doubles.
4. You can change the units in which the microbenchmark results are expressed with the `unit` parameter. Use `unit = "eps"` to show the number of evaluations needed to take 1 second. Repeat the benchmarks above with the `eps` unit. How does this change your intuition for performance?

21.3 Language performance

In this section, I'll explore three trade-offs that limit the performance of the R-language: extreme dynamism, name lookup with mutable environments, and lazy evaluation of function arguments. I'll illustrate each trade-off with a microbenchmark, showing how it slows GNU-R down. I benchmark GNU-R because you can't benchmark the R-language (it can't run code). This means that the results are only suggestive of the cost of these design decisions, but are nevertheless useful. I've picked these three examples to illustrate some of the trade-offs that are key to language design: the designer must balance speed, flexibility, and ease of implementation.

If you'd like to learn more about the performance characteristics of the R-language and how they affect real code, I highly recommend "Evaluating the Design of the R Language" (<http://r.cs.purdue.edu/pub/ecoop12.pdf>) by Floreal Morandat, Brandon Hill, Leo Osvald, and Jan Vitek. It uses a powerful methodology that combines a modified R interpreter and a wide set of code found in the wild.

21.3.1 Extreme dynamism

R is an extremely dynamic programming language. Almost anything can be modified after it is created. To give just a few examples, you can:

- Change the body, arguments, and environment of functions.
- Change the S4 methods for a generic.
- Add new fields to an S3 object, or even change its class.
- Modify objects outside of the local environment with `<->`.

Pretty much the only things you can't change are objects in sealed namespaces, which are created when you load a package.

The advantage of dynamism is that you need minimal upfront planning. You can change your mind at any time, iterating your way to a solution without having to start afresh. The disadvantage of dynamism is that it's difficult to predict exactly what will happen with a given function call. This is a problem because the easier it is to predict what's going to happen, the easier it is for an interpreter or compiler to make an optimisation. (If you'd like more details, Charles Nutter expands on this idea at *On Languages, VMs, Optimization, and the Way of the World* (<http://blog.headius.com/2013/05/on-languages-vms-optimization-and-way.html>)).) If an interpreter can't predict what's going to happen, it has to consider many options before it finds the right one. For example, the following loop is slow in R, because R doesn't know that `x` is always an integer. That means R has to

look for the right + method (i.e., is it adding doubles, or integers?) in every iteration of the loop.

```
x <- 0L
for (i in 1:1e6) {
  x <- x + 1
}
```

The cost of finding the right method is higher for non-primitive functions. The following microbenchmark illustrates the cost of method dispatch for S3, S4, and RC. I create a generic and a method for each OO system, then call the generic and see how long it takes to find and call the method. I also time how long it takes to call the bare function for comparison.

```
f <- function(x) NULL

s3 <- function(x) UseMethod("s3")
s3.integer <- f

A <- setClass("A", representation(a = "list"))
setGeneric("s4", function(x) standardGeneric("s4"))
setMethod(s4, "A", f)

B <- setRefClass("B", methods = list(rc = f))

a <- A()
b <- B$new()

microbenchmark(
  fun = f(),
  S3 = s3(1L),
  S4 = s4(a),
  RC = b$rc()
)
#> Unit: nanoseconds
#>   expr     min      lq    mean  median      uq     max neval
#>   fun     175    208    427    229    240   17,500    100
#>   S3     979  1,150 10903  1,210   1,370 933,000    100
#>   S4 12,200 12,600 30124 13,300  15,300 961,000    100
#>   RC    8,220  8,540 42353  8,820   9,410 3,320,000    100
```

The bare function takes about 200 ns. S3 method dispatch takes an additional 1,000 ns; S4 dispatch, 10,000 ns; and RC dispatch, 9,000 ns. S3 and S4 method dispatch are expensive because R must search for the right method every time the

generic is called; it might have changed between this call and the last. R could do better by caching methods between calls, but caching is hard to do correctly and a notorious source of bugs.

21.3.2 Name lookup with mutable environments

It's surprisingly difficult to find the value associated with a name in the R-language. This is due to combination of lexical scoping and extreme dynamism. Take the following example. Each time we print `a` it comes from a different environment:

```
a <- 1
f <- function() {
  g <- function() {
    print(a)
    assign("a", 2, envir = parent.frame())
    print(a)
    a <- 3
    print(a)
  }
  g()
}
f()
#> [1] 1
#> [1] 2
#> [1] 3
```

This means that you can't do name lookup just once: you have to start from scratch each time. This problem is exacerbated by the fact that almost every operation is a lexically scoped function call. You might think the following simple function calls two functions: `+` and `^`. In fact, it calls four because `{` and `(` are regular functions in R.

```
f <- function(x, y) {
  (x + y) ^ 2
}
```

Since these functions are in the global environment, R has to look through every environment in the search path, which could easily be 10 or 20 environments. The following microbenchmark hints at the performance costs. We create four versions of `f()`, each with one more environment (containing 26 bindings) between the environment of `f()` and the base environment where `+`, `^`, `(`, and `{` are defined.

```

random_env <- function(parent = globalenv()) {
  letter_list <- setNames(as.list(runif(26)), LETTERS)
  list2env(letter_list, envir = new.env(parent = parent))
}

set_env <- function(f, e) {
  environment(f) <- e
  f
}

f2 <- set_env(f, random_env())
f3 <- set_env(f, random_env(environment(f2)))
f4 <- set_env(f, random_env(environment(f3)))

microbenchmark(
  f(1, 2),
  f2(1, 2),
  f3(1, 2),
  f4(1, 2),
  times = 10000
)
#> Unit: nanoseconds
#>      expr min  lq  mean median  uq      max neval
#>  f(1, 2) 376 418 718    426 450 2,040,000 10000
#>  f2(1, 2) 681 715 1123   725 771 2,890,000 10000
#>  f3(1, 2) 703 745 867   758 809   39,800 10000
#>  f4(1, 2) 749 793 920   807 855   56,300 10000

```

Each additional environment between `f()` and the base environment makes the function slower by about 30 ns.

It might be possible to implement a caching system so that R only needs to look up the value of each name once. This is hard because there are so many ways to change the value associated with a name: `<-`, `assign()`, `eval()`, and so on. Any caching system would have to know about these functions to make sure the cache was correctly invalidated and you didn't get an out-of-date value.

Another simple fix would be to add more built-in constants that you can't override. This, for example, would mean that R always knew exactly what `+`, `-`, `{`, and `(` meant, and you wouldn't have to repeatedly look up their definitions. That would make the interpreter more complicated (because there are more special cases) and hence harder to maintain, and the language less flexible. This would change the R-language, but it would be unlikely to affect much existing code because it's such a bad idea to override functions like `{` and `(`.

21.3.3 Lazy evaluation overhead

In R, function arguments are evaluated lazily (as discussed in lazy evaluation and capturing expressions). To implement lazy evaluation, R uses a promise object that contains the expression needed to compute the result and the environment in which to perform the computation. Creating these objects has some overhead, so each additional argument to a function decreases its speed a little.

The following microbenchmark compares the runtime of a very simple function. Each version of the function has one additional argument. This suggests that adding an additional argument slows the function down by ~20 ns.

```
f0 <- function() NULL
f1 <- function(a = 1) NULL
f2 <- function(a = 1, b = 1) NULL
f3 <- function(a = 1, b = 2, c = 3) NULL
f4 <- function(a = 1, b = 2, c = 4, d = 4) NULL
f5 <- function(a = 1, b = 2, c = 4, d = 4, e = 5) NULL
microbenchmark(f0(), f1(), f2(), f3(), f4(), f5(), times = 10000)
#> Unit: nanoseconds
#>   expr  min   lq  mean median   uq  max neval
#>   f0() 158 183 263    187 192 437,000 10000
#>   f1() 180 203 312    208 216 474,000 10000
#>   f2() 219 235 359    241 252 477,000 10000
#>   f3() 246 260 470    265 276 905,000 10000
#>   f4() 286 299 788    304 318 3,040,000 10000
#>   f5() 313 326 533    333 350 530,000 10000
```

In most other programming languages there is little overhead for adding extra arguments. Many compiled languages will even warn you if arguments are never used (like in the above example), and automatically remove them from the function.

21.3.4 Exercises

1. `scan()` has the most arguments (21) of any base function. About how much time does it take to make 21 promises each time `scan` is called? Given a simple input (e.g., `scan(text = "1 2 3", quiet = TRUE)`) what proportion of the total run time is due to creating those promises?
2. Read “Evaluating the Design of the R Language” (<http://r.cs.purdue.edu/pub/ecoop12.pdf>). What other aspects of the R-language slow it down? Construct microbenchmarks to illustrate.

3. How does the performance of S3 method dispatch change with the length of the class vector? How does performance of S4 method dispatch change with number of superclasses? How about RC?
4. What is the cost of multiple inheritance and multiple dispatch on S4 method dispatch?
5. Why is the cost of name lookup less for functions in the base package?

21.4 Implementation performance

The design of the R language limits its maximum theoretical performance, but GNU-R is currently nowhere near that maximum. There are many things that can (and will) be done to improve performance. This section discusses some aspects of GNU-R that are slow not because of their definition, but because of their implementation.

R is over 20 years old. It contains nearly 800,000 lines of code (about 45% C, 19% R, and 17% Fortran). Changes to base R can only be made by members of the R Core Team (or R-core for short). Currently R-core has twenty members (<http://www.r-project.org/contributors.html>), but only six are active in day-to-day development. No one on R-core works full time on R. Most are statistics professors who can only spend a relatively small amount of their time on R. Because of the care that must be taken to avoid breaking existing code, R-core tends to be very conservative about accepting new code. It can be frustrating to see R-core reject proposals that would improve performance. However, the overriding concern for R-core is not to make R fast, but to build a stable platform for data analysis and statistics.

Below, I'll show two small, but illustrative, examples of parts of R that are currently slow but could, with some effort, be made faster. They are not critical parts of base R, but they have been sources of frustration for me in the past. As with all microbenchmarks, these won't affect the performance of most code, but can be important for special cases.

21.4.1 Extracting a single value from a data frame

The following microbenchmark shows five ways to access a single value (the number in the bottom-right corner) from the built-in `mtcars` dataset. The variation in performance is startling: the slowest method takes 30x longer than the fastest. There's no reason that there has to be such a huge difference in performance. It's simply that no one has had the time to fix it.

```

microbenchmark(
  "[32, 11]"      = mtcars[32, 11],
  "$carb[32]"      = mtcars$carb[32],
  "[[c(11, 32)]]" = mtcars[[c(11, 32)]],
  "[[11]][32]"     = mtcars[[11]][32],
  ".subset2"        = .subset2(mtcars, 11)[32]
)
#> Unit: nanoseconds
#>          expr    min     lq   mean median     uq    max neval
#>      [32, 11] 9,400 9,830 11086 10,000 10,300 56,200   100
#>      $carb[32] 5,040 5,270 6188  5,500  5,880 40,400   100
#> [[c(11, 32)]] 4,200 4,480 10366  4,690  5,030 520,000   100
#> [[11]][32]  3,960 4,210  4609  4,450  4,650 11,200   100
#>     .subset2   279   353   416    376   402  2,530   100

```

21.4.2 `ifelse()`, `pmin()`, and `pmax()`

Some base functions are known to be slow. For example, take the following three implementations of `squish()`, a function that ensures that the smallest value in a vector is at least `a` and its largest value is at most `b`. The first implementation, `squish_ife()`, uses `ifelse()`. `ifelse()` is known to be slow because it is relatively general and must evaluate all arguments fully. The second implementation, `squish_p()`, uses `pmin()` and `pmax()`. Because these two functions are so specialised, one might expect that they would be fast. However, they're actually rather slow. This is because they can take any number of arguments and they have to do some relatively complicated checks to determine which method to use. The final implementation uses basic subassignment.

```

squish_ife <- function(x, a, b) {
  ifelse(x <= a, a, ifelse(x >= b, b, x))
}

squish_p <- function(x, a, b) {
  pmax(pmin(x, b), a)
}

squish_in_place <- function(x, a, b) {
  x[x <= a] <- a
  x[x >= b] <- b
  x
}

x <- runif(100, -1.5, 1.5)

```

```

microbenchmark(
  squish_ife      = squish_ife(x, -1, 1),
  squish_p       = squish_p(x, -1, 1),
  squish_in_place = squish_in_place(x, -1, 1),
  unit = "us"
)
#> Unit: microseconds
#>          expr      min       lq     mean   median      uq      max neval
#>      squish_ife 20.90 24.2 57.7 30.50 33.9 2,490   100
#>      squish_p   12.40 13.2 39.9 13.90 15.5 1,700   100
#>  squish_in_place  2.77  3.4 34.0  3.95  4.6 2,960   100

```

Using `pmin()` and `pmax()` is about 2x faster than `ifelse()`, and using subsetting directly is about 4x as fast again. We can often do even better by using C++. The following example compares the best R implementation to a relatively simple, if verbose, implementation in C++. Even if you've never used C++, you should still be able to follow the basic strategy: loop over every element in the vector and perform a different action depending on whether or not the value is less than a and/or greater than b.

```

#include <Rcpp.h>
using namespace Rcpp;

// [[Rcpp::export]]
NumericVector squish_cpp(NumericVector x, double a, double b) {
  int n = x.length();
  NumericVector out(n);

  for (int i = 0; i < n; ++i) {
    double xi = x[i];
    if (xi < a) {
      out[i] = a;
    } else if (xi > b) {
      out[i] = b;
    } else {
      out[i] = xi;
    }
  }

  return out;
}

```

(You'll learn how to access this C++ code from R in Rcpp.)

```
microbenchmark(
  squish_in_place = squish_in_place(x, -1, 1),
  squish_cpp      = squish_cpp(x, -1, 1),
  unit = "us"
)
#> Unit: microseconds
#>          expr  min   lq   mean median   uq   max neval
#>  squish_in_place 3.44 4.65  5.83   5.33 5.84  43.1   100
#>    squish_cpp  2.51 3.11 19.40   3.30 3.85 1,550.0   100
```

The C++ implementation is around 2x faster than the best pure R implementation.

21.4.3 Exercises

1. The performance characteristics of `squish_ife()`, `squish_p()`, and `squish_in_place()` vary considerably with the size of `x`. Explore the differences. Which sizes lead to the biggest and smallest differences?
2. Compare the performance costs of extracting an element from a list, a column from a matrix, and a column from a data frame. Do the same for rows.

21.5 Alternative R implementations

There are some exciting new implementations of R. While they all try to stick as closely as possible to the existing language definition, they improve speed by using ideas from modern interpreter design. The five most mature open-source projects are:

- pqR (<http://www.pqr-project.org/>) (pretty quick R) by Radford Neal. Built on top of R 2.15.0, it fixes many obvious performance issues, and provides better memory management and some support for automatic multithreading.
- Renjin (<http://www.renjin.org/>) by BeDataDriven. Renjin uses the Java virtual machine, and has an extensive test suite (<http://packages.renjin.org/>).

- FastR (<https://github.com/allr/fastr>) by a team from Purdue. FastR is similar to Renjin, but it makes more ambitious optimisations and is somewhat less mature.
- Rho (<https://github.com/rho-devel/rho>) by Andrew Runnalls and Karl Millar, refactors R’s internal C code into clean C++, and implemented performance optimisations using LLVM. Rho development is currently suspended.
- Riposte (<https://github.com/jtalbot/riposte>) by Justin Talbot and Zachary DeVito. Riposte is experimental and ambitious. For the parts of R it implements, it is extremely fast. Riposte is described in more detail in Riposte: A Trace-Driven Compiler and Parallel VM for Vector Code in R (<http://www.justintalbot.com/wp-content/uploads/2012/10/pact080talbot.pdf>).

R is a huge language and it’s not clear whether any of these approaches will ever become mainstream. It’s a hard task to make an alternative implementation run all R code in the same way as GNU-R. Can you imagine having to reimplement every function in base R to be not only faster, but also to have exactly the same documented bugs? However, even if these implementations never make a dent in the use of GNU-R, they still provide benefits:

- Simpler implementations make it easy to validate new approaches before porting to GNU-R.
- Knowing which aspects of the language can be changed with minimal impact on existing code and maximal impact on performance can help to guide us to where we should direct our attention.
- Alternative implementations put pressure on the R-core to incorporate performance improvements.

One of the most important approaches that pqR, Renjin, FastR, and Riposte are exploring is the idea of deferred evaluation. As Justin Talbot, the author of Riposte, points out: “for long vectors, R’s execution is completely memory bound. It spends almost all of its time reading and writing vector intermediates to memory”. If we could eliminate these intermediate vectors, we could improve performance and reduce memory usage.

The following example shows a very simple example of how deferred evaluation can help. We have three vectors, `x`, `y`, `z`, each containing 1 million elements, and we want to find the sum of `x + y` where `z` is TRUE. (This represents a simplification of a pretty common sort of data analysis question.)

```
x <- runif(1e6)
y <- runif(1e6)
```

```

z <- sample(c(T, F), 1e6, rep = TRUE)

sum((x + y)[z])

```

In R, this creates two big temporary vectors: $x + y$, 1 million elements long, and $(x + y)[z]$, about 500,000 elements long. This means you need to have extra memory available for the intermediate calculation, and you have to shuttle the data back and forth between the CPU and memory. This slows computation down because the CPU can't work at maximum efficiency if it's always waiting for more data to come in.

However, if we rewrote the function using a loop in a language like C++, we only need one intermediate value: the sum of all the values we've seen:

```

#include <Rcpp.h>
using namespace Rcpp;

// [[Rcpp::export]]
double cond_sum_cpp(NumericVector x, NumericVector y,
                     LogicalVector z) {
  double sum = 0;
  int n = x.length();

  for(int i = 0; i < n; i++) {
    if (!z[i]) continue;
    sum += x[i] + y[i];
  }

  return sum;
}

cond_sum_r <- function(x, y, z) {
  sum((x + y)[z])
}

microbenchmark(
  cond_sum_cpp = cond_sum_cpp(x, y, z),
  cond_sum_r = cond_sum_r(x, y, z),
  unit = "ms"
)
#> Unit: milliseconds
#>          expr     min      lq    mean  median     uq      max  neval
#> cond_sum_cpp  5.24  5.3  5.38  5.34  5.39  6.9    100

```

```
#>     cond_sum_r 12.70 14.1 15.99 14.70 15.10 150.0 100
```

On my computer, this approach is about 3x faster than the vectorised R equivalent, which is already pretty fast.

The goal of deferred evaluation is to perform this transformation automatically, so you can write concise R code and have it automatically translated into efficient machine code. Sophisticated translators can also figure out how to make the most of multiple cores. In the above example, if you have four cores, you could split `x`, `y`, and `z` into four pieces performing the conditional sum on each core, then adding together the four individual results. Deferred evaluation can also work with for loops, automatically discovering operations that can be vectorised.

This chapter has discussed some of the fundamental reasons that R is slow. The following chapters will give you the tools to do something about it when it impacts your code.

Chapter 22

Optimising code

22.1 Introduction

“Programmers waste enormous amounts of time thinking about, or worrying about, the speed of noncritical parts of their programs, and these attempts at efficiency actually have a strong negative impact when debugging and maintenance are considered.”

— Donald Knuth.

Optimising code to make it run faster is an iterative process:

1. Find the biggest bottleneck (the slowest part of your code).
2. Try to eliminate it (you may not succeed but that’s ok).
3. Repeat until your code is “fast enough.”

This sounds easy, but it’s not.

Even experienced programmers have a hard time identifying bottlenecks in their code. Instead of relying on your intuition, you should **profile** your code: use realistic inputs and measure the run-time of each individual operation. Only once you’ve identified the most important bottlenecks can you attempt to eliminate them. It’s difficult to provide general advice on improving performance, but I try my best with six techniques that can be applied in many situations. I’ll also suggest a general strategy for performance optimisation that helps ensure that your faster code will still be correct code.

It’s easy to get caught up in trying to remove all bottlenecks. Don’t! Your time is valuable and is better spent analysing your data, not eliminating possible inefficiencies in your code. Be pragmatic: don’t spend hours of your time to

save seconds of computer time. To enforce this advice, you should set a goal time for your code and optimise only up to that goal. This means you will not eliminate all bottlenecks. Some you will not get to because you've met your goal. Others you may need to pass over and accept either because there is no quick and easy solution or because the code is already well optimised and no significant improvement is possible. Accept these possibilities and move on to the next candidate.

Outline

- Measuring performance describes how to find the bottlenecks in your code using line profiling.
- Improving performance outlines seven general strategies for improving the performance of your code.
- Code organisation teaches you how to organise your code to make optimisation as easy, and bug free, as possible.
- Already solved reminds you to look for existing solutions.
- Do as little as possible emphasises the importance of being lazy: often the easiest way to make a function faster is to let it to do less work.
- Vectorise concisely defines vectorisation, and shows you how to make the most of built-in functions.
- Avoid copies discusses the performance perils of copying data.
- Byte code compilation shows you how to take advantage of R's byte code compiler.
- Case study: t-test pulls all the pieces together into a case study showing how to speed up repeated t-tests by $\sim 1000x$.
- Parallelise teaches you how to use parallelisation to spread computation across all the cores in your computer.
- Other techniques finishes the chapter with pointers to more resources that will help you write fast code.

Prerequisites

In this chapter we'll be using the `lineprof` package to understand the performance of R code. Get it with:

```
devtools::install_github("hadley/lineprof")
```

22.2 Measuring performance

To understand performance, you use a profiler. There are a number of different types of profilers. R uses a fairly simple type called a sampling or statistical profiler. A sampling profiler stops the execution of code every few milliseconds and records which function is currently executing (along with which function called that function, and so on). For example, consider `f()`, below:

```
library(lineprof)
f <- function() {
  pause(0.1)
  g()
  h()
}
g <- function() {
  pause(0.1)
  h()
}
h <- function() {
  pause(0.1)
}
```

(I use `lineprof::pause()` instead of `Sys.sleep()` because `Sys.sleep()` does not appear in profiling outputs because as far as R can tell, it doesn't use up any computing time.)

If we profiled the execution of `f()`, stopping the execution of code every 0.1 s, we'd see a profile like below. Each line represents one “tick” of the profiler (0.1 s in this case), and function calls are nested with `>`. It shows that the code spends 0.1 s running `f()`, then 0.2 s running `g()`, then 0.1 s running `h()`.

```
f()
f() > g()
f() > g() > h()
f() > h()
```

If we actually profile `f()`, using the code below, we're unlikely to get such a clear result.

```
tmp <- tempfile()
Rprof(tmp, interval = 0.1)
f()
Rprof(NULL)
```

That's because profiling is hard to do accurately without slowing your code down by many orders of magnitude. The compromise that `RProf()` makes, sampling, only has minimal impact on the overall performance, but is fundamentally stochastic. There's some variability in both the accuracy of the timer and in the time taken by each operation, so each time you profile you'll get a slightly different answer. Fortunately, pinpoint accuracy is not needed to identify the slowest parts of your code.

Rather than focussing on individual calls, we'll visualise aggregates using the `lineprof` package. There are a number of other options, like `summaryRprof()`, the `proftools` package, and the `profr` package, but these tools are beyond the scope of this book. I wrote the `lineprof` package as a simpler way to visualise profiling data. As the name suggests, the fundamental unit of analysis in `lineprof()` is a line of code. This makes `lineprof` less precise than the alternatives (because a line of code can contain multiple function calls), but it's easier to understand the context.

To use `lineprof`, we first save the code in a file and `source()` it. Here `profiling-example.R` contains the definition of `f()`, `g()`, and `h()`. Note that you *must* use `source()` to load the code. This is because `lineprof` uses `srcrefs` to match up the code to the profile, and the needed `srcrefs` are only created when you load code from disk. We then use `lineprof()` to run our function and capture the timing output. Printing this object shows some basic information. For now, we'll just focus on the time column which estimates how long each line took to run and the ref column which tells us which line of code was run. The estimates aren't perfect, but the ratios look about right.

```
library(lineprof)
source("profiling-example.R")
l <- lineprof(f())
l
#>    time alloc release dups      ref      src
#> 1 0.074 0.001      0 0 profiling.R#2 f/pause
#> 2 0.143 0.002      0 0 profiling.R#3 f/g
#> 3 0.071 0.000      0 0 profiling.R#4 f/h
```

`lineprof` provides some functions to navigate through this data structure, but they're a bit clumsy. Instead, we'll start an interactive explorer using the shiny

package. `shine(1)` will open a new web page (or if you’re using RStudio, a new pane) that shows your source code annotated with information about how long each line took to run. `shine()` starts a shiny app which “blocks” your R session. To exit, you’ll need to stop the process using escape or `ctrl + c`.

#	Source code	t	r	a	d
1	<code>f <- function() {</code>				
2	<code> pause(0.1)</code>				
3	<code> g()</code>				
4	<code> h()</code>				
5	<code>}</code>				
6	<code>g <- function() {</code>				
7	<code> pause(0.1)</code>				
8	<code> h()</code>				
9	<code>}</code>				
10	<code>h <- function() {</code>				
11	<code> pause(0.1)</code>				
12	<code>}</code>				

The `t` column visualises how much time is spent on each line. (You’ll learn about the other columns in memory profiling.) While not precise, it allows you to spot bottlenecks, and you can get precise numbers by hovering over each bar. This shows that twice as much time is spent on `g()` as on `h()`, so it would make sense to drill down into `g()` for more details. To do so, click `g()`:

#	Source code	t	r	a	d
1	<code>f <- function() {</code>				
2	<code> pause(0.1)</code>				
3	<code> g()</code>				
4	<code> h()</code>				
5	<code>}</code>				
6	<code>g <- function() {</code>				
7	<code> pause(0.1)</code>				
8	<code> h()</code>				
9	<code>}</code>				
10	<code>h <- function() {</code>				
11	<code> pause(0.1)</code>				
12	<code>}</code>				

Then `h()`:

#	Source code	t	r	a	d
1	f <- function() {				
2	pause(0.1)				
3	g()				
4	h()				
5	}				
6	g <- function() {				
7	pause(0.1)				
8	h()				
9	}				
10	h <- function() {				
11	pause(0.1)				
12	}				

This technique should allow you to quickly identify the major bottlenecks in your code.

22.2.1 Limitations

There are some other limitations to profiling:

- Profiling does not extend to C code. You can see if your R code calls C/C++ code but not what functions are called inside of your C/C++ code. Unfortunately, tools for profiling compiled code are beyond the scope of this book (i.e., I have no idea how to do it).
- Similarly, you can't see what's going on inside primitive functions or byte code compiled code.
- If you're doing a lot of functional programming with anonymous functions, it can be hard to figure out exactly which function is being called. The easiest way to work around this is to name your functions.
- Lazy evaluation means that arguments are often evaluated inside another function. For example, in the following code, profiling would make it seem like `i()` was called by `j()` because the argument isn't evaluated until it's needed by `j()`.

```
i <- function() {
  pause(0.1)
  10
}
j <- function(x) {
  x + 10
}
j(i())
```

If this is confusing, you can create temporary variables to force computation to happen earlier.

22.3 Memory profiling with lineprof

`mem_change()` captures the net change in memory when running a block of code. Sometimes, however, we may want to measure incremental change. One way to do this is to use memory profiling to capture usage every few milliseconds. This functionality is provided by `utils::Rprof()` but it doesn't provide a very useful display of the results. Instead we'll use the `lineprof` (<https://github.com/hadley/lineprof>) package. It is powered by `Rprof()`, but displays the results in a more informative manner.

To demonstrate `lineprof`, we're going to explore a bare-bones implementation of `read.delim()` with only three arguments:

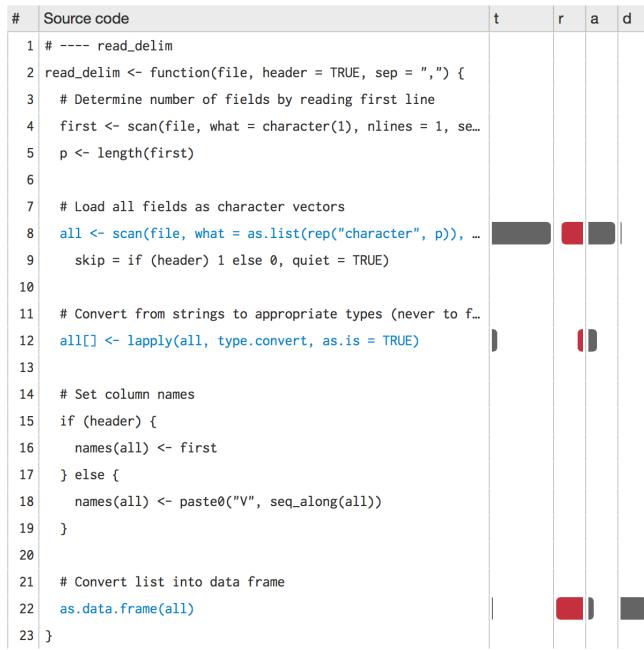
We'll also create a sample csv file:

```
library(ggplot2)
write.csv(diamonds, "diamonds.csv", row.names = FALSE)
```

Using `lineprof` is straightforward. `source()` the code, apply `lineprof()` to an expression, then use `shine()` to view the results. Note that you *must* use `source()` to load the code. This is because `lineprof` uses srcrefs to match up the code and run times. The needed srcrefs are only created when you load code from disk.

```
library(lineprof)

source("code/read-delim.R")
prof <- lineprof(read_delim("diamonds.csv"))
shine(prof)
```



`shiny()` will also open a new web page (or if you’re using RStudio, a new pane) that shows your source code annotated with information about memory usage. `shiny()` starts a shiny app which will “block” your R session. To exit, press escape or **ctrl + break**.

Next to the source code, four columns provide details about the performance of the code:

- **t**, the time (in seconds) spent on that line of code (explained in measuring performance).
- **a**, the memory (in megabytes) allocated by that line of code.
- **r**, the memory (in megabytes) released by that line of code. While memory allocation is deterministic, memory release is stochastic: it depends on when the GC was run. This means that memory release only tells you that the memory released was no longer needed before this line.
- **d**, the number of vector duplications that occurred. A vector duplication occurs when R copies a vector as a result of its copy on modify semantics.

You can hover over any of the bars to get the exact numbers. In this example, looking at the allocations tells us most of the story:

- `scan()` allocates about 2.5 MB of memory, which is very close to the 2.8 MB of space that the file occupies on disk. You wouldn’t expect the two

numbers to be identical because R doesn't need to store the commas and because the global string pool will save some memory.

- Converting the columns allocates another 0.6 MB of memory. You'd also expect this step to free some memory because we've converted string columns into integer and numeric columns (which occupy less space), but we can't see those releases because GC hasn't been triggered yet.
- Finally, calling `as.data.frame()` on a list allocates about 1.6 megabytes of memory and performs over 600 duplications. This is because `as.data.frame()` isn't terribly efficient and ends up copying the input multiple times. We'll discuss duplication more in the next section.

There are two downsides to profiling:

1. `read_delim()` only takes around half a second, but profiling can, at best, capture memory usage every 1 ms. This means we'll only get about 500 samples.
2. Since GC is lazy, we can never tell exactly when memory is no longer needed.

You can work around both problems by using `torture = TRUE`, which forces R to run GC after every allocation (see `gctorture()` for more details). This helps with both problems because memory is freed as soon as possible, and R runs 10–100x slower. This effectively makes the resolution of the timer greater, so that you can see smaller allocations and exactly when memory is no longer needed.

22.3.1 Exercises

1. When the input is a list, we can make a more efficient `as.data.frame()` by using special knowledge. A data frame is a list with class `data.frame` and `row.names` attribute. `row.names` is either a character vector or vector of sequential integers, stored in a special format created by `.set_row_names()`. This leads to an alternative `as.data.frame()`:

```
to_df <- function(x) {
  class(x) <- "data.frame"
  attr(x, "row.names") <- .set_row_names(length(x[[1]]))
  x
}
```

What impact does this function have on `read_delim()`? What are the downsides of this function?

2. Line profile the following function with `torture = TRUE`. What is surprising? Read the source code of `rm()` to figure out what's going on.

```
f <- function(n = 1e5) {
  x <- rep(1, n)
  rm(x)
}
```

22.4 Improving performance

“We should forget about small efficiencies, say about 97% of the time: premature optimization is the root of all evil. Yet we should not pass up our opportunities in that critical 3%. A good programmer will not be lulled into complacency by such reasoning, he will be wise to look carefully at the critical code; but only after that code has been identified.”

— Donald Knuth.

Once you've used profiling to identify a bottleneck, you need to make it faster. The following sections introduce you to a number of techniques that I've found broadly useful:

1. Look for existing solutions.
2. Do less work.
3. Vectorise.
4. Parallelise.
5. Avoid copies.
6. Byte-code compile.

A final technique is to rewrite in a faster language, like C++. That's a big topic and is covered in Rcpp.

Before we get into specific techniques, I'll first describe a general strategy and organisational style that's useful when working on performance.

22.5 Code organisation

There are two traps that are easy to fall into when trying to make your code faster:

1. Writing faster but incorrect code.

2. Writing code that you think is faster, but is actually no better.

The strategy outlined below will help you avoid these pitfalls.

When tackling a bottleneck, you're likely to come up with multiple approaches. Write a function for each approach, encapsulating all relevant behaviour. This makes it easier to check that each approach returns the correct result and to time how long it takes to run. To demonstrate the strategy, I'll compare two approaches for computing the mean:

```
mean1 <- function(x) mean(x)
mean2 <- function(x) sum(x) / length(x)
```

I recommend that you keep a record of everything you try, even the failures. If a similar problem occurs in the future, it'll be useful to see everything you've tried. To do this I often use R Markdown, which makes it easy to intermingle code with detailed comments and notes.

Next, generate a representative test case. The case should be big enough to capture the essence of your problem but small enough that it takes only a few seconds to run. You don't want it to take too long because you'll need to run the test case many times to compare approaches. On the other hand, you don't want the case to be too small because then results might not scale up to the real problem.

Use this test case to quickly check that all variants return the same result. An easy way to do so is with `stopifnot()` and `all.equal()`. For real problems with fewer possible outputs, you may need more tests to make sure that an approach doesn't accidentally return the correct answer. That's unlikely for the mean.

```
x <- runif(100)
stopifnot(all.equal(mean1(x), mean2(x)))
```

Finally, use the `microbenchmark` package to compare how long each variation takes to run. For bigger problems, reduce the `times` parameter so that it only takes a couple of seconds to run. Focus on the median time, and use the upper and lower quartiles to gauge the variability of the measurement.

```
microbenchmark(
  mean1(x),
  mean2(x)
)
#> Unit: nanoseconds
#>      expr    min     lq   mean median     uq    max neval
#> mean1(x) 3,130 3,200 14535  3,310  3,540 1,100,000    100
#> mean2(x)   647   722 24850    823   902 2,400,000    100
```

(You might be surprised by the results: `mean(x)` is considerably slower than `sum(x) / length(x)`. This is because, among other reasons, `mean(x)` makes two passes over the vector to be more numerically accurate.)

Before you start experimenting, you should have a target speed that defines when the bottleneck is no longer a problem. Setting such a goal is important because you don't want to spend valuable time over-optimising your code.

If you'd like to see this strategy in action, I've used it a few times on stackoverflow:

- <http://stackoverflow.com/questions/22515525#22518603>
- <http://stackoverflow.com/questions/22515175#22515856>
- <http://stackoverflow.com/questions/3476015#22511936>

22.6 Has someone already solved the problem?

Once you've organised your code and captured all the variations you can think of, it's natural to see what others have done. You are part of a large community, and it's quite possible that someone has already tackled the same problem. If your bottleneck is a function in a package, it's worth looking at other packages that do the same thing. Two good places to start are:

- CRAN task views (<http://cran.rstudio.com/web/views/>). If there's a CRAN task view related to your problem domain, it's worth looking at the packages listed there.
- Reverse dependencies of Rcpp, as listed on its CRAN page (<http://cran.r-project.org/web/packages/Rcpp>). Since these packages use C++, it's possible to find a solution to your bottleneck written in a higher performance language.

Otherwise, the challenge is describing your bottleneck in a way that helps you find related problems and solutions. Knowing the name of the problem or its synonyms will make this search much easier. But because you don't know what it's called, it's hard to search for it! By reading broadly about statistics and algorithms, you can build up your own knowledge base over time. Alternatively, ask others. Talk to your colleagues and brainstorm some possible names, then search on Google and stackoverflow. It's often helpful to restrict your search to R related pages. For Google, try rseek (<http://www.rseek.org/>). For stackoverflow, restrict your search by including the R tag, [R], in your search.

As discussed above, record all solutions that you find, not just those that immediately appear to be faster. Some solutions might be initially slower, but because they are easier to optimise they end up being faster. You may also be able to combine the fastest parts from different approaches. If you've found a solution that's fast enough, congratulations! If appropriate, you may want to share your solution with the R community. Otherwise, read on.

22.6.1 Exercises

1. What are faster alternatives to `lm`? Which are specifically designed to work with larger datasets?
2. What package implements a version of `match()` that's faster for repeated lookups? How much faster is it?
3. List four functions (not just those in base R) that convert a string into a date time object. What are their strengths and weaknesses?
4. How many different ways can you compute a 1d density estimate in R?
5. Which packages provide the ability to compute a rolling mean?
6. What are the alternatives to `optim()`?

22.7 Do as little as possible

The easiest way to make a function faster is to let it do less work. One way to do that is use a function tailored to a more specific type of input or output, or a more specific problem. For example:

- `rowSums()`, `colSums()`, `rowMeans()`, and `colMeans()` are faster than equivalent invocations that use `apply()` because they are vectorised (the topic of the next section).
- `vapply()` is faster than `sapply()` because it pre-specifies the output type.
- If you want to see if a vector contains a single value, `any(x == 10)` is much faster than `10 %in% x`. This is because testing equality is simpler than testing inclusion in a set.

Having this knowledge at your fingertips requires knowing that alternative functions exist: you need to have a good vocabulary. Start with the basics, and expand your vocab by regularly reading R code. Good places to read code are

the R-help mailing list (<https://stat.ethz.ch/mailman/listinfo/r-help>) and stackoverflow (<http://stackoverflow.com/questions/tagged/r>).

Some functions coerce their inputs into a specific type. If your input is not the right type, the function has to do extra work. Instead, look for a function that works with your data as it is, or consider changing the way you store your data. The most common example of this problem is using `apply()` on a data frame. `apply()` always turns its input into a matrix. Not only is this error prone (because a data frame is more general than a matrix), it is also slower.

Other functions will do less work if you give them more information about the problem. It's always worthwhile to carefully read the documentation and experiment with different arguments. Some examples that I've discovered in the past include:

- `read.csv()`: specify known column types with `colClasses`.
- `factor()`: specify known levels with `levels`.
- `cut()`: don't generate labels with `labels = FALSE` if you don't need them, or, even better, use `findInterval()` as mentioned in the “see also” section of the documentation.
- `unlist(x, use.names = FALSE)` is much faster than `unlist(x)`.
- `interaction()`: if you only need combinations that exist in the data, use `drop = TRUE`.

Sometimes you can make a function faster by avoiding method dispatch. As we saw in (Extreme dynamism), method dispatch in R can be costly. If you're calling a method in a tight loop, you can avoid some of the costs by doing the method lookup only once:

- For S3, you can do this by calling `generic.class()` instead of `generic()`.
- For S4, you can do this by using `getMethod()` to find the method, saving it to a variable, and then calling that function.

For example, calling `mean.default()` is quite a bit faster than calling `mean()` for small vectors:

```
x <- runif(1e2)

microbenchmark(
  mean(x),
  mean.default(x)
)
```

```
#> Unit: microseconds
#>          expr  min   lq  mean median   uq  max neval
#>  mean(x)  2.78 2.85 3.63   2.94 3.24 51.90   100
#> mean.default(x) 1.21 1.27 1.45   1.32 1.42  5.52   100
```

This optimisation is a little risky. While `mean.default()` is almost twice as fast, it'll fail in surprising ways if `x` is not a numeric vector. You should only use it if you know for sure what `x` is.

Knowing that you're dealing with a specific type of input can be another way to write faster code. For example, `as.data.frame()` is quite slow because it coerces each element into a data frame and then `rbind()`s them together. If you have a named list with vectors of equal length, you can directly transform it into a data frame. In this case, if you're able to make strong assumptions about your input, you can write a method that's about 20x faster than the default.

```
quickdf <- function(l) {
  class(l) <- "data.frame"
  attr(l, "row.names") <- .set_row_names(length(l[[1]]))
  l
}

l <- lapply(1:26, function(i) runif(1e3))
names(l) <- letters

microbenchmark(
  quick_df      = quickdf(l),
  as.data.frame = as.data.frame(l)
)
#> Unit: microseconds
#>          expr  min   lq  mean median   uq  max neval
#>  quick_df      6.7   9.36 51.2   17.5  22.9 3,310   100
#>  as.data.frame 1,060.0 1,100.00 1275.1 1,140.0 1,190.0 5,480   100
```

Again, note the trade-off. This method is fast because it's dangerous. If you give it bad inputs, you'll get a corrupt data frame:

```
quickdf(list(x = 1, y = 1:2))
#> Warning in format.data.frame(x, digits = digits, na.encode = FALSE):
#> corrupt data frame: columns will be truncated or padded with NAs
#>  x y
#> 1 1 1
```

To come up with this minimal method, I carefully read through and then rewrote

the source code for `as.data.frame.list()` and `data.frame()`. I made many small changes, each time checking that I hadn't broken existing behaviour. After several hours work, I was able to isolate the minimal code shown above. This is a very useful technique. Most base R functions are written for flexibility and functionality, not performance. Thus, rewriting for your specific need can often yield substantial improvements. To do this, you'll need to read the source code. It can be complex and confusing, but don't give up!

The following example shows a progressive simplification of the `diff()` function if you only want computing differences between adjacent values. At each step, I replace one argument with a specific case, and then check to see that the function still works. The initial function is long and complicated, but by restricting the arguments I not only make it around twice as fast, I also make it easier to understand.

First, I take the code of `diff()` and reformat it to my style:

```
diff1 <- function (x, lag = 1L, differences = 1L) {
  ismat <- is.matrix(x)
  xlen <- if (ismat) dim(x)[1L] else length(x)
  if (length(lag) > 1L || length(differences) > 1L ||
      lag < 1L || differences < 1L)
    stop("'lag' and 'differences' must be integers >= 1")

  if (lag * differences >= xlen) {
    return(x[0L])
  }

  r <- unclass(x)
  i1 <- -seq_len(lag)
  if (ismat) {
    for (i in seq_len(differences)) {
      r <- r[i1, , drop = FALSE] -
        r[-nrow(r):(nrow(r) - lag + 1L), , drop = FALSE]
    }
  } else {
    for (i in seq_len(differences)) {
      r <- r[i1] - r[-length(r):(length(r) - lag + 1L)]
    }
  }
  class(r) <- oldClass(x)
  r
}
```

Next, I assume vector input. This allows me to remove the `is.matrix()` test and the method that uses matrix subsetting.

```
diff2 <- function (x, lag = 1L, differences = 1L) {
  xlen <- length(x)
  if (length(lag) > 1L || length(differences) > 1L ||
      lag < 1L || differences < 1L)
    stop("'lag' and 'differences' must be integers >= 1")

  if (lag * differences >= xlen) {
    return(x[0L])
  }

  i1 <- -seq_len(lag)
  for (i in seq_len(differences)) {
    x <- x[i1] - x[-length(x):-(length(x) - lag + 1L)]
  }
  x
}
diff2(cumsum(0:10))
#> [1] 1 2 3 4 5 6 7 8 9 10
```

I now assume that `differences = 1L`. This simplifies input checking and eliminates the for loop:

```
diff3 <- function (x, lag = 1L) {
  xlen <- length(x)
  if (length(lag) > 1L || lag < 1L)
    stop("'lag' must be integer >= 1")

  if (lag >= xlen) {
    return(x[0L])
  }

  i1 <- -seq_len(lag)
  x[i1] - x[-length(x):-(length(x) - lag + 1L)]
}
diff3(cumsum(0:10))
#> [1] 1 2 3 4 5 6 7 8 9 10
```

Finally I assume `lag = 1L`. This eliminates input checking and simplifies subsetting.

```
diff4 <- function (x) {
  xlen <- length(x)
  if (xlen <= 1) return(x[0L])

  x[-1] - x[-xlen]
}
diff4(cumsum(0:10))
#> [1] 1 2 3 4 5 6 7 8 9 10
```

Now `diff4()` is both considerably simpler and considerably faster than `diff1()`:

```
x <- runif(100)
microbenchmark(
  diff1(x),
  diff2(x),
  diff3(x),
  diff4(x)
)
#> Unit: microseconds
#>      expr  min   lq   mean median   uq   max neval
#>  diff1(x) 3.75 4.35 200.39   4.74 5.50 19,500.0   100
#>  diff2(x) 3.26 3.69   4.87   4.04 4.68   48.4   100
#>  diff3(x) 2.68 3.25  86.04   3.63 4.09  8,200.0   100
#>  diff4(x) 2.04 2.48  39.24   2.81 3.27  3,590.0   100
```

You'll be able to make `diff()` even faster for this special case once you've read Rcpp.

A final example of doing less work is to use simpler data structures. For example, when working with rows from a data frame, it's often faster to work with row indices than data frames. For instance, if you wanted to compute a bootstrap estimate of the correlation between two columns in a data frame, there are two basic approaches: you can either work with the whole data frame or with the individual vectors. The following example shows that working with vectors is about twice as fast.

```
sample_rows <- function(df, i) sample.int(nrow(df), i,
  replace = TRUE)

# Generate a new data frame containing randomly selected rows
boot_cor1 <- function(df, i) {
  sub <- df[sample_rows(df, i), , drop = FALSE]
  cor(sub$x, sub$y)
```

```

}

# Generate new vectors from random rows
boot_cor2 <- function(df, i) {
  idx <- sample_rows(df, i)
  cor(df$x[idx], df$y[idx])
}

df <- data.frame(x = runif(100), y = runif(100))
microbenchmark(
  boot_cor1(df, 10),
  boot_cor2(df, 10)
)
#> Unit: microseconds
#>           expr  min   lq  mean median   uq  max neval
#>  boot_cor1(df, 10) 84.6 90.8 136   97.5 110.0 2,740   100
#>  boot_cor2(df, 10) 56.3 58.6 109   60.1  65.2 2,750   100

```

22.7.1 Exercises

1. How do the results change if you compare `mean()` and `mean.default()` on 10,000 observations, rather than on 100?
2. The following code provides an alternative implementation of `rowSums()`. Why is it faster for this input?

```

rowSums2 <- function(df) {
  out <- df[[1L]]
  if (ncol(df) == 1) return(out)

  for (i in 2:ncol(df)) {
    out <- out + df[[i]]
  }
  out
}

df <- as.data.frame(
  replicate(1e3, sample(100, 1e4, replace = TRUE))
)
system.time(rowSums(df))
#>    user  system elapsed

```

```
#> 0.060 0.016 0.076
system.time(rowSums2(df))
#> user system elapsed
#> 0.032 0.000 0.032
```

3. What's the difference between `rowSums()` and `.rowSums()`?
4. Make a faster version of `chisq.test()` that only computes the chi-square test statistic when the input is two numeric vectors with no missing values. You can try simplifying `chisq.test()` or by coding from the mathematical definition (http://en.wikipedia.org/wiki/Pearson%27s_chi-squared_test).
5. Can you make a faster version of `table()` for the case of an input of two integer vectors with no missing values? Can you use it to speed up your chi-square test?
6. Imagine you want to compute the bootstrap distribution of a sample correlation using `cor_df()` and the data in the example below. Given that you want to run this many times, how can you make this code faster? (Hint: the function has three components that you can speed up.)

```
n <- 1e6
df <- data.frame(a = rnorm(n), b = rnorm(n))

cor_df <- function(df, n) {
  i <- sample(seq(n), n, replace = TRUE)
  cor(df[i, , drop = FALSE])[2,1]
}
```

Is there a way to vectorise this procedure?

22.8 Vectorise

If you've used R for any length of time, you've probably heard the admonishment to "vectorise your code". But what does that actually mean? Vectorising your code is not just about avoiding for loops, although that's often a step. Vectorising is about taking a "whole object" approach to a problem, thinking about vectors, not scalars. There are two key attributes of a vectorised function:

- It makes many problems simpler. Instead of having to think about the components of a vector, you only think about entire vectors.
- The loops in a vectorised function are written in C instead of R. Loops in C are much faster because they have much less overhead.

Functionals stressed the importance of vectorised code as a higher level abstraction. Vectorisation is also important for writing fast R code. This doesn't mean simply using `apply()` or `lapply()`, or even `Vectorise()`. Those functions improve the interface of a function, but don't fundamentally change performance. Using vectorisation for performance means finding the existing R function that is implemented in C and most closely applies to your problem.

Vectorised functions that apply to many common performance bottlenecks include:

- `rowSums()`, `colSums()`, `rowMeans()`, and `colMeans()`. These vectorised matrix functions will always be faster than using `apply()`. You can sometimes use these functions to build other vectorised functions.

```
rowAny <- function(x) rowSums(x) > 0
rowAll <- function(x) rowSums(x) == ncol(x)
```

- Vectorised subsetting can lead to big improvements in speed. Remember the techniques behind lookup tables (lookup tables) and matching and merging by hand (matching and merging by hand). Also remember that you can use subsetting assignment to replace multiple values in a single step. If `x` is a vector, matrix or data frame then `x[is.na(x)] <- 0` will replace all missing values with 0.
- If you're extracting or replacing values in scattered locations in a matrix or data frame, subset with an integer matrix. See matrix subsetting for more details.
- If you're converting continuous values to categorical make sure you know how to use `cut()` and `findInterval()`.
- Be aware of vectorised functions like `cumsum()` and `diff()`.

Matrix algebra is a general example of vectorisation. There loops are executed by highly tuned external libraries like BLAS. If you can figure out a way to use matrix algebra to solve your problem, you'll often get a very fast solution. The ability to solve problems with matrix algebra is a product of experience. While this skill is something you'll develop over time, a good place to start is to ask people with experience in your domain.

The downside of vectorisation is that it makes it harder to predict how operations will scale. The following example measures how long it takes to use character subsetting to lookup 1, 10, and 100 elements from a list. You might expect that looking up 10 elements would take 10x as long as looking up 1, and that looking up 100 elements would take 10x longer again. In fact, the following example

shows that it only takes about 9 times longer to look up 100 elements than it does to look up 1.

```
lookup <- setNames(as.list(sample(100, 26)), letters)

x1 <- "j"
x10 <- sample(letters, 10)
x100 <- sample(letters, 100, replace = TRUE)

microbenchmark(
  lookup[x1],
  lookup[x10],
  lookup[x100]
)
#> Unit: nanoseconds
#>      expr    min     lq   mean median     uq    max neval
#>  lookup[x1] 540  585  827   712  954  3,490   100
#>  lookup[x10] 1,380 1,450 1918  1,590 1,840 26,100   100
#>  lookup[x100] 5,100 6,100 7086  6,640 7,340 23,300   100
```

Vectorisation won't solve every problem, and rather than torturing an existing algorithm into one that uses a vectorised approach, you're often better off writing your own vectorised function in C++. You'll learn how to do so in Rcpp.

22.8.1 Exercises

1. The density functions, e.g., `dnorm()`, have a common interface. Which arguments are vectorised over? What does `rnorm(10, mean = 10:1)` do?
2. Compare the speed of `apply(x, 1, sum)` with `rowSums(x)` for varying sizes of `x`.
3. How can you use `crossprod()` to compute a weighted sum? How much faster is it than the naive `sum(x * w)`?

22.9 Avoid copies

A pernicious source of slow R code is growing an object with a loop. Whenever you use `c()`, `append()`, `cbind()`, `rbind()`, or `paste()` to create a bigger object, R must first allocate space for the new object and then copy the old object to its new home. If you're repeating this many times, like in a for loop, this can be quite

expensive. You've entered Circle 2 of the "R inferno" (http://www.burns-stat.com/pages/Tutor/R_inferno.pdf).

Here's a little example that shows the problem. We first generate some random strings, and then combine them either iteratively with a loop using `collapse()`, or in a single pass using `paste()`. Note that the performance of `collapse()` gets relatively worse as the number of strings grows: combining 100 strings takes almost 30 times longer than combining 10 strings.

```
random_string <- function() {
  paste(sample(letters, 50, replace = TRUE), collapse = "")
}

strings10 <- replicate(10, random_string())
strings100 <- replicate(100, random_string())

collapse <- function(xs) {
  out <- ""
  for (x in xs) {
    out <- paste0(out, x)
  }
  out
}

microbenchmark(
  loop10  = collapse(strings10),
  loop100 = collapse(strings100),
  vec10   = paste(strings10, collapse = ""),
  vec100  = paste(strings100, collapse = "")
)
#> Unit: microseconds
#>      expr    min     lq    mean   median     uq    max neval
#>  loop10 20.1 21.50 23.3 22.60 24.50 35.7  100
#>  loop100 808.0 824.00 863.5 829.00 843.00 3,670.0  100
#>   vec10   4.9  5.15  6.2  5.57  6.14  44.7  100
#>   vec100 39.9 41.10 44.1 41.70 44.10 144.0  100
```

Modifying an object in a loop, e.g., `x[i] <- y`, can also create a copy, depending on the class of `x`. `Modification in place` discusses this issue in more depth and gives you some tools to determine when you're making copies.

22.10 Byte code compilation

R 2.13.0 introduced a byte code compiler which can increase the speed of some code. Using the compiler is an easy way to get improvements in speed. Even if it doesn't work well for your function, you won't have invested a lot of time in the effort. The following example shows the pure R version of `lapply()` from `functionals`. Compiling it gives a considerable speedup, although it's still not quite as fast as the C version provided by base R.

```

lapply2 <- function(x, f, ...) {
  out <- vector("list", length(x))
  for (i in seq_along(x)) {
    out[[i]] <- f(x[[i]], ...)
  }
  out
}

lapply2_c <- compiler::cmpfun(lapply2)

x <- list(1:10, letters, c(F, T), NULL)
microbenchmark(
  lapply2(x, is.null),
  lapply2_c(x, is.null),
  lapply(x, is.null)
)
#> Unit: microseconds
#>          expr  min   lq   mean median   uq   max neval
#>  lapply2(x, is.null) 1.82 1.86 42.13   1.94 2.21 3,970.00   100
#>  lapply2_c(x, is.null) 1.81 1.86  2.19   1.99 2.37      6.74   100
#>  lapply(x, is.null) 2.27 2.40  2.90   2.58 2.90   13.40   100

```

Byte code compilation really helps here, but in most cases you're more likely to get a 5-10% improvement. All base R functions are byte code compiled by default.

22.11 Case study: t-test

The following case study shows how to make t-tests faster using some of the techniques described above. It's based on an example in "Computing thousands of test statistics simultaneously in R" (<http://stat-computing.org/newsletter/issues/scgn-18-1.pdf>) by Holger Schwender and Tina Müller. I thoroughly rec-

ommend reading the paper in full to see the same idea applied to other tests.

Imagine we have run 1000 experiments (rows), each of which collects data on 50 individuals (columns). The first 25 individuals in each experiment are assigned to group 1 and the rest to group 2. We'll first generate some random data to represent this problem:

```
m <- 1000
n <- 50
X <- matrix(rnorm(m * n, mean = 10, sd = 3), nrow = m)
grp <- rep(1:2, each = n / 2)
```

For data in this form, there are two ways to use `t.test()`. We can either use the formula interface or provide two vectors, one for each group. Timing reveals that the formula interface is considerably slower.

```
system.time(for(i in 1:m) t.test(X[i, ] ~ grp)$statistic)
#>    user  system elapsed
#>  0.884   0.000   0.884
system.time(
  for(i in 1:m) t.test(X[i, grp == 1], X[i, grp == 2])$statistic
)
#>    user  system elapsed
#>  0.200   0.000   0.198
```

Of course, a for loop computes, but doesn't save the values. We'll use `apply()` to do that. This adds a little overhead:

```
compT <- function(x, grp){
  t.test(x[grp == 1], x[grp == 2])$statistic
}
system.time(t1 <- apply(X, 1, compT, grp = grp))
#>    user  system elapsed
#>  0.208   0.000   0.208
```

How can we make this faster? First, we could try doing less work. If you look at the source code of `stats:::t.test.default()`, you'll see that it does a lot more than just compute the t-statistic. It also computes the p-value and formats the output for printing. We can try to make our code faster by stripping out those pieces.

```
my_t <- function(x, grp) {
  t_stat <- function(x) {
    m <- mean(x)
```

```

n <- length(x)
var <- sum((x - m) ^ 2) / (n - 1)

list(m = m, n = n, var = var)
}

g1 <- t_stat(x[grp == 1])
g2 <- t_stat(x[grp == 2])

se_total <- sqrt(g1$var / g1$n + g2$var / g2$n)
(g1$m - g2$m) / se_total
}

system.time(t2 <- apply(X, 1, my_t, grp = grp))
#>    user  system elapsed
#>  0.028  0.000  0.026
stopifnot(all.equal(t1, t2))

```

This gives us about a 6x speed improvement.

Now that we have a fairly simple function, we can make it faster still by vectorising it. Instead of looping over the array outside the function, we will modify `t_stat()` to work with a matrix of values. Thus, `mean()` becomes `rowMeans()`, `length()` becomes `ncol()`, and `sum()` becomes `rowSums()`. The rest of the code stays the same.

```

rowtstat <- function(X, grp){
  t_stat <- function(X) {
    m <- rowMeans(X)
    n <- ncol(X)
    var <- rowSums((X - m) ^ 2) / (n - 1)

    list(m = m, n = n, var = var)
  }

  g1 <- t_stat(X[, grp == 1])
  g2 <- t_stat(X[, grp == 2])

  se_total <- sqrt(g1$var / g1$n + g2$var / g2$n)
  (g1$m - g2$m) / se_total
}

system.time(t3 <- rowtstat(X, grp))
#>    user  system elapsed

```

```
#> 0.012 0.000 0.013
stopifnot(all.equal(t1, t3))
```

That's much faster! It's at least 40x faster than our previous effort, and around 1000x faster than where we started.

Finally, we could try byte code compilation. Here we'll need to use `microbenchmark()` instead of `system.time()` in order to get enough accuracy to see a difference:

```
rowtstat_bc <- compiler::cmpfun(rowtstat)

microbenchmark(
  rowtstat(X, grp),
  rowtstat_bc(X, grp),
  unit = "ms"
)
#> Unit: milliseconds
#>           expr     min      lq    mean  median     uq    max neval
#>   rowtstat(X, grp) 0.575 0.596 0.786  0.876 0.918 1.06    100
#> rowtstat_bc(X, grp) 0.573 0.594 0.759  0.623 0.887 4.48    100
```

In this example, byte code compilation doesn't help at all.

22.12 Parallelise

Parallelisation uses multiple cores to work simultaneously on different parts of a problem. It doesn't reduce the computing time, but it saves your time because you're using more of your computer's resources. Parallel computing is a complex topic, and there's no way to cover it in depth here. Some resources I recommend are:

- *Parallel R* (<http://amzn.com/B005Z29QT4>) by Q. Ethan McCallum and Stephen Weston.
- *Parallel Computing for Data Science* (<http://amzn.com/1466587016>) by Norm Matloff.

What I want to show is a simple application of parallel computing to what are called "embarrassingly parallel problems". An embarrassingly parallel problem is one that's made up of many simple problems that can be solved independently. A great example of this is `lapply()` because it operates on each element independently of the others. It's very easy to parallelise `lapply()` on Linux and the Mac

because you simply substitute `mclapply()` for `lapply()`. The following code snippet runs a trivial (but slow) function on all cores of your computer.

```
library(parallel)

cores <- detectCores()
cores
#> [1] 2

pause <- function(i) {
  function(x) Sys.sleep(i)
}

system.time(lapply(1:10, pause(0.25)))
#>    user  system elapsed
#>    0.0    0.0    2.5
system.time(mclapply(1:10, pause(0.25), mc.cores = cores))
#>    user  system elapsed
#>  0.008  0.020  1.275
```

Life is a bit harder in Windows. You need to first set up a local cluster and then use `parLapply()`:

```
cluster <- makePSOCKcluster(cores)
system.time(parLapply(cluster, 1:10, function(i) Sys.sleep(i)))
#>    user  system elapsed
#>  0.004  0.000  40.064
```

The main difference between `mclapply()` and `makePSOCKcluster()` is that the individual processes generated by `mclapply()` inherit from the current process, while those generated by `makePSOCKcluster()` start with a fresh session. This means that most real code will need some setup. Use `clusterEvalQ()` to run arbitrary code on each cluster and load needed packages, and `clusterExport()` to copy objects in the current session to the remote sessions.

```
x <- 10
psock <- parallel::makePSOCKcluster(1L)
clusterEvalQ(psock, x)
#> Error: one node produced an error: object 'x' not found

clusterExport(psock, "x")
clusterEvalQ(psock, x)
#> [[1]]
#> [1] 10
```

There is some communication overhead with parallel computing. If the subproblems are very small, then parallelisation might hurt rather than help. It's also possible to distribute computation over a network of computers (not just the cores on your local computer) but that's beyond the scope of this book, because it gets increasingly complicated to balance computation and communication costs. A good place to start for more information is the high performance computing CRAN task view (<http://cran.r-project.org/web/views/HighPerformanceComputing.html>).

22.13 Other techniques

Being able to write fast R code is part of being a good R programmer. Beyond the specific hints in this chapter, if you want to write fast R code, you'll need to improve your general programming skills. Some ways to do this are to:

- Read R blogs (<http://www.r-bloggers.com/>) to see what performance problems other people have struggled with, and how they have made their code faster.
- Read other R programming books, like Norm Matloff's *The Art of R Programming* (<http://amzn.com/1593273843>) or Patrick Burns' *R Inferno* (<http://www.burns-stat.com/documents/books/the-r-inferno/>) to learn about common traps.
- Take an algorithms and data structure course to learn some well known ways of tackling certain classes of problems. I have heard good things about Princeton's Algorithms course (<https://www.coursera.org/course/algs4partI>) offered on Coursera.
- Read general books about optimisation like *Mature optimisation* (<http://carlos.bueno.org/optimization/mature-optimization.pdf>) by Carlos Bueno, or the *Pragmatic Programmer* (<http://amzn.com/020161622X>) by Andrew Hunt and David Thomas.

You can also reach out to the community for help. Stackoverflow can be a useful resource. You'll need to put some effort into creating an easily digestible example that also captures the salient features of your problem. If your example is too complex, few people will have the time and motivation to attempt a solution. If it's too simple, you'll get answers that solve the toy problem but not the real problem. If you also try to answer questions on stackoverflow, you'll quickly get a feel for what makes a good question.

Chapter 23

Rewriting R code in C++

23.1 Introduction

Sometimes R code just isn't fast enough. You've used profiling to figure out where your bottlenecks are, and you've done everything you can in R, but your code still isn't fast enough. In this chapter you'll learn how to improve performance by rewriting key functions in C++. This magic comes by way of the Rcpp (<http://www.rcpp.org/>) package, a fantastic tool written by Dirk Eddelbuettel and Romain Francois (with key contributions by Doug Bates, John Chambers, and JJ Allaire). Rcpp makes it very simple to connect C++ to R. While it is *possible* to write C or Fortran code for use in R, it will be painful by comparison. Rcpp provides a clean, approachable API that lets you write high-performance code, insulated from R's arcane C API.

Typical bottlenecks that C++ can address include:

- Loops that can't be easily vectorised because subsequent iterations depend on previous ones.
- Recursive functions, or problems which involve calling functions millions of times. The overhead of calling a function in C++ is much lower than that in R.
- Problems that require advanced data structures and algorithms that R doesn't provide. Through the standard template library (STL), C++ has efficient implementations of many important data structures, from ordered maps to double-ended queues.

The aim of this chapter is to discuss only those aspects of C++ and Rcpp that are absolutely necessary to help you eliminate bottlenecks in your code. We won't spend much time on advanced features like object oriented programming or templates because the focus is on writing small, self-contained functions, not big programs. A working knowledge of C++ is helpful, but not essential. Many good tutorials and references are freely available, including <http://www.learncpp.com/> and <http://www.cplusplus.com/>. For more advanced topics, the *Effective C++* series by Scott Meyers is a popular choice. You may also enjoy Dirk Eddelbuettel's *Seamless R and C++ integration with Rcpp* (<http://www.springer.com/statistics/computational+statistics/book/978-1-4614-6867-7>), which goes into much greater detail into all aspects of Rcpp.

Outline

- Getting started with C++ teaches you how to write C++ by converting simple R functions to their C++ equivalents. You'll learn how C++ differs from R, and what the key scalar, vector, and matrix classes are called.
- Using `sourceCpp` shows you how to use `sourceCpp()` to load a C++ file from disk in the same way you use `source()` to load a file of R code.
- Attributes & other classes discusses how to modify attributes from Rcpp, and mentions some of the other important classes.
- Missing values teaches you how to work with R's missing values in C++.
- Rcpp sugar discusses Rcpp "sugar", which allows you to avoid loops in C++ and write code that looks very similar to vectorised R code.
- The STL shows you how to use some of the most important data structures and algorithms from the standard template library, or STL, built-in to C++.
- Case studies shows two real case studies where Rcpp was used to get considerable performance improvements.
- Putting Rcpp in a package teaches you how to add C++ code to a package.
- Learning more concludes the chapter with pointers to more resources to help you learn Rcpp and C++.

Prerequisites

All examples in this chapter need version 0.10.1 or above of the `Rcpp` package. This version includes `cppFunction()` and `sourceCpp()`, which makes it very easy to connect C++ to R. Install the latest version of `Rcpp` from CRAN with `install.packages("Rcpp")`.

You'll also need a working C++ compiler. To get it:

- On Windows, install Rtools (<http://cran.r-project.org/bin/windows/Rtools/>).
- On Mac, install Xcode from the app store.
- On Linux, `sudo apt-get install r-base-dev` or similar.

23.2 Getting started with C++

`cppFunction()` allows you to write C++ functions in R:

```
library(Rcpp)
cppFunction('int add(int x, int y, int z) {
  int sum = x + y + z;
  return sum;
}')
# add works like a regular R function
add
#> function (x, y, z)
#> .Call(<pointer: 0x7f83e91c8f60>, x, y, z)
add(1, 2, 3)
#> [1] 6
```

When you run this code, `Rcpp` will compile the C++ code and construct an R function that connects to the compiled C++ function. We're going to use this simple interface to learn how to write C++. C++ is a large language, and there's no way to cover it all in just one chapter. Instead, you'll get the basics so that you can start writing useful functions to address bottlenecks in your R code.

The following sections will teach you the basics by translating simple R functions to their C++ equivalents. We'll start simple with a function that has no inputs and a scalar output, and then get progressively more complicated:

- Scalar input and scalar output
- Vector input and scalar output
- Vector input and vector output

- Matrix input and vector output

23.2.1 No inputs, scalar output

Let's start with a very simple function. It has no arguments and always returns the integer 1:

```
one <- function() 1L
```

The equivalent C++ function is:

```
int one() {
    return 1;
}
```

We can compile and use this from R with `cppFunction`

```
cppFunction('int one() {
    return 1;
}')
```

This small function illustrates a number of important differences between R and C++:

- The syntax to create a function looks like the syntax to call a function; you don't use assignment to create functions as you do in R.
- You must declare the type of output the function returns. This function returns an `int` (a scalar integer). The classes for the most common types of R vectors are: `NumericVector`, `IntegerVector`, `CharacterVector`, and `LogicalVector`.
- Scalars and vectors are different. The scalar equivalents of numeric, integer, character, and logical vectors are: `double`, `int`, `String`, and `bool`.
- You must use an explicit `return` statement to return a value from a function.
- Every statement is terminated by a `;`.

23.2.2 Scalar input, scalar output

The next example function implements a scalar version of the `sign()` function which returns 1 if the input is positive, and -1 if it's negative:

```

signR <- function(x) {
  if (x > 0) {
    1
  } else if (x == 0) {
    0
  } else {
    -1
  }
}

cppFunction('int signC(int x) {
  if (x > 0) {
    return 1;
  } else if (x == 0) {
    return 0;
  } else {
    return -1;
  }
}')

```

In the C++ version:

- We declare the type of each input in the same way we declare the type of the output. While this makes the code a little more verbose, it also makes it very obvious what type of input the function needs.
- The `if` syntax is identical — while there are some big differences between R and C++, there are also lots of similarities! C++ also has a `while` statement that works the same way as R's. As in R you can use `break` to exit the loop, but to skip one iteration you need to use `continue` instead of `next`.

23.2.3 Vector input, scalar output

One big difference between R and C++ is that the cost of loops is much lower in C++. For example, we could implement the `sum` function in R using a loop. If you've been programming in R a while, you'll probably have a visceral reaction to this function!

```

sumR <- function(x) {
  total <- 0
  for (i in seq_along(x)) {

```

```

    total <- total + x[i]
}
total
}

```

In C++, loops have very little overhead, so it's fine to use them. In STL, you'll see alternatives to `for` loops that more clearly express your intent; they're not faster, but they can make your code easier to understand.

```

cppFunction('double sumC(NumericVector x) {
  int n = x.size();
  double total = 0;
  for(int i = 0; i < n; ++i) {
    total += x[i];
  }
  return total;
}')

```

The C++ version is similar, but:

- To find the length of the vector, we use the `.size()` method, which returns an integer. C++ methods are called with `.` (i.e., a full stop).
- The `for` statement has a different syntax: `for(init; check; increment)`. This loop is initialised by creating a new variable called `i` with value 0. Before each iteration we check that `i < n`, and terminate the loop if it's not. After each iteration, we increment the value of `i` by one, using the special prefix operator `++` which increases the value of `i` by 1.
- In C++, vector indices start at 0. I'll say this again because it's so important: **IN C++, VECTOR INDICES START AT 0!** This is a very common source of bugs when converting R functions to C++.
- Use `=` for assignment, not `<-`.
- C++ provides operators that modify in-place: `total += x[i]` is equivalent to `total = total + x[i]`. Similar in-place operators are `-=`, `*=`, and `/=`.

This is a good example of where C++ is much more efficient than R. As shown by the following microbenchmark, `sumC()` is competitive with the built-in (and highly optimised) `sum()`, while `sumR()` is several orders of magnitude slower.

```

x <- runif(1e3)
microbenchmark(
  sum(x),
  sumC(x),

```

```

  sumR(x)
)
#> Unit: microseconds
#>   expr   min    lq   mean   median    uq   max neval
#>   sum(x) 1.34  1.40  1.63  1.45  1.60    8  100
#>   sumC(x) 3.37  3.63 13.98  3.91  4.42  970  100
#>   sumR(x) 38.50 38.80 88.50 39.00 43.50 4,450  100

```

23.2.4 Vector input, vector output

Next we'll create a function that computes the Euclidean distance between a value and a vector of values:

```

pdistR <- function(x, ys) {
  sqrt((x - ys) ^ 2)
}

```

It's not obvious that we want `x` to be a scalar from the function definition. We'd need to make that clear in the documentation. That's not a problem in the C++ version because we have to be explicit about types:

```

cppFunction('NumericVector pdistC(double x, NumericVector ys) {
  int n = ys.size();
  NumericVector out(n);

  for(int i = 0; i < n; ++i) {
    out[i] = sqrt(pow(ys[i] - x, 2.0));
  }
  return out;
}')

```

This function introduces only a few new concepts:

- We create a new numeric vector of length `n` with a constructor: `NumericVector out(n)`. Another useful way of making a vector is to copy an existing one: `NumericVector zs = clone(ys)`.
- C++ uses `pow()`, not `^`, for exponentiation.

Note that because the R version is fully vectorised, it's already going to be fast. On my computer, it takes around 8 ms with a 1 million element `y` vector. The C++ function is twice as fast, ~4 ms, but assuming it took you 10 minutes to write the C++ function, you'd need to run it ~150,000 times to make rewriting

worthwhile. The reason why the C++ function is faster is subtle, and relates to memory management. The R version needs to create an intermediate vector the same length as y ($x - ys$), and allocating memory is an expensive operation. The C++ function avoids this overhead because it uses an intermediate scalar.

In the sugar section, you'll see how to rewrite this function to take advantage of Rcpp's vectorised operations so that the C++ code is almost as concise as R code.

23.2.5 Matrix input, vector output

Each vector type has a matrix equivalent: `NumericMatrix`, `IntegerMatrix`, `CharacterMatrix`, and `LogicalMatrix`. Using them is straightforward. For example, we could create a function that reproduces `rowSums()`:

```
cppFunction('NumericVector rowSumsC(NumericMatrix x) {
  int nrow = x.nrow(), ncol = x.ncol();
  NumericVector out(nrow);

  for (int i = 0; i < nrow; i++) {
    double total = 0;
    for (int j = 0; j < ncol; j++) {
      total += x(i, j);
    }
    out[i] = total;
  }
  return out;
}')
set.seed(1014)
x <- matrix(sample(100), 10)
rowSums(x)
#> [1] 458 558 488 458 536 537 488 491 508 528
rowSumsC(x)
#> [1] 458 558 488 458 536 537 488 491 508 528
```

The main differences:

- In C++, you subset a matrix with `()`, not `[]`.
- Use `.nrow()` and `.ncol()` *methods* to get the dimensions of a matrix.

23.2.6 Using sourceCpp

So far, we've used inline C++ with `cppFunction()`. This makes presentation simpler, but for real problems, it's usually easier to use stand-alone C++ files and then source them into R using `sourceCpp()`. This lets you take advantage of text editor support for C++ files (e.g., syntax highlighting) as well as making it easier to identify the line numbers in compilation errors.

Your stand-alone C++ file should have extension `.cpp`, and needs to start with:

```
#include <Rcpp.h>
using namespace Rcpp;
```

And for each function that you want available within R, you need to prefix it with:

```
// [[Rcpp::export]]
```

Note that the space is mandatory.

If you're familiar with roxygen2, you might wonder how this relates to `@export`. `Rcpp::export` controls whether a function is exported from C++ to R; `@export` controls whether a function is exported from a package and made available to the user.

You can embed R code in special C++ comment blocks. This is really convenient if you want to run some test code:

```
/**/ R
# This is R code
/**/
```

The R code is run with `source(echo = TRUE)` so you don't need to explicitly print output.

To compile the C++ code, use `sourceCpp("path/to/file.cpp")`. This will create the matching R functions and add them to your current session. Note that these functions can not be saved in a `.Rdata` file and reloaded in a later session; they must be recreated each time you restart R. For example, running `sourceCpp()` on the following file implements `mean` in C++ and then compares it to the built-in `mean()`:

```
#include <Rcpp.h>
using namespace Rcpp;

// [[Rcpp::export]]
double meanC(NumericVector x) {
```

```

int n = x.size();
double total = 0;

for(int i = 0; i < n; ++i) {
    total += x[i];
}
return total / n;
}

/*** R
library(microbenchmark)
x <- runif(1e5)
microbenchmark(
    mean(x),
    meanC(x)
)
*/

```

NB: if you run this code yourself, you'll notice that `meanC()` is much faster than the built-in `mean()`. This is because it trades numerical accuracy for speed.

For the remainder of this chapter C++ code will be presented stand-alone rather than wrapped in a call to `cppFunction`. If you want to try compiling and/or modifying the examples you should paste them into a C++ source file that includes the elements described above.

23.2.7 Exercises

With the basics of C++ in hand, it's now a great time to practice by reading and writing some simple C++ functions. For each of the following functions, read the code and figure out what the corresponding base R function is. You might not understand every part of the code yet, but you should be able to figure out the basics of what the function does.

```

double f1(NumericVector x) {
    int n = x.size();
    double y = 0;

    for(int i = 0; i < n; ++i) {
        y += x[i] / n;
    }
    return y;
}

```

```
}

NumericVector f2(NumericVector x) {
    int n = x.size();
    NumericVector out(n);

    out[0] = x[0];
    for(int i = 1; i < n; ++i) {
        out[i] = out[i - 1] + x[i];
    }
    return out;
}

bool f3(LogicalVector x) {
    int n = x.size();

    for(int i = 0; i < n; ++i) {
        if (x[i]) return true;
    }
    return false;
}

int f4(Function pred, List x) {
    int n = x.size();

    for(int i = 0; i < n; ++i) {
        LogicalVector res = pred(x[i]);
        if (res[0]) return i + 1;
    }
    return 0;
}

NumericVector f5(NumericVector x, NumericVector y) {
    int n = std::max(x.size(), y.size());
    NumericVector x1 = rep_len(x, n);
    NumericVector y1 = rep_len(y, n);

    NumericVector out(n);

    for (int i = 0; i < n; ++i) {
        out[i] = std::min(x1[i], y1[i]);
    }
}
```

```

    }

    return out;
}

```

To practice your function writing skills, convert the following functions into C++. For now, assume the inputs have no missing values.

1. `all()`
2. `cumprod()`, `cummin()`, `cummax()`.
3. `diff()`. Start by assuming lag 1, and then generalise for lag n .
4. `range`.
5. `var`. Read about the approaches you can take on wikipedia (http://en.wikipedia.org/wiki/Algorithms_for_calculating_variance). Whenever implementing a numerical algorithm, it's always good to check what is already known about the problem.

23.3 Attributes and other classes

You've already seen the basic vector classes (`IntegerVector`, `NumericVector`, `LogicalVector`, `CharacterVector`) and their scalar (`int`, `double`, `bool`, `String`) and matrix (`IntegerMatrix`, `NumericMatrix`, `LogicalMatrix`, `CharacterMatrix`) equivalents.

All R objects have attributes, which can be queried and modified with `.attr()`. Rcpp also provides `.names()` as an alias for the name attribute. The following code snippet illustrates these methods. Note the use of `::create()`, a *class* method. This allows you to create an R vector from C++ scalar values:

```

#include <Rcpp.h>
using namespace Rcpp;

// [[Rcpp::export]]
NumericVector attrs() {
  NumericVector out = NumericVector::create(1, 2, 3);

  out.names() = CharacterVector::create("a", "b", "c");
  out.attr("my-attr") = "my-value";
  out.attr("class") = "my-class";
}

```

```

    return out;
}

```

For S4 objects, `.slot()` plays a similar role to `.attr()`.

23.3.1 Lists and data frames

Rcpp also provides classes `List` and `DataFrame`, but they are more useful for output than input. This is because lists and data frames can contain arbitrary classes but C++ needs to know their classes in advance. If the list has known structure (e.g., it's an S3 object), you can extract the components and manually convert them to their C++ equivalents with `as()`. For example, the object created by `lm()`, the function that fits a linear model, is a list whose components are always of the same type. The following code illustrates how you might extract the mean percentage error (`mpe()`) of a linear model. This isn't a good example of when to use C++, because it's so easily implemented in R, but it shows how to work with an important S3 class. Note the use of `.inherits()` and the `stop()` to check that the object really is a linear model.

```

#include <Rcpp.h>
using namespace Rcpp;

// [[Rcpp::export]]
double mpe(List mod) {
  if (!mod.inherits("lm")) stop("Input must be a linear model");

  NumericVector resid = as<NumericVector>(mod["residuals"]);
  NumericVector fitted = as<NumericVector>(mod["fitted.values"]);

  int n = resid.size();
  double err = 0;
  for(int i = 0; i < n; ++i) {
    err += resid[i] / (fitted[i] + resid[i]);
  }
  return err / n;
}

mod <- lm(mpg ~ wt, data = mtcars)
mpe(mod)
#> [1] -0.0154

```

23.3.2 Functions

You can put R functions in an object of type `Function`. This makes calling an R function from C++ straightforward. We first define our C++ function:

```
#include <Rcpp.h>
using namespace Rcpp;

// [[Rcpp::export]]
RObject callWithOne(Function f) {
    return f(1);
}
```

Then call it from R:

```
callWithOne(function(x) x + 1)
#> [1] 2
callWithOne(paste)
#> [1] "1"
```

What type of object does an R function return? We don't know, so we use the catchall type `RObject`. An alternative is to return a `List`. For example, the following code is a basic implementation of `lapply` in C++:

```
#include <Rcpp.h>
using namespace Rcpp;

// [[Rcpp::export]]
List lapply1(List input, Function f) {
    int n = input.size();
    List out(n);

    for(int i = 0; i < n; i++) {
        out[i] = f(input[i]);
    }

    return out;
}
```

Calling R functions with positional arguments is obvious:

```
f("y", 1);
```

But to use named arguments, you need a special syntax:

```
f(_["x"] = "y", _["value"] = 1);
```

23.3.3 Other types

There are also classes for many more specialised language objects: `Environment`, `ComplexVector`, `RawVector`, `DottedPair`, `Language`, `Promise`, `Symbol`, `WeakReference`, and so on. These are beyond the scope of this chapter and won't be discussed further.

23.4 Missing values

If you're working with missing values, you need to know two things:

- how R's missing values behave in C++'s scalars (e.g., `double`).
- how to get and set missing values in vectors (e.g., `NumericVector`).

23.4.1 Scalars

The following code explores what happens when you take one of R's missing values, coerce it into a scalar, and then coerce back to an R vector. Note that this kind of experimentation is a useful way to figure out what any operation does.

```
#include <Rcpp.h>
using namespace Rcpp;

// [[Rcpp::export]]
List scalar_missings() {
  int int_s = NA_INTEGER;
  String chr_s = NA_STRING;
  bool lgl_s = NA_LOGICAL;
  double num_s = NA_REAL;

  return List::create(int_s, chr_s, lgl_s, num_s);
}

str(scalar_missings())
#> List of 4
#> $ : int NA
#> $ : chr NA
```

```
#> $ : logi TRUE
#> $ : num NA
```

With the exception of `bool`, things look pretty good here: all of the missing values have been preserved. However, as we'll see in the following sections, things are not quite as straightforward as they seem.

23.4.1.1 Integers

With integers, missing values are stored as the smallest integer. If you don't do anything to them, they'll be preserved. But, since C++ doesn't know that the smallest integer has this special behaviour, if you do anything to it you're likely to get an incorrect value: for example, `evalCpp('NA_INTEGER + 1')` gives `-2147483647`.

So if you want to work with missing values in integers, either use a length one `IntegerVector` or be very careful with your code.

23.4.1.2 Doubles

With doubles, you may be able to get away with ignoring missing values and working with NaNs (not a number). This is because R's NA is a special type of IEEE 754 floating point number NaN. So any logical expression that involves a NaN (or in C++, NAN) always evaluates as FALSE:

```
evalCpp("NAN == 1")
#> [1] FALSE
evalCpp("NAN < 1")
#> [1] FALSE
evalCpp("NAN > 1")
#> [1] FALSE
evalCpp("NAN == NAN")
#> [1] FALSE
```

But be careful when combining them with boolean values:

```
evalCpp("NAN && TRUE")
#> [1] TRUE
evalCpp("NAN || FALSE")
#> [1] TRUE
```

However, in numeric contexts NaNs will propagate NAs:

```
evalCpp("NAN + 1")
#> [1] NaN
evalCpp("NAN - 1")
#> [1] NaN
evalCpp("NAN / 1")
#> [1] NaN
evalCpp("NAN * 1")
#> [1] NaN
```

23.4.2 Strings

`String` is a scalar string class introduced by Rcpp, so it knows how to deal with missing values.

23.4.3 Boolean

While C++'s `bool` has two possible values (`true` or `false`), a logical vector in R has three (`TRUE`, `FALSE`, and `NA`). If you coerce a length 1 logical vector, make sure it doesn't contain any missing values otherwise they will be converted to `TRUE`.

23.4.4 Vectors

With vectors, you need to use a missing value specific to the type of vector, `NA_REAL`, `NA_INTEGER`, `NA_LOGICAL`, `NA_STRING`:

```
#include <Rcpp.h>
using namespace Rcpp;

// [[Rcpp::export]]
List missing_sampler() {
  return List::create(
    NumericVector::create(NA_REAL),
    IntegerVector::create(NA_INTEGER),
    LogicalVector::create(NA_LOGICAL),
    CharacterVector::create(NA_STRING));
}

str(missing_sampler())
#> List of 4
```

```
#> $ : num NA
#> $ : int NA
#> $ : logi NA
#> $ : chr NA
```

To check if a value in a vector is missing, use the class method `::is_na()`:

```
#include <Rcpp.h>
using namespace Rcpp;

// [[Rcpp::export]]
LogicalVector is_naC(NumericVector x) {
    int n = x.size();
    LogicalVector out(n);

    for (int i = 0; i < n; ++i) {
        out[i] = NumericVector::is_na(x[i]);
    }
    return out;
}

is_naC(c(NA, 5.4, 3.2, NA))
#> [1] TRUE FALSE FALSE TRUE
```

Another alternative is the sugar function `is_na()`, which takes a vector and returns a logical vector.

```
#include <Rcpp.h>
using namespace Rcpp;

// [[Rcpp::export]]
LogicalVector is_naC2(NumericVector x) {
    return is_na(x);
}

is_naC2(c(NA, 5.4, 3.2, NA))
#> [1] TRUE FALSE FALSE TRUE
```

23.4.5 Exercises

1. Rewrite any of the functions from the first exercise to deal with missing values. If `na.rm` is true, ignore the missing values. If `na.rm` is false, return a missing value if the input contains any missing values. Some good functions

to practice with are `min()`, `max()`, `range()`, `mean()`, and `var()`.

2. Rewrite `cumsum()` and `diff()` so they can handle missing values. Note that these functions have slightly more complicated behaviour.

23.5 Rcpp sugar

Rcpp provides a lot of syntactic “sugar” to ensure that C++ functions work very similarly to their R equivalents. In fact, Rcpp sugar makes it possible to write efficient C++ code that looks almost identical to its R equivalent. If there’s a sugar version of the function you’re interested in, you should use it: it’ll be both expressive and well tested. Sugar functions aren’t always faster than a handwritten equivalent, but they will get faster in the future as more time is spent on optimising Rcpp.

Sugar functions can be roughly broken down into

- arithmetic and logical operators
- logical summary functions
- vector views
- other useful functions

23.5.1 Arithmetic and logical operators

All the basic arithmetic and logical operators are vectorised: `+`, `*`, `-`, `/`, `pow`, `<`, `<=`, `>`, `>=`, `==`, `!=`, `!`. For example, we could use sugar to considerably simplify the implementation of `pdistC()`.

```
pdistR <- function(x, ys) {
  sqrt((x - ys) ^ 2)
}

#include <Rcpp.h>
using namespace Rcpp;

// [[Rcpp::export]]
NumericVector pdistC2(double x, NumericVector ys) {
  return sqrt(pow((x - ys), 2));
}
```

23.5.2 Logical summary functions

The sugar function `any()` and `all()` are fully lazy so that `any(x == 0)`, for example, might only need to evaluate one element of a vector, and return a special type that can be converted into a `bool` using `.is_true()`, `.is_false()`, or `.is_na()`. We could also use this sugar to write an efficient function to determine whether or not a numeric vector contains any missing values. To do this in R, we could use `any(is.na(x))`:

```
any_naR <- function(x) any(is.na(x))
```

However, this will do the same amount of work regardless of the location of the missing value. Here's the C++ implementation:

```
#include <Rcpp.h>
using namespace Rcpp;

// [[Rcpp::export]]
bool any_naC(NumericVector x) {
  return is_true(any(is_na(x)));
}

x0 <- runif(1e5)
x1 <- c(x0, NA)
x2 <- c(NA, x0)

microbenchmark(
  any_naR(x0), any_naC(x0),
  any_naR(x1), any_naC(x1),
  any_naR(x2), any_naC(x2)
)
#> Unit: microseconds
#>          expr      min       lq      mean    median       uq      max neval
#> any_naR(x0) 603.00 628.00 792.95 640.00 659.00 6,230.0    100
#> any_naC(x0) 487.00 493.00 503.69 503.00 511.00   537.0    100
#> any_naR(x1) 469.00 622.00 632.11 630.00 641.00   726.0    100
#> any_naC(x1) 487.00 490.00 516.53 502.00 511.00 1,700.0    100
#> any_naR(x2) 380.00 473.00 501.34 486.00 502.00 1,800.0    100
#> any_naC(x2)   1.98    3.28    6.03    4.54    6.38    97.2    100
```

23.5.3 Vector views

A number of helpful functions provide a “view” of a vector: `head()`, `tail()`, `rep_each()`, `rep_len()`, `rev()`, `seq_along()`, and `seq_len()`. In R these would all produce copies of the vector, but in Rcpp they simply point to the existing vector and override the subsetting operator (`[]`) to implement special behaviour. This makes them very efficient: for instance, `rep_len(x, 1e6)` does not have to make a million copies of `x`.

23.5.4 Other useful functions

Finally, there’s a grab bag of sugar functions that mimic frequently used R functions:

- Math functions: `abs()`, `acos()`, `asin()`, `atan()`, `beta()`, `ceil()`, `ceiling()`, `choose()`, `cos()`, `cosh()`, `digamma()`, `exp()`, `expm1()`, `factorial()`, `floor()`, `gamma()`, `lbeta()`, `lchoose()`, `lfactorial()`, `lgamma()`, `log()`, `log10()`, `log1p()`, `pentagamma()`, `psigamma()`, `round()`, `signif()`, `sin()`, `sinh()`, `sqrt()`, `tan()`, `tanh()`, `tetragamma()`, `trigamma()`, `trunc()`.
- Scalar summaries: `mean()`, `min()`, `max()`, `sum()`, `sd()`, and (for vectors) `var()`.
- Vector summaries: `cumsum()`, `diff()`, `pmin()`, and `pmax()`.
- Finding values: `match()`, `self_match()`, `which_max()`, `which_min()`.
- Dealing with duplicates: `duplicated()`, `unique()`.
- `d/q/p/r` for all standard distributions.

Finally, `noNA(x)` asserts that the vector `x` does not contain any missing values, and allows optimisation of some mathematical operations. For example, when computing the mean of a vector with no missing values, Rcpp doesn’t need to check each value is not missing when computing the sum and the length.

23.6 The STL

The real strength of C++ shows itself when you need to implement more complex algorithms. The standard template library (STL) provides a set of extremely useful data structures and algorithms. This section will explain some of the most important algorithms and data structures and point you in the right direction to

learn more. I can't teach you everything you need to know about the STL, but hopefully the examples will show you the power of the STL, and persuade you that it's useful to learn more.

If you need an algorithm or data structure that isn't implemented in STL, a good place to look is boost (<http://www.boost.org/doc/>). Installing boost on your computer is beyond the scope of this chapter, but once you have it installed, you can use boost data structures and algorithms by including the appropriate header file with (e.g.) `#include <boost/array.hpp>`.

23.6.1 Using iterators

Iterators are used extensively in the STL: many functions either accept or return iterators. They are the next step up from basic loops, abstracting away the details of the underlying data structure. Iterators have three main operators:

1. Advance with `++`.
2. Get the value they refer to, or **dereference**, with `*`.
3. Compare with `==`.

For example we could re-write our sum function using iterators:

```
#include <Rcpp.h>
using namespace Rcpp;

// [[Rcpp::export]]
double sum3(NumericVector x) {
    double total = 0;

    NumericVector::iterator it;
    for(it = x.begin(); it != x.end(); ++it) {
        total += *it;
    }
    return total;
}
```

The main changes are in the for loop:

- We start at `x.begin()` and loop until we get to `x.end()`. A small optimization is to store the value of the end iterator so we don't need to look it up each time. This only saves about 2 ns per iteration, so it's only important when the calculations in the loop are very simple.
- Instead of indexing into `x`, we use the dereference operator to get its current

value: `*it`.

- Notice the type of the iterator: `NumericVector::iterator`. Each vector type has its own iterator type: `LogicalVector::iterator`, `CharacterVector::iterator`, etc.

Iterators also allow us to use the C++ equivalents of the `apply` family of functions. For example, we could again rewrite `sum()` to use the `accumulate()` function, which takes a starting and an ending iterator, and adds up all the values in the vector. The third argument to `accumulate` gives the initial value: it's particularly important because this also determines the data type that `accumulate` uses (so we use `0.0` and not `0` so that `accumulate` uses a `double`, not an `int`). To use `accumulate()` we need to include the `<numeric>` header.

```
#include <numeric>
#include <Rcpp.h>
using namespace Rcpp;

// [[Rcpp::export]]
double sum4(NumericVector x) {
  return std::accumulate(x.begin(), x.end(), 0.0);
}
```

`accumulate()` (along with the other functions in `<numeric>`, like `adjacent_difference()`, `inner_product()`, and `partial_sum()`) is not that important in Rcpp because Rcpp sugar provides equivalents.

23.6.2 Algorithms

The `<algorithm>` header provides a large number of algorithms that work with iterators. A good reference is available at <http://www.cplusplus.com/reference/algorithm/>. For example, we could write a basic Rcpp version of `findInterval()` that takes two arguments a vector of values and a vector of breaks, and locates the bin that each `x` falls into. This shows off a few more advanced iterator features. Read the code below and see if you can figure out how it works.

```
#include <algorithm>
#include <Rcpp.h>
using namespace Rcpp;

// [[Rcpp::export]]
IntegerVector findInterval2(NumericVector x, NumericVector breaks) {
  IntegerVector out(x.size());
```

```

NumericVector::iterator it, pos;
IntegerVector::iterator out_it;

for(it = x.begin(), out_it = out.begin(); it != x.end();
    ++it, ++out_it) {
    pos = std::upper_bound(breaks.begin(), breaks.end(), *it);
    *out_it = std::distance(breaks.begin(), pos);
}

return out;
}

```

The key points are:

- We step through two iterators (input and output) simultaneously.
- We can assign into an dereferenced iterator (`out_it`) to change the values in `out`.
- `upper_bound()` returns an iterator. If we wanted the value of the `upper_bound()` we could dereference it; to figure out its location, we use the `distance()` function.
- Small note: if we want this function to be as fast as `findInterval()` in R (which uses handwritten C code), we need to compute the calls to `.begin()` and `.end()` once and save the results. This is easy, but it distracts from this example so it has been omitted. Making this change yields a function that's slightly faster than R's `findInterval()` function, but is about 1/10 of the code.

It's generally better to use algorithms from the STL than hand rolled loops. In *Effective STL*, Scott Meyers gives three reasons: efficiency, correctness, and maintainability. Algorithms from the STL are written by C++ experts to be extremely efficient, and they have been around for a long time so they are well tested. Using standard algorithms also makes the intent of your code more clear, helping to make it more readable and more maintainable.

23.6.3 Data structures

The STL provides a large set of data structures: `array`, `bitset`, `list`, `forward_list`, `map`, `multimap`, `multiset`, `priority_queue`, `queue`, `deque`, `set`, `stack`, `unordered_map`, `unordered_set`, `unordered_multimap`, `unordered_multiset`, and `vector`. The most important of these data structures are the `vector`, the

`unordered_set`, and the `unordered_map`. We'll focus on these three in this section, but using the others is similar: they just have different performance trade-offs. For example, the `deque` (pronounced "deck") has a very similar interface to vectors but a different underlying implementation that has different performance trade-offs. You may want to try them for your problem. A good reference for STL data structures is <http://www.cplusplus.com/reference/stl/> — I recommend you keep it open while working with the STL.

Rcpp knows how to convert from many STL data structures to their R equivalents, so you can return them from your functions without explicitly converting to R data structures.

23.6.4 Vectors

An STL vector is very similar to an R vector, except that it grows efficiently. This makes vectors appropriate to use when you don't know in advance how big the output will be. Vectors are templated, which means that you need to specify the type of object the vector will contain when you create it: `vector<int>`, `vector<bool>`, `vector<double>`, `vector<String>`. You can access individual elements of a vector using the standard `[]` notation, and you can add a new element to the end of the vector using `.push_back()`. If you have some idea in advance how big the vector will be, you can use `.reserve()` to allocate sufficient storage.

The following code implements run length encoding (`rle()`). It produces two vectors of output: a vector of values, and a vector `lengths` giving how many times each element is repeated. It works by looping through the input vector `x` comparing each value to the previous: if it's the same, then it increments the last value in `lengths`; if it's different, it adds the value to the end of `values`, and sets the corresponding length to 1.

```
#include <Rcpp.h>
using namespace Rcpp;

// [[Rcpp::export]]
List rleC(NumericVector x) {
  std::vector<int> lengths;
  std::vector<double> values;

  // Initialise first value
  int i = 0;
  double prev = x[0];
  lengths.push_back(1);
  values.push_back(prev);

  for (int j = 1; j < x.size(); j++) {
    if (x[j] == prev) {
      lengths.back()++;
    } else {
      values.push_back(x[j]);
      lengths.push_back(1);
      prev = x[j];
    }
  }
}
```

```

values.push_back(prev);
lengths.push_back(1);

NumericVector::iterator it;
for(it = x.begin() + 1; it != x.end(); ++it) {
  if (prev == *it) {
    lengths[i]++;
  } else {
    values.push_back(*it);
    lengths.push_back(1);

    i++;
    prev = *it;
  }
}

return List::create(
  _["lengths"] = lengths,
  _["values"] = values
);
}

```

(An alternative implementation would be to replace `i` with the iterator `lengths.rbegin()` which always points to the last element of the vector. You might want to try implementing that yourself.)

Other methods of a vector are described at <http://www.cplusplus.com/reference/vector/vector/>.

23.6.5 Sets

Sets maintain a unique set of values, and can efficiently tell if you've seen a value before. They are useful for problems that involve duplicates or unique values (like `unique`, `duplicated`, or `in`). C++ provides both ordered (`std::set`) and unordered sets (`std::unordered_set`), depending on whether or not order matters for you. Unordered sets tend to be much faster (because they use a hash table internally rather than a tree), so even if you need an ordered set, you should consider using an unordered set and then sorting the output. Like vectors, sets are templated, so you need to request the appropriate type of set for your purpose: `unordered_set<int>`, `unordered_set<bool>`, etc. More details are available at <http://www.cplusplus.com/reference/set/set/> and <http://www>.

cplusplus.com/reference/unordered_set/unordered_set/.

The following function uses an unordered set to implement an equivalent to `duplicated()` for integer vectors. Note the use of `seen.insert(x[i]).second`. `insert()` returns a pair, the `.first` value is an iterator that points to element and the `.second` value is a boolean that's true if the value was a new addition to the set.

```
// [[Rcpp::plugins(cpp11)]]
#include <Rcpp.h>
#include <unordered_set>
using namespace Rcpp;

// [[Rcpp::export]]
LogicalVector duplicatedC(IntegerVector x) {
  std::unordered_set<int> seen;
  int n = x.size();
  LogicalVector out(n);

  for (int i = 0; i < n; ++i) {
    out[i] = !seen.insert(x[i]).second;
  }

  return out;
}
```

Note that unordered sets are only available in C++ 11, which means we need to use the `cpp11` plugin, `[[Rcpp::plugins(cpp11)]]`.

23.6.6 Map

A map is similar to a set, but instead of storing presence or absence, it can store additional data. It's useful for functions like `table()` or `match()` that need to look up a value. As with sets, there are ordered (`std::map`) and unordered (`std::unordered_map`) versions. Since maps have a value and a key, you need to specify both types when initialising a map: `map<double, int>`, `unordered_map<int, double>`, and so on. The following example shows how you could use a map to implement `table()` for numeric vectors:

```
#include <Rcpp.h>
using namespace Rcpp;

// [[Rcpp::export]]
```

```
std::map<double, int> tableC(NumericVector x) {
  std::map<double, int> counts;

  int n = x.size();
  for (int i = 0; i < n; i++) {
    counts[x[i]]++;
  }

  return counts;
}
```

Note that unordered maps are only available in C++ 11, so to use them, you'll again need `[[Rcpp::plugins(cpp11)]]`.

23.6.7 Exercises

To practice using the STL algorithms and data structures, implement the following using R functions in C++, using the hints provided:

1. `median.default()` using `partial_sort`.
2. `%in%` using `unordered_set` and the `find()` or `count()` methods.
3. `unique()` using an `unordered_set` (challenge: do it in one line!).
4. `min()` using `std::min()`, or `max()` using `std::max()`.
5. `which.min()` using `min_element`, or `which.max()` using `max_element`.
6. `setdiff()`, `union()`, and `intersect()` for integers using sorted ranges and `set_union`, `set_intersection` and `set_difference`.

23.7 Case studies

The following case studies illustrate some real life uses of C++ to replace slow R code.

23.7.1 Gibbs sampler

The following case study updates an example blogged about (<http://dirk.eddelbuettel.com/blog/2011/07/14/>) by Dirk Eddelbuettel, illustrating the conversion of a Gibbs sampler in R to C++. The R and C++ code shown below

is very similar (it only took a few minutes to convert the R version to the C++ version), but runs about 20 times faster on my computer. Dirk's blog post also shows another way to make it even faster: using the faster random number generator functions in GSL (easily accessible from R through the `RcppGSL` package) can make it another 2–3x faster.

The R code is as follows:

```
gibbs_r <- function(N, thin) {
  mat <- matrix(nrow = N, ncol = 2)
  x <- y <- 0

  for (i in 1:N) {
    for (j in 1:thin) {
      x <- rgamma(1, 3, y * y + 4)
      y <- rnorm(1, 1 / (x + 1), 1 / sqrt(2 * (x + 1)))
    }
    mat[i, ] <- c(x, y)
  }
  mat
}
```

This is straightforward to convert to C++. We:

- add type declarations to all variables
- use `(` instead of `[` to index into the matrix
- subscript the results of `rgamma` and `rnorm` to convert from a vector into a scalar

```
#include <Rcpp.h>
using namespace Rcpp;

// [[Rcpp::export]]
NumericMatrix gibbs_cpp(int N, int thin) {
  NumericMatrix mat(N, 2);
  double x = 0, y = 0;

  for(int i = 0; i < N; i++) {
    for(int j = 0; j < thin; j++) {
      x = rgamma(1, 3, 1 / (y * y + 4))[0];
      y = rnorm(1, 1 / (x + 1), 1 / sqrt(2 * (x + 1)))[0];
    }
    mat(i, 0) = x;
```

```

        mat(i, 1) = y;
    }

    return(mat);
}

```

Benchmarking the two implementations yields:

```

microbenchmark(
  gibbs_r(100, 10),
  gibbs_cpp(100, 10)
)
#> Unit: microseconds
#>          expr     min      lq    mean   median      uq     max neval
#>  gibbs_r(100, 10) 5,690 5,770 6703  5,820 5,980 16,600   100
#>  gibbs_cpp(100, 10)   306    336   367     352    369   1,730   100

```

23.7.2 R vectorisation vs. C++ vectorisation

This example is adapted from “Rcpp is smoking fast for agent-based models in data frames” (<https://gweissman.github.io/babelgraph/blog/2017/06/15/rcpp-is-smoking-fast-for-agent-based-models-in-data-frames.html>). The challenge is to predict a model response from three inputs. The basic R version of the predictor looks like:

```

vacc1a <- function(age, female, ily) {
  p <- 0.25 + 0.3 * 1 / (1 - exp(0.04 * age)) + 0.1 * ily
  p <- p * if (female) 1.25 else 0.75
  p <- max(0, p)
  p <- min(1, p)
  p
}

```

We want to be able to apply this function to many inputs, so we might write a vector-input version using a for loop.

```

vacc1 <- function(age, female, ily) {
  n <- length(age)
  out <- numeric(n)
  for (i in seq_len(n)) {
    out[i] <- vacc1a(age[i], female[i], ily[i])
  }
}

```

```
    out
}
```

If you're familiar with R, you'll have a gut feeling that this will be slow, and indeed it is. There are two ways we could attack this problem. If you have a good R vocabulary, you might immediately see how to vectorise the function (using `ifelse()`, `pmin()`, and `pmax()`). Alternatively, we could rewrite `vacc1a()` and `vacc1()` in C++, using our knowledge that loops and function calls have much lower overhead in C++.

Either approach is fairly straightforward. In R:

```
vacc2 <- function(age, female, ily) {
  p <- 0.25 + 0.3 * 1 / (1 - exp(0.04 * age)) + 0.1 * ily
  p <- p * ifelse(female, 1.25, 0.75)
  p <- pmax(0, p)
  p <- pmin(1, p)
  p
}
```

(If you've worked R a lot you might recognise some potential bottlenecks in this code: `ifelse`, `pmin`, and `pmax` are known to be slow, and could be replaced with `p * 0.75 + p * 0.5 * female`, `p[p < 0] <- 0`, `p[p > 1] <- 1`. You might want to try timing those variations yourself.)

Or in C++:

```
#include <Rcpp.h>
using namespace Rcpp;

double vacc3a(double age, bool female, bool ily){
  double p = 0.25 + 0.3 * 1 / (1 - exp(0.04 * age)) + 0.1 * ily;
  p = p * (female ? 1.25 : 0.75);
  p = std::max(p, 0.0);
  p = std::min(p, 1.0);
  return p;
}

// [[Rcpp::export]]
NumericVector vacc3(NumericVector age, LogicalVector female,
                    LogicalVector ily) {
  int n = age.size();
  NumericVector out(n);
```

```

    for(int i = 0; i < n; ++i) {
        out[i] = vacc3a(age[i], female[i], ily[i]);
    }

    return out;
}

```

We next generate some sample data, and check that all three versions return the same values:

```

n <- 1000
age <- rnorm(n, mean = 50, sd = 10)
female <- sample(c(T, F), n, rep = TRUE)
ily <- sample(c(T, F), n, prob = c(0.8, 0.2), rep = TRUE)

stopifnot(
    all.equal(vacc1(age, female, ily), vacc2(age, female, ily)),
    all.equal(vacc1(age, female, ily), vacc3(age, female, ily))
)

```

The original blog post forgot to do this, and introduced a bug in the C++ version: it used 0.004 instead of 0.04. Finally, we can benchmark our three approaches:

```

microbenchmark(
    vacc1 = vacc1(age, female, ily),
    vacc2 = vacc2(age, female, ily),
    vacc3 = vacc3(age, female, ily)
)
#> Unit: microseconds
#>      expr      min       lq     mean   median      uq     max neval
#>  vacc1 1,730.0 1,870.0 2095.7 1,960.0 2,030.0 5,760    100
#>  vacc2   116.0   129.0   228.0   155.0   187.0  6,490    100
#>  vacc3    30.3    32.5    52.9    38.3   43.1  1,410    100

```

Not surprisingly, our original approach with loops is very slow. Vectorising in R gives a huge speedup, and we can eke out even more performance (~10x) with the C++ loop. I was a little surprised that the C++ was so much faster, but it is because the R version has to create 11 vectors to store intermediate results, where the C++ code only needs to create 1.

23.8 Using Rcpp in a package

The same C++ code that is used with `sourceCpp()` can also be bundled into a package. There are several benefits of moving code from a stand-alone C++ source file to a package:

1. Your code can be made available to users without C++ development tools.
2. Multiple source files and their dependencies are handled automatically by the R package build system.
3. Packages provide additional infrastructure for testing, documentation, and consistency.

To add `Rcpp` to an existing package, you put your C++ files in the `src/` directory and modify/create the following configuration files:

- In `DESCRIPTION` add

```
LinkingTo: Rcpp
Imports: Rcpp
```

- Make sure your `NAMESPACE` includes:

```
useDynLib(mypackage)
importFrom(Rcpp, sourceCpp)
```

We need to import something (anything) from `Rcpp` so that internal `Rcpp` code is properly loaded. This is a bug in R and hopefully will be fixed in the future.

To generate a new `Rcpp` package that includes a simple “hello world” function you can use `Rcpp.package.skeleton()`:

```
Rcpp.package.skeleton("NewPackage", attributes = TRUE)
```

To generate a package based on C++ files that you’ve been using with `sourceCpp()`, use the `cpp_files` parameter:

```
Rcpp.package.skeleton("NewPackage", example_code = FALSE,
                      cpp_files = c("convolve.cpp"))
```

Before building the package, you’ll need to run `Rcpp::compileAttributes()`. This function scans the C++ files for `Rcpp::export` attributes and generates the code required to make the functions available in R. Re-run `compileAttributes()` whenever functions are added, removed, or have their signatures changed. This is done automatically by the `devtools` package and by Rstudio.

For more details see the Rcpp package vignette, `vignette("Rcpp-package")`.

23.9 Learning more

This chapter has only touched on a small part of Rcpp, giving you the basic tools to rewrite poorly performing R code in C++. The Rcpp book (<http://www.rcpp.org/book>) is the best reference to learn more about Rcpp. As noted, Rcpp has many other capabilities that make it easy to interface R to existing C++ code, including:

- Additional features of attributes including specifying default arguments, linking in external C++ dependencies, and exporting C++ interfaces from packages. These features and more are covered in the Rcpp attributes vignette, `vignette("Rcpp-attributes")`.
- Automatically creating wrappers between C++ data structures and R data structures, including mapping C++ classes to reference classes. A good introduction to this topic is Rcpp modules vignette, `vignette("Rcpp-modules")`
- The Rcpp quick reference guide, `vignette("Rcpp-quickref")`, contains a useful summary of Rcpp classes and common programming idioms.

I strongly recommend keeping an eye on the Rcpp homepage (<http://www.rcpp.org>) and Dirk's Rcpp page (<http://dirk.eddelbuettel.com/code/rcpp.html>) as well as signing up for the Rcpp mailing list (<http://lists.r-forge.r-project.org/cgi-bin/mailman/listinfo/rcpp-devel>). Rcpp is still under active development, and is getting better with every release.

Other resources I've found helpful in learning C++ are:

- *Effective C++* (<http://amzn.com/0321334876?tag=devtools-20>) and *Effective STL* (<http://amzn.com/0201749629?tag=devtools-20>) by Scott Meyers.
- *C++ Annotations* (<http://www.icce.rug.nl/documents/cplusplus/cplusplus.html>), aimed at “knowledgeable users of C (or any other language using a C-like grammar, like Perl or Java) who would like to know more about, or make the transition to, C++”.
- *Algorithm Libraries* (<http://www.cs.helsinki.fi/u/tpkarkka/alglib/k06/>), which provides a more technical, but still concise, description of important STL concepts. (Follow the links under notes).

Writing performance code may also require you to rethink your basic approach: a solid understanding of basic data structures and algorithms is very helpful here. That's beyond the scope of this book, but I'd suggest the *Algorithm Design Manual* (<http://amzn.com/0387948600?tag=devtools-20>), MIT's *Introduction to Algorithms* (<http://ocw.mit.edu/courses/electrical-engineering-and-computer-science/6-046j-introduction-to-algorithms-sma-5503-fall-2005/>), *Algorithms* by Robert Sedgewick and Kevin Wayne which has a free online textbook (<http://algs4.cs.princeton.edu/home/>) and a matching coursera course (<https://www.coursera.org/course/algs4partI>).

23.10 Acknowledgments

I'd like to thank the Rcpp-mailing list for many helpful conversations, particularly Romain Francois and Dirk Eddelbuettel who have not only provided detailed answers to many of my questions, but have been incredibly responsive at improving Rcpp. This chapter would not have been possible without JJ Allaire; he encouraged me to learn C++ and then answered many of my dumb questions along the way.

References

- Abelson, Harold, Gerald Jay Sussman, and Julie Sussman. 1996. *Structure and Interpretation of Computer Programs*. MIT Press.
- Bache, Stefan Milton, and Hadley Wickham. 2014. *Magrittr: A Forward-Pipe Operator for R*. <http://magrittr.tidyverse.org/>.
- Bates, Douglas, and Martin Maechler. 2018. “Matrix: Sparse and Dense Matrix Classes and Methods.” <https://CRAN.R-project.org/package=Matrix>.
- Bawden, Alan. 1999. “Quasiquotation in Lisp.” In *PEPM '99*, 4–12. <http://repository.readscheme.org/ftp/papers/pepm99/bawden.pdf>.
- Bengtsson, Henrik. 2003. “The R.oo Package - Object-Oriented Programming with References Using Standard R Code.” In *Proceedings of the 3rd International Workshop on Distributed Statistical Computing (Dsc 2003)*, edited by Kurt Hornik, Friedrich Leisch, and Achim Zeileis. Vienna, Austria: <https://www.r-project.org/conferences/DSC-2003/Proceedings/>. <https://www.r-project.org/conferences/DSC-2003/Proceedings/Bengtsson.pdf>.
- Chambers, John M. 1998. *Programming with Data: A Guide to the S Language*. Springer Science & Business Media.
- . 2008. *Software for Data Analysis: Programming with R*. Springer.
- . 2014. “Object-Oriented Programming, Functional Programming and R.” *Statistical Science* 29 (2). Institute of Mathematical Statistics:167–80. https://projecteuclid.org/download/pdfview_1/euclid.ss/1408368569.
- . 2016. *Extending R*. CRC Press.
- Chambers, John M, and Trevor J Hastie. 1992. *Statistical Models in S*. Wadsworth & Brooks/Cole Advanced Books & Software.
- Chang, Winston. 2017. *R6: Classes with Reference Semantics*. <https://CRAN.R-project.org/package=R6>.

- Fowler, Martin. 2010. *Domain-Specific Languages*. Pearson Education. <http://amzn.com/0321712943>.
- Grolemund, Garrett, and Hadley Wickham. 2011. “Dates and Times Made Easy with lubridate.” *Journal of Statistical Software* 40 (3):1–25. <http://www.jstatsoft.org/v40/i03/>.
- Grothendieck, Gabor, Louis Kates, and Thomas Petzoldt. 2016. *Proto: Prototype Object-Based Programming*. <https://CRAN.R-project.org/package=proto>.
- Henry, Lionel, and Hadley Wickham. 2018. *Rlang: Functions for Base Types and Core R and 'Tidyverse' Features*. <https://rlang.r-lib.org>.
- Hester, Jim. 2018. *Bench: High Precision Timing of R Expressions*. <http://bench.r-lib.org/>.
- Hunt, Andrew, and David Thomas. 1990. *The Pragmatic Programmer*. Addison Wesley.
- Lumley, Thomas. 2001. “Programmer’s Niche: Macros in R.” *R News* 1 (3):11–13. https://www.r-project.org/doc/Rnews/Rnews_2001-3.pdf.
- Müller, Kirill, and Hadley Wickham. 2018. *Tibble: Simple Data Frames*. <https://CRAN.R-project.org/package=tibble>.
- R Core Team. 2018a. “R Internals.” *R Foundation for Statistical Computing*. <https://cran.r-project.org/doc/manuals/r-devel/R-exts.html>.
- . 2018b. “Writing R Extensions.” *R Foundation for Statistical Computing*. <https://cran.r-project.org/doc/manuals/r-devel/R-ints.html>.
- Teator, Nathan. 2018. *Zeallot: Multiple, Unpacking, and Destructuring Assignment*. <https://CRAN.R-project.org/package=zeallot>.
- Van-Roy, Peter, and Seif Haridi. 2004. *Concepts, Techniques, and Models of Computer Programming*. MIT press.
- Wickham, Hadley. 2011. “Mutatr: Mutable Objects for R.” *Computational Statistics* 26 (3):405–18. <https://doi.org/10.1007/s00180-011-0235-7>.
- . 2018. *Forcats: Tools for Working with Categorical Variables (Factors)*. <http://forcats.tidyverse.org>.

Index

- ..., 120
- .Data, 356
- .Primitive, 105
- <-, 248, 512
- [, 81, 514
- [[, 87
- \$, 89
- %%, 131
- ` , 30, 129
- abstract syntax tree, 380
- alternative implementations, 517
- anaphoric functions, 439
- anonymous functions, 103
- apply(), 239
- arrays, 54
 - list-arrays, 64
 - subsetting, 83
- as.data.frame(), 73
- as_tibble(), 73
- assign(), 144
- assignment, 29, 125
 - replacement functions, 132
 - subassignment,
- 92
- atomic vectors, 48
 - subsetting, 81
- attach(), 263
- attr(), 52
- attributes, 52
 - class, 288, 298
 - in C++, 562
 - names, 53, 56
- attributes(), 52
- avoiding copies, 543
- backticks, *see* `
- base types
 - implicit class, 316
- bindings, 29
 - active, 145
 - delayed, 145
- body(), 104
- Boolean algebra, 98
- bootstrapping generator, 258
- bootstrapping, 94, 538
- bottlenecks, 522
- Box-Cox transformation, 257
- breakpoints, 502
- browser(), 502
- bugs, 496
- byte-code compiler, 544
- c(), 48
- C++, 551
- call stack, 498, 502
- calls, 387
- class(), 298
- classes
 - S3, 298
- closures, *see* functions
- environment, 158
- scoping, 110
- coercion, 50
- compiler, 544
- conditions
 - custom, 185
 - handling, 176
 - objects, 177
 - signalling, 169
- constants, 385
- contributors, 15
- copy-on-modify exceptions, 248
- cppFunction(), 553
- data frames, 65
 - in C++, 563
- list-column, 73

matrix-column, 74
 remove columns, 96
 subsetting, 84
data.frame(), 67
debug(), 502
 debugger, interactive, 499
 debugging, 496
 C code, 504
 messages, 503
 warnings, 503
 deferred evaluation, 518
delay_by(), 274
 dictionaries, 164
diff(), 536
do.call(), 135
 dot-dot-dot, 120
dot_every(), 274
drop = FALSE, 86
dump.frames(), 501
 dynamic scoping, 160
 ellipsis, 120
env_bind(), 263
 environments, 137
 calling, 160
 creating, 139
 empty, 142
 execution, 155
 function, 152
 of a function, 104
 errors
 catching, 176
 throwing, 169
 escaping, 476
exists(), 144
 expression vector, 406
expression(), 406
 factors, 57
 FastR, 518
fexprs, 408
 Fibonacci series, 272
find_assign(), 400
findGlobals(), 112
findInterval(), 573
 fitting many models, 271
 fold, 231
 for loops, 207
force(), 114
formals(), 104
 function
 variadic, 120
 function factories, 243
 function operators, 267
 functional programming, 203
 functionals, 207
 functions, 101
 anaphoric, 439
 anonymous, 103
 arguments, 130
 body, 104
 default values, 117
 environment, 104
 environments, 150
 formals, 104
 in C++, 564
 infix, 131
 invisible results, 124
 lazy evaluation, 114
 predicate, *see* predicates
 primitive, *see* primitive functions
 replacement, 132
 return value, 123
 garbage collector, 44
gc(), 44
 generics
 S4, 345
get(), 144
 Gibbs sampler, 579
 group generics, 317
 handler
 exit, 126
 handlers
 calling, 181
 exiting, 179
 hashmaps, 164
 help, 15
 HTML, 474
I(), 73
ifelse(), 515
imap(), 226
 implicit class, 316
 improving performance, 530
 strategy, 531
 infix functions, 131
integrate(), 241
invisible(), 124
is.data.frame(), 73
is.object(), 288
is_tibble(), 73
 iterators, 572

language definition, 506
`lapply()`, 209
LaTeX, 483
lazy evaluation, 114
 overhead of, 513
lexical scoping, 108
line profiling, 524
list-arrays, 64
lists, 61
 in C++, 563
 removing an element, 92
 subsetting, 83, 87
local(), 445
lookup tables, 93
loops
 avoiding copies, 41
 common patterns, 226
macros, 408
`Map()`, 227
`map()`, 209
`map2()`, 222
`mapply()`, 227
maps, 577
`match()`, 93
matching & merging, 93
matrices, *see* arrays
matrix algebra, 541
maximum likelihood, 259
`mclapply()`, 548
memoisation, 272
`memoise()`, 272
memory
 profiling, 527
methods
 cost of dispatch, 510
 cost of dispatch, avoiding, 534
 S4, 345
`microbenchmark()`, 531
microbenchmarks, 507
missing argument, 405
missing values
 in C++, 565
`missing()`, 117
`mode()`, 288, 289
`modify()`, 221
multicore, 547
`NA`, 48
names
 cost of lookup, 511
 in C++, 562
`names()`, 53
namespaces, 153
non-standard evaluation, 369
non-syntactic names, 30
`obj_size`, 38
object-oriented programming, 281
`object_size`, 38
objects
 S3, *see* S3
`on.exit()`, 126, 181
`optim()`, 259
optimisation, 521
`optimise()`, 241, 259
`options(error)`, 500
`order()`, 95
pairlists, 404
parallel computing, 547
`parLapply()`, 548
`parse()`, 406
`paste()`, 543
`pause()`, 523
performance, 505
 improving, 530
 measuring, 523
`pmap()`, 227
`pmax()`, 515
`pmin()`, 515
point-free programming, 108
`pqr`, 517
predicates, 236
primitive functions, 105
profiling, 523
promises, 116
R-core, 514
`Rcpp`, 551
 in a package, 583
`read_delim()`, 527
`recover()`, 501
recursion
 over ASTs, 396
 over environments, 147
`reduce()`, 231
Renjin, 517
replacement functions, 132
reserved names, 30
`return()`, 123
`rho`, 518

Riposte, 518
rm(), 44, 144
RProf(), 524
S3, 293
 classes, 298
 group generics, 317
 new generic, 305
 vectors, 56
S4
 generics, 345
 methods, 345
 subsetting, 91
safely(), 269
sample(), 94
 sampling, 94
sapply(), 130
 scalars, 49
 scoping
 dynamic, 160
 lexical, *see* lexical scoping
 search path, 150
search(), 150
 searching, 532
 set algebra, 98
setBreakpoint(), 502
setClass(), 340
setGeneric(), 345
setMethod(), 346
setNames(), 53
 sets, 577
 sorting, 95
 source(), 447
 sourceCpp(), 559
standard template library, 572
standardGeneric(), 345
standardise_call(), 388
stopifnot(), 531
 string pool, 37
stringsAsFactors, 57, 67
structure(), 52
subset(), 97
 subsetting, 79
 arrays, 83
 atomic vectors, 81
 data frames, 84
 lists, 83, 87
 out of bounds, 90
 performance, 514
 preserving, 86
 S4, 91
 simplifying, 86
 subassignment, 92
 with character vectors, 82
 with logical vectors, 81, 97
 with NA & NULL, 90
 with negative integers, 81
 with positive integers, 81
suppressMessages(), 174
suppressWarnings(), 174
 symbol, 405
 symbols, 386
t.test(), 545
 tacit programming, 108
 thunks, *see* promises
tibble(), 67
 tibbles, 65
trace(), 502
traceback(), 498
try(), 174
tryCatch(), 179
typeof(), 49, 289
uniroot(), 241
UseMethod(), 305
varargs, 120
 vectorising code, 540
 vectors
 atomic, *see* atomic vectors
 in C++, 575
 lists, *see* lists
walk(), 224
walk2(), 224
 website, 18
which(), 98
with(), 263