C and Data Structures - a well-structured approach

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Preface

This textbook introduces data structures to 1^{st} year computer science students through the medium of the C programming language. It supports delivery of the 3^{rd} quarter of the University of Oregon's introductory computer science sequence.

Why C?

You may ask "Why C?" for such a course in the 21^{st} century? The first two quarters of the Oregon introductory sequence cover computational thinking and object-oriented programming using Python as the language of artifact expression. An earlier version of the data structure course used Java as the medium through which to convey basic data structure concepts.

When students who had completed the Java-based course were finally confronted with designing and constructing moderately-sized application and system programs, we discovered that they were insufficiently exposed to the actual mechanics involved in building such data structures for use in anger.

The burgeoning growth of the Internet of Things, and the prevalence of programming these devices in C and C++, provide further impetus to introduce students to programming in these languages early in their academic careers.

General approach of the text

The foci of this text are three-fold:

- introduce the essential aspects of C to enable students to construct well-engineered data structure implementations; not all of the language elements are covered, so the interested student is referred to the many excellent texts on C; our preference is Brian W. Kernighan and Dennis M. Ritchie, *The C Programming Language*, 2nd edition, Prentice Hall, ISBN 978-0131103627;
- introduce the concept of Abstract Data Types, and a well-structured approach to building ADTs in C that provides a bridge to similar usage in C++; and

- introduce data types of increasing complexity, implemented as ADTs; of particular note is a section on well-designed hash functions for use in hash tables.

Questions to aid self-study are provided in each section of the text, and there are suggested programming exercises at the end of each chapter.

All of the examples in the text are taken directly from a 64-bit Debian Linux[1] image running under Oracle's VirtualBox[2] virtualization environment. The Debian Linux image described in the report provided by your instructor provides instructions for students to install VirtualBox and to access and install a 64-bit Debian Linux image to run in that environment.

In gratitude

Three books produced by Bell Laboratories colleagues were seminal in my acquisition and exploitation of programming languages, programming concepts and UNIX™:

- Brian W. Kernighan and P.J. Plauger. 1976. *Software Tools*. Addison-Wesley Longman Publishing Co., Inc., Boston, MA, USA. ISBN:020103669X.
- Brian W. Kernighan and Dennis M. Ritchie. 1988. *The C Programming Language (2nd ed.)*. Prentice Hall Professional Technical Reference. ISBN:0131103709.
- Brian W. Kernighan and Rob Pike. 1984. *The UNIX Programming Environment*. Prentice Hall Professional Technical Reference. ISBN:013937681X.

I am particularly indebted to Brian Kernighan for his excellent writing style in these books, as it made it particularly easy to rapidly internalize the material. I have tried to emulate that style in this textbook.

I would also like to thank the support of my colleagues in the Department of Computer and Information Science at the University of Oregon for their input to the course syllabus, and for their careful review of drafts of the text.

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[1]https://www.debian.org/
[2]https://www.virtualbox.org/

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Chapter 1

Introduction

Computer Science is an interesting mix of mathematics, logic, problem solving, and engineering. This book is focused on the mathematics and engineering aspects, in that it addresses data structures and their implementation.

There has been significant emphasis upon "coding" from both political and commercial perspectives. Code academies, days of code, coder dojos, and many other activities/events have sprung up to entice people, young and old, to actively participate in the computer science revolution. While such activities can give an individual an idea of the power of being able to "code", this is very different from being a computer scientist.

A computer scientist must think computationally, as initially defined by Jeannette M. Wing: "Thinking like a computer scientist means more than being able to program a computer. It requires thinking at multiple levels of abstraction."[1] One particular abstraction level requires the computer scientist to select the most efficient data structure to solve a particular problem. This selection usually involves understanding the inherent space and time complexity of each possible data structure, and then determining the *best* data structure for the problem.

This book focuses on basic data structures, and their space and time complexities. It also attempts to provide you with a rationale for making choices among competing data structures to address a particular problem. Besides familiarizing you with the complexity of these data structures, this course is particularly focused on showing you how to implement the data structures, enabling you to see for yourself how the space and time complexities manifest themselves.

[1] Jeannette M. Wing, "Computational Thinking", *Communications of the ACM*, Vol. 49, No. 3, pp. 33-35, March 2006.

1.1 Assumptions

This book assumes that you have had an introduction to computational thinking, and have learned how to realize designs to solve problems using an object-oriented language; those who have completed the prior two courses in the UO introductory sequence will have done so in the Python programming language. It also assumes that you have learned to use the object-oriented features of that language to create abstractions for use in your solutions. Finally, it assumes that you have done most, if not all, of your object-oriented programming using an Integrated Development Environment (IDE); for Python, this would likely be IDLE[2] or PyCharm[3].

1.2 Outline for the book

1.2.1 A beginner's guide to Linux

In order to achieve the goals of the course, we must introduce you to two basic realities for computer scientists:

- the Linux operating environment, and its program development tools; and
- the C programming language.

Thus, the first section of the textbook will focus on the Linux operating environment. It will present the command line environment provided by the shell, some of the useful standard commands distributed in the Linux environment, an introduction to the file system provided by Linux, and the "pipes and filters" philosophy behind standard Linux programs.

1.2.2 The C programming language

Programs written in C must be compiled and linked to be executed. This section will first describe the edit, compile, link, execute program development cycle to be used with C. As part of this discussion, you are introduced to `gcc`, the program we use to compile C source files and to link the resulting object files into executable image files that can be invoked from `bash`.

Three simple example programs are then presented that show how to perform simple output, process command arguments, and how to perform line at a time input.

Then the discussion turns to:

- types, operators, and expressions;
- control flow;

[2] `https://en.wikipedia.org/wiki/IDLE`
[3] `https://en.wikipedia.org/wiki/PyCharm`

- functions and program structure;
- pointers and arrays;
- structures; and
- input and output.

The section finishes with some example programs, showing how to build them using `make` and `gcc`, and how to use `gdb` and `valgrind` to debug your logic and track down heap memory problems.

1.2.3 Abstract data types

C is *not* an object-oriented language. Prior to the invention of OO languages, there was significant research and development around Abstract Data Types (ADTs); an abstract data type (ADT) is a mathematical model for a data type, defined by its behavior from the point of view of a user of the data, specifically in terms of possible values, possible operations on data of this type, and the behavior of these operations - in other words, describes **what** it can do, not how to do it. ADTs were first proposed by Barbara Liskov and Stephen N. Zilles in 1974, as part of the development of the CLU language.[4] One particular implication of this approach is that there can be several different implementations that meet the behavior requirements specified in an ADT's interface.

Data structures are concrete representations of data, and are the point of view of an implementer, not a user. Since this book is focused on both interface *and* implementation, this section focuses on a well-structured C implementation approach for defining the interface to an ADT, and programming (one or more) implementations of an ADT that incorporate information hiding and method dispatch. This implementation approach also introduces a standard mechanism to address the lack of garbage collection in C.

Several examples of this approach are demonstrated, concluding with an ADT for arraylists; an ADT for mutable strings is provided in Appendix C.

1.2.4 Data Structures

This section starts off with a discussion of how to measure the runtime performance of a Linux program and how to instrument C source code to measure the runtime performance of a selected portion of a program. We then move on to a discussion of complexity metrics for data structures, in general, and big O notation, in particular.

It then proceeds to describe the interfaces, and make the interfaces concrete using the previously described implementation approach, for ADTs of the following types:

[4] Barbara Liskov and Stephen Zilles, "Programming with abstract data types", Proceedings of the ACM SIGPLAN Symposium on Very High Level Languages, SIGPLAN Notices, Vol. 9, pp. 50–59, 1974.

- stacks;
- queues;
- linked lists;
- deques;
- priority queues;
- searching and sorting;
- maps; and
- heaps.

1.2.5 The appendices

The book concludes with a number of appendices to support the mainline text.

A. Examples of a `Student` class and a main program that uses that class in C++, Java, and Python. This is in support of the discussion in chapter 4 justifying the use of Abstract Data Types in this book.

B. All of the generic ADT implementations for the classes described in the book are here.

C. A mutable string data type interface and implementation are provided here; you may need it for some of the end of chapter exercises.

D. A review of the principal aspects of Python that you are expected to have mastered.

E. A brief review of the von Neumann architecture that underlies nearly all computation.

1.3 Styles used in the textbook

The following styles have been used in the book to emphasize certain categories of text.

- Dialogues of bash commands and their output are shown in orange color boxes, as shown below.

```
$ echo this that and the other thing
this that and the other thing
$ date
Fri, Jul 30, 2021 10:29:31 AM
```

- Fragments of source code are shown in yellow color boxes, as shown below.

```
#include <stdio.h>
void printDouble(double d, FILE  *f);
```

- Exercises interspersed throughout the text are shown in blue color boxes, as shown below.

> **Exercise 1.1** Exercise text.

- Other types of text that should standout (e.g., pseudocode, `gdb` output, `valgrind` output) are shown in grey color boxes, as shown below.

```
line 1 of output
line 2 of output
* * *
last line of output
```

- Information that you should think about very carefully and remember is shown in a box with an exclamation icon in the upper left hand corner, as shown below.

> Important information.

- Suggestions that will help you understand the reading are shown in a box with a hand icon pointing to the right, as shown below.

> Suggestions to aid your reading.

Chapter 2

A beginner's guide to Linux

2.1 Some history

It is likely that you have been using computers since you were very young. I recall sitting my 2-year old niece down in front of one of the first Macintosh^{TM} computers to play a game called "Lode Runner" in 1985. Admittedly a poor baby sitting approach, but it did the trick; she happily punched the keys for nearly an hour while I was trying to finish up a section of a research paper (using paper and pencil).

Model 33 teletype

The very first interactive computers had a single "console" upon which output from programs was displayed and through which input could be provided using the keyboard. The input and output speeds on such consoles were maddeningly slow, but one could at least get on with the job. The console shown in the figure also had a paper tape reader, a very early form of mass storage for digital information☺.

adm3a terminal

As processors became more powerful and memory became more plentiful, computers were fitted with serial line devices that enabled one to connect "terminals" to the system. Such terminals provided a similar interface to the system as the console, but usually consisted of a cathode ray tube for display and a keyboard; a window of 80 character lines x 24 lines of fixed-width font characters was provided on the CRT, and the typical transmission speeds of such devices was ˜30 times faster than for the earlier consoles. Multiple people could be connected to the system at one time, leading to "time-sharing" systems; one particular time-sharing system that was popular in universities and among computer science researchers was UNIX^{TM}.

UNIX^{TM} was developed by Ken Thompson and Dennis Ritchie at Bell Laboratories, along with contributions from many of the other researchers at the Bell Labs Murray Hill facility.

It had originally been implemented to ease the withdrawal experienced by Thompson and Ritchie when they were recalled from the Multics Project[1]. UNIX™ was used internally within Bell Labs until Thompson spent a sabbatical year at Berkeley; as with all good computer scientists, Thompson took his environment (UNIX™) with him; when others at Berkeley discovered the power and simplicity of the environment, Western Electric (Bell Labs parent company) was persuaded to create an academic license that enabled Berkeley and other university computer science departments to have access to the system.

Students who graduated from institutions in which UNIX™ was used found themselves also experiencing withdrawal when they went off to employment in industry or the national laboratories - the licensing of UNIX™ was restricted to universities. Computer system vendors, such as HP, IBM, and Sun, observed this demand and negotiated licensing arrangements with Western Electric to produce vendor-specific versions of UNIX™ for their workstations and servers (HP/HP-UX, IBM/AIX, Sun/SunOS). Since these were vendor-specific, they presented slightly different libraries and system calls, complicating porting of code between the platforms. To eliminate most of the differences, the vendors, through the activities of a variety of consortia, worked with the IEEE to create the POSIX standards to define a standard set of library functions that could be depended upon when programming on a POSIX-compliant system.

One particularly unique innovation of UNIX™ was how it obtained commands from a user, commonly called a command line interpreter (CLI). Prior operating systems usually provided a privileged program, sometimes embedded in the kernel itself, for reading and executing commands typed by the user through their terminal. The UNIX™ kernel provided a complete set of system calls enabling processes to create and manage other processes; thus, the CLI could simply be another program. These user-level CLI's have come to be known as "shells", since the very first such CLI was called the shell, and the command one typed to invoke the shell was `sh`; `sh` was written by Steve Bourne[2].

Beginning in 1991, Linus Torvalds[3] began work to create a new, free operating system kernel. This kernel, coupled with the applications from the GNU project[4], has eventually become known as Linux. Linux is open source, licensed under the GNU General Public License. Given its open-source nature, it is now the dominant operating system used in academia, replacing the many, vendor-specific flavors of UNIX™.

2.2 The user interface

The primary interface between a user and Linux is the terminal window - i.e., a window on the screen that emulates the 80x24 character terminals found on earlier UNIX™ systems. A command line interpreter, usually *bash*[5], reads each command line typed by

[1] Elliott I. Organick. 1972. The Multics system: an examination of its structure. MIT Press, Cambridge, MA, USA.

[2] `https://en.wikipedia.org/wiki/Stephen_R._Bourne`

[3] `https://en.wikipedia.org/wiki/Linus_Torvalds`

[4] `https://en.wikipedia.org/wiki/GNU_Project`

[5] The name is an acronym for *Bourne-again shell*, a pun on the [Bourne] shell that it replaced.

the user in the window, creates one or more processes needed to execute the command line, and (normally) waits for those processes to finish execution before prompting the user for another command line.

This is obviously quite different from the point-and-click mechanism with which you are undoubtedly familiar; Linux systems do provide one or more graphical user interfaces that support the point-and-click mechanism where it is appropriate - e.g., invocation of your browser, creation of another terminal window. Program development on Linux systems is nearly always performed using the command line interface provided by a terminal window in which `bash` is executing. We will, therefore, restrict our discussion to this environment.

2.3 The command line interpreter - bash

`bash` reads the commands typed by a user in its terminal window and executes those commands. `bash` displays a prompt string, reads the line of input typed, and executes the command. The prompt string can be customized, as will be shown later; until then, we will use the string “$ ” as the prompt.

☞ You are encouraged to try these commands on your Linux system as you read along. You should see the same or similar output from the commands.

Consider the following example:

```
$ date                    show today's date
Tue Jun 27 15:09:02 PDT 2017
$ pwd                     print the current working directory
/home/me
$ date; pwd               a semicolon is a command separator
Tue Jun 27 15:09:43 PDF 2017
/home/me
```

☞ In the examples in this chapter, the text that you type is in **`boldface`**, while that displayed by the shell and commands is in `normalface`.

From the last example, you see that you can place more than one command on a single command line. A **`;`** is a command separator; “a ; b” tells the shell to first execute *a*, then execute *b*.

After `bash` displays the prompt string, it reads everything you type up to when you press the `Enter` key. (On some systems the key is labeled `Return`; we will refer to it as the `Enter` key in this text.) If you wish to erase a character before pressing `Enter`, you should press the `Backspace` key. If you have made a number of mistakes, and wish to simply erase the entire line and start again, you can type *ctl-u*[6]; sometimes *ctl-u* is called the *line kill* character.

[6]The expression *ctl-x* means you should press the `x` key while holding down the `Ctrl` key.

Both `date` and `pwd` are commands that do not require any additional information in order to do their jobs.[7] Nearly all programs require additional *command arguments* to provide additional information to the program while it is executing.

Consider the program `echo` - it has a particularly simple job: print the supplied arguments and exit, as in the following examples:

```
$ echo this                 print 'this' on the output
this
$ echo this and that        print 'this and that'
this and that
$ echo this  and that       two spaces between 'this' and 'and'
this and that               the extra space has disappeared
$ echo 'this  and that'     quote the input
this  and that              the extra space was maintained
```

These examples demonstrate a number of features of `bash`.

- The shell breaks up the line of input that you type into separate words; the words can be separated by blanks or tabs, or by punctuation like the semicolon.
- The first word in a command (`echo` above) is the program to execute; we will discuss later how the shell looks for the program file that corresponds to that word.
- The other words in the command are provided to the program as a list of words, for it to do with as it sees fit. `echo` simply prints each of these words, placing a single space between each pair of words.
- It does not matter how many spaces or tabs separate two words; it does not change the list of words that the shell gives to the program.
- If you want to have many words in a single argument, you can quote the phrase using `'` or `"`. In the last example above, `echo` received a list with a single "word" in it, consisting of the phrase `'this  and that'` *without* the quote characters.

We saw earlier that `bash` gives a special meaning to the character `;` — now we see that it gives special meaning to `'` and `"`, as well. In fact, `bash` gives special meanings to most non-alphanumeric characters. If you want to provide an argument to a program that contains a non-alphanumeric character, the easiest way to prevent the shell from giving it its special meaning is to quote the argument. For example:

```
$ echo A semi-colon '(;)' is a command separator.
A semi-colon (;) is a command separator.
```

A command argument that needs to contain an apostrophe, `'`, can be escaped using a quotation mark, `"`, and vice versa.

By convention, command arguments that start with `-` are considered options to a program

[7] `date` *can* take a number of arguments that determine how to format the date string that it prints. Type "linux man date" as a search string in your favorite browser to read about the arguments that `date` understands.

- i.e., they change the way the program does its task; these are usually a single letter following the hyphen, and are called *short options*. If additional information is required when a short option is specified, that information must be the next word that immediately follows the short option, as in `-n name`. Finally, if you wish to specify several short options on a single command line, you can usually collapse them into a single command argument word - e.g., `command -a -b -c` can usually be written as `command -abc`.

A second option convention, called *long options*, has an option starting with `--`, and is usually written out in full; for example, `command -a` might be the same as `command --all`. If additional information is required when a long option is specified, it is written as `--name=value` - i.e., the information associated with the option is part of the same command argument word. You will note in the previous example that a hyphen, `-`, is not special to `bash`, nor is a period, `.`[8]. The equals sign, `=`, is another non-alphanumeric character that has no special meaning to `bash`. The non-special nature of these characters enables these two option conventions.

⚠ Since the hyphen character is *not* special to `bash`, this means that both short and long option arguments are passed to the **program** to process.

Let's look at examples of the use of both short and long options. The command `ls` lists the files found in one or more directories; if no directories are specified, the files in the current directory are listed. `ls` understands a number of options that dictate how it displays the files in a directory - see the man page for `ls` for a complete list of supported options. The examples below show both the short and long form of some of these options.

```
$ ls                    list the contents of the current directory
book  calendar.data  Music  Pictures  shopping.list  src
$ ls -a                 list the entire contents of the current directory
.   .bashrc   .vimrc  calendar.data  Pictures      src
..  .profile  book    Music          shopping.list
$ ls --all              long form of -a
.   .bashrc   .vimrc  calendar.data  Pictures      src
..  .profile  book    Music          shopping.list
$ ls --group-directories-first  places directories first, no short version
book  Music  Pictures  src  calendar.data  shopping.list
$ ls -p                 append / to indicate directories
bin/  calendar.data  Music/  Pictures/  shopping.list  src/
$ ls --indicator-style=slash    long version of -p
bin/  calendar.data  Music/  Pictures/  shopping.list  src/
$ ls -t *.*             display files ordered by modification time, newest first
shopping.list  calendar.data
$ ls -rt *.*            same, but oldest first (reverse sort)
calendar.data  shopping.list
$ ls -w 20 *.*          output is 20 characters wide
```

[8]This latter assertion is not completely true - if the 1st "word" in a command is `.`, `bash` does something special.

```
calendar.data
shopping.list
$ ls --width=20 *.*      the long form of -w 20
calendar.data
shopping.list
```

After any options, what about the other arguments to a command? Most commands need to work on files, so the non-option arguments are typically filenames. There are other sorts of information that a command might need; for example, a program that searches for textual patterns in a file requires at least one argument indicating the pattern we wish to find.

In the last four examples above, we provided "*.*" as an argument to `ls`. What does that mean?

As we mentioned previously, most of the non-alphanumeric characters available on the keyboard have a special meaning to `bash`. When `bash` breaks up the command into words, it looks for four particular special characters, (`*`, `?`, `[`, and `]`) in each word, as these indicate that `bash` should perform a pattern match against filenames in the current directory. In the last four `ls` examples above, "*.*" indicates that `bash` should replace that string by all filenames that consist of 1 or more characters before a `.`, and 0 or more characters after. In our directory, this pattern matches exactly two files, `calendar.data` and `shopping.list`. `bash` replaces the single "word", "*.*", by two words in the list presented to `ls`. The wildcard character, `*`, is often used in the shell to select a subset of files to be processed by the command.

Exercise 2.1. Execute the following commands in your home directory:

```
$ pwd
$ echo *
$ ls *
```

How does the output from `echo` and `ls` differ? Do they display the same information?

A `?` in a command argument indicates that it matches any single character at that point in a filename - e.g., "jo?n" matches `john` or `joan`, but not `johan`. Square brackets enable the specification of a range of characters to match at a particular location in the filename - e.g., "ls a.[ch]" would match files named `a.c` and `a.h` in the current directory, but would *not* match `a.x`. One can also specify a range of characters within the square brackets - e.g., "ls *.[a-d]" would match any files that end in `.a`, `.b`, `.c`, or `.d`.

⚠ Note that the wildcard expansion is done by `bash`, *not* by the command itself (in this case, `ls`). By performing such substitution in the command line interpreter, it means that all programs benefit from this feature.

What should you do if you start a program by mistake? Most commands can be stopped by typing *ctl-c*, often known as the `INTERRUPT` character. Some programs, like text editors, will stop whatever the program is doing when you type the `INTERRUPT` character, but enable you to issue another command to the program after it has stopped. Closing the terminal window will stop most programs, as well.

2.4 Simple commands

Linux provides you with a number of simple commands to manipulate files and your environment. This section covers some of the more useful ones.

⚠ It is important that, as each command is introduced in this section, you access the man page as described below and **study what the man page says**.

2.4.1 Obtaining help

Online manual pages for all of the commands in Linux are available over the Internet; it is a good idea to maintain an open browser window while you are working so that you can access these manual pages. A search query of the form "linux man *command*" will yield several links to online man pages for *command*. Additionally, there is a directory available at `http://man7.org/linux/man-pages/dir_all_by_section.html`; you can skim it quickly for commands that might be relevant to what you want to do. There is also an introduction to the system at `http://www.tldp.org/LDP/intro-linux/intro-linux.pdf` that gives an overview of how things work.

Depending upon how complete a Linux system you have, the man pages for most of your commands may also be available on your Linux system. If so, you can display the manual page for *command* by typing "man *command*" to `bash`. Thus, to read about the `ls` command, type

```
$ man ls
```

2.4.1.1 General layout of a manual page

Each manual page consists of the following sections:

- NAME - provides the name of the command and a one-line description of what the command does;
- SYNOPSIS - provides a short-hand description of how one invokes the command;
- DESCRIPTION - describes in more detail what the program does; it lists all of the options that the program understands;
- EXAMPLES - some manual pages provide example command invocations;
- SEE ALSO - lists other manual pages that are related to the one you are viewing; and

- many more sections that are optional.

2.4.1.2 Interpreting the SYNOPSIS section of a manual page

As indicated above, the SYNOPSIS section provides a short-hand description of legal invocations of the program. It briefly describes the command's interface by showing the syntax of the command and its arguments. Brackets (`[]`) surround optional arguments, vertical bars (`|`) separate choices, and ellipses (...) indicate repetition. If an argument is listed and is *not* enclosed in brackets, it indicates a mandatory argument that should occur in that relative position in the command line.

A generic SYNOPSIS line will look as follows:

```
command [OPTION] ... REQUIRED [FILE] ...
```

This indicates that `command` has one mandatory argument (`REQUIRED`) that follows 0 or more `OPTIONs` and which precedes 0 or more `FILE` names.

An option can either be a short option (e.g., `-x`) or a long option (e.g., `--all`). Multiple short options can be concatenated together (e.g., `-xyz`).

A mandatory argument could be a particular sub-command to `command` (e.g., the `c` sub-command to `tar`), the pattern used by `grep`, the name of a file of commands needed by `command`, and many others. Some programs might require two or three mandatory arguments in a particular order; this will be indicated in the SYNOPSIS section, as well.

Finally, if `command` requires the names of files to process, these will be the last set of arguments. If `[FILE]` is specified without the trailing ellipsis, that indicates that `command` will accept at most one filename. When `[FILE]` is specified as optional, whether followed by an ellipsis or not, then that program will default to reading standard input if no files are specified. Finally, if a filename consisting of a single hyphen (`-`) is specified in the list of filename arguments, a program will process standard input when it encounters that argument.

> ⚠ The standard input for `command` defaults to your keyboard unless you have redirected standard input to a file or pipe, as described in sections 2.6.2.1 and 2.6.3.

2.4.1.3 Example synopses

- `wc [OPTION] ... [FILE] ...`
- `sort [OPTION] ... [FILE] ...`
- `grep [OPTION] ... PATTERN [FILE] ...`
- `ls [OPTION] ... [FILE] ...`
- `diff [OPTION] ... FILE1 FILE2`
- `base64 [OPTION] ... [FILE]`

Exercise 2.2. Which of these commands have one or more mandatory arguments? Which of these commands accept 0 or more optional filenames? Which of these commands accepts exactly one optional filename?

2.4.2 Creating files

Information on Linux systems is stored in files. In order to enter information into a file, as well as to modify that information, you will need to use a text editor. It is likely that you have experience using *document* editors, such as Microsoft™ Word. Document editors not only enable you to enter and edit information in a document, it also enables you to specify how that information should be formatted when it is displayed. Most files in a Linux system do not require such formatting information - i.e., the content of the file is a sequence of characters, with the end of line being the only type of formatting needed.

Every Linux system has several screen editors; the one you choose to use is a matter of personal taste. The Debian Linux image described in the report provided by your instructor includes

- `nano` (`https://wiki.archlinux.org/index.php/nano`),
- `vim` (`https://wiki.archlinux.org/index.php/Vim`), and
- `subl` (`https://www.sublimetext.com/`).

You may also install[9] any of a number of other editors, such as `emacs` and `gedit`. See `https://en.wikipedia.org/wiki/List_of_text_editors` for a list of text editors that has been compiled in Wikipedia.

Exercise 2.3. Choose a screen editor. If your editor is named "editor", it is likely that you can find a tutorial (or three) available on the web with a search query of the form "editor tutorial".

- Work your way through your chosen tutorial, creating and editing the example files found therein.
- Use your editor to create a new file in your home directory (the directory in which you are placed when you create a new terminal window) named `Jabberwocky` and containing the following four lines[a]:

  ```
  'Twas brillig, and the slithy toves
  Did gyre and gimble in the wabe;
  All mimsy were the borogoves,
  And the mome raths outgrabe.
  ```

- Use your editor to create `Jabberwocky1`, starting with the contents of `Jabberwocky`, and with line 1 translated into modern English using the following equivalences:
  - `'Twas` -> `It was`
  - `brillig` -> `evening`
  - `slithy` -> `smooth, active`

[9] To install another editor into your Debian Linux image, you must search the web to find the package name for your editor in the Debian repositories, and then use the `apt` program to install it.

  - `toves` –> `badgers`
- Use your editor to create `Jabberwocky2`, starting with the contents of `Jabberwocky1`, and with line 2 translated into modern English using the following equivalences:
  - `gyre` –> `scratch`
  - `gimble` –> `bore holes`
  - `wabe` –> `hill side`
- Use your editor to create `Jabberwocky3`, starting with the contents of `Jabberwocky2`, and with line 3 translated into modern English using the following equivalences:
  - `mimsy` –> `unhappy`
  - `borogoves` –> `parrots`
- Use your editor to create `Jabberwocky4`, starting with the contents of `Jabberwocky3`, and with line 4 translated into modern English using the following equivalences:
  - `mome` –> `solemn`
  - `raths` –> `turtles`
  - `outgrabe` –> `squeaked out`

When you have finished, `Jabberwocky4` should read as:

```
It was evening, and the smooth, active badgers
Did scratch and bore holes in the hill side;
All unhappy were the parrots,
And the solemn turtles squeaked out.
```

[a] This is the first stanza from the poem entitled "Jabberwocky" by Lewis Carroll.

2.4.3 Listing your files

We have previously encountered `ls` in section 2.3. In this section, we will provide examples of one other option to `ls` that is heavily used.

Linux stores a number of items of information about each file in the file system; this information is referred to as *metadata*. `ls` can be used to see some of this metadata:

```
$ ls -l
total 24
drwxrwxr-x 2 me me 4096 Jul  6 14:59 book
-rw-rw-r-- 1 me me  141 Jul  6 14:59 calendar.data
drwxrwxr-x 2 me me 4096 Jul  6 14:59 Music
drwxrwxr-x 2 me me 4096 Jul  6 14:59 Pictures
-rw-rw-r-- 1 me me   86 Jul  6 14:59 shopping.list
drwxrwxr-x 2 me me 4096 Jul  6 14:59 src
```

As you can see, the `-l` option gives a "long" listing that provides this metadata; the first line indicates the number of blocks of disk space occupied by the listed files. Each subsequent line provides information about an individual file:

- the first character indicates if the file is a directory (`d`) or a normal file (`-`);
- the next 9 characters indicate permissions to read, write, or execute the file; the first 3 characters are for the owner of the file (`me` in this case); the next 3 characters are

for the group with which this file is associated (`me` is the associated group); the next 3 characters are for everyone else;
- next we have the number of links to the file; this indicates the number of different names in the file system that point at this particular file;
- the owner of the file (`me`) and the associated group (`me`) follow;
- next we have the size of the file (in bytes);
- this is followed by the month, day, and time of last modification;
- and finally, we have the name of the file.

We previously noted that after all of the options, one can specify one or more file names to `ls`, which then restricts its activity to those files. For example,

```
$ ls -l calendar.data
-rw-rw-r-- 1 me me  141 Jul  6 14:59 calendar.data
```

Exercise 2.4. Use `ls` to perform a long listing of your `Jabberwocky` files. How does the size of the file change going from the original to the final translated version? Is it as you expected?

[colback=orange!10!white]

2.4.4 Naming your files

Most operating systems, and Linux is no exception, have rules about creating legal filenames. Firstly, there is usually a limit on the length of a filename; early operating systems had very severe restrictions; Linux restricts the length of a filename to 255 characters. It is unusual for anyone to want to type that many characters as an argument to a command, so, in practice, you will usually use far fewer characters in your filenames.

Secondly, what are the legal characters in a filename? Linux allows any character in a filename except for `/` and a null character; this does *not* mean that you should start putting lots of strange characters in your filenames. The POSIX specification[10] is quite clear on characters to use in filenames that are portable across *all* POSIX-conformant systems[11]:

- any upper-case character from the set `"ABCDEFGHIJKLMNOPQRSTUVWXYZ"`;
- any lower-case character from the set `"abcdefghijklmnopqrstuvwxyz"`;
- any digit from the set `"0123456789"`; and
- any character from the set `"._-"`.

We have already seen that `-` is used to introduce options in bash command lines, so you are *strongly* recommended to avoid starting your filenames with a `-`. We have also seen above that filenames that start with a `.` are *hidden* - i.e., they are not displayed by `ls`

[10] `http://pubs.opengroup.org/onlinepubs/9699919799/basedefs/V1_chap03.html#tag_03_280`
[11] Linux is a POSIX-conformant system

unless you specify the `-a` or `--all` options; thus, you should avoid starting your filenames with a `.` unless you want their existence to be hidden in this way.

2.4.5 What's in a file?

We often try to give files descriptive names in order to remember their contents. When that fails, one often resorts to displaying the contents of the file to jog one's memory.

You could certainly use your favorite editor to display the contents, using whatever commands it provides. While this works, it is not the most efficient way to display the contents, since the editor is designed to enable you to *modify* the file.

Linux provides several commands that can be used to display the contents of a file:

- The simplest program is `cat`, which simply prints the contents of each file argument on the terminal.

```
$ cat shopping.list
1 bottle of milk
2 granny smith apples
10 hot house tomatoes
1 six-pack of Coca Cola
```

- `cat` works perfectly well for short files, like `shopping.list`, but for very long files the contents will be displayed so rapidly in your terminal window that you will only see the last screenful of lines (normally 24 lines) in the terminal window. Linux provides two commands that will show one screenful at a time, waiting for an action from the user to continue the display, to search for a pattern, or to perform other tasks.
  - `more` is an especially primitive program for paging through text one screenful at a time. Often, this is all that is needed.
  - Counterintuitively, `less` is a program similar to `more`, but with more features, such as backward movement in the file; additionally, `less` does not have to read the entire input file before starting, so with large input files it starts up *much* faster than text editors like `vim`.

2.4.6 Moving, copying, removing files - `mv`, `cp`, `rm`

In your prior experience with computer systems, you will have had the occasional need to rename a file. On Linux, this is done with the `mv` command:

```
$ mv shopping.list Shopping.List
$ ls *.*
calendar.data  Shopping.List
$ cat shopping.list
cat: shopping.list: No such file or directory
```

The file `shopping.list` has been "moved" to a file named `Shopping.List`. The old filename has disappeared, as evidenced by the output from `ls` and `cat`. This example also shows that filenames are case-sensitive - i.e., the name `shopping.list` is different from `Shopping.List`.

⚠ **If the target filename in an `mv` command already exists, it is replaced.**

To make a *copy* of a file, one uses the `cp` command:

```
$ cp Shopping.List 20170706-shopping.list
```

saves an archive copy of the file `Shopping.List`.

⚠ **If the target filename in an `cp` command already exists, it is replaced.**

To remove a file, one uses the `rm` command:

```
$ rm Shopping.List shopping.list
rm: cannot remove 'shopping.list': No such file or directory
```

As you can see, `rm` warns you if one of the files specified did not exist. You can then invoke `ls` to verify that `rm` did its job:

```
$ ls *.*
20170706-shopping.list  calendar.data
```

2.4.7 Other useful programs

Let's re-create our shopping list file (recall that we removed it above) for use with the other programs described in this section.

```
$ cp 20170706-shopping.list shopping.list
$ cat shopping.list
1 bottle of milk
2 granny smith apples
10 hot house tomatoes
1 six-pack of Coca Cola
```

2.4.7.1 Count lines, words, and characters - `wc`

Suppose we need to know the number of different types of items that are contained in the shopping list. We could count the number of lines on the screen after displaying the file using `cat`; this type of processing of files happens often enough that the program `wc` is provided - `wc` counts the number of characters, words (each word is a sequence of non-whitespace characters, separated from other words by whitespace), and lines. The number of lines in `shopping.list` is exactly what we need:

```
$ wc shopping.list
 4 17 85 shopping.list
$ wc -l shopping.list
4 shopping.list
$ wc -w shopping.list calendar.data
 17 shopping.list
 19 calendar.data
 36 total
```

If we simply invoke `wc` without any options, it will print the number of lines, number of words, and number of characters for each file specified in the command line. If we specify `-l`, `wc` restricts itself to counting lines; `-w` or `-c` restricts `wc` to counting words or characters, respectively. If more than one file is specified in the command line, `wc` displays the counts for each file, and provides a total in each category at the end.

2.4.7.2 Translate or delete characters - `tr`

It often happens that you have a need to translate and/or delete characters in a file. `tr` copies its standard input to standard output, translating or deleting characters as described by its arguments. Let's look at some simple examples.

☞ The standard output for a command defaults to your terminal window unless you have redirected standard output to a file or pipe, as described in sections 2.6.2.2 and 2.6.3.

```
$ tr a A
abacus
AbAcus
ctl-d                you type this to indicate end-of-file
$ tr -d x
xerxes
eres
ctl-d
$ tr '[:upper:]'  '[:lower:]'
This Is A Test
this is a test
```

```
ctl-d
$ tr -s '[:blank:]'  '\n'
This Is  A   Test
This
Is
A
Test
ctl-d
```

The first invocation tells `tr` to replace all occurrences of ‘a’ by ‘A’. Since `tr` is a simple filter (only reads standard input and writes to standard output), it reads `abacus` from the keyboard, and writes `AbAcus` to the terminal window. **Note the use of *ctl-d* typed on the keyboard to indicate end of file from the keyboard.**

The second invocation indicates that `tr` should delete all occurrences of the letter ‘x’ found in the standard input.

The third invocation indicates that all upper-case characters on standard input must be converted to their lower-case equivalents. `tr` understands a number of character class arguments (such as `[:upper:]`); see the `tr` man page for a complete list.

The final invocation tells `tr` to translate each horizontal white space character (blank or tab) to an end of line character. Sequences of multiple horizontal white space characters are “squeezed” into a single horizontal white space character before the translation is performed. As you can see, this causes each “word” in the file to be placed on a line of its own.

2.4.7.3 Report, omit, or count repeated lines - `uniq`

The default behavior for `uniq` is to copy standard input to standard output, replacing each sequence of matching lines by a single instance of that line. If the `-c` option is specified, it precedes each line by the number of occurrences in that sequence.

```
Original file                   Result of running 'uniq -c'
=============                   ===========================
This                            1 This
file                            1 file
is                              1 is
demonstrating                   1 demonstrating
this                            1 this
program                         1 program
                                1
the                             1 the
quick                           1 quick
brown                           1 brown
fox                             1 fox
```

```
jumped                          1 jumped
over                            1 over
the                             1 the
lazy                            1 lazy
dog                             1 dog
```

The preceding shows an original file for which there are *no* sequences of matching lines, and the resulting output when that file is processed using `uniq -c`.

As one would expect, all of the lines of input are reproduced on the output, preceded by a count of 1.

Now let's see what happens if we sort the input file (using `sort`) and the output that results when the sorted file is processed using `uniq -c`.

```
Original file                   Result of running 'uniq -c'
=============                   ===========================
                                1
brown                           1 brown
demonstrating                   1 demonstrating
dog                             1 dog
file                            1 file
fox                             1 fox
is                              1 is
jumped                          1 jumped
lazy                            1 lazy
over                            1 over
program                         1 program
quick                           1 quick
the                             2 the
the                             1 this
this                            1 This
This
```

As expected, `uniq` discovered two successive lines consisting solely of "the"; it only output one line for "the", but preceded by a count of 2. Note that `uniq` is case-sensitive, so although the sorted file contained successive lines of "this" followed by "This", these were not seen as a sequence of matching lines, and each was output with a count of 1.

We will use `uniq` later in this chapter (Exercise 2.6) to show the power of pipelines in `bash`.

2.4.7.4 Find occurrence of a pattern - `grep`

Suppose we do not remember whether we added apples to our shopping list. The command `grep`, which stands for **g**et **r**egular **e**xpression and **p**rint, will search the file arguments for lines that match a pattern. The following shows us using `grep` to answer our question about apples.

```
$ grep apple shopping.list
2 granny smith apples
```

Thus we see that we did add granny smith apples to the list.

We see that the first non-option argument to `grep` is the pattern to search for - in this case, it is simply the string “apple”. `grep` understands much more powerful patterns, called *regular expressions*; we recommend that you consult the Linux man page for `grep` for more discussion concerning these more powerful patterns.

Suppose that your friend purchased apples on the way home from class, so that you do not need to purchase them when you go to the store; the following shows how to print all lines that do *not* match the pattern.

```
$ grep -v apple shopping.list
1 bottle of milk
10 hot house tomatoes
1 six-pack of Coca Cola
```

If you specify two or more *file* arguments to `grep`, it will prefix each matching line with the name of the file in which it was found.

```
$ grep apple shopping.list calendar.data
shopping.list:2 granny smith apples
```

Unsurprisingly, the term “apple” is not found in `calendar.data`; even so, since we specified two filenames in the `grep` command, it prefixes the matching line in `shopping.list` with the name of the file.

2.4.7.5 Sorting files - `sort`

This command sorts its input into alphabetical order, by default. The order can be changed using various options which will be shown below. Let’s sort our shopping list.

```
$ sort shopping.list
10 hot house tomatoes
1 bottle of milk
1 six-pack of Coca Cola
2 granny smith apples
```

Note that the default sorting order of characters is digit, then blank, then upper-case letter, then lower-case letter. This explains why the “milk” line appears before the “Coke” line (s in ‘six’ comes after b in ‘bottle’), why the “tomatoes” line appears before the “milk” line (‘10’ comes before ‘1 ’), and why the “apple” line comes last (‘2’ comes after ‘1’).

As indicated above, `sort` has many options to control the sort order - e.g., numerical order, by field within each line, reverse the order. Here are some examples, again using `shopping.list`.

```
$ sort -r shopping.list           reverse the order of the sort
2 granny smith apples
1 six-pack of Coca Cola
1 bottle of milk
10 hot house tomatoes
$ sort -n shopping.list           numeric sort on first field
1 bottle of milk
1 six-pack of Coca Cola
2 granny smith apples
10 hot house tomatoes
$ sort -k 2 shopping.list         sort on 2nd field
1 bottle of milk
2 granny smith apples
10 hot house tomatoes
1 six-pack of Coca Cola
```

Note that a field is defined as a sequence of non-whitespace characters separated from other fields by characters. Thus, **b**ottle < **g**ranny < **h**ot < **s**ix in the last example above.

2.4.7.6 Beginning and end of a file - `head` and `tail`

We discussed `more` and `less` above for displaying the contents of a file. A very common occurrence is the need to just see the first few lines, or the last few lines, of a file. This capability is provided by `head` and `tail`, respectively, as shown in the following examples.

```
$ head shopping.list              print the first 10 lines
1 bottle of milk
2 granny smith apples
10 hot house tomatoes
1 six-pack of Coca Cola
$ head -n 1 shopping.list         print the first line
1 bottle of milk
$ head --lines=1 shopping.list    print the first line
1 bottle of milk
$ tail shopping.list              print the last 10 lines
1 bottle of milk
2 granny smith apples
10 hot house tomatoes
1 six-pack of Coca Cola
$ tail -n 1 shopping.list         print the last line
```

```
1 six-pack of Coca Cola
$ tail --lines=1 shopping.list      print the last line
1 six-pack of Coca Cola
```

2.4.7.7 Comparing files - `cmp` and `diff`

It is common to need to compare files to understand *if* they are different, and if they are, *how* they differ. Earlier in this chapter, we made a copy of `shopping.list` named `20170706-shopping.list`. Perhaps, as part of a dietary regimen, we need to keep the shopping list that we use each day.

```
$ cat 20170706-shopping.list
1 bottle of milk
2 granny smith apples
10 hot house tomatoes
1 six-pack of Coca Cola
```

We have discovered that we do not eat enough tomatoes, such that we are building up a tomato mountain in the kitchen. Therefore, we change the quantity of tomatoes in `shopping.list` to 3 instead of 10, as shown below.

```
$ cat shopping.list
1 bottle of milk
2 granny smith apples
3 hot house tomatoes
1 six-pack of Coca Cola
```

Just before you go to the store, you cannot remember if you changed the quantity of tomatoes or not. You could just display the file, and look for the changes, but there may have been many changes, and we sometimes do not see subtle textual differences. Therefore, we can rely upon comparison tools to help us out.

The first comparison program, `cmp`, compares the two files and reports the first difference that it finds.

```
$ cmp shopping.list 20170706-shopping.list
shopping.list 20170706-shopping.list differ: byte 40, line 3
```

While `cmp` has indicated we made some change to `shopping.list`, we want to verify that we made the correct change, just in case. This is where `diff` comes in handy.

```
$ diff shopping.list 20170706-shopping.list
3c3
< 3 hot house tomatoes
---
> 10 hot house tomatoes
```

The '3c3' line indicates that only line 3 of the two files are different; lines preceded by < are lines in the first file (`shopping.list` in this case), and lines preceded by > are lines in the second file (`20170706-shopping.list` in this case). If there had been more than one difference in the two files, each such difference would have been shown in this way.

Exercise 2.5. Use `diff` to compare your `Jabberwocky` files. An easy way to do this is to use the following command[a] to `bash`:

```
$ for n in 1 2 3 4; do
> diff Jabberwocky Jabberwocky$n
> done
```

Note how `diff` shows you the smallest number of changes needed to convert from the first file argument to the second. Is the output as you expected?

[a]This bash command is described in more detail in section 2.6.4.3.

2.5 The file system

We have introduced the basic notion of a file, and metadata about a file, in the previous section. Now we need to understand how Linux organizes the file system.

In your previous computing experience, you have undoubtedly been exposed to folders via a graphical user interface. A folder contains files and, often, other folders. Double clicking on a folder usually causes its contents to be displayed. Double clicking on a file in a folder usually causes an application associated with that type of file to execute on that file. Most systems provide some way to visualize the file tree hierarchy; here is the hierarchy for the current state of this book. Note that directories are shown in **blue** and files are shown in **green**.

Different folders can each contain a file with the same name, such as `shopping.list`, for example, although the contents of the files are different. This means that the unique name for a file is a sequence of directories from the root to the file itself; for example, in this directory tree, rooted at `CaDS`, the unique name for `shopping.list` is the sequence of names `{ CaDS, ch02, me, shopping.list }`. This complete sequence of names is termed a *pathname*, as it describes a path from the root to the file that is of interest.

Linux provides a hierarchical file system of this type. The root of the tree has the name `/`, and the complete pathname for `shopping.list`, assuming that `CaDS` is a directory in the root, would be `/CaDS/ch02/me/shopping.list` - i.e., the complete pathname starts with the root, and each subsequent pair of names in the path are separated by `/`. While this overloading of the use of `/` may seem strange, one quickly becomes accustomed to it.

Given such a hierarchical structure, it is common to use family terms to describe the relationships between directories. If a directory `a` contains a directory `b`, `a` is the *parent* of `b`, and `b` is the *child* of `a`. `a`'s parent is the *grandparent* of `b`, and so on.

```
CaDS
├── book.tex
├── ch00
│   ├── Preface.pdf
│   ├── Preface.synctex.gz
│   └── Preface.tex
├── ch01
│   ├── ch01.pdf
│   ├── ch01.synctex.gz
│   └── ch01.tex
├── ch02
│   ├── adm3a.jpg
│   ├── ch02.pdf
│   ├── ch02.synctex.gz
│   ├── ch02.tex
│   ├── me
│   │   ├── 20170706-shopping.list
│   │   ├── book
│   │   ├── calendar.data
│   │   ├── Music
│   │   ├── Pictures
│   │   ├── shopping.list
│   │   └── src
│   ├── me.tgz
│   └── model33teletype.jpg
├── Outline.pdf
├── Outline.synctex.gz
└── Outline.tex
```

Partial directory tree

2.5.1 Current working directory and home directory

It would be extremely tedious to have to type the full pathname each time you wanted to refer to a file, so `bash` maintains a notion of your *current working directory*. It also maintains a notion of your *home directory*, which has been assigned to you when your account was created; whenever you start up a terminal window, your current working directory is your home directory. If you type a file name that does *not* start with a `/`, it assumes that you are naming the file relative to the current working directory. All of the examples in the previous sections of this chapter assume that our current working directory is `/CaDS/ch02/me`, such that invoking `cat shopping.list` will yield the contents of `shopping.list` on the screen.

For the purposes of this textbook, your home directory is `/home/me`. Your home directory never changes, while your current working directory can, as we will now show.

☞ We will no longer show the text you type in **boldface**. It should be obvious as it follows the `bash` prompt, "$ ".

```
$ pwd                         what is our current working directory
/home/me                      just started bash, we are in our home directory
$ ls -p                       what's in our home directory?
20170706-shopping.list  calendar.data  Pictures/     src/
book/                   Music/         shopping.list
$ cd Music                    change into the Music directory
$ pwd                         let's see if we were successful
/home/me/Music                yes we were
$ ls                          what's in the Music directory? nothing
$ cd ..; pwd                  go up one level in the directory hierarchy
/home/me                      we are back home
```

```
$ cd src; pwd; cd; pwd          cd into src; what does cd without a directory do?
/home/me/src
/home/me                        ok, cd without a directory takes us home
$ cd /home/me/Pictures; pwd     we can specify a full pathname to cd, as well
/home/me/Pictures
$ cd ~; pwd                     what does '~' mean?
/home/me                        ok, it's shorthand for home
```

You may wonder why we need the `'~'` shorthand for the home directory; it can be used as the first character of a pathname, as in `~/shopping.list`, to access files that are in your home directory. Thus, no matter where your current working directory is in the hierarchy, you can easily access files that are directly reachable from your home directory.

The use of `'..'` seems a little strange for referring to the parent of our current working directory. Why is this the case? Remember when we used the `-a` option to `ls` earlier:

```
$ pwd
/home/me
$ ls -a
.   .bashrc   .vimrc  calendar.data  Pictures       src
..  .profile  book    Music          shopping.list
```

Notice that there are two entries in the directory named `'.'` and `'..'`. These entries were placed in the directory when the directory was created. `'..'` points to the parent of this directory (here it points to `/home`); `'.'` points to the directory itself (here it points to `/home/me`.

Let's navigate up the tree to see what happens.

```
$ cd Music; pwd                 let's start somewhere interesting
/home/me/Music
$ cd ..; pwd                    go up one level
/home/me
$ cd ..; pwd                    again
/home
$ cd ..; pwd                    and again
/
$ cd ..; pwd                    will this work?
/
```

We see from this little experiment that the root is its own parent; we can ask to change our working directory to root's parent, but we stay in the same place.

Just as we can use `'~'` as shorthand for our home directory, we can use use `'.'` as shorthand for our current directory and `'..'` as shorthand for the parent of our current directory. Consider the following commands; the examples refer to the file system shown on page 27.

```
$ pwd
/CaDS/ch02/me
$ ls -p ..
adm3a.jpg  ch02.synctex.gz  DirectoryTree.pdf  me.tgz
ch02.pdf   ch02.tex         me/                model33teletype.jpg
$ cd Music; pwd
/CaDS/ch02/me/Music
$ cat ../shopping.list              Need to look at shopping list again
1 bottle of milk
2 granny smith apples
3 hot house tomatoes
1 six-pack of Coca Cola
$ head -n 1 ../../me/shopping.list    Admittedly unusual, but works
1 bottle of milk
$ cd ..; tail -n 1 ./shopping.list    ./name treated identically to name
1 six-pack of Coca Cola
```

The last two examples are meant to show that you can introduce `'.'` and `'..'` as elements of a pathname. The last example may seem strange, but later you will see a situation where using `'./'` comes in handy.

2.5.2 Creating a new directory - `mkdir`

Let's suppose that we want to create a directory to hold all of our archival shopping lists.

```
$ cd                        go home
$ mkdir ShoppingLists       create our directory
$ cd ShoppingLists          make it our working directory
$ ls -a                     what's in a newly-created directory?
.  ..                       only the link to our parent and ourselves
$ cd ..                     up to our parent
$ ls -l ShoppingLists       it's empty, so no output from ls
$ ls -dl ShoppingLists      -d option says describe the directory
drwxrwxr-x 2 me me 4096 Jul 11 16:00 ShoppingLists
```

There is also an `rmdir` command that can be used to remove a directory; this will only work *if* the directory is empty - i.e., the only entries in the directory are `'.'` and `'..'`.

2.5.3 The Linux hierarchical file system structure

Linux organizes all of the files in the system into a single hierarchy. There can be millions of files in the file system of a single Linux system; for the Debian Linux system used in this book, there are >160,000 files and >13,000 directories.

```
/
├── bin
├── boot
├── dev
├── etc
├── home
│   └── me
├── lib
├── lib64
├── lost+found
├── mnt
├── opt
├── proc
├── root
├── run
├── sbin
├── srv
├── sys
├── tmp
└── usr
    ├── bin
    ├── include
    ├── lib
    ├── lib64
    ├── local
    │   ├── bin
    │   ├── etc
    │   ├── games
    │   ├── include
    │   ├── lib
    │   ├── man
    │   ├── sbin
    │   ├── share
    │   └── src
    ├── sbin
    ├── share
    └── src
```

For typical use of a Linux system, the most important directories are:

- `/bin` - contains basic progams (like `bash`) that are required during the boot process;
- `/sbin` - contains programs that must be accessed by the system administrator;
- `/lib` - contains dynamic libraries and static support files needed in the boot process;
- `/etc` - contains configuration files for the system;
- `/home` - contains the home directory for each user (`/home/me` in our case);
- `/usr` - has several important sub-directories:
  - `/usr/bin` - contains programs that are accessed by all users,
  - `/usr/sbin` - contains programs that must be accessed by the system administrator,
  - `/usr/lib` - contains dynamic libraries and static support files for the programs in `/usr/bin` and `/usr/sbin`,
  - `/usr/include` - contains include files needed by C and C++ programs,
  - `/usr/share/doc` and `/usr/share/man` - contain manuals, documentation, examples, etc.,
  - `/usr/local` - has `bin`, `include`, `lib`, `etc`, etc. directories for locally added software.

2.6 Back to the shell

2.6.1 Environment variables

We have already discussed how the shell breaks up the command you typed into words, uses the 1st word in that sequence to find the program to run, and passes all of the other words to the program for it to interpret. Besides passing these arguments to a program, it also maintains a set of (name, value) pairs that it provides to the program for it to use if the program wishes - this set of (name, value) pairs is known as the *environment*.

The command to type to see what is currently in the environment is `env`:

```
$ env                       display the environment
 * * *                      variables specific to particular programs
XTERM_SHELL=/bin/bash       the shell reading an xterm window
USER=me                     my identity
PWD=/home/me                my current working directory
HOME=/home/me               my home directory
 * * *                      variables specific to particular programs
PATH=/usr/local/bin:/usr/bin:/bin
 * * *                      variables specific to particular programs
```

Each environment variable has a name consisting of upper-case letters, digits, and underscores (`'_'`). Each is displayed in the form "NAME=value". We can use our friend `echo` to see the current value of a particular environment variable as follows:

```
$ echo $USER                what is the value of USER?
me                          as we expected
```

When `bash` encounters `$ENVIRONMENT_VARIABLE_NAME` in a command line, it replaces it with the current value of that variable. Thus, in the example above, `bash` replaces `$USER` with `me`, sending that as the command argument to `echo`, which dutifully prints `me` on the terminal.

Environment variables are just a specific case of shell variables, which enable the user to assign values to names and refer to those values using the `$name` syntax.

How does one establish the value of a variable? How does one remove a variable? How does one make that variable part of the environment? The easiest way to answer these questions is to show a number of examples.

```
$ ID=/usr/local/include     'ID' has a very long value
$ echo $ID                  did it work?
/usr/local/include          yes
$ bash                      create a child process running bash
$ echo $ID                  see if the child process knows the value of 'ID'
                            no, it is not part of the environment
$ exit                      exit the child bash process
$ export ID                 make this variable part of the environment
$ bash                      create a child process running bash
$ echo $ID                  see if the child process knows the value of 'ID'
/usr/local/include          yes
$ exit                      exit the child bash process
$ unset ID                  remove 'ID' from the set of variables
$ echo $ID                  make sure it has been removed
                            yes, it has no value
```

`bash` makes the environment available to the process that it creates to run your program;

the program can access the value associated with an environment variable through a library call (`getenv()`) provided by the system.

One particular environment variable, `PATH`, is of special importance to `bash`, as it tells `bash` where to look for the program that you have requested. `PATH` consists of a sequence of directory names separated by colons (`:`). After `bash` has broken up your command into words, it then proceeds to search for an executable file with the command name you have specified in each component of `PATH` until it either finds such a file, or it has exhausted the `PATH`. In the former case, it then runs the program in a process, giving it the remaining arguments for it to use.

A standard program is provided which will perform this search *without* starting up the program - `which`. Let's look at it in action.

```
$ which bash            where is bash stored?
/usr/bin/bash
$ which wc              where is wc stored?
/usr/bin/wc
$ which pyhton3         look for python3, but a typo
which: no pyhton3 in (/usr/local/bin:/usr/bin:/bin)
$ pyhton3               let's see what bash says
bash: pyhton3: command not found
```

From these examples, we can deduce a couple of things:

- most of the standard programs are in `/usr/bin`; and
- if the command you have typed cannot be found using `PATH`, `bash` will report it, and `which` will also report the search path used.

While this is interesting, if the search path was fixed, then there would not be much point in discussing it. Fortunately, since `PATH` is an environment variable, you can change it, and `bash` will begin to use the new version of `PATH` on the very next command you type. Before showing you how this is done, why might we want to change `PATH`?

We've previously discussed the `/usr/local` branch of the file system as a place where site-specific programs are typically installed on your system. You really wouldn't want to put these programs in `/usr/bin`, since the next release of the operating system would require you to remember all of the non-standard programs that you placed in `/usr/bin` so that you could reinstall them. Sometimes you want a site-specific version of one of the standard programs, and whenever that program is invoked, you want the site-specific version to be found instead of the standard one. And, finally, you might want to have a number of your own programs (it is very easy to do) that you use regularly, and you want `bash` to be able to find them in the same way.

Note that the search performed by `bash` goes from left to right in the sequence of directories that make up `PATH`. Thus, if you want to find your version of `ls` instead of the one stored in `/usr/bin`, then your version will have to be in a directory that is earlier in `PATH` than `/usr/bin`. Let's experiment with this a bit.

```
$ mkdir ~/bin             let's create a personal bin directory
$ cp /usr/bin/ls ~/bin    make a copy of ls in that directory
$ sudo cp /usr/bin/ls /usr/local/bin  make a copy in /usr/local/bin
[sudo] password for me:   type your password, followed by Enter; no echo
$ ls -l ~/bin/ls /usr/local/bin/ls /usr/bin/ls
-rwxr-xr-x 1 me   me   130552 Jul 12 15:11 /home/me/bin/ls
-rwxr-xr-x 1 root root 130552 Mar 12 07:09 /usr/bin/ls
-rwxr-xr-x 1 root root 130552 Jul 12 15:10 /usr/local/bin/ls
$ PATH=/usr/bin:/bin      set path to just /usr/bin and /bin
$ which ls
/usr/bin/ls               found it in /usr/bin
$ PATH=/usr/local/bin:$PATH             insert /usr/local/bin at the front
$ which ls
/usr/local/bin/ls         found it in /usr/local/bin
$ PATH=~/bin:$PATH        insert ~/bin at the front
$ which ls
/home/me/bin/ls           found it in ~/bin
$ rm ~/bin/ls             remove copy from ~/bin
$ which ls
/usr/local/bin/ls         found it in /usr/local/bin
$ sudo rm /usr/local/bin/ls             remove copy from /usr/local/bin
[sudo] password for me:
$ which ls
/usr/bin/ls               found it in /usr/bin
$ echo $PATH
/home/me/bin:/usr/local/bin:/usr/bin:/bin
```

Only two tricky things in this exercise:

- as can be done in most programming languages, we can define a new value for a variable in terms of its previous value; thus, the expression `PATH=/usr/local/bin:$PATH` causes the shell to append the current value of `PATH` (`$PATH`) to the string `/usr/local/bin:`, and to assign the concatenated string as the new value of `PATH`; and
- there is a command available in Linux, `sudo`, that allows you to become the root user to exercise one command; if you perform `ls -dl /usr/local/bin`, you will see that it is owned by the `root` user, and you do not have write permission to that directory; by using the `sudo` command, you can perform the requested command (first `cp` to create the copy there, and later `rm` to remove the copy) as if you were the root user; the Debian Linux virtual machine knows that your account (`me`) is permitted to use `sudo`, all you need to do is type your password to be able to perform the command.

2.6.2 Input, output, error output

So far, we have focused on typing commands on the keyboard to the shell, the shell parses each command to determine which program to run, it creates a process to run that program, and the shell makes the arguments and the environment available to that program. The shell then waits for that program to finish before prompting the user for another command. All of our examples so far take some action and output the results to the screen; if a program detects something wrong, it displays an error message on the screen. Computers would be not nearly as useful to us if this was all that could be done.

When a program comes to life, three data channels are defined:

- standard input - this is the default channel from which the program can read data; it is normally the keyboard;
- standard output - this is the default channel to which the program can write results of its processing; it is normally the terminal window; and
- standard error output - this is the default channel to which the program can write error messages; it is normally the terminal window.

The shell sets up these standard channels for a program when it starts it in a process. Thus, the shell is in a position to *redirect* these channels to files or other objects in the system.

2.6.2.1 Input redirection

First, let's focus on taking our input from a file instead of the keyboard; consider the following example.

```
$ cd                      make sure we are home
$ cat shopping.list       reacquaint ourselves with shopping.list
1 bottle of milk
2 granny smith apples
3 hot house tomatoes
1 six-pack of Coca Cola
$ cat                     invoke without a filename
line 1                    you type this
line 1                    cat echoes the line
ctl-d                     you type this to indicate end-of-file
$ cat <shopping.list      what is this?
1 bottle of milk          we obtain the same results as before
2 granny smith apples
3 hot house tomatoes
1 six-pack of Coca Cola
```

There are several things going on here that make this work:

- when `cat` is invoked, if any file arguments are supplied, it copies the contents of those files to the terminal window;
- if invoked without any file arguments, it copies the standard input to the terminal window;
- in the examples above where `cat` was invoked without arguments, the standard input was the keyboard; thus, you had to type on the keyboard to provide `cat` with characters that it could write to the terminal window; note that *ctl-d* is the character to type at the keyboard to indicate an end of file;
- in the second case above, the shell interpreted `<shopping.list` to mean that standard input for `cat` should come from `shopping.list`, not from the keyboard; it resets standard input for `cat` to be from the file *and* removes `<shopping.list` from the set of arguments made available to `cat`;
- `cat` doesn't care, as it has been invoked without any arguments, so it simply reads from standard input until an end of file is detected.

Thus we see that `bash` interprets yet another special character, `<`, to indicate that the standard input for the program should come from a file rather than from the keyboard. This redirection occurs without *any* knowledge on the part of the program (`cat` in this case). Correct behavior does demand that the program read from standard input if it has not received any file arguments.

> Some programs, such as `cat`, understand an argument consisting solely of a hyphen (-) to mean that it should also read from the standard input, as in `cat file1 - file2` - i.e., copy contents of `file1` to the terminal window, then copy the contents from standard input to the terminal window, and finally copy contents of `file2` to the terminal window. The man page for a particular command will indicate if a particular program interprets a bare '-' in this way.

2.6.2.2 Output redirection

Often one would like to capture the output of a program into a file, not have it displayed in the terminal window; in fact, in creating this textbook, a large number of files have been generated in this way in order to show you the actual interaction dialogs that occur on the system. Let's consider the following example:

```
$ echo '$ ls -l'; ls -l  show command and output
$ ls -l
total 24
drwxrwxr-x 2 me me 4096 Jul  6 14:59 book
-rw-rw-r-- 1 me me  141 Jul  6 14:59 calendar.data
drwxrwxr-x 2 me me 4096 Jul  6 14:59 Music
drwxrwxr-x 2 me me 4096 Jul  6 14:59 Pictures
-rw-rw-r-- 1 me me   86 Jul  6 14:59 shopping.list
drwxrwxr-x 2 me me 4096 Jul  6 14:59 src
$ echo '$ ls -l' >tmp.out where is the output?
```

```
$ ls -l >>tmp.out          and this output?
$ cat tmp.out              maybe it's in here?
$ ls -l                    yes, it is
total 24
drwxrwxr-x 2 me me 4096 Jul  6 14:59 book
-rw-rw-r-- 1 me me  141 Jul  6 14:59 calendar.data
drwxrwxr-x 2 me me 4096 Jul  6 14:59 Music
drwxrwxr-x 2 me me 4096 Jul  6 14:59 Pictures
-rw-rw-r-- 1 me me   86 Jul  6 14:59 shopping.list
drwxrwxr-x 2 me me 4096 Jul  6 14:59 src
```

Thus, we see that there is yet another special character understood by the shell. If it detects an argument of the form `>filename`, it redirects the program's standard output to that file. If it detects an argument of the form `>>filename`, it redirects the program's standard output to the end of that file (i.e., its output is appended to the current contents of the file).

The ability to perform such redirection *again* depends upon each program writing to standard output by default.

It's a bit clunky having to break up our original command line (`echo '$ ls -l'; ls -l`) into separate commands, and appending the output of all but the first command to the file. The shell also understands grouping commands to act as a single "command", such that you can redirect the input or output for the "command" in one go, as in:

```
$ (echo '$ ls -l'; ls -l) >tmp.out group the enclosed commands
$ cat tmp.out
$ ls -l
total 24
drwxrwxr-x 2 me me 4096 Jul  6 14:59 book
-rw-rw-r-- 1 me me  141 Jul  6 14:59 calendar.data
drwxrwxr-x 2 me me 4096 Jul  6 14:59 Music
drwxrwxr-x 2 me me 4096 Jul  6 14:59 Pictures
-rw-rw-r-- 1 me me   86 Jul  6 14:59 shopping.list
drwxrwxr-x 2 me me 4096 Jul  6 14:59 src
```

Parentheses (more special characters) can be used to group the enclosed commands into a single "command", and all of the output, appropriately serialized, can be directed to a file. The way that this is done is that the shell acts as if you had typed the following command:

```
$ bash -c "echo '$ ls -l'; ls -l" >tmp.out
```

i.e., it creates a subshell executing the enclosed commands, with the standard output of that subshell redirected to `tmp.out`. This also shows you that the standard input and standard output of commands executed by a shell in the absence of redirection are the standard input and standard output of the shell, itself.

2.6.2.3 Error redirection

It stands to reason that since we can redirect standard input and standard output, it is likely that we can redirect standard error output, as well. You might think that the right way to do this would be to select another special character, say ☹, and for `bash` to interpret `☹filename` to mean redirect standard error output to `filename`, and to interpret `☹☹filename` to mean to redirect standard error output to the end of `filename`. Unfortunately, `bash` has used up all of the special characters (we have not introduced all of them yet). Instead, `bash` interprets `2>filename` and `2>>filename` to mean that standard error output should be redirected.

Let's look at some examples of standard error output redirection:

```
$ cat Shoping.list                     typo in filename
cat: Shoping.list: No such file or directory
$ cat Shoping.list 2>tmp.err           capture the error message in a file
$ cat tmp.err                          see if it is there
cat: Shoping.list: No such file or directory
$ cat readme.1st 2>>tmp.err            try another non-existent file
$ cat tmp.err                          see if it is there
cat: Shoping.list: No such file or directory
cat: readme.1st: No such file or directory
```

Usually one does not redirect standard error output to a file; instead, we want the error messages to be displayed on the screen so that we can see the error messages as our programs run. Occasionally, especially if a set of commands are all being executed by the shell with the output of the commands redirected to a file, we would also like to see the error messages embedded in the same file so we can see the context in which the errors occur, much as we would (on the screen) if neither output nor error output were redirected. `bash` has a syntax for specifying this, shown below.

```
$ cat shopping.list Shoping.list >tmp.out 2>&1
$ cat tmp.out
1 bottle of milk
2 granny smith apples
3 hot house tomatoes
1 six-pack of Coca Cola
cat: Shoping.list: No such file or directory
```

The non-intuitive expression `2>&1` means redirect standard error output onto the same stream as the standard output (the `1` at the end of the expression).

⚠ The order of the two redirections is important here, as `bash` will process them from left to right; thus, in this case, it redirects standard output to `tmp.out`, then redirects standard error output to wherever standard output is being sent. If you did them in the other order, standard error output would be set to `bash`'s standard output, and then `cat`'s standard output is set to `tmp.out`, not what you wanted at all.

In the same way that standard error output is represented by `2`, standard output is represented by `1`. In fact, we could redirect standard output in the following way:

```
$ cat shopping.list 1>tmp.out
$ cat tmp.out
1 bottle of milk
2 granny smith apples
3 hot house tomatoes
1 six-pack of Coca Cola
```

That is, `digit>` works for each output stream known to `bash`. In this book, we restrict ourselves to standard output (`1`) and standard error output (`2`).

2.6.3 Pipes and multiple processes

In the previous section we described how `bash` performs input, output, and error output redirection. Being able to do so would be pretty useless if commands did not read from standard input by default, write results to standard output by default, and write error messages to standard error output by default. Given that programs do conform to this standard, `bash` can now provide significant expressive and computational power by managing multiple processes and enabling these processes to talk to each other *without knowing that they are doing so*. This is done through an abstraction known as *pipelines*.

Suppose you wanted to know the number of files in a particular directory. How would you do so? One has to invoke `ls` on the directory to access its contents. We could make a special version of `ls` that understood an option `--count`, which would indicate that it would simply print the number of files found in each directory specified on the command line. `--all` could also be specified with this new option, indicating that hidden files that start with a period (`.`) would also be counted. Seems reasonable so far.

We already have `wc` which will count lines, words, and characters in a file. If there was some easy way to put the output of `ls` into a file, and then have `wc` take its input from that file, we would have a solution without modifying `ls`. But we just discussed redirection in the last section, so we can already do this! Let's try it on the current directory.

```
$ ls .
book  calendar.data  Music  Pictures  Shopping.List  src  tmp.err  tmp.out
$ ls . >tmp.out
$ wc -w <tmp.out          count the words in tmp.out
8
$ rm tmp.out
```

It is clear that this works. There's the problem that we have to choose a temporary filename for the output that does not collide with one of the files already in the directory (which we did *not* do), that the temporary file will be listed by `ls` (and, thus, be counted by `wc`), and that we have to remember to remove the temporary file after we are done.

Operating systems have long supported the ability for processes running programs to communicate with each other (called *interprocess communication (IPC)*, oddly enough☺). Linux supports several different types of IPC that enable different styles of interaction. In this case, we would like to have a way for two child processes to interact, with one process writing data as if to a file and the other process reading that data, as if coming from a file. Linux provides an abstraction in the operating system called a *pipe* which provides this ability; each pipe has a write end and a read end; if one process is given the write end, and another the read end, the two processes interact without knowing that a process is on the other end.

☞ In the same way that we discussed parent/child relationships between directories and files, when `bash` creates a process to run your command, it is the process's parent, and the process is `bash`'s child.

`bash` is already able to redirect input, output, and error output. So, if it knows you wanted to plumb your two processes together, it could ask the operating system for a pipe, redirect one process's standard output to the pipe, and the redirect the other process's standard input to the pipe. As you might have guessed, `bash` has another special character that indicates the need for plumbing two processes together.

```
$ ls .
book  calendar.data  Music  Pictures  Shopping.List  src  tmp.err
$ ls . | wc -w
7
```

This works exactly as intended. Note that we removed `tmp.out` in our previous example, so there are only `7` files in the directory.

A vertical bar (`|`) is the special character that separates the communicating programs. `bash` reads everything up to a semicolon or the end of line, then breaks that line up into individual commands separated by `|` characters. It then creates a pipe for each `|` symbol, and redirects standard output for the command to the left of the `|` to the pipe, and the standard input for the command to right of the `|` to the pipe. After starting each of these processes, it waits for each of them to complete.

Note that pipelines are only concerned with standard output and input; they do not affect standard error output. If you need to have both the output and error messages go through a pipe, the previous syntax continues to work:

```
$ cat shopping.list Shoping.list 2>&1 | more
1 bottle of milk
2 granny smith apples
3 hot house tomatoes
1 six-pack of Coca Cola
cat: Shoping.list: No such file or directory
```

As described above, `bash` first looks for pipe symbols (`|`) in each line that it reads, redirecting the left process's standard output to the pipe, and redirecting the right process's standard input to the pipe. It then processes any other IO redirection for each command. Thus, in the above example, `cat`'s standard output is already set to the pipe, and the `2>&1` is interpreted to mean that `cat`'s standard error output is to be redirected to the same place as standard output - in this case, to the pipe.

A common use of this mixing of output and error messages on a pipe is when you wish to observe the programs in action *and* you want to capture the blended output in a file. The program `tee` copies its standard input to its standard output, as well as to each of the files in its argument list.

```
$ command [arguments, if any] 2>&1 | tee log
```

will cause `command` to run and display its output and error output in the terminal window, as if it was not being piped into `tee`. When the command is finished, `log` will have an exact copy of the output and error messages, in context, as well. This is often used when marking programming projects, as it enables the marker to observe the student's program under test as well as to capture a log to give to the student as part of the assessment.

Exercise 2.6. Suppose that you have been asked to determine the frequency of words used in a file. We could write a program, say in Python or C, to perform this task. Fortunately, with the standard programs available in Linux and with `bash`'s support of pipes, all one has to type is a single pipeline command to `bash`.
We know from Section 2.4.7.2 that we can use `tr` to break up a file into one word per line. We also know from Section 2.4.7.5 that we can use `sort` to sort a file. We also know from Section 2.4.7.3 that we can use `uniq` to count the number of successive matching lines in a file. This is all we need for our pipeline.
Recall that the following command places each word in the standard input on its own line.[a]

```
$ tr -s '[:blank:]' '\n'
```

If `sort` is invoked without filename arguments, it sorts the standard input lexicographically (as characters).
Finally, if presented with a sorted file on standard input, `uniq` replaces each sequence of identical lines by a single copy of that line on standard output; if the `-c` option has been specified, it precedes that line by the number of identical lines in that sequence.

Therefore, given a file `document`, the following pipeline will produce the frequency of each word in the document.

```
$ tr -s '[:blank:]' '\n' <document | sort | uniq -c
```

- As discussed in Section 2.4.7.3, `uniq` is case sensitive, such that "this" and "This" would be considered separate words. Add another invocation of `tr` to the pipeline above to eliminate this artefact.
- The pipeline above outputs the results according to the sort order of the words. It is more likely that you wish to see the words by frequency, from high to low. Add another invocation of `sort` to the pipeline above to present the output by frequency, from highest to lowest.
- Our definition of a "word" means that punctuation is included in a word - e.g., the last word in "I must go to the store." is "store.". Add another invocation of `tr` to the pipeline above so that punctuation characters *and* white space characters delimit words.

[a] In this case, a "word" is a sequence of non-whitespace characters, separated from other words by a blank, tab, or end of line.

2.6.4 Shell scripts

`bash` is actually programmable, itself. We can assemble several commands to `bash` in a file, and then request that `bash` execute those commands; such a file containing `bash` commands is called a *shell script*.

Besides executing canned commands, we can pass arguments to a shell script, can perform conditional and looping actions in the script, and many other things. This section describes the simplest things you can do in a shell script; for more detail, see `https://www.tutorialspoint.com/unix/shell_scripting.htm`.

2.6.4.1 A simple example

Suppose that upon changing your working directory, you nearly always invoke `pwd` to make sure that you have ended up in the right place, and you nearly always invoke `ls` to see what files are in that directory. Let's create a file named `pwdandls`.

```
$ cd
$ pwd; ls
/home/me
bin   book  calendar.data  Music  Pictures  shopping.list  src
$ echo 'pwd; ls' >pwdandls
$ bash pwdandls
/home/me
bin   book  calendar.data  Music  Pictures  shopping.list  src
```

As we can see, if we invoke the command `bash pwdandls` to the shell in our terminal window, it invokes another process running the `bash` program, which executes the commands it finds in `pwdandls`.

Recall from section 2.4.3 that `ls -l filename` lists the metadata about the file named `filename`. Let's do that with `pwandls`.

```
$ ls -l pwandls
-rw-r--r-- 1 me me ... pwandls
```

As described in section 2.4.3, the first 10 characters of the output from `ls` indicate that `pwandls` is a regular file, the owner (me) has read and write access but not execute access, the group (me) has read access but not write and execute access, and the rest of the world has read access but not write and execute access.

There is a command, `chmod` that you can invoke to change the protections on one or more files. For example,

```
$ chmod +w pwandls
$ ls -l pwandls
-rw-rw-rw- 1 me me ... pwandls
```

causes the file to be writable by owner, group, and world.

For a shell script like `pwandls`, we can make it executable by owner, group, and world with a command of the form:

```
$ chmod +x pwandls
```

After doing this, we can invoke `pwandls` as

```
$ ./pwdandls
/home/me
bin   calendar.data  Pictures       src
book  Music          shopping.list
```

This works fine if the file `pwdandls` is in the current directory; since we like to do this no matter where we are in the directory structure, and assuming that we have added `~/bin` to our search path, we can move our script file into `~/bin`, and can then invoke it anywhere.

```
$ mv pwandls ~/bin
$ cd book
$ pwandls
/home/me/book
book.tex  ch00  ch01  ch02  Outline.pdf  Outline.synctex.gz  Outline.tex
```

2.6.4.2 Arguments to scripts

We have already seen that `bash` supports environment variables; if the variable name is `NAME`, then we can produce the value assigned to that variable by specifying `$NAME`. When a script is invoked with arguments, `bash` leverages this `$` syntax to obtain the arguments.

Let's change `pwdandls` to take an argument which are options to be used in the `ls` invocation.

```
$ cd
$ echo 'pwd; ls $1' >~/bin/pwdandls
$ pwdandls
/home/me
bin   calendar.data  Pictures       src
book  Music          shopping.list
$ pwandls -a
/home/me
.   .bashrc   .vimrc  calendar.data  Pictures  src
..  .profile  bin     book           Music     shopping.list
```

Note that the `ls` command in `pwdandls` has been changed to `ls $1`; this tells `bash` that it should replace `$1` by the first argument word that followed the invocation of `pwdandls`. In the first example, `pwdandls` was invoked without an argument, so `$1` was replaced by the empty string. In the second example, it was invoked with an argument of `-a`; thus, `ls -a` was invoked, and the files in the directory that started with `.` are listed.

Obviously, there can be up to 9 arguments to a script, referred to as `$1` through `$9`. There are also other special things that one can do with arguments that are beyond the scope of this discussion.

2.6.4.3 Simple flow control

The scripting language supported by `bash` is a reasonably complete language. Here, we will cover the three most frequently used flow control structures supported by this language.

The `for` - `do` - `done` statement `bash` understands a `for` flow control construct that enables a sequence of commands to be executed for each of a number of values. The best way to motivate this is through a simple example:

```
$ # place the following three lines in a file named sloop
for v in 1 2 3 4 5; do
    echo $v-th time through the loop
done
$ chmod +x sloop
$ ./sloop
1-th time through the loop
2-th time through the loop
3-th time through the loop
4-th time through the loop
5-th time through the loop
```

From this we can see that the essence of the for loop is for a variable (in this case `v`) to take on first the value 1, then 2, ..., then 5; within the loop, `$v` is the current value of the variable.

Often, one has multiple items, one per line, in a file; there is a feature of `bash` that is particularly useful if you want to have those items used by a `for` loop.

As always, let's look at an example.

```
$ echo -e "word1\nword2\nword3" >mylist
$ cat mylist
word1
word2
word3
$ echo `cat mylist`
word1 word2 word3
$ echo $(cat mylist)
word1 word2 word3
```

What just happened here? We used `echo` with the `-e` flag to create `mylist` consisting of three lines; that is what the first `cat` command shows us. What does `` `cat mylist` `` do? What does `$(cat mylist)` do?

In both cases, the shell runs `cat`, capturing its output. It then constructs a single string from all of the lines in the output, replacing all newline characters with spaces. The resulting set of blank-separated words are then passed to `echo` as its arguments, and it dutifully displays the arguments on standard output with a blank between each pair of arguments. It is not often that `bash` provides two syntaxes for the same feature; the `` `...` `` syntax is maintained for backward compatibility to previous shells, while the `$(...)` syntax is preferred.

It should be readily apparent that this ability to create arguments from the output of programs can be readily used in the `for` syntax. For example, when I am marking project submissions, I usually have a file named `students` with the names of students who have submitted the project. I then can mark each submission using a `for` loop as follows:

```
$ for s in `cat students`; do
>    read -p "$s? "
>    # commands to mark the project submission from that student
> done
```

The `read` command simply prints the prompt, waiting for me to hit ENTER. Although this discussion is taking place in a section about scripts, I have shown the sequence above as I typed it to `bash`, showing the continuation prompts from bash until the command is complete.

The `case - esac` statement `bash` understands a `case` flow control construct that enables one to take different actions depending upon the value of a variable. This is different from the `for` construct, in which the same actions are taken as the value of a variable changes.

Again, the best way to motivate this is through a simple example. The previous example using the `for` construct violated standard English usage, since it should have stated 1-st, 2-nd, and 3-rd in its output. We can put this right by including a `case` construct within the commands inside of the `for` loop. The `cat` invocation shows you the modified implementation of `sloop`.

```
$ cat sloop
for v in 1 2 3 4 5; do
x="$v-th"
case $v in
    1) x="1-st"
       ;;
    2) x="2-nd"
       ;;
    3) x="3-rd"
       ;;
esac
echo $x time through the loop
done
$ ./sloop
1-st time through the loop
2-nd time through the loop
3-rd time through the loop
4-th time through the loop
5-th time through the loop
```

We can see that the value of `v` is compared with the values that precede the right parenthesis; if a match is found, all of the commands starting with that line are executed until `;;` is seen, or `esac` is reached. With this change, the English grammar police are now happy with our script.

The `if - then - else - fi` statement `bash` understands an `if` flow control construct that enables simple if .. then .. else processing. Again, we will motivate its use by a simple, if silly, example. The `cat` invocation shows you `weather`, a silly script for telling you what to do based upon the current temperature.

```
$ cat weather
if [[ $1 -ge 72 ]]; then
    echo off to the beach ':-)'
else
    echo stay at home ':-('
fi
$ chmod +x weather
$ ./weather 99
off to the beach :-)
$ ./weather 55
stay at home :-(
```

The syntax for the conditions used in an `if` statement are described at `https://linuxacademy.com/blog/linux/conditions-in-bash-scripting-if-statements/`.

2.7 Compression and file packaging

It is not uncommon to need to share an entire directory of files with another user, on a different machine. The mechanism by which such inter-machine sharing is achieved is beyond the scope of this book. The mechanism by which you package such files before you share them is an important aspect of Linux use, so we will cover the basics here.

Consider the directory tree shown on page 27. Here, we will use another standard program, `find`, which will perform commands on all files in a directory tree; the following will print the name of each file found in the tree rooted at `CaDS`:

```
$ find CaDS -print
CaDS
CaDS/book.tex
CaDS/ch00
CaDS/ch00/Preface.pdf
CaDS/ch00/Preface.synctex.gz
CaDS/ch00/Preface.tex
```

```
CaDS/ch01
CaDS/ch01/ch01.pdf
CaDS/ch01/ch01.synctex.gz
CaDS/ch01/ch01.tex
CaDS/ch02
CaDS/ch02/adm3a.jpg
CaDS/ch02/ch02.pdf
CaDS/ch02/ch02.synctex.gz
CaDS/ch02/ch02.tex
CaDS/ch02/dir.out
CaDS/ch02/me
CaDS/ch02/me/20170706-shopping.list
CaDS/ch02/me/book
CaDS/ch02/me/calendar.data
CaDS/ch02/me/Music
CaDS/ch02/me/Pictures
CaDS/ch02/me/shopping.list
CaDS/ch02/me/src
CaDS/ch02/me.tgz
CaDS/ch02/model33teletype.jpg
CaDS/Outline.pdf
CaDS/Outline.synctex.gz
CaDS/Outline.tex
```

Definitely a less informative representation than the figure on page 27 ☺.

There are a number of ways that we could share each of these files with other individuals (or ourselves) on another machine that does not share this file system: by attaching each file to an email message, by using a network file transfer program (such as `scp` or `ftp`), or by copying each file to a cloud storage provider (such as DropBox, Apple's iCloud, or Microsoft's OneDrive). While this one-file-at-a-time approach would work, it does not make it easy to share all the files at once in an easy and consistent way. A better way would be to make a new file that contains the contents of all of the other files along with meta-information about each contained file so that the individual files can be extracted at the other end. You have probably used ZIP files for such things in your previous computer experience.

2.7.1 `tar`

The `tar` program packages many files together into a single disk file (often called an *archive*), and can restore individual files from the archive. `tar` is named after **t**ape **ar**chive, as it was initially created to move files to/from magnetic tapes.

Let's create an archive of the files in the `CaDS` directory:

```
$ tar -cvf CaDS.tar CaDS | column
CaDS/                                   CaDS/ch02/dir.out
CaDS/book.tex                           CaDS/ch02/me/
CaDS/ch00/                              CaDS/ch02/me/20170706-shopping.list
CaDS/ch00/Preface.pdf                   CaDS/ch02/me/book/
CaDS/ch00/Preface.synctex.gz            CaDS/ch02/me/calendar.data
CaDS/ch00/Preface.tex                   CaDS/ch02/me/Music/
CaDS/ch01/                              CaDS/ch02/me/Pictures/
CaDS/ch01/ch01.pdf                      CaDS/ch02/me/shopping.list
CaDS/ch01/ch01.synctex.gz               CaDS/ch02/me/src/
CaDS/ch01/ch01.tex                      CaDS/ch02/me.tgz
CaDS/ch02/                              CaDS/ch02/model33teletype.jpg
CaDS/ch02/adm3a.jpg                     CaDS/Outline.pdf
CaDS/ch02/ch02.pdf                      CaDS/Outline.synctex.gz
CaDS/ch02/ch02.synctex.gz               CaDS/Outline.tex
CaDS/ch02/ch02.tex
```

The options to `tar` that we have used have the following meanings: `-c` means create an archive, `-v` means write the name of each file on standard output as it is added, and `-f filename` means to create the archive in `filename`. As you can see, `tar` allows you to collect all options into a single argument; since `f` is included in the option argument, the name of the archive file to be created must immediately follow `-cvf`. The filename arguments for inclusion can either be regular files, or the name of a directory; in the latter case, all files contained in the directory are included in the archive; if an included file is a directory, then its contents are also included in the archive. Note that we have used another Linux command, `column`, to pack the list of file and directory names into columns across the screen to more efficiently use the vertical space in the book; if we had not piped the output of `tar` into `column`, each filename would have appeared on a separate line.

Suppose I have received `CaDS.tar` from someone, and it is currently stored in `/home/jsven`. To check the contents of the archive, I can say

```
$ tar -tf CaDS.tar | column
CaDS/                                   CaDS/ch02/dir.out
CaDS/book.tex                           CaDS/ch02/me/
CaDS/ch00/                              CaDS/ch02/me/20170706-shopping.list
CaDS/ch00/Preface.pdf                   CaDS/ch02/me/book/
CaDS/ch00/Preface.synctex.gz            CaDS/ch02/me/calendar.data
CaDS/ch00/Preface.tex                   CaDS/ch02/me/Music/
CaDS/ch01/                              CaDS/ch02/me/Pictures/
CaDS/ch01/ch01.pdf                      CaDS/ch02/me/shopping.list
CaDS/ch01/ch01.synctex.gz               CaDS/ch02/me/src/
CaDS/ch01/ch01.tex                      CaDS/ch02/me.tgz
CaDS/ch02/                              CaDS/ch02/model33teletype.jpg
CaDS/ch02/adm3a.jpg                     CaDS/Outline.pdf
```

```
CaDS/ch02/ch02.pdf                       CaDS/Outline.synctex.gz
CaDS/ch02/ch02.synctex.gz                CaDS/Outline.tex
CaDS/ch02/ch02.tex
```

The `-t` command to `tar` indicates that I want to see a table of contents. Again, we have used `column` to pack the output into columns.

If I execute the following:

```
$ tar -tvf CaDS.tar CaDS/ch02/ch02.tex
-rw-r--r-- me/me   94095 2017-07-14 11:28 CaDS/ch02/ch02.tex
```

I see a verbose listing about `CaDS/ch02/ch02.tex`. It looks very similar to the output of `ls -l`, in that it shows each file's protections, owner/group, size, modification date, and its name.

If I want to extract all of the files into my home directory, I would say the following:

```
$ tar -xf CaDS.tar
```

I can check to see that it has worked by executing

```
$ ls CaDS
book.tex  ch00  ch01  ch02  Outline.pdf  Outline.synctex.gz  Outline.tex
```

Sometimes you want to extract a particular file onto the standard output. This can be achieved using the following command:

```
$ tar -xOf CaDS.tar CaDS/ch01/ch01.tex >chapter1.tex
```

There are many other options supported by `tar`. See `tar(1)` for more information.[12]

2.7.2 Compression

Files on a computer system often have a significant amount of redundancy in them, such that they occupy more space than is theoretically required to represent the contained information. Linux provides the following tools for performing compression/inflation using Lempel-Ziv coding (LZ77) to remove redundancy:

- `gzip` encodes the content of a file using Lempel-Ziv coding;
- `gunzip` decodes an encoded file, producing the original file; and
- `zcat` decodes an encoded file, producing the original file on the standard output.

[12] This indicates that you should look at the man page for `tar` in section 1 of the Linux users manual. This can be achieved using a browser, as indicated earlier in the chapter, or by typing `man 1 tar` to the shell.

The default behavior of `gzip` is to replace each file argument by an encoded file with an extension of `.gz`, while keeping the same ownership modes, access, and modification times. For example,

```
$ cp shopping.list sl.1      make a file to compress
$ gzip sl.1                  Encode sl.1 to sl.1.gz, remove sl.1
```

The default behavior of `gunzip` is to replace each file argument with an extension of `.gz`, by an unencoded file with the `.gz` removed from the name while keeping the same ownership modes, access, and modification times. For example,

```
$ gunzip sl.1.gz             Unencode sl.1.gz to sl.1, remove sl.1.gz
```

The default behavior of `zcat` is to unencode each file argument with an extension of `.gz`, respectively, and write the unencoded content to standard output. For example,

```
$ zcat sl.1.gz              Unencode sl.1.gz, writing contents to standard output
```

The most common use of these types of tools is for very large data files. The principle use of compression technologies is in conjunction with file packaging tools for files that are to be exchanged. These are described in the next section

2.7.3 Compression and File Packaging

2.7.3.1 `gzip` and `tar`

We described the use of `tar` in section 2.7.1 to create `tar` archives and to extract files from `tar` archives. We also described in section 2.7.2 the use of `gzip` to compress files. Therefore, you can easily create a compressed `tar` archive by using `tar` and `gzip` as follows:

```
$ tar -cf CaDS.tar CaDS; gzip CaDS.tar
```

After completing these commands, you will be left with a file `CaDS.tar.gz`, and `CaDS.tar` will have been deleted. To access the files in the compressed archive, you will need to execute

```
$ gunzip CaDS.tar.gz; tar -tf CaDS.tar
```

Remember that the `gunzip` invocation deletes the `CaDS.tar.gz` file. While this approach works, it suffers from several deficiencies:

- The constant conversion from uncompressed to compressed and back again represents significant wasted computational resources.

- During `gzip` and `gunzip` processing, both uncompressed and compressed versions of the `tar` archive are resident on the disk.
- If the long-term stored form of the `tar` archive is the compressed form, having to convert back to uncompressed for *any* access is unintuitive, at best.

Fortunately, `tar` can compress and uncompress as part of its processing. The `-z` option tells `tar` to create a compressed archive during creation and file addition, and to uncompress the data in a compressed archive when extracting files or listing its contents.

The commands:

```
$ tar -zcf CaDS.tar.gz CaDS
$ tar -ztf CaDS.tar.gz
$ tar -zxf CaDS.tar.gz CaDS/ch01/ch01.tex
$ tar -zxOf CaDS.tar.gz CaDS/ch01/ch01.tex >chapter1.tex
```

creates a gzipped `tar` archive containing the files in the `CaDS` directory, lists the table of contents of the archive, extracts a particular file from the archive into the current working directory, and extracts a particular file from the archive onto standard output, respectively.

Gzipped `tar` archives are so prevalent in Linux systems that such an archive is usually named with a `.tgz` extension, as in

```
$ tar -zcf CaDS.tgz CaDS
```

We will use the `.tgz` extension in the rest of the book when we have need for a gzip'ed `tar` archive.

2.7.3.2 `zip` and `unzip`

While use of `tar` to create compressed archives is the predominant method on Linux for creating compressed packages of files, there is another method which you may find useful, especially if you are exchanging packages with non-Linux systems. If you have encountered ZIP files in your previous computer use, you will know that a ZIP archive is similar to a compressed `tar` archive; the contents have been compressed such that some of the redundancy in the contained files has been *squeezed* out in the archive. To extract one or more files from the ZIP archive, you need a program that can also uncompress the data as it is extracted.

Linux provides the `zip` and `unzip` commands for creating ZIP archive files and extracting files from a ZIP archive, respectively. The following dialog shows use of `zip` and `unzip` to create, list, extract to standard output, and extract the contents of an archive `example.zip`. It assumes that we have a directory named `tmp` in the current working directory.

```
$ ls tmp
cat   cat.c   tento6.txt
$ zip example.zip tmp/*
  adding: tmp/cat (deflated 70%)
  adding: tmp/cat.c (deflated 36%)
  adding: tmp/tento6.txt (deflated 80%)
$ unzip -l example.zip
Archive:  example.zip
  Length      Date    Time    Name
---------  ---------- -----   ----
     8710  2016-08-30 12:44   tmp/cat
      327  2016-08-30 12:43   tmp/cat.c
 46301948  2016-08-30 12:44   tmp/tento6.txt
---------                     -------
 46310985                     3 files
$ unzip -p example.zip tmp/cat.c >mycat.c
$ unzip -o example.zip
Archive:  example.zip
  inflating: tmp/cat
  inflating: tmp/cat.c
  inflating: tmp/tento6.txt
```

This creates `example.zip` containing all of the files in `tmp` using a different (from `gzip`) adaptive Lempel-Ziv encoding. As each file is added, `zip` prints the size of the file, the compressed size, and the percentage of compression on standard output. The `unzip -l` command enables you to determine the contents of an archive. The `unzip -p` command enables you to extract a member of the archive to standard output; in this case, we redirect standard output to `mycat.c`. Finally, to extract the entire contents of an archive, you invoke `unzip archive-name`; the files are extracted into the current working directory; if a filename includes a directory name (e.g., `tmp/cat.c`), the file will be extracted into that directory; the directory will be created if it does not exist. If a file already exists, `unzip` will prompt you about each file unless you have specified the `-o` option, which indicates it should overwrite existing files without prompting.

2.7.3.3 A professional way to create a gzipped `tar` archive

As described in section 2.7.3.1, you can create your TGZ archive using a command of the form:

```
$ tar -zcvf archive-name.tgz file1 file2 file3
```

This a lot to type, and it often happens that one forgets to include the archive name argument, in which case `file1` will be overwritten with a gzip-compressed tar archive of `file2` and `file3`. Definitely not what you want to have happen!

A *manifest*, customs *manifest* or cargo document is a document listing the cargo, passengers, and crew of a ship, aircraft, or vehicle, for the use of customs and other officials. In software terms, a manifest is a list of files that should be included in an archive.

Let's assume that all of the files that you want to put into your archive are located in the current directory, and they are named `file1`, `file2`, and `file3`. Furthermore, let's assume that you want to place these files into an archive named `archive-name.tgz`.

Now let's create a file named `manifest` in the current directory using the following `echo` command[13]

```
$ echo -e "file1\nfile2\nfile3" >manifest
$ cat manifest
file1
file2
file3
```

Armed with the `manifest`, `file1`, `file2`, and `file3` files, creation of the TGZ file becomes

```
$ tar -zcvf archive-name.tgz $(cat manifest)
```

As described in section 2.6.4.3, the `$(cat manifest)` expression causes the shell to invoke `cat` on the file named `manifest`; instead of displaying the contents on the standard output, the output from `cat` is captured by the shell, and it merges all of the lines into a sequence of blank separated words; this merged list then provides the additional arguments given to `tar`.

2.8 Summary

This chapter has introduced you to the Linux system as experienced by a user.

It started off discussing the basic features of the shell, how commands are initiated and provided arguments, and presented a number of basic commands that will enable you to get started using the system. As we discuss C programming in a later chapter, we will introduce additional programs that are needed to develop software written in C for use on Linux (and other Posix-compliant systems).

We then moved on to discuss the major aspects of the file system, and the most important directories in the file system for a software developer.

Armed with knowledge of the file system, we then returned to additional features of the shell that enable sophisticated use of the shell.

[13] Of course, you could create this file using your editor, as well.

Finally, we described how to create files (archives) that contain other files for sharing with other users, both in uncompressed and compressed formats.

The C Programming Language

This section of the book focuses on C programming on Linux, tools provided to facilitate that programming, and a well-structured approach to constructing Abstract Data Type implementations in C. We assume that you have sound knowledge of imperative and object-oriented programming in Python, albeit using an Integrated Development Environment (IDE) like IDLE or PyCharm. Appendix D reviews the primary elements of Python programming with which you should be comfortable.

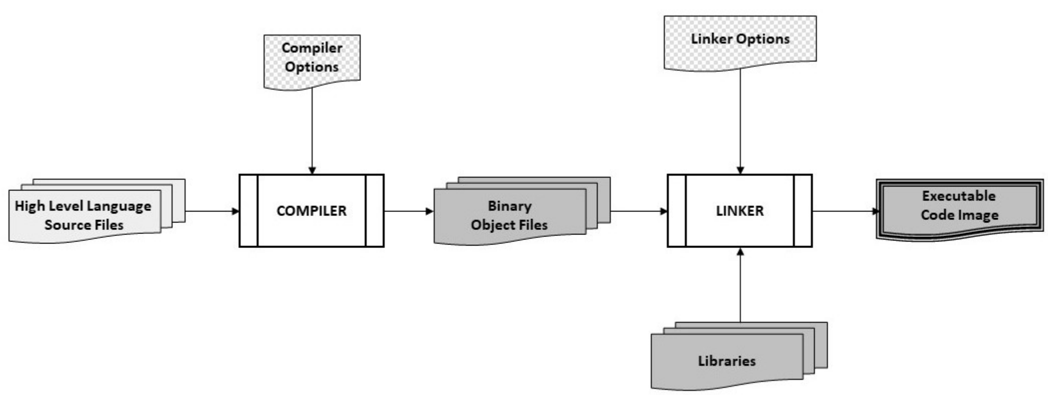
We first describe the program development cycle used in Linux to develop programs written in C and the overall structure of a C program. Subsequently we delve into aspects of C necessary to understand and exploit basic data structures, the ultimate goal of the book. This is followed by a discussion of two important tools to support C program development: `gdb` and `valgrind`. We finish by describing a well-structured approach to constructing Abstract Data Type implementations in C.

Chapter 3

C programming on Linux

3.1 The edit-compile-link-execute (ECLE) cycle

Some programming languages are interpreted - Python is an example. You present blocks written in Python to the interpreter; it interprets the code, executing as it goes along. C and many other programming languages are *not* interpreted.



A programmer using these languages must perform the following steps:

- use an **E**ditor or other tools to generate one or more files containing program fragments in that language; these are called *source* files;
- **C**ompile/transform each of these files from source to a more binary representation; the tool used to perform this transformation is called a *compiler*, and the binary representation for each source file is called an *object* file;

- **L**ink together each of the object files, along with any code needed from system libraries, into a single executable program file; and, finally,
- **E**xecute the program file, with suitable arguments and inputs, to see if it performs correctly.

If the program does not perform correctly, you will need to edit one or more of the source files, compile, link, and execute again. Do this until the program executes correctly; thus, the *ECLE cycle*.

3.1.1 gcc - the C compilation system on Linux

The GNU Compiler Collection is a compilation system that enables you to compile source files written in C, C++, Objective-C, Fortran, Ada and Go. This system has been adopted as part of Linux.

`gcc` is the name of the C compiler on Linux. `gcc` also acts as the linker to create executable program files from object files and libraries of object files. `gcc` has a large number of options, only a few of which we will cover in this book.

Suppose we have a source file named `prog.c` that we have created using our favorite editor. Note that, by convention, C source files have a `.c` extension. Now suppose that we wish to compile `prog.c` into a binary object file. The command needed to do so is:

```
$ gcc -c prog.c
```

The `-c` option tells `gcc` to compile only (`gcc` also performs the link task); if there are no errors in `prog.c`, `gcc` will leave the compilation results in a file named `prog.o`. Note that `.o` is the conventional extension for an object file.

`gcc` can also link object files into an executable program. Assuming that `prog.c` contains all of the user-defined logic needed, then the following command will produce an executable program in a file named `prog`:

```
$ gcc -o prog prog.o
```

Finally, you can execute your program by typing the following command:

```
$ ./prog
```

You may wonder why you have to type `./prog`. Recall that `bash` uses the `PATH` environment variable to find the executable program file corresponding to the command you have typed. If you simply typed `prog`, `bash` would look in each of the directories found in `PATH`. By typing a command with a slash(`/`) in it, `bash` does not search through those directories, instead simply executing the file as typed. And, as we recall from section 2.5.1, the directory `'.'` simply means the current directory, so `./prog` will cause the executable file named `prog` in the current directory to be executed, and the `/` in the name turns off the search by `bash`. Of course, you could add `.` to the front of `PATH`, but this can sometimes cause trouble if you give your program an identical name to one of the standard programs provided in Linux.

Having to invoke `gcc` twice to build `prog` may seem like one invocation too many. In fact, for simple programs like `prog.c`, it can all be done in one command, as in:

```
$ gcc -o prog prog.c
```

The presence of a `.c` file in the argument list causes `gcc` to first compile it into an object file, to then link that object file into the executable program, *and* to then delete the object file.

Most programs will consist of multiple source files, each providing different functionality. As you use the ECLE cycle to debug your program, you seldom change all of the source files at once; usually, you only need to change one source file to resolve the current bug that the program is exhibiting; this requires that you compile that particular source file again, and then link all of the object files together into your executable program file.

If your C source file has language errors, `gcc` will report these errors on standard error output. There are a large number of options to `gcc` that control the reporting of warnings regarding your usage of the C language; some of these warnings are indicative of poor programming practices that will likely lead to your program executing incorrectly. Decades of experience recommend that you specify `-W -Wall` as compilation options when compiling your source files, as these warning options will do a reasonable job of reporting such poor programming practices. Therefore, we **strongly** recommend that your compile command lines look like:

```
$ gcc -c -W -Wall prog.c
```

Section 3.5.6 describes a tool to help you with the ECLE cycle, automating the necessary recompiles and the relink of your program after you have made changes to source files.

3.1.2 What does a compiler and linker do?

When you compile your C source files into the corresponding object files, the compiler places the following information in each object file:

- global names that you are defining in the C source file - these represent functions that code in other source files might invoke, or the names of any global variables for which you have defined storage (declared them) and which might be accessed by code in other source files;
- variable/function names that were not resolved in the C source file - e.g., any functions invoked by the code in this C source file that are not also defined in this source file, or any variables that were declared to be global (through use of `extern` declarations); and

- the machine instructions that implement the C statements in the C source file.

Given this information in each of the object files specified in the link command line, the linker first attempts to match unresolved global names in each object file with global names defined in the other object files.

It then consults libraries to match any remaining unresolved global names in the object files with global names that have been defined in library modules.

If it manages to resolve all global names through this process, it then creates the output file, which is an executable image that can be invoked in `bash`.

If there are any unresolved global names after this process, it will print appropriate error messages about the unresolved global names, and will NOT create the executable image.

3.2 Some simple, example programs

The example programs in this section show how to make a program achieve a set of simple capabilities. We will go into the C language in more detail later in the chapter, but this should give you an idea of how simple it is to get started in C.

When you link together your object files to create an executable program file, one of those object files *must* define a function named `main`. Later, we will describe in detail the meaning of the function signature.

`main()` returns an integer; the return values are two defined symbols in `<stdlib.h>`, `EXIT_SUCCESS` and `EXIT_FAILURE`. We will be using these in the programs that follow.

3.2.1 Hello world!

One of the first things that you usually try to work out when programming in a new language is how to generate output. This program simply prints out "Hello world!" on the standard output. We put the following C source statements into a file named `hello.c`.

```
#include <stdio.h>       /* gives us access to functions for input/output */
#include <stdlib.h>      /* gives us access to EXIT_SUCCESS */
int main(int argc, char *argv[]) { /* we have to define main */
    printf("Hello world!\n");      /* print on standard output */
    return EXIT_SUCCESS;           /* indicates successful execution */
}                                  /* the end of our program */
```

Now let's compile and link this program to produce an executable file named `hello`. If that is successful, we will execute our program.

```
$ gcc -W -Wall -o hello hello.c
hello.c: In function `main':
hello.c:3:14: warning: unused parameter `argc' [-Wunused-parameter]
    3 | int main(int argc, char *argv[]) { /* we have to define main */
      |          ~~~~^~~~
hello.c:3:26: warning: unused parameter `argv' [-Wunused-parameter]
    3 | int main(int argc, char *argv[]) { /* we have to define main */
      |                    ~~~~~~^~~~~~
$ ./hello
Hello world!
$ ./hello >hello.out
$ cat hello.out
Hello world!
$ rm hello.out
```

Admittedly, a very simple program. The `#include <stdio.h>` statement defines the function signature for `printf()`, which is a function that enables programs to write formatted output on standard output; as you know from the previous chapter on Linux, standard output is the terminal window unless the standard output has been redirected, as in the second invocation of `hello` above. The `#include <stdlib.h>` statement defines `EXIT_SUCCESS` for our use in the return statement. The character sequence `\n` in the format string to `printf()` indicates that a newline character should be printed (generates a carriage return and a line feed on the terminal window).

What are the two warning messages from the compiler that immediately follow our `gcc` command to compile and link our program? The signature for `main()` takes two parameters: `argc` and `argv`. We have not used these arguments in our program. Years of experience has shown that if a function argument or a variable is declared but *not* used, it is usually a sign of an error in the program. Warnings about these unused arguments/variables are generated if one specifies `-W -Wall` as options to `gcc`.

`gcc` has provided a set of extensions for specifying attributes in your source code; one of those attributes enables you to indicate that a particular parameter or variable is unused **on purpose**. If you annotate a parameter or variable with this attribute, `gcc` will not issue the corresponding warning, since you have proactively indicated that it will not be used. The attribute to be used to indicate that a function argument is purposely not being used is `__attribute__((unused))`. The preferred way to use this attribute in such a situation is to replace the signature for `main()` as follows.

```
#define UNUSED __attribute__((unused))
int main(UNUSED int argc, UNUSED char *argv[]) {
```

Exercise 3.1. Using your editor, create `hello.c`, compile and link to produce `hello`, and test `hello` using `bash`.

3.2.2 Accessing command arguments

We described in significant detail in the Linux chapter how `bash` makes command arguments available to programs. This is not only true for standard programs provided in Linux, it is also available to your own programs. The arguments that `bash` has collected when your program is invoked are available to your program through the `argv` argument to `main()`. This program simply prints out the arguments, one per line, on standard output. We put the following C source statements into a file named `args.c`.

```
#include <stdio.h>       /* gives us access to functions for input/output */
#include <stdlib.h>      /* gives us access to EXIT_SUCCESS */
int main(int argc, char *argv[]) { /* we have to define main */
    int i;                         /* need a loop variable */
    for (i = 0; i < argc; i++)     /* loop over strings in argv */
        printf("argv[%d] = \"%s\"\n", i, argv[i]); /* print argv[i] = "word" */
    return EXIT_SUCCESS;           /* indicates successful execution */
}                                  /* the end of our program */
```

Now let’s compile and link this program to produce an executable file named `args`. If that is successful, we will execute our program.

```
$ gcc -W -Wall -o args args.c
$ ./args
argv[0] = "./args"
$ ./args a b c
argv[0] = "./args"
argv[1] = "a"
argv[2] = "b"
argv[3] = "c"
$ ./args "a  b  c"
argv[0] = "./args"
argv[1] = "a  b  c"
$
```

This looks like a very verbose version of the `echo` program. We needed to declare an integer loop variable, `i`, so we can loop over the strings in `argv[]`. We can see that `argc` is the number of arguments stored in `argv[]`. The format string to printf has three new items:

- the character sequence `%d` indicates that the next argument to `printf()` should be formatted as a decimal integer;
- the character sequence `%s` indicates that the next argument to `printf()` is a character string and should be inserted at that point; and
- since the `"` character delimits the format string, if we want to embed a `"` in the string to be printed, we need to escape it by specifying `\"` in the format string.

In a subsequent section of this chapter, we will demonstrate a function `getopt()` that helps you process your arguments.

Exercise 3.2. Using your editor, create `args.c`, compile and link to produce `args`, and test `args` using `bash`.

3.2.3 Simple file copy

We described in significant detail in the Linux chapter how `bash` redirects standard input and standard output without the program being aware that this has happened. We can take advantage of this to write a very simple file copy program. We put the following C source statements into a file named `fcopy.c`.

```
#include <stdio.h>       /* gives us access to functions for input/output */
#include <stdlib.h>      /* gives us access to EXIT_SUCCESS */
#define UNUSED __attribute__((unused))
int main(UNUSED int argc, UNUSED char *argv[]) {
    char buf[BUFSIZ];              /* character array to read into */
    while (fgets(buf, BUFSIZ, stdin) != NULL) /* read line from standard input */
        printf("%s", buf);         /* write the line on standard output */
    return EXIT_SUCCESS;           /* indicates successful execution */
}                                  /* the end of our program */
```

Now let's compile and link this program to produce an executable file named `fcopy`; note that since we are not using `argc` and `argv` in the program, we have flagged them as unused. If the compilation and linking are successful, we will execute our program.

```
$ gcc -W -Wall -o fcopy fcopy.c
$ ./fcopy
line 1
line 1
line 2
line 2   # type ctl-d to indicate end of file
$ ./fcopy <hello.c
#include <stdio.h>   /* gives us access to functions for input/output */
#include <stdlib.h>  /* gives us access to EXIT_SUCCESS */
int main(int argc, char *argv[]) { /* we have to define main */
    printf("Hello world!\n";       /* print on standard output */
    return EXIT_SUCCESS;           /* indicates successful execution */
}                                  /* the end of our program */
$ ./fcopy <hello.c >tmp.c
$ diff hello.c tmp.c
$ rm tmp.c
```

```
$ ./fcopy <hello.c | diff - hello.c
$
```

We declared a character array, `buf`, to receive the characters of the next line returned by `fgets()`; if there are no more lines, then `fgets()` returns the value `NULL`. For each line successfully read, we print the line on standard output.

We first show what happens if neither standard input or standard output are redirected; `fcopy` echoes each line read from standard input on standard output; we type *ctl-d* to indicate end of file on standard input.

Next we invoke `fcopy` with standard input redirected to `hello.c`. Since standard output has not been redirected, `fcopy` simply prints each line read onto the terminal screen.

Next we invoke `fcopy` with both standard input and standard output redirected. In this case, `fcopy` simply makes a copy of `hello.c` in a file named `tmp.c`. The invocation of `diff` shows that it is an exact copy. We finish by removing `tmp.c`.

Finally, we show that the prior copy and compare can be achieved with the pipeline shown.

Exercise 3.3. Using your editor, create `fcopy.c`, compile and link to produce `fcopy`, and test `fcopy` using `bash`.

3.3 Variables, types, operators, and expressions

3.3.1 Variable names

The names of variables in C are made up of alphabetic letters, digits, and the underscore (`_`) character. The first character of a name must be a letter or an underscore; you are urged *not* to begin variable names with an underscore as system library routines often use the underscore as the first letter to avoid collisions with names you define. Upper and lower case letters are distinct. Conventional practice is to use all upper case for defined symbolic constants (e.g., `BUFSIZ`). Conventions for variables vary:

- all lower case: in this situation, if you have a variable name with two or more words, use the underscore to separate the words (e.g., `modification_time`);
- mixed case/start lower: for single word variable names, all lower case; for multi-word variable names, use "camel case" - i.e., capitalize the first letter of the 2nd and subsequent words (e.g., `modificationTime`);
- mixed case/start upper: as we shall see in the next chapter, we will capitalize the first letter of each word in the name for an abstract data type (e.g., `PriorityQueue`).

At least the first 31 characters of a variable name are significant (more on Linux, but if you are going to port your programs to other C compilers on other operating systems, the language standard only guarantees 31.) Keywords in the language, such as `if`, `else`, `int`, `float`, ... are reserved words and must be in lower case.

In this book, we will use mixed case/start lower and mixed case/start upper in our examples.

Variables must be declared before they are used. In order to declare variables, we first need to understand the data types that C supports.

Exercise 3.4. Which of these are illegal variable names? How would you change them to be legal?

- _my_professor
- 9Lives
- first-time
- camelCase
- j
- double

□

3.3.2 Basic data types

C has a small number of basic data types:

- `char` - this is a single byte, capable of holding one character in the local character set;
- `int` - this is an integer; there are a number of sizes of both signed and unsigned integer types; and
- `float and double` - floating point numbers (think scientific notation).

Each of these types are described in turn below.

3.3.2.1 Characters

The `char` data type is an 8-bit byte; it holds one character in the local character set. For most Linux systems, the local character set is the ASCII subset of the UTF-8 encoding[1].

A `char` can also be used as an 8-bit integer. This is described in section 3.3.2.2 below.

3.3.2.2 Integers

What do we mean by an integer?[2] We know from mathematics that an integer is a number that can be written without a fractional component. In computer systems, we often talk about signed integers and unsigned integers. The set of unsigned integers

[1] `https://en.wikipedia.org/wiki/UTF-8`

[2] The following text has been adapted from the Wikipedia entry at `https://en.wikipedia.org/wiki/Integer`.

consists of zero (0) and the positive natural numbers $(1, 2, 3, ...)$. The set of signed integers consists of zero (0), the positive natural numbers $(1, 2, 3, ...)$, and their additive inverses (the negative integers, i.e., $-1, -2, -3, ...$).

Mathematically, both sets are closed under addition and multiplication. For computer programming languages like C, where integers are represented in finite sizes that the processor instructions are able to manipulate, these two types of integers satisfy different types of arithmetic.

In the following discussion, we will use w to represent the number of bits that are used to represent an integer. A particular integer then consists of an array of w bits, indexed from 0 up to $w-1$. Each such bit has a value of 0 or 1. If x is such an integer/array, we represent the i^{th} bit/element of the array as x_i.

Unsigned integers For unsigned integers, all w bits are used to represent a power of 2 that contributes to the value of the integer.

Given x as described above, we can represent the value of an unsigned integer x as

$$\sum_{i=0}^{w-1} x_i \cdot 2^i \tag{3.1}$$

Consider the case when w is equal to 8 - i.e., we are using a single byte to represent our integer. In this case, the possible values for such an integer are the closed interval $[0, 255]$. What should happen if we have an 8-bit integer $q = 255$, and we add 1 to it? If we were not limited to 8 bits for representing the result, it would result in 256; unfortunately, 256 cannot be represented in an 8-bit unsigned integer. For unsigned integers, additions always use modular arithmetic - e.g., $q + 1 = (q + 1)\, mod\, 2^w = 0$, since q was already equal to 255, the largest possible value for an 8-bit unsigned integer. Thus, it is important that you choose a large enough value of w when declaring your unsigned integer variables so that you do not encounter this wraparound situation.

Signed integers For signed integers, the highest order bit is the *sign* bit; if the sign bit has a value of 1, the number is negative; if it has a value of 0, then the number is positive. This is called the Two's Complement representation.[3]

Given the definition of x as defined above, we can represent the value of a signed integer x as

$$-x_{w-1} \cdot 2^{w-1} + \sum_{i=0}^{w-2} x_i \cdot 2^i \tag{3.2}$$

Again, consider the case when w is equal to 8 to represent our integers. In this case, the possible values for such an integer are the closed interval $[-128, 127]$. What should

[3]In the early days of computing, there was also a One's Complement representation, used in early CDC and Cray machines; it had the odd feature that there were positive and negative values for 0. Consult `https://en.wikipedia.org/wiki/Ones%27_complement` if your interest is piqued.

Type	unsigned	signed	
		min	max
char	UCHAR_MAX (255)	SCHAR_MIN (-128)	SCHAR_MAX (127)
short	USHRT_MAX (65535)	SHRT_MIN (-32768)	SHRT_MAX (32767)
int	UINT_MAX (4294967295)	INT_MIN (-2147483648)	INT_MAX (2147483647)
long	ULONG_MAX 18446744073709551615	LONG_MIN -9223372036854775808	LONG_MAX 9223372036854775807
long long	ULLONG_MAX 18446744073709551615	LLONG_MIN -9223372036854775808	LLONG_MAX 9223372036854775807

happen if we have an 8-bit signed integer $r = 127$, and we add 1 to it? If we were not limited to 8 bits for representing the result, it would result in 128; unfortunately, 128 cannot be represented in an 8-bit signed integer. If we add 1 to r, it will set the sign bit and clear bits 0-6, yielding a value of -128. Likewise, if we subtract 1 from -128, it will clear the sign bit, yielding a value of 127. Thus, it is important that you choose a large enough value of w when declaring your signed integer variables so that you do not encounter these wraparound situations.

Integer sizes C supports the declaration of integers, both signed and unsigned, of different widths. `char` is used to declare 8-bit integers. `int` is used to declare an integer of the natural size for your processor architecture; it is usually 32-bits in modern computers; many older processors naturally supported 16-bit integers.

`short` and `long` qualifiers apply to integers; for example `short int i` or `long int counter`, or even `long long int packetCount`; note that these examples show how one declares the type of a variable in your program. The name `int` can be omitted when using the `short` or `long` qualifiers.

As described above, the actual precision for an `int` can vary from machine to machine, thus making it hard to write completely portable source code. Thus, the standard has specified that the following are true:

- `char` is always 8 bits of precision;
- `short int` is at least 16 bits of precision;
- `long int` is at least 32 bits of precision; and
- `long long int` is at least 64 bits of precision.

`signed` and `unsigned` qualifiers can be applied to `char` or any integer type:

<limits.h> defines symbolic constants for the max value of unsigned integer types, and the min and max values for signed integer types. The table above shows the values in the Debian Linux virtual machine.

<stdint.h> defines the following alias types when your code needs to use integer types

that have exactly N bits of precision - e.g., when you are encoding encryption or hash algorithms.

Bits of precision	unsigned	signed
8	uint8_t	int8_t
16	uint16_t	int16_t
32	uint32_t	int32_t
64	uint64_t	int64_t

3.3.2.3 Floating Point Types

The Institute of Electronic and Electrical Engineers (IEEE) has defined three standard representations for floating point numbers: single precision (32-bit representation), double precision (64-bit representation), and extended precision (80-bit representation). These map directly to C's floating point types.

double This is the double precision IEEE type. It is the standard way that floating point values are used in C programs. All of the standard functions in `<math.h>` take doubles as input arguments and produce doubles as their values.

float This is the single precision IEEE type. It is primarily used when one needs to use a GPU accelerator that only supports the IEEE single precision representation.

long double This is the extended precision IEEE type. It is not often used, and will not be used in this book.

3.3.2.4 Whither Booleans?

George Boole developed an algebraic representation of logic in the 19^{th} century, called appropriately enough, Boolean Algebra.[4] Boolean variables can take on values of $true$ and $false$, and in programming languages are typically encoded as $true$ being 1 and $false$ being 0.

If A and B are two Boolean variables, the algebra describes four operations that one can perform on these variables; each operation yields either $true$ or $false$, so this algebra is closed under these operations. The actions of these operations are usually shown as truth tables, which you may have seen in your high school mathematics course.

[4] `https://en.wikipedia.org/wiki/Boolean_algebra`

and This operation yields a *true* value if both A and B are *true*. This operation is depicted variably as *and* or & in different programming languages, and application is usually portrayed in an infix form, such as $A\&B$. The truth table for the *and* operation is shown below.

A & B	0	1
0	0	0
1	0	1

or This operation yields a *true* value if either A or B are *true*. This operation is depicted variably as *or* or | in different programming languages, and application is usually portrayed in an infix form, such as $A|B$. The truth table for the *or* operation is shown below.

A | B	0	1
0	0	1
1	1	1

exclusive or This operation yields a *true* value if either A or B are *true*, but *not* both. This operation is depicted variably as *xor* or ˆ in different programming languages, and application is usually portrayed in an infix form, such as $A\hat{}B$. The truth table for the *xor* operation is shown below.

A ˆ B	0	1
0	0	1
1	1	0

not This unary operator yields *true* if A is $false$ and $false$ if A is *true*. This operation is depicted variably as *not* or ~in different programming languages, and the application is usually portrayed as ~A. The truth table for the *not* operation is shown below.

A	0	1
~A	1	0

C does not have a boolean basic data type. Instead, we declare a boolean as an `int`. Logical true is non-zero, and logical false is zero.

Syntactically, C uses `&&`, `||`, and `!` for the *and*, *or*, and *not* operations between boolean values. It does *not* provide a syntax for the *xor* operation between boolean variables.

As of the C99 version of the language standard, `<stdbool.h>` defines a set of macros for declaring boolean variables, and the different values that can be assigned to boolean variables: `bool`, `true`, and `false`. We strongly recommend that you

`#include <stdbool.h>` in your source files when you are using boolean variables, that you declare them as `bool`, and that when you assign them values, you use the symbolic constants `true` and `false`.

We will see later in this chapter that C also supports bit operations between integer variables that conform bitwise to the truth tables and boolean operations shown above. In particular, it offers the `&`, `|`, `^`, and `~` operators for the *and*, *or*, *xor*, and *not* bitwise operations.

3.3.2.5 Bytes occupied by C's data types on your 64-bit Debian Linux VM

The following table shows the number of bytes of memory occupied by different data types in your 64-bit Debian Linux image.

Data type	No of bytes
signed char	1
unsigned char	1
signed short int	2
unsigned short int	2
signed int	4
unsigned int	4
signed long int	8
unsigned long int	8
signed long long int	8
unsigned long long int	8
float	4
double	8
long double	16
pointer	8

Knowledge of these sizes will be important when we start to use generic container ADTs with C's basic types.

Exercise 3.5. Which data types in your 64-bit Debian Linux image occupy 8 bytes? 4 bytes? 2 bytes? 1 byte? Which data type is not included in your previous answers?

3.3.3 Structured types

C supports the creation of arrays of a given type, accessed via indexing. For example, one would declare an array of `25` integers as follows:

```
int myArray[25];
```

Arrays indices start at `0`; thus, the legal indices for `myArray` above are `0 .. 24`. One refers to the element at index `10` as `myArray[10]`.

C does *not* have a special built-in type for *strings*. Instead, a *string* is an array of characters, as in

```
char buf[1024];
```

We will discuss strings in more detail later in the chapter.

Exercise 3.6. Given the following declaration:

```
long long int lli[27];
```

why would your program not work correctly if you attempted to access `lli[27]`?

C also supports the definition of *structures*. We will discuss structures later in this chapter.

3.3.4 Constants/literals

You will need to be able to use literal values for different types in your program; these are usually termed *constants* in C. The following table indicates how to express constant integer values for different integer types.

signed short integer	`short`	`(short)1234`
signed integer	`int`	`1234`
signed long integer	`long`	`1234L`
signed long long integer	`long long`	`1234LL`
unsigned short integer	`unsigned short`	`(unsigned short)1234`
unsigned integer	`unsigned`	`1234U`
unsigned long integer	`unsigned long`	`1234UL`
unsigned long long integer	`unsigned long long`	`1234ULL`

Floating point constants contain a decimal point or an exponent or both; the type of the constant is `double` unless a suffix is provided.

single-precision floating point	`float`	`123.4f`	`1e-2f`	`1.2e7f`
double-precision floating point	`double`	`123.4`	`1e-2`	`1.2e7`
extended-precision floating point	`long double`	`123.4L`	`1e-2L`	`1.2e7L`

3.3.5 Character and string constants

A character constant is an integer, written as a single character within single quotes, such as `'x'`. Escape sequences, such as `'\n'`, are character constants. The following table shows the legal escape sequence character constants.

\a	alert (bell)	\b	backspace
\f	formfeed	\n	newline (end of line)
\r	carriage return	\t	horizontal tab
\v	vertical tab	\\	backslash
\?	question mark	\'	single quote
\"	double quote	\0	null (end of string)

A string constant/literal is a sequence of 0 or more characters surrounded by double quotes ("); the quotes are *not* part of the string, only serving to delimit the string contents. As described previously, a string is an array of characters; a string constant is just such an array of characters, with a null character ('\0') at the end.

The following paragraph is **very** important - your Python experience tells you that 'a' and "a" are the same thing; this is **NOT** true in C.

It is important to understand the difference between character and string literals. 'x' is an 8-bit integer, representing the numerical value of the letter x in the machine's character set. "x" is an array of characters, 2 characters long, consisting of 'x' followed by '\0'.

Given what we have seen so far, we can write a simple function that calculates the length of a string.

```
int strlen(char s[]) {
    int i, len;

    len = 0;
    for (i = 0; s[i] != '\0'; i = i + 1) {
        len += 1;
    }
    return len;
}
```

You should convince yourself that this function works correctly if passed an empty string (i.e., ""). The production version of strlen(), along with many other useful string-manipulation functions, is defined in <string.h> and can be used if you #include <string.h> in your source files.

3.3.6 Variable declarations

All variables must be declared before use. Each declaration specifies a type, and associates one or more variable names with that type; for example:

```
int first, last, step;
char c, buf[1024];
```

A variable may be initialized in its declaration, as in:

```
int formatChar = '%';
int bufferSize = MAXBUF + 1;
char keyword[] = "expedite";
int first, last, increment = 5;
```

The penultimate example above shows that one does not need to specify the size of a character array if you are initializing it with a string literal. The last example shows that you can intermix uninitialized and initialized variables in the same declaration line. Only `increment` is given an initial value (6); both `first` and `last` have *not* been initialized.

Exercise 3.7. Consider the following set of variable declarations:

```
int x, y;
long z;
double b;
float c;
unsigned long long q;
char a[100];
```

what are the types of each expression below?

- a[5]
- z
- q
- y

3.3.7 Variable scope

Variables can be declared outside of any function definition, in which case they are referred to as *external* variables. External variables can be accessed by *any* code in any function in *any* source file that is linked together with the file that declares that external variable. For external variables, initialization is done only once, before the program starts to execute; as a result, the initializer must be a constant expression. If an external variable is not explicitly initialized, it is initialized to zero by default.

Variables declared at the top of a block (after an opening left curly brace `{`) are referred to as *automatic* variables. An explicitly initialized automatic variable is initialized each time the defining block is entered; the initializer can be any expression. An automatic variable for which there is no explicit initializer has an undefined value.

The qualifier `const` can be applied to the declaration of any variable to indicate that its value will not change, as in:

```
const char errmsg[] = "processing error";
```

`const` can also be used with arguments to functions to indicate that the function does not change that argument, as in:

```
int strlen(const char str[]);
```

3.3.8 Arithmetic operators

The binary operators `+`, `-`, `*`, and `/` are defined for both integer and floating point types; the modulus operator, `%`, is also defined for integer types. **For integers `x` and `y`**, `x / y` yields the integral number of times that `y` goes into `x`, while `x % y` yields the remainder from that division. Or more succinctly, `y * (x / y) + (x % y)` is identical to `x`.

3.3.9 Relational and logical operators

These operators apply to variables of type `bool`, as described in section 3.3.2.4. The relational and logical operators described below return `true` when the result is true, `false` when false.

The following comparison operators, when used with numeric types, generate boolean values:

`x < y`	x is strictly less than y
`x <= y`	x is less than or equal to y
`x > y`	x is strictly greater than y
`x >= y`	x is greater than or equal to y
`x == y`	x is equal to y
`x != y`	x is not equal to y

Boolean values can be combined using the usual boolean operators:

`x || y`	if x is `false`, then y, else x	y is only evaluated if x is `false`
`x && y`	if x is `false`, then x, else y	y is only evaluated if x is `true`
`!x`	if x is `false`, then `true`, else `false`	has lower priority than non-Boolean operators, so `!a == b` is interpreted as `!(a == b)`

3.3.10 Bit operations

As alluded to at the end of section 3.3.2.4, C supports bit operations between unsigned integer variables. Following on from the discussion in section 3.3.2.2, let's assume that we are using w bit unsigned integers, x and y. This means that the actual value held by x and y are as follows.

$$x = \sum_{i=0}^{w-1} x_i \cdot 2^i \quad and \quad y = \sum_{i=0}^{w-1} y_i \cdot 2^i \tag{3.3}$$

Furthermore, assume that X and Y are 8-bit unsigned integers (unsigned char) with bit values of 10110010 and 01101011, respectively.

> ⚠ C uses `&&` and `||` as operators between boolean variables, as described in section 3.3.2.4. It uses `&` and `|` as bit operators. **It is absolutely essential that you not use the wrong operators in the wrong circumstances.** We will not be using the bit operators much in this course, so use of `&` or `|` will **almost always be the wrong thing to do**.

3.3.10.1 x & y

The *and* operation between two unsigned integers produces an output unsigned integer z where $z_i = x_i \& y_i$ for each bit.

$$z = \sum_{i=0}^{w-1} (x_i \ \& \ y_i) \cdot 2^i \tag{3.4}$$

Specifically, for $Z = X \& Y$, we have:

- $X_0 = 0, Y_0 = 1 \implies Z_0 = 0$
- $X_1 = 1, Y_1 = 1 \implies Z_1 = 1$
- $X_2 = 0, Y_2 = 0 \implies Z_2 = 0$
- $X_3 = 0, Y_3 = 1 \implies Z_3 = 0$
- $X_4 = 1, Y_4 = 0 \implies Z_4 = 0$
- $X_5 = 1, Y_5 = 1 \implies Z_5 = 1$
- $X_6 = 0, Y_6 = 1 \implies Z_6 = 0$
- $X_7 = 1, Y_7 = 0 \implies Z_7 = 0$

or, $Z = 00100010$.

3.3.10.2 x | y

The *or* operation between two unsigned integers produces an output unsigned integer z where $z_i = x_i | y_i$ for each bit.

$$z = \sum_{i=0}^{w-1} (x_i \mid y_i) \cdot 2^i \tag{3.5}$$

Specifically, for $Z = X|Y$, we have:

- $X_0 = 0, Y_0 = 1 \implies Z_0 = 1$
- $X_1 = 1, Y_1 = 1 \implies Z_1 = 1$
- $X_2 = 0, Y_2 = 0 \implies Z_2 = 0$
- $X_3 = 0, Y_3 = 1 \implies Z_3 = 1$
- $X_4 = 1, Y_4 = 0 \implies Z_4 = 1$
- $X_5 = 1, Y_5 = 1 \implies Z_5 = 1$
- $X_6 = 0, Y_6 = 1 \implies Z_6 = 1$

- $X_7 = 1, Y_7 = 0 \implies Z_7 = 1$

or, $Z = 11111011$.

3.3.10.3 x ^ y

The *xor* operation between two unsigned integers produces an output unsigned integer z where $z_i = x_i \;\hat{}\; y_i$ for each bit.

$$z = \sum_{i=0}^{w-1} (x_i \hat{} y_i) \cdot 2^i \tag{3.6}$$

Specifically, for $Z = X \;\hat{}\; Y$, we have:

- $X_0 = 0, Y_0 = 1 \implies Z_0 = 1$
- $X_1 = 1, Y_1 = 1 \implies Z_1 = 0$
- $X_2 = 0, Y_2 = 0 \implies Z_2 = 0$
- $X_3 = 0, Y_3 = 1 \implies Z_3 = 1$
- $X_4 = 1, Y_4 = 0 \implies Z_4 = 1$
- $X_5 = 1, Y_5 = 1 \implies Z_5 = 0$
- $X_6 = 0, Y_6 = 1 \implies Z_6 = 1$
- $X_7 = 1, Y_7 = 0 \implies Z_7 = 1$

or, $Z = 11011001$.

3.3.10.4 ~x

The *not* operation on an unsigned integer produces an output unsigned integer z where $z_i = \;\sim x_i$ for each bit.

$$z = \sum_{i=0}^{w-1} (1 - x_i) \cdot 2^i \tag{3.7}$$

Specifically, for $Z = \;\sim X$, we have:

- $X_0 = 0 \implies Z_0 = 1$
- $X_1 = 1 \implies Z_1 = 0$
- $X_2 = 0 \implies Z_2 = 1$
- $X_3 = 0 \implies Z_3 = 1$
- $X_4 = 1 \implies Z_4 = 0$
- $X_5 = 1 \implies Z_5 = 0$
- $X_6 = 0 \implies Z_6 = 1$
- $X_7 = 1 \implies Z_7 = 0$

or, $Z = 01001101$.

3.3.10.5 Bit shifting

C also supports two additional binary operators for bit shifting, `>>` for right shifting and `<<` for left shifting. These operators can be applied to both signed and unsigned integers, but the behavior of right shifting a signed integer can be different on different machines, so you are encouraged to restrict usage of these operators to unsigned integers.

Left shift If `x` and `n` are unsigned integers, the expression `x << n` causes the bits in `x` to be shifted `n` bits to the left; the vacated low-order bits are set to 0; this is equivalent to multiplying `x` by 2^n.

Assuming `x` and `z` are unsigned integers of width w,

$$\begin{array}{l} for\ i = w - 1\ downto\ n \\ \quad z_i = x_{i-n} \\ for\ i = n - 1\ downto\ 0 \\ \quad z_i = 0 \end{array}$$

`Z = X << 2` yields 11001000.

Right shift If `x` and `n` are unsigned integers, the expression `x >> n` causes the bits in `x` to be shifted `n` bits to the right; the vacated high-order bits are set to 0; this is equivalent to dividing `x` by 2^n.

Assuming `x` and `z` are unsigned integers of width w,

$$\begin{array}{l} for\ i = 0\ upto\ w - n - 1 \\ \quad z_i = x_{i+n} \\ for\ i = w - n\ upto\ w - 1 \\ \quad z_i = 0 \end{array}$$

`Z = X >> 2` yields 00101100.

3.3.11 Type conversions

When an operator has operands of different types, they are converted to a common type according to a small number of rules. In general, the only automatic conversions are those that convert a "narrower" operand into a "wider" one without losing information, such as converting an integer to floating point in an expression like `f + i`.

Expressions that do not make sense, like using a floating point value as an index into an array, are illegal, and will generate compiler errors. Expressions that might lose information, such as assigning a wider integer type to a narrower one, are *not* illegal, but will generate a warning from the compiler to alert you to the potential danger in doing so.

Of particular importance is to note that a `char` is just a small integer, so, as unusual as it may seem, `char` variables and constants may be freely used in arithmetic expressions. One must exercise caution, though, as many such uses make assumptions about contiguity of sequences of digits or letters, or about the relationship between lower and upper case letters. It is much safer to rely upon functions in `<ctype.h>` for performing such manipulations: `isalnum()`, `isalpha()`, `iscntrl()`, `isdigit()`, `isgraph()`, `islower()`, `isprint()`, `ispunct()`, `isspace()`, `isupper()`, `isxdigit()`, `tolower()`, and `toupper()`.

If a binary operator has operands of different types, the “narrower” type is promoted to the “wider” type before the operation proceeds, and the result is of the “wider” type. If neither operand is an unsigned integer type, the following informal rules are followed:

```
if either operand is long double
    convert the other to long double
else if either operand is double
    convert the other to double
else if either operand is float
    convert the other to float
else
    convert char and short to int
    if either operand is long long
        convert the other to long long
    else if either operand is long
        convert the other to long
```

Exercise 3.8. Consider the following set of variable declarations:

```
int x, y;
long z;
double b;
float c;
unsigned long long q;
char a[100];
```

what are the types of each expression below?

- x + a[5]
- b - z
- c + q

Conversions take place across assignments; the value of the right hand side is converted to the type of the left hand side, which is the type of the result; “wider” integers are converted to “narrower” ones by dropping the excess high order bits. Floating point to integer conversions cause truncation of any fractional part.

You can avoid depending upon implicit conversions by explicitly coercing the result of an expression using a *cast*; these are of the form (*type-name*) *expression*. The result of *expression* is converted to *type-name* using the type conversions rules. For example, given an integer `N`, we take its square root by invoking `sqrt((double)N)`. In this case, the compiler converts the integral value of `N` to a `double` before invoking `sqrt()`. The cast produces the value of `N` of the proper type; **`N` itself is not altered**.

3.3.12 Increment and decrement operators

Incrementing and decrementing variables happens so often in C programs that there is special syntax for it.

`++x`	adds `1` to `x` before returning its value
`x++`	adds `1` to `x` after returning its value
`--x`	subtracts `1` from `x` before returning its value
`x--`	subtracts `1` from `x` after returning its value

Consider the following code fragment:

```
int x, y, n = 5;

x = n++;
y = ++n
printf("%d %d %d\n", n, x, y);
```

What do you think will be printed out?

`n` starts out as `5`. `x = n++` says to assign the current value of `n` to `x`, then increment `n`; this leaves `x` with a value of `5`, and `n` with a value of `6`. `y = ++n` says to increment `n`, and then assign the value of `n` to `y`; this leaves `n` with a value of `7`, and `y` with a value of `7`. Thus, when `printf()` is invoked, we should see the following on standard output:

```
7 5 7
```

Postfix autoincrement (`x++`) is often used when assembling strings in a character array, as in:

```
if (c == '\n')
    buf[i++] = c;
```

It is also used with pointers, which will be discussed later in this chapter.

3.3.13 Assignments and assignment operators

Assignment of the value of an expression to a variable has the following syntax:

```
variable = expression;
```

Note the semicolon (`;`) at the end of the statement.

The entire assignment statement is also an expression, and returns a value - i.e., the value that was assigned to the variable. As a result, the following types of statements are not only legal, they are examples of efficient and elegant C source:

```
var1 = var2 = expression;
if ((status = fetch(...)) != EOF) ...
```

The first example above simply shows that one can assign the same value to several variables in a single line; this statement is processed right to left - i.e., `expression` is evaluated and assigned to `var2`. The value of that assignment is the value of `expression`, and this value is assigned to `var1`. The second example shows invocation of the function `fetch()`, assigning its returned value to `status`; the value of this assignment is then compared to `EOF` to conditionally execute the body of the `if` statement.

Besides normal assignment, it is often the case that one wants to evaluate an expression, then perform a binary operation between a variable and that expression, and reassign the result of that binary operation to the variable. C has very rich support for these *assignment operators*, all of the form `variable op= expression`; this is equivalent to `variable = (variable) op (expression)` except that `variable` is only evaluated once. The operators `+`, `-`, `*`, `/`, `%`, `&`, `|`, `^`, `<<`, and `>>` all have assignment operator forms.

As with assignments, assignment operators have a value (the final value of the variable), and can occur in expressions. For example

```
while ((n += 5) < LIMIT) ...
```

3.3.14 Conditional expressions

C has a ternary operator that is useful in many situations. It has the form:

```
x = expr1 ? expr2 : expr3;
```

This is equivalent to

```
if (expr1) {
    x = expr2;
else
    x = expr3;
}
```

except that it also returns a value which can be exploited in an expression, just like assignment and assignment operators. Let's look at a motivating example of its use.

An invocation of the standard `echo` program in Linux is shown below:

```
$ echo the quick, brown fox
the quick, brown fox
```

As you can see, `echo` prints out each argument word following the `echo` command word on standard output, with a single space separating each pair of words. How might we write `echo` in C?

```
#include <stdio.h>
#include <stdlib.h>

int main(int argc, char *argv[]) {
    int i;

    for (i = 1; i < argc; i++)
        if (i == 1)
            printf("%s", argv[i]);
        else
            printf(" %s", argv[i]);
    printf("\n");
    return EXIT_SUCCESS;
}
```

You should type this code into your editor and save it to a file named `myecho.c`. Compile and link it with the following command to `bash`:

```
$ gcc -W -Wall -o myecho myecho.c
```

To make sure that this works correctly, type the following commands to `bash`:

```
$ ./myecho the quick, brown fox
the quick, brown fox
$ ./myecho the quick, brown fox | cat -A
the quick, brown fox$
```

`cat -A` in the second invocation causes causes `cat` to show non-printing characters using `^` and `M-` notation, to display TAB characters as `^I`, and to show the end of line as `$`.
`cat -A` is a very useful tool to make sure that your files do not have extraneous blanks or embedded control or meta characters in them.

The if-else clause in `myecho.c` is very repetitive; it is simply there to make sure that we do *not* print a blank before the first word output to standard output. The entire if-else clause can be replaced by the following single statement:

```
printf("%s%s", (i == 1) ? "" : " ", argv[i]);
```

What does this statement say?

- `printf` is expecting two character string arguments;
- the ternary expression will yield an empty character string if `i == 1`; it yields a character string consisting of a single blank if not; and
- the second character string to `printf` is `argv[i]`.

Use of the ternary statement in situations such as this is quite elegant use of the power of C. We will see many examples of its use in the remainder of the textbook.

3.4 Control flow

3.4.1 Statements and blocks

An expression becomes a *statement* when it is followed by a semicolon.

```
x = 0;
i++;
printf(...);
```

Unlike some other languages, where the semicolon is a statement separator, in C the semicolon is a statement terminator. Curly braces (`{}`) are used to group declarations and statements together into a *compound statement*, also known as a *block*. A block is syntactically equivalent to a single statement.

3.4.2 Conditional execution, `if-else`

There are occasions where you will want different bits of code to be executed depending upon the state of your program. The syntax for `if-else` is

```
if (expression)
    statement1
else
    statement2
```

with the `else` part optional. `expression` is evaluated; if it is true (i.e., has a non-zero value), `statement`$_1$ is executed; if false, `statement`$_2$ is executed.

Since the `else` part is optional, there is an ambiguity when an `else` is omitted from a nested sequence of `if`'s. This ambiguity is resolved by associating the `else` with the closest previous `else`-less `if`.

To perform multi-way decisions in C, one does the following:

```
if (expression1)
    statement1
else if (expression2)
    statement2
else if (expression3)
    statement3
. . .
else
    statementN
```

The expressions are evaluated in order; if any expression is true, the statement associated with it is executed, and the processing of the entire chain is terminated. Again, the trailing `else` can be omitted, although this is not a particularly good idea; if the preceding expressions capture all of the legal situations, then the `else` clause can catch illegal usage of your code.

3.4.2.1 Effective use of boolean variables

While the tables in Section 3.3.9 indicate how to generate and combine boolean values, it is important to understand how to use booleans to simplify your code. Consider having to write the following function:

```
bool contains(char st[], char subst[], bool invert);
/*  if invert is false, returns true if subst is contained in st
                        returns false if subst is not contained in st
 *  if invert is true, returns false if subst is contained in st
                       returns true if subst is not contained in st */
```

Seems simple enough. A novice programmer would probably write the following implementation.

```
#include <string.h>
bool contains(char st[], char subst[], bool invert) {
    bool matches;
    if (invert)
        matches = (strstr(st, subst) == NULL);
    else
        matches = (strstr(st, subst) != NULL);
    return matches;
}
```

`strstr()` is a function defined in `<string.h>` that tests whether its second argument is a substring of its first argument; it returns `NULL` if it is not a substring, and returns `!NULL` if it is a substring.

This certainly works, but lets take advantage of boolean operations.

```
#include <string.h>
bool contains(char st[], char subst[], bool invert) {
    bool matches;
    /* assume invert is false */
    matches = (strstr(st, subst) != NULL);
    if (invert)
        matches = !matches;
    return matches;
}
```

This produces the same results, but let's the reader see a more linear version of the code; assume that `invert == false` to generate the original value for `matches`; invert the value of `matches` if `invert == true`.

While one can quibble with the efficacy of this approach if only a single boolean drives the functionality, consider the case when two booleans must be considered.

```
bool contains(char st[], char subst[], bool invert, bool caseInsensitive);
/*  if caseInsensitive is false, see if subst is contained in st
 *  if caseInsensitive is true, see if lower(subst) is contained in lower(st)
 *  if invert is false, returns true if containment is true, false otherwise
 *  if invert is true, returns false if containment is true, true otherwise */
```

The natural approach to this for a novice programmer is a nested set of if statements.

```
#define _GNU_SOURCE
#include <string.h>
bool contains(char st[], char subst[], bool invert, bool caseInsensitive) {
    bool matches;
    if (caseInsensitive) {
        if (invert)
            matches = (strcasestr(st, subst) == NULL);
        else
            matches = (strcasestr(st, subst) != NULL);
    } else {
        if (invert)
            matches = (strstr(st, subst) == NULL);
        else
            matches = (strstr(st, subst) != NULL)
    return matches;
}
```

While this certainly works, there is significant duplication in the code, which makes it very hard to get right for two booleans; can you imagine how hard it is for three or four?

As with our previous improved solution, we will linearize this code to make it less error prone and more understandable.

```
#define _GNU_SOURCE
#include <string.h>
bool contains(char st[], char subst[], bool invert, bool caseInsensitive) {
    bool matches;
    /* assume invert is false */
    if (caseInsensitive)
        matches = (strcasestr(st, subst) != NULL);
    else
        matches = (strstr(st, subst) != NULL);
    if (invert)
        matches = !matches;  /* handle inversion */
    return matches;
}
```

This linearization has enabled separation of concerns (case sensitivity versus inverted test) into separate portions of the code; the reduced complexity substantially enhances our ability to reason about and achieve correct behavior.

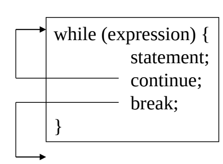
This is not to say that `if ... else` constructs should not be used; we are simply saying that deeply nested `if ... else` constructs are difficult to code and get right, usually entail substantial duplication of code, and are difficult for an observer of your code to understand. Linearizing your code, using boolean variables and, if necessary, temporary storage, usually leads to cleaner, more understandable, less error-prone solutions.

3.4.3 Test at the top - `while` and `for`

The safest way to loop through code until a terminating condition is reached is to test before entering the loop each time. C provides a `while` statement and a `for` statement for test-at-the-top iteration.

The syntax for the `while` statement is as follows:

```
while (expression)
    statement
```



`expression` is evaluated; if it is non-zero/true, `statement` is executed and `expression` is re-evaluated. This cycle continues until `expression` is zero/false, at which point execution resumes *after* `statement`. C provides a `break` statement that enables an early exit from a `while` loop.[5] The `break` statement in a `while` loop causes execution to resume after `statement`. C also provides

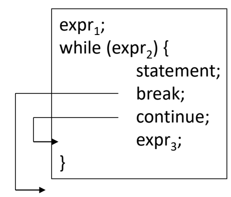
[5]`break` can also be used to achieve an early exit from `for` and `switch` statements, as well.

a `continue` statement to cause the next iteration of the `while` loop; in particular, execution will resume at the test of `expression`.[6]

The syntax for the `for` statement is as follows:

```
for (expr1; expr2; expr3)
    statement
```

`expr`$_1$ is known as the initialization field, and `expr`$_3$ is known as the update or reinitialization field.



This is equivalent to:

```
expr1;
while (expr2) {
    statement
    expr3;
}
```

except that the behavior of the `continue` statement differs; in a `for` loop, a `continue` causes `expr`$_3$ to be executed immediately, and then the test of `expr`$_2$.

While it is possible to put any legal C statements into `expr`$_1$ and `expr`$_3$, it is bad style to force unrelated computations into these fields in a `for` statement; these are best reserved for loop control operations appropriate to the situation.

What happens if you need to perform two or more statements in the initialization or update fields of a `for` loop? C provides a *comma* operator that enables one to specify multiple expressions in a statement; a pair of expressions separated by a comma (`,`) is evaluated left to right, and the type and value of the result are the type and value of the rightmost expression.

The comma operator can be used legally anywhere in your program, but is most often used in the initialization and update fields of a `for` statement, as in

```
for (i=0, j=0; i <= M; i++, j++)
    statement /* that refers to i and j */
```

⚠ While use of the comma operator is legal anywhere, such use outside of the initialization and update fields of a `for` statement should be avoided, as it leads to potentially obscure code.

---

[6] `continue` can also be used to cause the next iteration in a `for` statement, as well.

3.4.3.1 Using arrays in C

Assume the following declarations and code.

```
#define NUMBER_OF_TEMPERATURES 31
double temps[NUMBER_OF_TEMPERATURES], mean;
int i;
/* code that initializes the 31 elements of `temps' */
```

The following shows how to traverse an array using a `for` loop, and what an instance of an additive accumulator looks like in C.

```
mean = 0.0;   /* initialize sum of temperatures */
for (i = 0; i < NUMBER_OF_TEMPERATURES; i++)
    mean += temps[i];
mean /= (double)NUMBER_OF_TEMPERATURES;
```

This code computes the average temperature of the values in `temps`. First we initialize the accumulator variable (`mean`) to `0.0`. We then loop over all of the elements of the array (remember that legal indices for a C array of size N are [0..N-1]) adding the temperature value at index `i` to `mean`. After we have summed all of the temperatures, we then divide `mean` by the number of items to yield the average temperature.

3.4.4 Multi-way decision based upon constants

While being very general, the multi-way decision control described above using nested `if-else` statements is not particularly efficient if one is attempting to compare the result of an expression against a set of constant values and take different actions based upon the result. C provides the `switch` statement to enable an efficient mechanism for such tests.

The syntax for the `switch` statement is as follows:

```
switch (expression) {
    case const-expr1: statements1
    case const-expr2: statements2
    case const-expr3: statements3
    . . .
    case default: statementsN
}
```

In the switch statement, the cases simply serve as labels. If the `expression` matches one of the constants in a particular label, execution starts at the `statements` associated with that `case` label and continues *until the end of the `switch` statement* or until it encounters a `break` statement, at which point it will execute the first statement after the `switch` statement.

⚠ Since the default semantics (continue to the end) is almost **never** what one wants to happen, it is **critical** that you always include a `break` statement at the end of the set of statements associated with each `case` label. In other words, this is how you should use it!

```
switch (expression) {
case const-expr1:  statements1; break;
case const-expr2:  statements2; break;
case const-expr3:  statements3; break;
.  .  .
case default:  statementsN
}
```

3.4.5 Labels and goto as a last resort

Most assembly languages, and some earlier "high-level" languages, support inserting labels in your source code and being able to force execution to continue at one of those labels. Sound software engineering principles proscribe use of the goto.[7]

Unfortunately, sometimes one needs to abandon processing in some deeply-nested control structure. The `break` statement enables us to escape from the innermost loop or `switch`, but cannot help us if we are several levels deep. Thus, labels and goto are most commonly used in such situations, as depicted below.

```
for (. . .)
    for (. . .) {
        . . .
        if (disaster)
            goto error;
    }
error:   /* code to clean up the mess */
```

A label has the same form as a variable name, and is followed by a colon (`:`). A label can be attached to any statement *in the same function* as the `goto` statement. The scope of a label is the entire function.

3.4.5.1 Stylized use of `goto` in your `main()` function

Languages that support exceptions and exception handlers, such as Python, enable one to segregate mainline code (code that runs assuming no exceptions) from the exception handling machinery. Languages like C, which do not support exceptions and exception handling, typically require that error checking and handling be intertwined with mainline code. The author has found that the following stylized use of `goto` in your `main()` can help to ease this problem.

[7] See Edgar Dijkstra, "Go To Statement Considered Harmful", Communications of the ACM, Vol. 11, No. 3, pp. 147-148, March 1968.

Consider a program that handles one or more short options, opens one or more files, and allocates one or more items from the heap.[8] The following stylized pseudocode enables separation of exception concerns and mainline functionality while supporting cleanup before return to bash.

```
include required header files
int main(int argc, char *argv[]) {
    declare variables for option settings, suitably initialized
    declare variables for open files, initialized to NULL
    declare variables for heap-allocated structures, initialized to NULL
    int exitStatus = EXIT_FAILURE;  /* assume an error */

    process options; if error, fprintf message to user and goto cleanup
    process remaining arguments; if a file argument
        open file
        if error, fprintf message to user and goto cleanup
    while additional heap structures needed
        allocate structure
        if error, fprintf message to user and goto cleanup
    perform mainline function
    exitStatus = EXIT_SUCCESS;
cleanup:
    free heap structures
    close files
    return exitStatus;
}
```

3.5 Functions and program structure

A C program is composed of functions and global data. One of the functions *must* be named `main()`, as the runtime will call that function after it has initialized the process in which your program will execute.

3.5.1 Functions

Each function definition has the following form:

```
return-type function-name(argument declarations) {
    declarations and statements
}
```

[8]All of these will be explained in further detail later in this chapter.

Various parts of the function declaration may be absent. If the return type is omitted, it defaults to `int`. Code that is dependent upon this default behavior is very dangerous; good software engineering practice dictates that one must *always* use function prototypes to declare the types of the function arguments and its return type, as this enables the compiler to make sure that you are calling the function correctly.

Communication between functions is via arguments to and return values from a function; functions can also communicate through external global data variables.

> ⚠ Global data variables, and their use for inter-function communication, should be minimized. The only time you should resort to such use is when it is absolutely essential for functions in two source files to access these global variables **and** it is impossible for these functions to obtain the address of the shared variables through their arguments.

Functions can occur in any order in the source file, and the source program can be split into multiple files. A single function must be completely defined in a single source file - i.e., it *cannot* be split over two or more files. One can pre-declare function signatures in a source file to guarantee that their uses in the source file are type-correct; alternatively, the functions can be defined in an order that guarantees that a function is defined prior to first use in the source file.

Returning a value from a function to its caller is achieved via the `return` statement:

```
return expression;
```

The calling function is free to ignore the returned value, although this is not good software engineering practice.

> ⚠ If you are explicitly ignoring the return value from a function, you should indicate this by casting (see Section 3.3.11) the return result to `(void)`.

An `expression` is not required after the `return` keyword; in such a situation, no value is returned to the caller. Control also returns to the caller (with no return value) if execution encounters the closing `}` in the function definition.

It is not illegal, but most likely a sign of trouble, if a function returns a value in one place but not in another. If a function fails to return a value, its “value”, if checked by the caller, is most definitely undefined.

3.5.2 An example program

Let’s construct a program to print each line of standard input that contains a particular “pattern” or string of characters - a limited version of the Linux `grep` program. The main program falls neatly into three pieces:

```
while (there's another line)
    if (the line contains the pattern)
        print the line
```

The *print the line* is simply a call to `printf()`, defined in `<stdio.h>`. The *while (there's another line)* is a call to the function `fgets()` defined in `<stdio.h>`; we previously saw its use in the `fcopy()` example in Section 3.2.3. Its signature is the following:

```
char *fgets(char buf[], int size, FILE *stream);
```

You pass `fgets()` a character array (`buf[]`), the size of that array (`size`), and a stream of characters from an open file (`stream`). Each time `fgets()` is called, it copies the next line of input from `stream` into `buf`, and places `'\0'` after the line so that `buf` is a legal string in C; if it copied a line into `buf`, it returns the address of `buf` as its function value. If there are no more lines on `stream` when `fgets()` is called, it returns `NULL` as its function value and does nothing to `buf`. We have seen this before in Section 3.2.3.

⚠ `<stdio.h>` defines a constant, `BUFSIZ`, which is the size of the buffer that you should declare for use in `fgets()`.

⚠ It is **essential** that you provide storage, via a character array, into which `fgets()` will read the next line of the file; this requirement for you to explicitly manage the memory in your program is a major aspect of programming in C.

Thus, our `main()` is starting to look as follows:

```
#include <stdio.h>
#include <stdlib.h>

#define UNUSED __attribute__((unused))

int main(UNUSED int argc, UNUSED char *argv[]) {
    char buf[BUFSIZ];

    while (fgets(buf, BUFSIZ, stdin) != NULL) {
        if (the line contains the pattern)
            printf("%s", buf);
    }
    return EXIT_SUCCESS;
}
```

In fact, if you simply delete the *if (the line contains the pattern)* from this program, you will have a filter that simply copies its standard input to its standard output.[9]

So, how do we determine if one string is included in another string? We could write a

[9] The program `fcopy` from Section 3.2.3.

function to do this, and we will show this later. But, in the meantime, we should look in `<string.h>` to see if such a function has been supplied by the standard library. This can be easily done by asking your search engine to look for "linux man string"; somewhere in the first few results of the search you will see an entry entitled "string(3) - Linux manual page - man7.org".

A perusal of that page will yield the signature

```
char *strstr(const char *haystack, const char *needle);
```

seemingly just the function we need. Clicking on the link for `strstr(3)` in the "SEE ALSO" section gets us to the man page for `strstr()`, which indicates that it returns `NULL` if `needle` is *not* contained in `haystack`, and the address of the location in `haystack` where `needle` is first found if it is.

Thus, our completed program (named `find.c`) looks as follows:

```
#include <stdio.h>
#include <string.h>
#include <stdlib.h>

#define UNUSED __attribute__((unused))

int main(UNUSED int argc, UNUSED char *argv[]) {
    char buf[BUFSIZ];
    char pattern[] = "ould";   /* pattern to search for */

    while (fgets(buf, BUFSIZ, stdin) != NULL) {
        if (strstr(buf, pattern) != NULL)
            printf("%s", buf);
    }
    return EXIT_SUCCESS;
}
```

How would we build our `find` program? Using the following `bash` command:

```
$ gcc -W -Wall -o find find.c
```

A program that has a static pattern to search for is not particularly useful, as we would have to edit and recompile the program to search for other patterns. We will look at how to make the program more dynamic later in the chapter.

Exercise 3.9. Create, build, and test `find`. How well did it work?

3.5.3 External variables

A C program consists of a set of external objects which are either variables or functions. External variables are defined outside of any function, and are thus potentially accessible by many functions. Functions are *always* external since C does not permit functions to be defined inside of other functions. External variables and functions have the property that all references to them using the same name, even from functions compiled in separate files, are references to the same thing.

The *scope* of a name is the part of the program within which the name can be used. For an automatic variable declared at the beginning of a block, the scope is the block in which the name is declared. The scope of an external variable or a function lasts from the point at which it is declared to the end of the file being compiled.

If an external variable is to be referenced before it is defined, or it is defined in a different source file from the one in which it is being used, then an `extern` declaration is required.

It is important to distinguish between the *declaration* of an external variable and its *definition*. A declaration announces the properties of a variable, primarily its type; a definition also causes storage to be set aside for the variable.

For example, if the lines

```
int sp;
double val[MAXVAL];
```

appear outside of any function, they **define** the external variables `sp` and `val`, cause storage to be set aside for each of them, and serve as a declaration for the rest of that source file.

On the other hand, the lines

```
extern int sp;
extern double val[];
```

declare for the rest of the source file that `sp` is an `int` and that `val` is a `double` array; they do **not** create the variables or reserve storage for them.

Only one *definition* of an external variable is allowed among all of the files that make up a program; initialization is restricted to that single definition.

3.5.4 Static variables

External variables enable two types of access to named storage: 1) by functions within a source file, and 2) by functions in other source files. Often we require external storage so that functions within a file can share, but wish to hide that information from functions in other source files. The keyword `static`, if prefixed to external variable **definitions**, achieves this level of hiding - i.e., all functions in the source file can access the static variables, but they are hidden from functions in other source files.

The following example declarations

```
static int sp;
static double val[MAXVAL];
```

define the types and cause storage to be created for `sp` and `val`. These variables can only be accessed by functions in the source file where these declarations occur.

External static declarations can be used for functions, as well. If a function is declared `static`, its name is *invisible* outside of the file in which it is declared. We will exploit `static` functions in later chapters when defining abstract data type methods.

Finally, `static` can also be applied to variables declared within functions. Internal `static` variables are only visible within the function in which they are declared, just as automatic variables; unlike automatics, the `static` variables retain their values across calls to the defining function. The following example shows a typical use of an internal `static` variable:

```
int someFunction(void) {
    static int initialized = 0;

    if (! initialized) {
        initialized++;
        /* perform required initialization */
    }
    /* logic of someFunction() */
    return /* appropriate value */
}
```

The first time `someFunction` is called, `initialized` will be false; on that occasion, the `if` statement will be true, at which point `initialized` will be set to true, and the required initialization will be performed. On all subsequent invocations of `someFunction`, `initialized` will be true, causing the `if` statement to be false, meaning that execution is continued at `logic of someFunction()`.

3.5.5 Header files

We use header files (ending in `.h`) to specify types, symbolic constants and function prototypes. We use source files (ending in `.c`) to define (and initialize) external variables and define functions. In our pattern matching program, we included `<stdio.h>`, which defined the extern variable `stdin`, the symbolic constant `BUFSIZ`, and the functions `fgets()` and `printf()`; we also included `<string.h>`, which defined the function `strstr()` and `<stdlib.h>`, which defined `EXIT_SUCCESS`.

Let's suppose that we wish to replace our call to `strstr()` by our own function, with the signature

```
bool isSubString(const char *needle, const char *haystack);
```

where `isSubString()` returns `true` if `needle` is contained in `haystack`, and `false` if not. We will create two files: `issubstring.h`, which defines the function signature, and `issubstring.c`, which implements the function.

issubstring.h

```
#include <stdbool.h>
bool isSubString(const char *needle, const char *haystack);
```

issubstring.c

```
#include "issubstring.h"
#include <string.h>

bool isSubString(const char *needle, const char *haystack) {
    return (strstr(haystack, needle) != NULL);
}
```

Admittedly, `isSubString()` is a very simple function, simply using `strstr()` to do the hard work, and returning the correct return type. Note that our source file includes `issubstring.h` using quotes (`""`) around the name instead of angle brackets (`<>`) - files included using angle brackets are searched for in standard directories in the file system; files included using quotes are first searched for in the current directory, then in the standard directories.

You may ask, why include the header file in the source? This guarantees that the file signature defined in the header, which will be used by other files, is identical to that defined in the source.

Our main program, `find.c`, must now look as follows:

```
#include "issubstring.h"
#include <stdio.h>
#include <stdlib.h>

#define UNUSED __attribute__((unused))

int main(UNUSED int argc, UNUSED char *argv[]) {
    char buf[BUFSIZ];
    char pattern[] = "ould";   /* pattern to search for */
```

```
    while (fgets(buf, BUFSIZ, stdin) != NULL) {
        if (isSubString(pattern, buf))
            printf("%s", buf);
    }
    return EXIT_SUCCESS;
}
```

We no longer need to include `<string.h>` here, since this code does not use `strstr()`. It *does* need to include `"issubstring.h"`, since we are now calling that function. And, obviously, we replace the call to `strstr()` with a call to `isSubString()`.

This version of `find` now depends upon two source files in our directory. How do we build it?

```
$ gcc -W -Wall -o find find.c issubstring.c
```

Exercise 3.10. Build and test this version of `find`.

3.5.6 `make` - a tool to help you with the ECLE cycle

It should be clear that one can establish a set of dependencies between the files that make up your executable program. The executable program file depends upon the constituent object files; if one of them changes, then the program file must be regenerated by relinking the object files. Likewise, each object file depends upon its source file; if the source file has changed, then the object file must be recreated by recompiling the source file; since the object file has now changed, the executable program file must be recreated. Clearly, a tool that keeps track of these (and other) dependencies, and what actions are required to recreate a file that depends upon a file that has changed will be extremely useful. `make` is such a tool.

`make` requires that **YOU** specify the dependencies between your files. It also requires that **YOU** specify what action to take to recreate a dependent file when one of the files upon which it depends has changed. Finally, it has built in rules for the most common types of actions (e.g., recompiling a `.c` file that is newer than the current `.o` file).

How can `make` possibly work? Recall from Chapter 2 that the file system keeps metadata about each file, and that one such piece of metadata was the modification date/time for the file. Given a specification of the dependencies between your files, `make` can determine if a dependent file needs to be recreated if any of the files upon which the dependent file depends has a later modification date than the dependent file. Upon detection of such a situation, it then applies the action[s] that you have specified for recreating the dependent file (or applies one of the built-in, implicit rules) to recreate the dependent file, which will, of course, now have a modification date later than any of the files upon which it depends.

By convention, we keep all source files for a related set of programs in a separate directory. In that directory, a file named `Makefile` contains the specification of the file dependencies, and the actions that should be taken. Let's look at an example `Makefile` for an as-yet undefined program named `prog`:

```
CFLAGS=-W -Wall
OBJECTS=prog.o

prog: $(OBJECTS)
	gcc -o prog $(OBJECTS)

prog.o: prog.c
```

What does this mean? Let's look at each line in turn.

- `CFLAGS=-W -Wall`
  The built-in rule for converting from a C source file to a C object file knows to look for a variable named `CFLAGS`; if this is defined, it will use it in the `gcc` command to compile a source file into its object file.
- `OBJECTS=prog.o`
  It is good practice to create a variable named `OBJECTS` for all of the object files that must be linked together to create our program. In this case, there is only one; if there had been other files, the entire set would have been listed as part of the definition of `OBJECTS`, with the filenames separated by blanks.
- `prog: $(OBJECTS)`
  `        gcc -o prog $(OBJECTS)`
  The first line says that `prog` depends upon the definition of `OBJECTS`; since `OBJECTS` is defined as `prog.o`, this means that `prog` depends upon `prog.o`. `make` checks the modification date for `prog.o`; if the file does not exist, it looks for a rule in the Makefile to see how to create `prog.o`, and executes that rule. Armed with the modification date for `prog.o`, it compares it to the modification date for `prog`, and if it is newer, executes the second line, which is the rule used to update `prog`. **Note that the action lines must be indented by a TAB character**; there can be multiple action lines, each indented by a TAB; an empty line indicates the end of the action lines associated with that rule.
- `prog.o: prog.c`
  This indicates that `prog.o` depends upon `prog.c`. The absence of a rule for updating `prog.o` tells `make` to use its built-in rule.

The lines starting with `prog:` and `prog.o:` define *targets*. You can ask `make` to "make" one of the targets defined in a `Makefile` by typing the following command to `bash`:

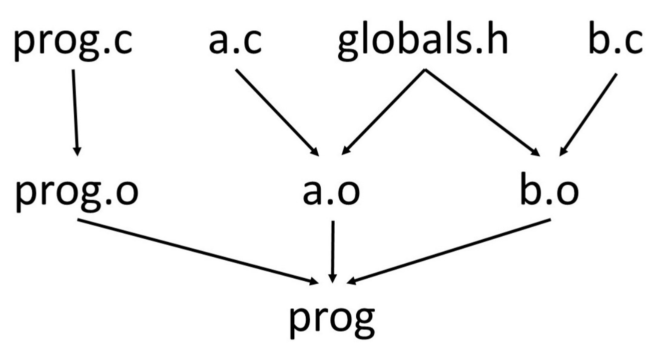
```
$ make name_of_target
```

In our particular case, we could type any of the following commands:

```
$ make prog.o
$ make prog
$ make
```

The first command asks `make` to compile `prog.c` to produce `prog.o` if and only if `prog.c` is newer than `prog.o`. The second command asks `make` to link `prog.o` to produce `prog` if and only if `prog.o` is newer than `prog`; as a side effect, if `prog.c` is newer than `prog.o`, `make` would compile `prog.c` first, and then would have to recreate `prog`, since `prog.o` has to be newer than `prog` in that case. The third command asks `make` to produce the first target that it finds, top to bottom, in `Makefile`; in this case, it would recreate `prog` if necessary.

If all of our programs were just a single source file, like `prog`, `make` might seem like overkill. Usually your programs will consists of several source files, and need to link to special libraries; in such cases, capturing the knowledge of the dependencies between files and the actions to take to update a target if it is older than any of the files upon which it depends in a `Makefile`, and using `make` to make sure our targets are up-to-date, is a definite benefit. Let's assume that the code in `prog.c` refers to functions defined in `a.c` and `b.c`. Furthermore, let's assume that some global definitions needed by `a.c` and `b.c` are in `globals.h`. This yields the following dependency graph between source files, object files, and program files.



The following `Makefile` captures this dependency graph along with any non-built-in rules needed to update a target if it is older than any of its dependencies:

```
CFLAGS=-W -Wall
OBJECTS=prog.o a.o b.o

prog: $(OBJECTS)
        gcc -o prog $(OBJECTS)

prog.o: prog.c
a.o: a.c globals.h
b.o: b.c globals.h
```

What has changed from our previous `Makefile`? We have augmented the definition for `OBJECTS` to include `a.o` and `b.o`, and we have added dependencies for these two additional object files.

Let's summarize what we have learned so far:

- we store all of the source, object, and program files for a particular program in its own directory;
- we create a file named `Makefile` in that directory that captures the dependencies between source, object, and program files, and provides custom rules needed to update a target if it needs to be updated;
- we define a variable named `CFLAGS` at the top of the makefile to specify some of the command arguments needed when compiling a C source file to its object file;
- we define a variable named `OBJECTS` at the top of the makefile to collect together the object file names needed to build our program;
- the first target shows the dependency of our program file upon the objects, and provides the appropriate `gcc` command to link those together to create `prog`;
- this is followed by a dependency line for each object file, showing the dependency upon the relevant source file *and* any files "included" by that source file;
- we do not provide rules to perform the compilation, instead relying upon the built-in rule within `make` for compiling C source files.

There are many other things one can specify in the `Makefile` which are beyond the scope of this book. This final section describes a couple of the more common things you will see in makefiles, and which you are encouraged to add to your makefiles, when appropriate. As with our previous discussion, we will motivate the discussion with an example `Makefile`.

```
CFLAGS=-W -Wall
OBJECTS=a.o b.o
PROGRAMS=prog1 prog2

all: $(PROGRAMS)

prog1: prog1.o $(OBJECTS)
        gcc -o prog1 prog1.o $(OBJECTS)

prog2: prog2.o $(OBJECTS)
        gcc -o prog2 prog2.o $(OBJECTS)

prog1.o: prog1.c
prog2.o: prog2.c
a.o: a.c globals.h
b.o: b.c globals.h

clean:
        rm -f prog1.o prog2.o $(OBJECTS) $(PROGRAMS)
```

This is a slightly more complicated use case - we have two programs, `prog1` and `prog2`, that use the functions defined in `a.c` and `b.c`. It makes sense to build both programs in the same directory. Thus, we have made the following changes to the previous `Makefile`:

- `OBJECTS=a.o b.o`
  we have removed `prog.o` from the variable `OBJECTS`, as we only want to capture here those object files needed by both programs;
- `PROGRAMS=prog1 prog2`
  we have added a variable named `PROGRAMS` in which we can record all of the programs that can be built by this `Makefile`; we didn't have to do this, but it is good practice, especially as in the future there is every likelihood that you will add one or more new programs to this set;
- `all: $(PROGRAMS)`
  we define the first target to be dependent upon all programs *without* an update rule; if you type `make` or `make all`, this will cause `make` to check that all of the programs are up-to-date, and if not, bring them up-to-date;
- ```
  prog1: prog1.o $(OBJECTS)
          gcc -o prog1 prog1.o $(OBJECTS)
  ```
  the old dependency and rule for `prog` is modified to build `prog1`; note that since we removed `prog.o` from `OBJECTS`, we have to include `prog1.o` in the dependency line and the rule; we also add an equivalent target and rule for `prog2`;
- `prog1.o: prog1.c`
  `prog2.o: prog2.c`
  we obviously need to replace the old target for `prog.o` by equivalent targets for `prog1.o` and `prog2.o`;
- ```
  clean:
          rm -f prog1.o prog2.o $(OBJECTS) $(PROGRAMS)
  ```
  finally, it is common to add a target named `clean`; when you invoke `make clean`, it executes the `rm` command to remove all of the object files and the program files, leaving only the source files and the makefile; note the `-f` option to `rm` - this has the effect of preventing `rm` from asking you if "you are really sure" about removing the specified files; it also prevents it from warning you if any of the specified files do not exist.

3.5.7 `find` redux

Given what we have just learned about `make`, all that is left to support ease of building and debugging `find` is to create a Makefile for our pattern matching program. If you have not yet done so, create a directory to contain `find.c`, `issubstring.h`, and `issubstring.c` and move those files there. Create a file named `Makefile` in that directory containing the following commands for `make`.

```
CFLAGS=-W -Wall
OBJECTS=find.o issubstring.o

find: $(OBJECTS)
	gcc -o find $(OBJECTS)

find.o: find.c issubstring.h
issubstring.o: issubstring.c issubstring.h

clean:
	rm -f $(OBJECTS) find
```

You might ask "Why indicate a dependency for `find.o` upon `issubstring.h` but not for `stdio.h` or `stdlib.h`?". The standard header files are very stable, and do not change. Our local header files, on the other hand, are likely to change as we debug the program. Thus, we want `make` to include our local header files in the dependency graph.

Now, let's eliminate the dependancy of `find` on a compiled pattern. We want our program to take a single argument, which is the pattern we wish to look for. We showed how to access command arguments in Section 3.2.2. Here is the absolute final version of `find.c`.

```
#include "issubstring.h"
#include <stdio.h>
#include <stdlib.h>

int main(int argc, char *argv[]) {
    char buf[BUFSIZ];
    char *pattern;   /* pattern to search for, taken from argv[1] */
    int exitStatus = EXIT_FAILURE;  /* assume abnormal termination */

    if (argc != 2) {
        printf("usage: %s pattern\n", argv[0]);
        goto cleanup;
    }
    pattern = argv[1];
    while (fgets(buf, BUFSIZ, stdin) != NULL) {
        if (isSubString(pattern, buf))
            printf("%s", buf);
    }
    exitStatus = EXIT_SUCCESS;  /* normal termination */
cleanup:
    return exitStatus;
}
```

Note that we removed the `#define` of `UNUSED`, as well as application of that attribute to `argc` and `argv`, since we *are* using the argument parameters. We first check that the user has provided a pattern argument by comparing `argc` with the value `2` - remember that `argv[0]` is the command name specified in the `bash` command line, and `argv[1]` is the first real argument to the program. If the user has either not specified the pattern, or provided too many arguments, we remind the user of the correct command line and return `EXIT_FAILURE`, indicating an error. Otherwise, we use the pattern in argv[1].

Exercise 3.11. Build and test this version of `find`.

3.5.8 Block structure

While functions *cannot* be defined inside of other functions, variables can be defined in a block-structured fashion within a function. Declarations of variables, including initializations, can follow the left brace (`{`) that introduces any compound statement, not just the one that begins a function. Variables declared in this way hide any identically named variables in outer blocks, and remain in existence until the matching right brace (`}`).

Good software engineering practice recommends that you avoid variable names that conceal names in an outer scope, as the potential for confusion and error is too great. Consider the following example - what number will be printed out?

```
#include <stdio.h>
#include <stdlib.h>

int number = 42;

int main(int argc, char *argv[]) {
    int number = 10;
    int i, j;

    i = 5;
    j = 23;
    {
        int number;

        for (number = i; number < j; number++)
            ;
    }
    printf("%d\n", number);
    return EXIT_SUCCESS;
}
```

3.5.9 Initialization

In the absence of explicit initialization, external and static variables are guaranteed to be initialized to zero. Automatic variables have undefined initial value - i.e., in the absence of explicit initialization, they should be assumed to contain garbage. Scalar variables can be initialized when they are defined by following the name with `=` and an expression. For external and static variables, the initializer *must* be a constant expression; the initialization is done once, before the program begins execution. For automatic variables, the initializer is not restricted to being a constant - it may be any expression involving previously defined values, even function calls; the explicit initialization of automatic variables is performed each time the function or block is entered.

An array may be initialized by following its declaration with a list of initializers enclosed in braces and **separated** by commas, as in

```
int days[] = { 31,28,31,30,31,30,31,31,30,31,30,31 };
```

If the size of the array is omitted, as in this example, the compiler computes the length of the array from the number of initializers. If the size of the array *is* specified, and there are fewer initializers than its declared size, the missing elements will be zero for external, static, and automatic variables; if there are more initializers than elements in the array, a compiler error is generated.

C does not maintain the length of an array at runtime. When using an initialization as for `days[]` above, your code may need to know the number of elements that the compiler actually created. There are two common ways to do this:

- you can append a value to the list of initializers that is obviously different from the others (e.g., a `-1` in `days[]`), such that at runtime you can count the number of items in the array until hitting the terminating value; such a value is called a *sentinel*; or
- a more C-savvy way to do this is to use the `sizeof` compile-time operator to define a constant that is the length of the array; `sizeof(type-name)` is replaced at compile time by the number of bytes that an instance of `type-name` will occupy in memory; `sizeof variable-name` is replaced at compile time with the number of bytes that the variable will occupy in memory; the following code shows how to exploit this to yield a defined constant that is the size of `days[]`:

  ```
  int days[] = { 31,28,31,30,31,30,31,31,30,31,30,31 };
  #define DAYS_LENGTH (sizeof days / sizeof(int))
  ```

  Your code may refer to `DAYS_LENGTH` whenever it needs to limit its accesses to the legal index values.

⚠ You should only use the sentinel approach described above if you can find a value of the type of the array that will *NEVER* occur in the array; if you cannot find such a value, then you will have to resort to remembering its size through the use of the `#define` method.

3.5.10 The C preprocessor

Every C compiler consists of multiple passes. The preprocessor is the first pass of the compiler; during this pass, the preprocessor replaces commands that it understands with other text, obtained from other files or from symbolic constants. The commands that are understood are: `#include`, `#define`, `#if`, `#ifdef`, and `#ifndef`.

3.5.10.1 File inclusion

We have already encountered this earlier. Any source line of the form

```
#include "filename"
#include <filename>
```

is *replaced* by the contents of `filename`.

If `filename` is delimited by quotes, the preprocessor first searches for the file in the directory in which the source file is found. If it is not found there, or if `filename` is delimited by angle brackets, a set of known directories are searched for `filename`. An included file may itself contain `#include` lines.

Note that file inclusion simply replaces each `#include` statement with the contents of that file. It does not import names from other name spaces.

There are often several `#include` lines at the beginning of a source file. These include common `#define` statements, type declarations (e.g., `struct` and `typedef` statements), function prototype declarations, and if absolutely necessary, extern declarations; for example, we `#include <stdio.h>` in order to access the defined symbol `NULL`, the type `FILE *`, the external variables `stdin`, `stdout`, and `stderr`, and the function prototype declarations for `fopen()`, `fgets()`, and `fclose()`.

`#include` is the preferred way to tie the declarations together for a large program. Note that when such an included file is changed, all files that depend upon the included file must be recompiled. Note that the standard include files, such as `<stdio.h>`, are very stable, and do not change. Therefore, you do **not** include such files in your Makefile dependencies.

3.5.10.2 Macro substitution

A macro definition has the form

```
#define name replacement-text
```

Subsequent occurrences of `name` in the source file will be replaced by `replacement-text`. `name` has the same form as a C variable name, while `replacement-text` is arbitrary.

Normally, `replacement-text` is the rest of the macro definition line; a long definition may be continued onto several lines by placing a `\` at the end of each line to be continued. The scope of `name` is from the point of definition to the end of the source file being compiled.

A macro definition may use previous definitions. Substitutions do *not* take place within quoted strings or variable names - e.g., if `YES` is a defined macro name, there would be no substitution in `printf("YES")` or `YESMAN`.

A name may be defined with absolutely any replacement text; for example, the following is legal and often used:

```
#define forever for(;;)  /* infinite loop */
```

Macros can be defined with arguments, as in

```
#define min(A,B) (((A) < (B)) ? (A) : (B))
```

When invoked in your code, although it looks like a function call, `min()` expands into in-line code. Each occurrence of a formal parameter to the macro is replaced by the corresponding actual argument. For the `min` macro defined above, the following invocation

```
x = min(p+q, r+s);
```

is replaced by

```
x = (((p+q) < (r+s)) ? (p+q) : (r+s));
```

If an expression causes side effects (e.g., `n++`), macros can give the wrong results; for example, `x = min(i++, j++);` will yield the wrong results, as the smaller of `i` or `j` will be incremented twice.

As you may have noticed in our `min()` example, you must also be extremely generous with parentheses to make sure that the appropriate order of evaluation is preserved. For example, if we define

```
#define square(x) x * x
```

what happens if we invoke

```
square(z+1)
```

Exercise 3.12. Fix the definition of `square()` in order to obtain the correct results.

3.5.10.3 Conditional evaluation

There are a number of statements that are used to control preprocessing, thus providing a way to include code selectively, depending upon the value of conditions evaluated during compilation. `#if` evaluates a constant integer expression; the expression may *not* include `sizeof` or casts. If the expression is true/non-zero, subsequent lines until an `#endif` or `#elif` or `#else` are processed; if the expression is false/zero:

- if an `#elif expr1` is found, then `expr1` is evaluated; if true/non-zero, subsequent lines until an `#endif/#elif/#else` are processed; if false/zero, repeat this step;
- if an `#else` is found, then subsequent lines until an `#endif` are processed.

The expression `defined(name)` is `true/false` if `name` is defined/not.

If the contents of a header file are included more than once while compiling a source file, it can lead to all kinds of difficulties. To make sure that the contents of a header file (e.g., `hdr.h`) are included only once, one includes conditionals in `hdr.h` like this:

```
#if !defined(_HDR_H_)
#define _HDR_H_

/* actual contents of hdr.h go here */

#endif /* _HDR_H_ */
```

This allows a header file to include all other header files upon which it depends without having to worry about multiple inclusions of some common header files. All of the standard header files (e.g., `<stdio.h>`) do this; you should do this with your header files, as well.

There is nothing special about using `_HDR_H_` as the defined symbol to indicate that the file has been included; you just need to pick a name that will not collide with other defined constants. Leading and trailing underscores, replacing the `.` by an underscore, and converting all letters to upper case is a common approach used by C and C++ programmers.

The `#elif` construct is to enable a switch-like choice of lines to process, as in

```
#if SYSTEM == OSX
    #define HDR "osx.h"
#elif SYSTEM == LINUX
    #define HDR "linux.h"
#elif SYSTEM == WINDOWS
    #define HDR "windows.h"
#else
    #define HDR "default.h"
#endif /* SYSTEM */
#include HDR
```

Finally, `#ifdef name` is a synonym for `#if defined(name)`, and `#ifndef name` is a synonym for `#if !defined(name)`.

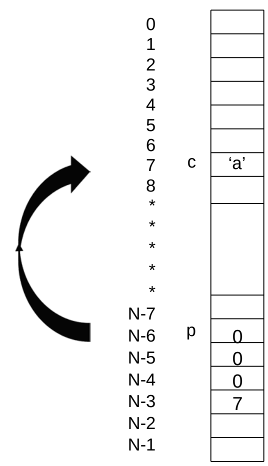
3.6 Pointers and arrays

Up to this point, it is not clear why C would be preferred over any other language. The set of basic data types is sparse, and arrays are the only structured built-in type. What's so special about C?

C supports a pointer data type; a pointer is a *data variable* that contains the address of (i.e., *points to*) another variable. Pointers to data are integrally related to arrays. Additionally, C supports pointers to functions, a feature that we will exploit when we introduce abstract data types.

3.6.1 Pointers to data

A typical computer has an array of consecutively numbered (or addressed) memory cells that can be manipulated individually or in contiguous groups; in the figure to the right, we are assuming `N` cells, numbered `0 .. N-1`.



Now suppose that we have a `char` variable named `c`, and that it is assigned to address `7`.[10] Furthermore, we have a pointer to a character, `p`, that is assigned to address `N-6`. The figure assumes that a pointer occupies 4 bytes (a 32-bit architecture); if we were on a 64-bit architecture, it would occupy 8 bytes.

We can make `p` point to `c` with a statement of the form `p = &c;`. The unary operator `&` gives the address of a variable, and it is verbalized as "address of". After executing such a statement, `p` is said to "point to" `c`. After executing this statement, we can see that the pointer `p` contains the value 7, which is the address of `c`.[11]

`&` can only be applied to variables and array elements; it cannot be applied to expressions or constants.

Once one has a pointer, how do you get at the contents of the variable to which it points? The unary operator `*` is the indirection or dereferencing operator; when applied to a pointer, it accesses the object to which the pointer points. In our previous example, `*p` would yield `'a'`, which is the character stored in `c`. The following artificial sequence of statements show the use of `&` and `*`.

[10] The linker decides where to place variables when linking the program together.

[11] The representation in the figure assumes that the system upon which we are executing is big-endian - i.e., the address of a variable that occupies more than one byte is the address of the highest-order byte.

```
int x = 1, y = 2, z[10];
int *p, *q;        /* p and q are pointers to an int */

p = &x;            /* point now points to x */
y = *p;            /* y is now 1 */
*p = 0;            /* x is now 0 */
q = &z[0];         /* q now points to z[0] */
p = q;             /* p now points to z[0] */
```

Note that the declaration for a pointer to an `int` is `int *p;` - i.e., it indicates that the expression `*p` can be used anywhere that an `int` is legal; it also indicates that `p` must be dereferenced to yield an `int` - i.e., `p` is a pointer to an `int`.

Pointers are constrained to point to a particular type of object - in this case, `p` is a pointer to an `int`.

3.6.2 Call by value and pointers

When you call a C function, the value of each argument is passed to the function. The function can not only read the values passed, but it can also modify them; **since they are copies, the caller's copies of those values ARE NOT changed**. Thus, given call by value, there is no direct way for a function to alter a variable in the calling function.

Suppose we need a function to swap two values as part of an algorithm. A *naive* approach would be as follows:

```
void bad_swap(int x, int y) {   /* WILL NOT WORK! */
    int temp;
    temp = x;
    x = y;
    y = temp;
}
 ... in another function ...
int a = 3, b = 4;
bad_swap(a, b);
```

Since `bad_swap()` is swapping copies of the actual arguments, after the call to `bad_swap()`, `a` will still be 3 and `b` will still be 4.

What happens if we modify our swap function as follows?

```
void good_swap(int *px, int *py) {   /* swap *px and *py */
    int temp;
    temp = *px;
    *px = *py;
    *py = temp;
}
 ... in another function ...
int a = 3, b = 4;
good_swap(&a, &b);
```

Since `good_swap()` is swapping the values through the pointers, after the call to `good_swap()`, `a` will now be 4 and `b` will be 3. **Note that we use the "address of" operator to pass the addresses of `a` and `b` to the `good_swap()` function. If you call a function that wants to change the value of one of your variables, the function signature will indicate a pointer to the type of variable; you must have a variable of that type in your function and you must use the "address of" operator on that variable in the call to the function.**

By passing pointer parameters to a function, the function can modify the variables to which the pointers point, as well as return a function value.

Exercise 3.13. Create a file named `swaptest.c` that includes the above functions `bad_swap()`, `good_swap()`, and a `main()` function that does the following:

- expects to be called with two integer arguments - e.g., `./swaptest 10 20`
- declares two integer variables, `a` and `b`
- uses the function `atoi()` in `<stdlib.h>` to assign the value passed in via `argv[1]` to `a`, and the value passed in via `argv[2]` to `b`
- prints out the values of `a` and `b`, separated by a space and terminated by a newline
- invokes `bad_swap()` on `a` and `b`
- prints out the values of `a` and `b`, separated by a space and terminated by a newline
- invokes `good_swap()` on `&a` and `&b`
- prints out the values of `a` and `b`, separated by a space and terminated by a newline
- returns `EXIT_SUCCESS`

3.6.3 Pointers and arrays

Pointers and arrays are strongly related in C, in that any operation that can be achieved by array subscripting can also be done with pointers.

Consider the following declaration:

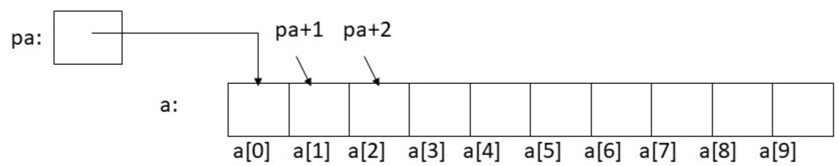
```
int a[10];
```

This defines an integer array named `a` of size `10` - i.e., a block of `10` consecutive `int` objects in memory named `a[0]`, `a[1]`, ..., `a[9]`. `a[i]` refers to the element of the array at index `i`.

Now assume that `pa` is a pointer to an integer, declared as

```
int *pa;
```

The assignment `pa = &a[0];` causes `pa` to point to element zero of `a` - i.e., `pa` contains the address of `a[0]`. If `x` is an integer, the assignment `x = *pa;` copies the contents of `a[0]` into `x`. ***By definition***, `pa + 1` points to the next element past `pa`; `pa + i` points `i` elements past `pa`; and, `pa - i` points `i` elements before `pa`.



The preceding statements are true regardless of the type or size of the variables in the array `a`. The meaning of "add 1 to a pointer", and by extension, all pointer arithmetic, is that `pa + 1` points to the next object of that type beyond `pa`, and that `pa + i` points to the `i`th object of that type beyond `pa`.

The value of a variable of type array is the address of the `0`th element of the array - i.e., `a == &a[0]`. Thus, the following are equivalent:

```
pa = &a[0];
pa = a;
```

There are several ramifications of this strong relationship between pointers and arrays:

- a reference to `a[i]` can be written as `*(a + i)`;
- a reference to `&a[i]` is identical to `a + i`;
- `pa[i]` is identical to `*(pa + i)`;
- since a pointer is a variable, expressions like `pa = a` and `pa++` are legal;
- since an array name is not a variable, expressions like `a = pa` and `a++` are *illegal*;
- when an array name is passed as an argument to a function, what is passed is the address of the initial element; within the called function, the argument is a local variable; thus, an array name parameter is a pointer;
- as formal parameters in a function definition, `s[]` and `*s` are equivalent; thus, if an array name has been passed as the actual argument in a call, the function can believe that it has been handed either an array or a pointer;
- a part of an array can be passed to a function by passing a pointer to the beginning of the sub-array - e.g., `f(&a[2])` or `f(a+2)`.

3.6.4 Pointer arithmetic

If p is a pointer to some element of an array, then p++ increments p to point to the next element, and p += i increments it to point i elements beyond the current element.

There is a distinguished pointer value, NULL, which means that the pointer does not point at anything valid; NULL is defined in <stdio.h>, <stdlib.h> and <string.h>.[12]

Pointer values can be compared using ==, !=, >, >=, <, and <=.

Adding or subtracting an integer from a pointer causes the behavior defined previously. Subtracting two pointers is also valid; if p and q point to elements of the same array, and if p < q, then q - p + 1 is the number of elements from p to q, inclusive.

Thus, valid pointer arithmetic operations are:

- assignment of pointers of the same type;
- adding or subtracting a pointer and an integer;
- subtracting or comparing two pointers to members of the same array;
- assigning or comparing to NULL.

The following operations on pointers are *invalid*:

- add, multiply, or divide two pointers;
- add a float or double to a pointer;
- assign a pointer of one type to a pointer of another type.[13]

3.6.5 void * pointers and heap memory

3.6.5.1 void * pointers

As we shall see later in this chapter, pointers to structures act somewhat like object references in object-oriented languages. Nearly all object-oriented languages have a base class Object from which all other classes inherit. C provides a generic pointer, void *; any pointer can be cast to void * and back again without loss of information. void * is used to construct modules that provide generic capabilities at runtime; we will be using these in our abstract data types.

One important aspect of void * pointers is that you *cannot* dereference them; attempts to do so will generate a compiler or a runtime error.

The most common initial exposure to void * pointers is through the dynamic memory allocation routines defined in <stdlib.h>.

[12] It is defined in several places since it is used by functions defined in each of these include files.

[13] It is possible to use an explicit cast to assign pointers of different types. This will be discussed in the following section.

3.6.5.2 Heap memory

Many of the data structures used to solve problems grow dynamically - i.e., one cannot know when the program starts how much memory a particular data structure will occupy. Languages like C provide *heap memory* that can be allocated as a data structure needs to grow.

C provides a set of routines for allocating and freeing heap memory (in `<stdlib.h>`), but does not track references to heap-allocated memory, so does not provide garbage collection. Thus, your program *itself* must keep track of references to heap blocks, and free blocks when there are no more references. Failure to do so causes *memory leaks* in your program, which must be assiduously avoided.[14] We will discuss the `valgrind` program later in this chapter which helps you find memory leaks.

The function prototypes for the routines in `<stdlib.h>` are as follows:

```
/* malloc: return a pointer to space for an object of size `size' bytes, or
 *   NULL if the request cannot be satisfied. The space is uninitialized. */
void *malloc(size_t size);

/* free: deallocates space pointed to by `ptr'; it does nothing if `ptr' is
 *   NULL. `ptr' must be a pointer to space previously allocated by malloc(),
 *   calloc() or realloc(). */
void free(void *ptr);

/* calloc: returns a pointer to space for an array of `nmemb' elements, each
 *   of size `size' bytes, or NULL if the request cannot be satisfied.
 *   The space is initialized to zero bytes. */
void *calloc(size_t nmemb, size_t size);

/* realloc: adjusts the size of the memory block pointed to by `ptr' to `size'
 *   bytes, returning a pointer to the resized block; the contents will be
 *   unchanged in the range from the start of the region up to the minimum of
 *   the old and new sizes; if the new size is larger, the added memory will not
 *   be initialized; if a new block had to be allocated, a free(ptr) was done */
void *realloc(void *ptr, size_t size);
```

These prototypes use a type `size_t`, which is also defined in `<stdlib.h>`. Think of it as an integer.

How do you know the number of bytes that you need to ask for? We discussed `sizeof`

[14] Many of you will find employment working on software that runs in embedded, potentially real-time, environments. Usually such code is written in C. You may have access to a heap, but cost concerns on embedded systems usually limit the amount of random access memory with which such systems are configured. Additionally, such embedded systems are expected to run for very long periods of time (essentially, forever). Thus, if you are using heap memory, you cannot afford to leak this memory because you are sloppy at returning the memory when you are finished with it.

earlier, as this *compile-time* expression is replaced by the number of bytes needed for an instance of a type or for a particular variable. When you invoke malloc() to allocate some heap memory, a pointer to the first byte in the block is returned to you as a void *. Let's look at an example.

```
#include <stdlib.h>
#include <stdio.h>

int *p;

p = (int *)malloc(sizeof(int));
if (p != NULL) {
    *p = 42;
    /* other uses of the allocated memory */
    free(p);    /* deallocate the memory when done */
} else {
    fprintf(stderr, "Error allocating memory for integer\n");
}
```

What does this code do? We include <stdlib.h> so that we can call malloc() and refer to NULL; we also include <stdio.h> so that we can call fprintf(). We declare a pointer of the appropriate type. We then call malloc(), using sizeof() to specify the number of bytes needed for an integer. We use the cast (int *) to explicitly convert from a void * pointer (returned by malloc()) to an int *. We check to see if the malloc() was successful; if so, we use the allocated memory, then return it to the heap; if not, we print an error message.

One does not usually use the heap to allocate temporary basic or structured data types; for example, for temporary use of an int in your function, you just declare it as an automatic; the compiler allocates storage for it on the stack, and when your function returns, that storage is popped off the stack. **We use the heap to allocate data items that must survive a return from the function in which they are allocated, usually arrays and structures**.

There are two important aspects to this example:

- you should *always* check the return result from malloc() (or calloc() or realloc()); if the allocation failed, and your code attempts to dereference a NULL, your program will abort with a *segmentation violation*; if the returned value is NULL, your program needs to take appropriate action;
- the line

  ```
  int *p = (int *)malloc(sizeof(int));
  ```

  is an integer-specific version of a standard pattern that you will see in code that uses malloc(); for any given type type, the allocation of an instance of that type will look as follows:

```
type *p = (type *)malloc(sizeof(type));
```

- i.e., `sizeof(type)` is the argument to `malloc()`, the `void *` return from `malloc()` is cast to `type *`, and the result is assigned to a variable of `type *`.

Note that due to the strong association of pointers and arrays, the pattern to use for an array of `type` of size `N` would be

```
type *p = (type *)malloc(N * sizeof(type));
```

3.6.5.3 An example program

The following program reads up to the first 100 lines from standard input, stores those lines in dynamic memory, prints each of the stored lines, and then frees the dynamic memory. We use a function from `<string.h>`, `strdup()`, which duplicates its argument on the heap, returning a `char*` pointer to the duplicate. This example program also uses a number of other aspects of the language that we have discussed so far.

```
#include <stdio.h>
#include <stdlib.h>
#include <string.h>

#define UNUSED __attribute__((unused))
#define NLINES 100

int main(UNUSED int argc, UNUSED char *argv[]) {
    char *lines[NLINES];
    char buf[BUFSIZ];
    char *p;
    int i;
    int nl = 0;

    while (nl < NLINES && fgets(buf, BUFSIZ, stdin) != NULL) {
        p = strdup(buf);
        lines[nl++] = p;
    }
    for (i = 0; i < nl; i++)
        printf("%s", lines[i]);
    for (i = 0; i < nl; i++)
        free((void *)lines[i]);
    return EXIT_SUCCESS;
}
```

Exercise 3.14. Build and test this program. Be sure to create a `Makefile` to use for this purpose.

3.6.6 Character pointers and functions

The most common pointers that you will encounter are pointers to characters. Strings are arrays of characters, with each character in the string occupying one position in the array; one additional position at the end of the string holds the 0-byte, `'\0'`, to terminate the string.

A string literal is written as: `"This is a string"`. The literal is stored as an array of characters in *read-only* memory, with the terminating 0-byte; the leading and trailing `'"'` characters are *not* stored in the array. When a string literal/constant is specified as an argument to a function, a `char *` pointer to the first character in the literal is passed to the function.

Note that C does NOT provide any operators for processing an entire string as a unit! Arrays of characters are used, and a library of functions, defined in `<string.h>`, enables typical string manipulation.

Consider the following two declarations:

```
char amsg[] = "this is a string";
char *pmsg = "this is a string";
```

`amsg` is an array, just big enough to hold the sequence of characters and the 0-byte; this array is placed in read-write memory, and the characters in the array can be changed by subsequent logic. `pmsg` is a pointer, and it points to the first character of an array in read-only memory that holds the sequence of characters and the 0-byte; the characters in the array *cannot* be changed, but subsequent logic can cause `pmsg` to point to a different string in memory.

3.6.7 Pointer arrays - pointers to pointers

Since pointers are variables themselves, they can be stored in arrays just as other data types can. In fact, we have seen variables that are arrays of pointers earlier in the chapter: `argv` (the argument vector that is passed as the second argument in the call to `main`) and `lines` (the array to hold lines in the example program in section 3.6.5.3).

As you may recall, `argv` was declared as `char *argv[]` - what does this mean? It means that `argv[0]` is of type `char *`; thus our previous assertion that `argv` is a list/array of strings; since strings are arrays of characters, then each element of `argv` is a pointer to an array of characters - i.e., points to the first character in the array.

3.6.7.1 Initializing arrays of pointers

Suppose you wanted to define a list of keywords that your program would understand as user commands. For example, suppose you have a simple image display program that supports the commands `up`, `down`, `left`, `right`, `zoom in`, and `zoom out`. You can declare and initalize an array of pointers to these keywords with the following code:

```
char *keywords[] = {
    "up",
    "down",
    "left",
    "right",
    "zoom in",
    "zoom out",
    NULL
};
```

Note the addition of `NULL` at the end of the array of pointers; we described earlier how one can put a *sentinel* value at the end of a compiler-constructed array so you know how big it is; `NULL` is an excellent value to use when you have an array of pointers since its value is guaranteed different from all valid address values. By the way, `argv[]` actually is terminated by `NULL` in this way, as well.

3.6.8 Multi-dimensional arrays

C provides rectangular multi-dimensional arrays, although in practice they are much less used than arrays of pointers. A multi-dimensional array is declared as follows:

```
int matrix[100][50];
```

This indicates that `matrix` has 100 rows, each with 50 elements. The value in `matrix` at the `i`th row and `j`th column is `matrix[i][j]`.

One can initialize a multi-dimensional array. The following code shows how to do so for a small, two-dimensional array.

```
int matrix[2][4] = {
    { 1, 2, 3, 4 },
    { 5, 6, 7, 8 }
};
```

3.6.9 Pointers to functions

A function itself is not a variable in C, but it is possible to define pointers to functions. These can be assigned to pointer variables, placed in arrays, passed as arguments to functions, returned by functions, etc. Let's look at one use of function pointers.

Consider a sort program that sorts strings in files, like the standard `sort` program in Linux. Sometimes, we want to sort the strings lexicographically (i.e., as character strings); at other times, there may be a number at the beginning of each line, and we would like the lines to be sorted numerically according to the leading number. As with the standard `sort` program, the user should be able to choose the type of sort by specifying an option argument when invoking the program.

The pseudocode for our `main()` looks something like the following:

process command arguments
read all lines of input
sort them
print them in order

Assuming that there is a `sort()` function that performs the *sort them* part of the pseudocode, we need to have some way to inform that function how we want the strings to be compared. If the function prototype for `sort()` has the following form, we can achieve this flexible form of sorting.

```
void sort(char *lines[], int left, int right, int (*comp)(char *l1, char *l2));
```

What does this prototype tell us?

- `sort()` sorts the array of pointers to strings, `lines[]`;
- it actually sorts a slice of the array, specified by `left` and `right`; and
- whenever `sort()` needs to compare two entries in `lines[]`, it will invoke the function pointed to by `comp`; this function takes two `char *` arguments, and the return value from the function will be a value `< 0` if `l1 < l2`, the value `0` if `l1 == l2`, or a value `> 0` if `l1 > l2`. The function `strcmp()` in `<string.h>` is exactly such a function, and compares the strings lexicographically.

Suppose we have read `n` lines of text, such that `lines[0] .. lines[n-1]` have valid pointers. If we wanted to do a lexicographical sort, `main()` would invoke `sort()` as:

```
#include <string.h>

sort(lines, 0, n-1, strcmp);
```

Now suppose that we want to do a numeric sort. To do so, we will have to define a numeric compare function that matches the prototype for the function pointer argument in `sort()`. The following will do the trick.

```
#include <stdlib.h>

int numcmp(char *l1, char *l2) {
    int i1 = atoi(l1);
    int i2 = atoi(l2);
    return i1 - i2;
}
```

and `main()` would invoke `sort()` as

```
sort(lines, 0, n-1, numcmp);
```

3.6.9.1 Care when defining function pointers

Due to the precedence of C's operators, you have to be careful when defining function pointers. For example, consider the following function prototype:

```
int *f(void *arg);
```

this defines a function named `f` that returns a pointer to an integer, while

```
int (*pf)(void *arg);
```

defines `pf` as a pointer to a function returning an integer.

In general, when defining a function pointer, you should always surround the name of the pointer (`*name`) by parentheses to avoid such mistakes. We will use function pointers when constructing abstract data types in C, so we will have plenty of practice.

3.6.9.2 C functions as first-class entities

C functions are first-class entities, in that a pointer to a function can be stored in a variable, passed as a parameter to another function, returned from a function, and can be stored in data structures such as arrays, structs, ...

One typical use of functions as first class objects is to provide a function that will apply a function argument to data supplied in other arguments; this is exactly what our `sort()` function described above does.

Let's look at an example implementation of a function that applies a function argument.

```
#include <stdio.h>
#include <stdlib.h>

void apply(long (*func)(long), long lst[], long N, long ans[]) {
    long i;
    for (i = 0; i < N; i++) {
        ans[i] = (*func)(lst[i]);
    }
}

long times2(long v) {
    return (2L * v);
}

long square(long v) {
    return (v * v);
}

void printArray(long array[], long N) {
    long i;

    for (i = 0; i < N; i++)
        printf("%s%ld", (i == 0) ? "" : " ", array[i]);
    printf("\n");
}

int main(int argc, char *argv[]) {
    long in[200], out[200], i, v;

    for (i = 1; i < argc; i++) {
        sscanf(argv[i], "%ld", &v);
        in[i-1] = v;
    }
    printArray(in, argc-1);
    apply(times2, in, argc-1, out);
    printArray(out, argc-1);
    apply(square, in, argc-1, out);
    printArray(out, argc-1);
    return EXIT_SUCCESS;
}
```

The function `apply()` will apply `func` to each element in `lst`, storing the result of that application in the corresponding element of `ans`. `times2()` and `square()` are two functions that match the function signature for `func`.

`main()` converts its arguments to long integers in `in`, prints the contents of `in`, invokes `apply()` to multiple each element of `in` by 2, placing the result in `out`, and then prints the contents of `out`. It does the same thing using `square()`.

We will use function pointers to enable our generic abstract data type implementations to assist the programmer in returning heap-allocated storage, among other uses.

Exercise 3.15. Create, build, and test this program.
Add a function `times10` and add invocation of `times10` to main; build and test.
Add a function `cube` and add invocation of `cube` to main; build and test.

3.7 Structures

A *structure* is a collection of one or more variables, possibly of different types, grouped together under a single name for convenient handling. A structure declaration looks as follows:

```
struct [tag] {
    declarations
};
```

The keyword `struct` introduces a structure declaration, which is a list of variable declarations enclosed in curly braces; the `tag` is an optional name that can be used to refer to this structure type in the future. The variables named in the declarations within the braces are called *members*.

A `struct` declaration defines a type. The right brace that terminates the list of members may be followed by a list of variable names, as in

```
struct { . . . } x, y, z;
```

A `struct` declaration that is *not* followed by a list of variables reserves no storage; it merely describes a template or the shape of a structure. In such a case, a `tag` **MUST** be specified in order to define instances of the structure later.

Suppose that we have defined the following `struct`:

```
struct point {
    int x;
    int y;
};
```

We can declare an instance of a `point` using

```
struct point pt;
```

We can initialize a structure in its declaration as in

```
struct point maxpt = { 320, 200 };
```

We can refer to a member of a particular `struct` as *structure-name.member-name*, as in

```
printf("(%d,%d)\n", pt.x, pt.y);
```

Structures can be nested; for example, if we represent a rectangle as a pair of points denoting diagonally opposite corners, we can define

```
struct rect {
    struct point ll;
    struct point ur;
};
```

If we declare `screen` as

```
struct rect screen;
```

then `screen.ll.x` refers to the `x` coordinate of the lower left corner (`ll`) of `screen`.

3.7.1 Legal operations on a structure

- Copy it as a unit.
- Assign to it as a unit.
- Pass it by value as a function argument.
- Return it by value as a function return value.
- Takes its address using `&`.
- Access its members.
- A global structure may be initialized using a list of constant member values.
- An automatic structure may be initialized using runtime expressions, as with automatic variables.
- It may **NOT** be compared with another structure using `==` or `!=`.

3.7.2 Pointers to structures

Passing large structures by value can be very inefficient. We can declare pointers to structures just as we do for built-in data types, as in

```
struct point *pp;
```

This indicates that `pp` is a pointer to structures of type `struct point`. If `pp` points to a `point` structure, then `*pp` is the structure itself, and `(*pp).x` and `(*pp).y` are the members.

Pointers to structures are so frequently used that an alternative notation is provided to access members. If `p` is a pointer to a structure, then `p->member-name` is equivalent to `(*p).member-name`.[15]

3.7.3 Arrays of structures

Of course, we can create an array of structures. Recall our previous example of an array of keywords. Let's modify it slightly and show how it might be used:

```
struct key {
    char *word;
    int value;
};

struct key keywords[] = {
    { "up", 1},
    { "down", 2},
    { "left", 3},
    { "right", 4},
    { "zoom in", 5},
    { "zoom out", 6},
    { NULL, -1}
};

int mapKeyword(char *word) {
    int i;

    for (i = 0; keywords[i].word != NULL; i++)
        if (strcmp(word, keywords[i].word) == 0)
            return keywords[i].value;
    return keywords[i].value;
}
```

The function `mapKeyword()` maps from one of the string commands to an integer value. The code that solicited the string command from the user would call this routine, and then process the return value in a `switch` statement to perform the requested action.

3.7.4 Self-referential structures

As we shall see later in the text, many data structures that we use for common algorithms require that a structure contain one or more members that can *point at* instances of that

[15] Real C programmers almost *NEVER* use the `(*ptr).member` syntax, preferring the `ptr->member` syntax; you are strongly encouraged to follow their example.

structure - e.g., linked lists, binary trees. For a singly-linked list of integers, we would define the following structure type for nodes in the list:

```
struct node {
    struct node *next;
    int value;
};
```

In C, as soon as the compiler has seen `struct tag`, any subsequent code can refer to this tag; for members of that struct, one can declare **pointers** to instances of that structure. It makes no sense for a structure to contain a member which is an instance of that structure; where would the recursion end?

3.7.5 Typedefs

C provides a facility for creating synonyms for data type *names*. For example,

```
typedef int Length;
```

makes the name `Length` a synonym for `int`.

The type name `Length` can be used in declarations, casts, etc. in exactly the same way that `int` can be used; for example:

```
Length len, maxlen;
Length *lengths[25];
```

We can use `typedef` to also define synonyms for pointers.

```
typedef char *String;
```

makes `String` a synonym for `char *`.

The most common use of `typedef` is with respect to structures. Let's revisit our point structure and define a synonym for it.

```
typedef struct point {
    int x;
    int y;
} Point;
```

This particular style is extremely common - i.e., the tag for the structure starts with a lower-case letter, while the synonym starts with an upper-case letter; in this example, the tag is `point`, while the synonym for `struct point` is `Point`. With the above definition of `Point`, our definition for a rectangle can become

```
typedef struct rectangle {
    Point ll;
    Point ur;
} Rectangle;
```

and we can declare the variable `screen` as `Rectangle screen;`.

Note that `typedef` does *not* create a new type in any sense; it merely adds a synonym for some existing type. For example, we can declare variables as `struct point p1;` or as `Point p2;`. Both declarations achieve the same goal, of creating a variable that holds a `struct point` - i.e., both `p1` and `p2` have exactly the same properties.

It is also possible to create a synonym for function pointers. For example:

```
typedef int (*PFI)(char *, char *);
```

creates the type name `PFI` for "pointer to function (of two `char *` arguments) returning an `int`"; it could be used as in the following:

```
PFI strcmp, numcmp;
```

3.7.6 Structs and the heap

The `sizeof` compile time operator works with `struct`'s just like it does for built-in types. This enables us to create instances of our structures on the heap using `malloc()`.

Consider the following example:

```
typedef struct node {
    struct node *next;
    int val;
} Node;

Node *head = NULL;    /* head of singly-linked list */
Node *tail = NULL;    /* tail of singly-linked list */

int addNode(int value) { /* add node to tail of list */
    Node *n = (Node *)malloc(sizeof(Node));
    int success = (n != NULL);

    if (success) {
        n->val = value;
        n->next = NULL;
        if (head == NULL)
```

```
            head = n;
        else
            tail->next = n;
        tail = n;
    }
    return success;    /* return success/failure indication */
}
```

The call to `malloc()` looks just like those we have seen before. Through the cast, we have a pointer to our structure, and can manipulate the members of the allocated structure. This example is for a singly-linked list, which we will see later in the textbook.

3.8 Input and output

Input and output facilities are not part of the C language itself. The standard I/O library, defined in `<stdio.h>`, provides the ANSI standard library of I/O functions. A program comes to life with standard input (`stdin`), standard output (`stdout`), and standard error output (`stderr`) predefined - i.e., they are **already opened files** which you can begin using immediately. In particular, **they are not the names of files that can be opened using `fopen()`**. By default, `stdin` is associated with your keyboard, and `stdout` and `stderr` are associated with your terminal window. If the program was invoked with I/O redirection in the command line, the associated standard streams will point to the file or pipe specified.

3.8.1 Single character input and output

The simplest input mechanism is to read one character at a time from `stdin`, using `getchar()`:

```
int getchar(void);
```

`getchar()` returns the next input character from `stdin` each time it is called, or `EOF` when it encounters the end of file.

The function

```
int putchar(int ch);
```

puts the character `ch` onto `stdout`. We have previously seen that `printf()` also prints its output on `stdout`. Calls to `putchar()` and `printf()` can be interleaved - output appears in the order in which the calls were made.

3.8.2 Formatted output - `printf()`

We introduced `printf()` in section 3.2.1.

```
int printf(char *format, ...);
```

`printf()` copies characters from "format" to standard output; when a conversion specification is encountered in "format", the next argument in the call is formatted onto standard output according to that specification. The return value from the call to `printf()` is the number of characters that were written onto standard output.

While the next table describes these conversion specifications in detail, we have already encountered several of these in previous examples in this chapter:

- `%s` in the "format" argument indicates that the next argument is a C string (`char *`), and that the characters in that string should be copied to standard output;
- `%d` indicates that the next argument is an `int`, and its decimal representation should be copied to stdout;
- `%ld` indicates that the next argument is a `long`, and its decimal representation should be copied to stdout.

It is important to learn how to use these formatted output capabilities so that the output from your programs is readable by the users of your programs.

The basic `printf()` conversions are shown in the following table. All conversion specifications consist of the character `%`, 0 or more flags (in any order), an optional number that specifies the minimum field width for the converted argument, a period `.` which separates the field width from the precision, the precision (the number of digits to print after a decimal point), and a length modifier which indicates a non-default type for the integer or floating point argument.

The flags that can be specified are:

- `-` indicates that the converted argument should be left-justified in its output field;
- `+` specifies that a number will always be printed with a sign (plus or minus);
- `0` for numeric conversions, the converted argument will be padded to the field width with zeros instead of blanks.

character	**input data**	**argument type**	**comment**
`d`	decimal integer	`int`	`hd` -> `short`, `ld` -> `long`, `Ld` -> `long long`

`u`	unsigned decimal integer	`unsigned`	`hu` -> `unsigned short`
			`lu` -> `unsigned long`,
			`Lu` -> `unsigned long long`

`c`	character	`char`	the character is copied
`s`	character string	`char *`	the characters in the string are copied
`f`	floating point number	`double`	decimal notation of the form `[-]mmm.ddd`, where the number of `d`'s is specified by the precision; the default precision is 6; a precision of 0 suppresses the decimal point
`e`	floating point number	`double`	decimal notation of the form `[-]m.dddddde`±`xx`, where the number of `d`'s is specified by the precision; the default precision is 6; a precision of 0 suppresses the decimal point
`%`	literal %	no argument is processed	print a %

3.8.3 Formatted input - `scanf()`

The function `scanf()` is the input analog to `printf()`, providing many of the same conversion facilities in the opposite direction:

```
int scanf(char *format, ...);
```

`scanf()` reads characters from standard input, interprets them according to the specification in `format`, and stores the results in the remaining arguments. Note that all of the arguments into which `scanf()` stores the results **MUST** be pointers, as we discussed in section 3.6.2. `scanf()` stops when it reaches the end of the format string, or when some input fails to match the control specification in the format string. `scanf()` returns as its value the number of successfully matched and assigned input items. If an end of file is detected while scanning, `EOF` is returned. The next call to `scanf()` resumes scanning standard input immediately after the last character scanned in the current call.

The `scanf()` format string usually contains conversion specifications, which are used to control conversion of input. It may contain:

- blanks or tabs, which are ignored;
- ordinary characters (not `%`), which are expected to match the next non-white-space character of the input stream;
- conversion specifications, consisting of the character `%`, an optional number specifying a maximum field width, an optional `h`, `l` or `L` indicating the width of the target, and a conversion character.

The basic `scanf()` conversions are shown in the following table.

character	input data	argument type	comment
d	decimal integer	int *	hd -> short *, ld -> long *, Ld -> long long *
u	unsigned decimal integer	unsigned *	hu -> unsigned short *, lu -> unsigned long *, Lu -> unsigned long long *
c	character	char *	the next input character is copied; the normal skip over white space is suppressed
s	character string	char *	address of an array of characters large enough for the string and a terminating '\0'
e,f,g	floating point number	float *	with optional sign, optional decimal point and optional exponent; lf -> double *, Lf -> long double *
%	literal %	no assignment	

Here are a couple of examples.

- Suppose we want to read input lines that contain dates of the form "dd Month yyyy":

```
int day, year;
char monthname[20];

if (scanf("%d %s %d", &day, monthname, &year) != 3) {
    fprintf(stderr, "input was not in the form dd Month yyyy\n");
}
```

- Now suppose that the required format is "mm/dd/yyyy":

```
int day, month, year;

if (scanf("%d/%d/%d", &month, &day, &year) != 3) {
    fprintf(stderr, "input was not in the form mm/dd/yyyy\n");
}
```

3.8.4 File access

Given the name of a file as a string, one can open it for reading/writing, read from it or write to it, and close it. <stdio.h> defines a stream type FILE *; a successful file open returns one of these streams, and the I/O routines and the close routine take one of these streams as an argument. <stdio.h> defines stdin, stdout, and stderr as instances of FILE *. The function prototypes are as follow.

prototype	**comment**
`FILE *fopen(char *name, char *mode);`	most common mode values are `"r"` to open for reading, `"w"` to open for writing (overwriting any existing contents), and `"a"` to open for appending
`int getc(FILE *fp);`	return next character from stream, returning `EOF` if end of file
`int putc(int c, FILE *fp);`	write character to stream
`int fclose(FILE *fp);`	close stream
`int fscanf(FILE *fp, char *format, ...);`	scan stream according to `format`
`int fprintf(FILE *fp, char *format, ...);`	output values to stream according to `format`
`char *fgets(char *buf, int size, FILE *fp);`	fetch next line, including `'\n'` into buf, returning `buf` if successful, `NULL` if end of file
`int fputs(char *buf, FILE *fp);`	output characters in `buf` to stream

There are also versions of `scanf()` and `printf()` that work with character arrays instead of `FILE *` streams.

```
int sscanf(char *buf, char *format, ...);
int sprintf(char *buf, char *format, ...);
```

Finally, while functions in the `scanf()` family return the number of conversions that were successfully completed, the functions in the `printf()` family return the number of characters written to the stream/buffer; `sprintf()` always writes a terminating 0-byte, but does not include it in the returned count. Thus, the following pattern is sometimes seen in code that is constructing a complex string in an array.

```
char *p, buf[4096];

p = buf;
p += sprintf(p, format1, v1, v2, ..., vn);
p += sprintf(p, format2, w1, w2, ..., wm);
p += sprintf(p, format3, x1, x2, ..., xo);
* * *
/* buf contains the concatenated formatted outputs */
```

3.9 Environment variable & command argument conventions

There are a variety of ways for providing information to programs that you invoke in `bash`:

- A program can indicate that it will obtain the value of an environment variable if it is defined; for example, `make` will obtain the value of an environment variable `CFLAGS` if it is defined in its environment, and will use that value unless `CFLAGS` is explicitly defined in the makefile. In this latter case, it will use the value defined in the makefile.

> ⚠ You are strongly advised to *NOT* define `CFLAGS` in the environment, and to *ALWAYS* define `CFLAGS` at the top of each Makefile. From personal experience, you will forget that you have defined `CFLAGS` in the environment when you port your code to another system, and spend quite a bit of time figuring out what is wrong.

- A program can indicate that it will change its functionality if particular options are specified in the command line. These options come in two flavors:
  - ⋆ "short" options - these are of the form `-<character>`, where `<character>` is replaced by a single letter; the man page for the program will tell you how the program interprets such an argument. By convention, an argument of this form indicates to the program that you are selecting a particular way that the program should perform its function. For example, `ls` without an option indicates that `ls` should list the names of the files in the current working directory. `ls -l`, on the other hand, indicates that `ls` should display a *long* listing of each file in the current working directory, one per line.
    Most commands permit one to specify several short option characters in a single argument - consider `ls -lrt`. The `-l` option indicates that one should do a long listing, the `-r` option indicates that it should reverse the order of the presentation, and the `-t` option indicates that the files should be ordered by modification time. It is perfectly legal to invoke this as `ls -l -r -t`, but users require compounding individual options so often that, by convention, most programs support this approach.
    Sometimes an argument of this type requires an additional piece of information; For example, `ls -w 50` indicates that `ls` should restrict its output to 50 columns on the output. The number of columns `50` must follow the `-w` immediately on the command line as a separate argument to the command. When a short option requires additional information, it cannot be combined with other short options *unless* it is the last short option, as in `ls -lw 65`.
  - ⋆ "long" options - such options are introduced by two hyphens, as in `--all` or `ls --width=50`. In such cases, the option text (`width`) and its value (`50`) are a single string argument as seen by the program.
- All other arguments are usually names of files; occasionally, for example for programs like `grep`, the first non-option argument is considered a pattern for which `grep` must search in the files named in subsequent arguments.

From this discussion, you should infer that Linux *strongly* discourages starting a filename with a hyphen (`'-'`). If you do so, you will need to consult online help to rename the file to remove the leading hyphen.

If you are writing a program in C to be invoked from `bash`, you will need to provide logic in your `main()` to obtain the arguments that were specified when your program was invoked. For your program to be a good citizen in the Linux environment, you should adhere to the following rules:

- If information (such as `CFLAGS` to `make`) can be provided via an environment variable, this information should be obtained before processing any command arguments.

- While some programs enable one to intersperse options between filenames, it is strongly recommended that you *not* do that. In other words, all options should occur before the first non-option argument.
- If an argument starts with `'-'`, and it is *not* a bare `'-'`, it is an option; if it *is* a bare `'-'`, most programs consider this to be shorthand for `standard input`.
- For an option, if the next character is another `'-'`, it is a long option. The processing of an option will depend upon this distinction.
  - ⋆ If it is a short option, your code should process each character that appears after the leading hyphen.
  - ⋆ If it is a short option, and the last character that follows the hyphen requires additional information, you need to process the next argument for that additional information.
  - ⋆ If it is a long option, and the option requires additional information, it will be found in the same argument following the `'='` sign.
  - ⋆ If the option is providing the same information as an environment variable, the value provided by the option *overrides* any value that was obtained from an environment variable.

3.10 Processing command line arguments in C programs

When you write your C programs, you will need to process command line arguments in your `main()`. Your command line argument processing should conform to the rules outlined above. This section shows you how to process command line arguments where short options are used to specify options to the program.

Consider a simplified version of the command `comm` with the following synopsis:

```
comm [OPTION]... FILE1 FILE2
```

with the following description:
compare sorted files FILE1 and FILE2 line by line.

When FILE1 or FILE2 (not both) is -, read standard input.

With no options, produce three-column output. Column one contains lines unique to FILE1, column two contains lines unique to FILE2, and column three contains lines common to both files.

The legal options are:

- -1, suppress column 1 (lines unique to FILE1)
- -2, suppress column 2 (lines unique to FILE2)
- -3, suppress column 3 (lines that appear in both files)

`<unistd.h>` provides the function signature for a function `getopt()` and extern declarations for several global variables that are associated with `getopt()`'s processing;

see `http://man7.org/linux/man-pages/man3/getopt.3.html` for the complete man page for `getopt()`.

Here is an example source file that processes the arguments for legal invocations of the simplified `comm` command; explanations will follow the source.

```
#include <unistd.h>  /* for getopt(), opterr, optind, and optopt */
#include <stdio.h>   /* for fprintf() and stderr */
#include <stdlib.h>  /* for EXIT_SUCCESS and EXIT_FAILURE */
#include <stdbool.h> /* for bool, true, and false */
#define USAGESTR "usage: %s [-123] FILE1 FILE2\n"

int main(int argc, char *argv[]) {
    int opt;
    bool print1, print2, print3;
    int nOptions = 0; /* count number of options detected */

    print1 = print2 = print3 = true;
    opterr = 0; /* tells getopt to NOT print an illegal option error message */
    while ((opt = getopt(argc, argv, "123")) != -1) {
        switch(opt) {
            case '1': print1 = false; nOptions++; break;
            case '2': print2 = false; nOptions++; break;
            case '3': print3 = false; nOptions++; break;
            default: fprintf(stderr, "%s: illegal option, '-%c'\n", argv[0], optopt);
                     fprintf(stderr, USAGESTR, argv[0]);
                     return EXIT_FAILURE;
        }
    }
    /* at this point, optind is the index into argv[] for the first non-option */
    /* since comm requires two files, (optind + 2) == argc must be true */
    if ((optind + 2) != argc) {
        fprintf(stderr, USAGESTR, argv[0]);
        return EXIT_FAILURE;
    }
    /* process files using print1, print2, and print3 booleans */
    return EXIT_SUCCESS;
}
```

We `#include <unistd.h>` to avail ourselves of the function signature for `getopt()`, and access to `opterr`, `optind`, and `optopt`, which are three global variables through which `getopt()` accesses/returns additional information.

The call to `getopt()` takes three arguments: `argc`, `argv`, and a string literal in which we have enumerated legal options for our program; in this case, we have specified `"123"` for suppressing the printing of particular columns.

The first time we call `getopt()`, it starts with `argv[1]`, looking for arguments that start with a hyphen, `'-'`. It returns as its function value the option character that it found; the next call picks up where it left off; `getopt()` processes compound option arguments, where two or more option characters have been included in a single argument, as in `-12`. When it has found the first element of `argv[]` which does not start with a hyphen, or it has exhausted all of the elements of `argv[]`, it returns a function value of `-1`. **After it has returned a `-1`**, the global variable `optind` will either be equal to `argc`, in which case no non-option arguments were provided, or it will be the index into `argv[]` of the first non-option argument.

3.11 How the compiler and linker build your executable programs

When you compile your .c files into the corresponding .o files, the compiler places the following information in each .o file:

- global names that you are defining in the .c file - e.g., `main()`, other functions, the names of any global variables for which you have defined storage
- variable/function names that were not resolved in the .c file - e.g., `fopen()`, anything that was declared as `extern`
- the machine instructions that implement the C statements in the .c file

Given this information from each of the .o files specified in the link command line, the linker first attempts to match unresolved global names from each .o file with global names defined in the other .o files.

It then consults libraries to match any remaining unresolved global names in the .o files with global names that have been defined in .o files stored in each library; if it finds a global defined in a .o file in a library, that .o file is added to the list of object files to assemble into the executable file.

If it manages to resolve all global names through this process, it then creates the output file, which is an executable image that can be invoked in bash.

If there are any unresolved global names after this process, it will print appropriate error messages about the unresolved global names, and will NOT create the executable image.

Consider the program showing how to use `getopt()` in section 3.10; call the source file that contains this program `getoptexample.c`. As the compiler generates `getoptexample.o`, it notes the following in the object file for the linker to use:

- the program defines a single global name, `main()`;
- through the inclusion of `<unistd.h>`, it accesses four global names that are *not* defined in this source file: `opterr`, `getopt()`, `optind`, and `optopt`; and
- through the inclusion of `<stdio.h>`, it accesses two global names that are *not* defined in this source file: `fprintf()` and `stderr`.

- through the inclusion of `<stdlib.h>`, it accesses two defined symbols, `EXIT_SUCCESS` and `EXIT_FAILURE`.

When you invoke the linker to create `getoptexample`, the only object file that you provide is `getoptexample.o`. The linker notes that your code uses the six undefined global symbols listed above, and that there are no other object files that define those symbols. It then consults the C system library to find those undefined symbols.

A library consists of a set of object files and an index that maps each global symbol **defined** in an object file to that object file. The first unresolved global symbol referenced is `opterr`; the C system library indicates that an object file that it contains, `getopt.o`, defines `opterr`. The linker then includes `getopt.o` in the set of files that it is linking together; it also notes that besides `opterr`, `getopt.o` also defines `getopt()`, `optind`, and `optopt`. Thus, it can match those missing global references to the definitions in `getopt.o`.

The next unresolved global symbol referenced in `getoptexample.o` is `fprintf()`. The C system library indicates that an object file that it contains, `stdio.o`, defines `fprintf()`. The linker then includes `stdio.o` in the set of files that it is linking together; it also notes that besides `fprintf()`, `stdio.o` also defines `stderr`. Thus, it can match that missing global reference to the definition in `stdio.o`.

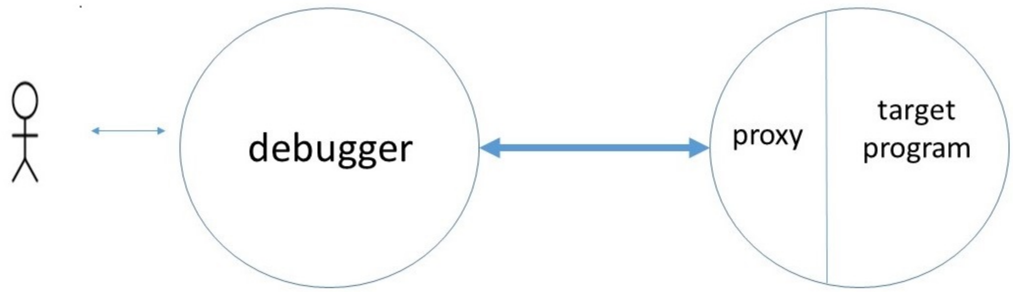
At this point, there are no unresolved global symbol references, so the linker can build the executable image file, `getoptexample`, using `getoptexample.o`, `getopt.o` from the C system library, and `stdio.o` from the C system library.

3.12 Debugging your programs

A *debugger* is a computer program used to test and debug another program (the *target* program). The main use of a debugger is to run the target program under controlled conditions that permit the programmer to track its operations in progress and monitor changes in computer resources (most often memory areas used by the target program or the computer's operating system) that may indicate malfunctioning code. Typical debugging facilities include the ability to run or halt the target program at specific points, display the contents of memory, CPU registers or storage devices (such as disk drives), and modify memory or register contents in order to enter selected test data that might be a cause of faulty program execution.[16]

The general architecture of a debugger is shown below. The debugger communicates with a process that contains the target program **and** proxy code that communicates with the debugger process.

[16] `https://en.wikipedia.org/wiki/Debugger`



The GNU debugger, usually called GDB and named `gdb` as an executable file, is the standard debugger for the Linux operating system. It can be used to debug programs written in a number of programming languages, including C, C++, Objective-C, Fortran, Java, and many others.

GDB was first written by Richard Stallman in 1986 as part of the GNU system. It is free software, released under the GNU General Public License, and is included in all Linux distributions.

GDB enables you to inspect what a program is doing at certain points of execution. Errors like *segmentation faults* are often quite easy to find with the help of `gdb`.

This section provides a brief introduction into the use of `gdb`. Complete documentation for `gdb` may be obtained from `https://www.gnu.org/software/gdb/documentation/`.

3.12.1 Preparing your program for use with gdb

Normally, you compile your program as follows:

```
$ gcc [options] -o <executable file> <source files>
```

As advised in Section 3.1.1, `[options]` should be replaced by `-W -Wall`. In order for the `executable file` to be used with `gdb`, one must add an additional option, `-g`, to the command line, as in the following example:

```
$ gcc -W -Wall -g -o prog prog.c
```

During the compile phase, the `-g` flag tells `gcc` to include the source lines of your code in the object file for `gdb` to show you while you are debugging your code. During the link phase, the `-g` flag tells `gcc` to incorporate the proxy code along with the linked object files.

You can now execute `prog` under `gdb`'s control using the following command:

```
$ gdb ./prog
```

This command simply starts up gdb; section 3.12.2 describes how to proceed with actually running the program under gdb.

gdb provides an interactive shell, enabling you to recall history using the arrow keys and to auto-complete (most) words using the TAB key. At any time, you may ask gdb for help with a command by typing the following to the gdb prompt:

```
(gdb) help command
```

3.12.2 Running the program under gdb

To run your program under gdb, you type the following command:

```
(gdb) run [arguments]
```

If your program requires arguments, obtained through argv[] in main(), you must specify them after the run command. You may also specify I/O redirection (<file and/or >file) along with the command arguments.

This runs the program - if there are no serious problems, the program should run to successful completion. If the program has issues, gdb assumes control after the program unsuccessfully terminates, and displays some useful information about the program, such as the line number where it terminated, parameters to the enclosing function, etc.

Consider the following program in a file test.c:

```
#include <stdio.h>
#include <stdlib.h>
#include <string.h>

#define UNUSED __attribute__((unused))

size_t foo_len(const char *s) {
    return strlen(s);
}

int main(UNUSED int argc, UNUSED char *argv[]) {
    const char *a = NULL;

    printf("size of a = %ld\n", foo_len(a));
    return 0;
}
```

The following dialog shows execution of this program using gdb:

```
GNU gdb (GDB) 7.9
Copyright (C) 2015 Free Software Foundation, Inc.
License GPLv3+: GNU GPL version 3 or later <http://gnu.org/licenses/gpl.html>
This is free software: you are free to change and redistribute it.
There is NO WARRANTY, to the extent permitted by law.  Type "show copying"
and "show warranty" for details.
This GDB was configured as "x86_64-unknown-linux-gnu".
Type "show configuration" for configuration details.
For bug reporting instructions, please see:
<http://www.gnu.org/software/gdb/bugs/>.
Find the GDB manual and other documentation resources online at:
<http://www.gnu.org/software/gdb/documentation/>.
For help, type "help".
Type "apropos word" to search for commands related to "word"...
Reading symbols from ./test...done.
(gdb) run
Starting program: /home/cis415/LPE/gdb/test

Program received signal SIGSEGV, Segmentation fault.
0x00007ffff7ab820a in strlen () from /usr/lib/libc.so.6
(gdb)
```

As you can see, we encountered a *segmentation fault* in `strlen()`, which caused the program to terminate. You may recall that segmentation faults result from attempting to access virtual address `0`. Thus, it is likely that the argument to `strlen()` is a NULL pointer. Since we define `a` to be `NULL` in `main()`, pass `a` to `foo_len()`, which then passes `a` on to `strlen()`, we have found the source of our segmentation fault. [17]

If we change the declaration for `a` to the following:

```
const char *a = "This is a test string";
```

the following dialog results:

```
GNU gdb (GDB) 7.9
Copyright (C) 2015 Free Software Foundation, Inc.
License GPLv3+: GNU GPL version 3 or later <http://gnu.org/licenses/gpl.html>
This is free software: you are free to change and redistribute it.
There is NO WARRANTY, to the extent permitted by law.  Type "show copying"
and "show warranty" for details.
This GDB was configured as "x86_64-unknown-linux-gnu".
Type "show configuration" for configuration details.
For bug reporting instructions, please see:
<http://www.gnu.org/software/gdb/bugs/>.
Find the GDB manual and other documentation resources online at:
<http://www.gnu.org/software/gdb/documentation/>.
```

[17] Note that if we had simply invoked `test` in the shell, the shell would have yielded the relatively unhelpful message of `Segmentation fault (core dumped)`

```
For help, type "help".
Type "apropos word" to search for commands related to "word"...
Reading symbols from ./test...done.
(gdb) run
Starting program: /home/cis415/LPE/gdb/test
size of a = 21
[Inferior 1 (process 26063) exited normally]
(gdb)
```

To exit from `gdb`, one uses the `quit` command. If you are attempting to `quit` after a program has terminated successfully, `gdb` lets you `quit` directly, as in:

```
(gdb) quit
```

If, on the other hand, the program has terminated unsuccessfully, `gdb` requests that you verify your intention to quit, as in:

```
(gdb) quit
A debugging session is active.

        Inferior 1 [process 26028] will be killed.

Quit anyway? (y or n) y
```

3.12.3 Other useful commands

If all `gdb` provided was extra information about the source of the fault that killed your program, it would not have to be interactive. The real power of a debugger is that it lets you stop the execution of your program, inspect the contents of memory, and view other aspects of your program as it executes.

One useful command to `gdb` is to inspect the sequence of calls that resulted in the faulty termination of your program. This command is `bt` (for *backtrace* – `backtrace` is also a legal command to obtain this functionality). Let's ask for the backtrace after our faulty program above exits with a segmentation fault:

```
(gdb) bt
#1  0x00007ffff7ab8201 in strlen () from /usr/lib/libc.so.6
#2  0x000000000040055e in foo_len (s=0x0) at test.c:8
#3  0x0000000000400583 in main (argc=1, argv=0x7fffffff3878) at test.c:14
(gdb)
```

For this simple example, the backtrace corroborates our logic above regarding the source of the segmentation fault.

A particularly useful command to `gdb` is to set a *breakpoint* in the program; this is done with a command of the form:

```
(gdb) break location
```

When your program reaches a breakpoint, it will pause and control returns to `gdb`. You must set your initial breakpoint[s] before you `run` the program; you may introduce additional breakpoints whenever your program has paused and `gdb` has regained control.

Let's set a breakpoint in our faulty program before we execute it [18]:

```
(gdb) break foo_len
Breakpoint 1 at 0x400552: file test.c, line 8.
(gdb) run
Starting program: /home/cis415/LPE/gdb/test

Breakpoint 1, foo_len (s=0x0) at test.c:8
8     return strlen(s);
(gdb) print s
$1 = 0x0
(gdb)
```

We specified that a breakpoint should be set at the start of `foo_len()`. Alternatively, since we know that the function starts at line 8 of test.c, we could have specified

```
(gdb) break test.c:8
```

In fact, you can set a breakpoint at any statement in your source files, they do not have to coincide with the start of a function. Since you typically will not know the line numbers for your source files, setting breakpoints at the start of a function is a very easy way to pause your program before a bug manifests itself.

When we issue the `run` command, the program starts to execute `main()`; when `foo_len()` is invoked, control returns to `gdb`. At the `gdb` prompt, we may then issue other commands. In this case, we invoked the `print` command to see what the value is for the argument `s`, which is shown to be `0x0`; note that the function arguments are automatically provided when the breakpoint is encountered. Note also that when we asked `gdb` to print the value of `s`, it printed '`$1 = 0x0`'; we could equally have asked it to print the value of `$1`, as `gdb` represents the arguments to a function positionally as `$1`, `$2`, ...

You can use the `print` command to not only display the values of function arguments by name, but of any local or global variables by name, as well. If a variable is a pointer, say '`struct foo *p;`', specifying `print *p` to `gdb` will cause the contents of the `struct foo` to which `p` currently points to be printed out.

Any time `gdb` regains control after the program starts running, we can continue the

[18] The boilerplate text from `gdb` will no longer be shown in dialogs.

execution of the program by issuing the `c` (for *continue* – `continue` is also a legal command to obtain this functionality) command.

We can also single step our program after execution is paused. There are two forms of the single step functionality:

- The next line of code is executed by specifying the `step` command. This will execute *just* the next line of code. If the next line of code contains a function invocation, `step` *steps* into that function. This enables you to dive deep into a sequence of call frames to get to the bottom of your problem.
- You can also execute the next line of code by specifying the `next` command. If the next line of code contains a function invocation, using `next` does *not* step into that function. Thus, `next` simply enables you to step through the current function.

Typing `step` or `next` many times is extremely tedious. `gdb` interprets a bare carriage return to mean "re-execute the previous command". Thus, if you need to step/next through many lines of code, repeatedly typing `ENTER/RETURN` will eliminate a bit of the tedium.

We can clear a breakpoint by issuing the `clear` command; this command requires the same argument as used in a `break` command to set the breakpoint. In our example above, a '`clear foo_len`' command will remove the breakpoint set upon entry to `foo_len()`.

Breakpoints permit `gdb` to regain control when a statement is about to be executed. Another way for `gdb` to regain control is through *watchpoints*. A watchpoint allows you to monitor the values of variables, pausing the program when a watched variable changes value.

To set a watchpoint, you use the `watch` command:

```
(gdb) watch my_var
```

Now, whenever `my_var`'s value is modified, the program is paused and the old and new values are printed. `gdb` interprets the scope of the variable name in a `watch` command based upon the program scope at the time the `watch` command is executed. This means that you can set watchpoints for global variables before running the program; if you wish to set a watchpoint for a static local variable within a function, you need to set a breakpoint for that function, set a watchpoint for that variable when the function is entered the first time, and then clear the breakpoint.

There are a multitude of other features provided by `gdb`. Please consult materials at `https://www.gnu.org/software/gdb/documentation/` as you become familiar with `gdb`.

3.13 Managing heap memory

Valgrind is a program-execution monitoring framework. It comes with many tools; the tool upon which we are focused is the *memcheck* tool.

Memcheck detects and reports the following types of memory errors:

- Use of uninitialized memory.
- Reading/writing to heap memory after it has been freed.
- Reading/writing off the end of malloc'd blocks.
- Heap allocated memory leaks.
- Memory leaks due to not closing open files.
- Mismatched use of malloc vs free.
- And many more ...

3.13.1 Invoking `valgrind`

To test whether '`./prog arguments`' correctly allocates and uses memory, we run it with `valgrind` as follows:

```
$ valgrind ./prog arguments
```

As with `gdb`, the source files must be compiled with the `-g` option to `gcc`. `valgrind` supports a large number of options; the user manual may be consulted at `http://valgrind.org/docs/manual/manual.html`.

3.13.2 Use of uninitialized memory

`valgrind` keeps track of each program variable and each block allocated by `malloc()` to determine when that variable/block has been written to. If your program attempts to read from a variable or heap block before it has been initialized, `valgrind` will identify each occurrence appropriately.

Consider the following program.

```
#include <stdlib.h>

#define UNUSED __attribute__((unused))

int main(UNUSED int argc, UNUSED char *argv[]) {
    int x, y;

    if (x < 3)           /* x not initialized */
        y = 4;
    else
```

```
        y = 5;
    return EXIT_SUCCESS;
}
```

When executed by `valgrind`, the following output results:

```
==26569== Memcheck, a memory error detector
==26569== Copyright (C) 2002-2013, and GNU GPL'd, by Julian Seward et al.
==26569== Using Valgrind-3.10.1 and LibVEX; rerun with -h for copyright info
==26569== Command: ./uninit
==26569==
==26569== Conditional jump or move depends on uninitialised value(s)
==26569==    at 0x4004C5: main (uninit.c:8)
==26569==
==26569==
==26569== HEAP SUMMARY:
==26569==     in use at exit: 0 bytes in 0 blocks
==26569==   total heap usage: 0 allocs, 0 frees, 0 bytes allocated
==26569==
==26569== All heap blocks were freed -- no leaks are possible
==26569==
==26569== For counts of detected and suppressed errors, rerun with: -v
==26569== Use --track-origins=yes to see where uninitialised values come from
==26569== ERROR SUMMARY: 1 errors from 1 contexts (suppressed: 0 from 0)
```

As you can see, `valgrind` indicates that an unitialized value was used in main, at line 8 of uninit.c.

3.13.3 Reading/writing to heap memory after it has been freed

`valgrind` keeps track of each `malloc()` allocated block to determine when it is returned to the heap. Attempts to access an already freed heap block cause `valgrind` to identify each occurrence appropriately.

Consider the following program.

```
#include <stdlib.h>
#include <string.h>
#define UNUSED __attribute__((unused))

int main(UNUSED int argc, UNUSED char *argv[]) {
    char *s, *str="this is a string";
    int c, n;

    n = strlen(str) + 1;
    s = (char *)malloc(n);
    free(s);
    strcpy(s, str);       /* accessing freed heap memory */
    return EXIT_SUCCESS;
```

```
}
```

When executed by `valgrind`, the following output results:

```
==26628== Memcheck, a memory error detector
==26628== Copyright (C) 2002-2013, and GNU GPL'd, by Julian Seward et al.
==26628== Using Valgrind-3.10.1 and LibVEX; rerun with -h for copyright info
==26628== Command: ./alreadyfree
==26628==
==26628== Invalid write of size 1
==26628==    at 0x4C2D610: strcpy (in /usr/lib/valgrind/vgpreload_memcheck-amd64-linux.so)
==26628==    by 0x40062E: main (alreadyfree.c:12)
==26628==  Address 0x51d9040 is 0 bytes inside a block of size 17 free'd
==26628==    at 0x4C2B200: free (in /usr/lib/valgrind/vgpreload_memcheck-amd64-linux.so)
==26628==    by 0x40061B: main (alreadyfree.c:11)
==26628==
==26628== Invalid write of size 1
==26628==    at 0x4C2D623: strcpy (in /usr/lib/valgrind/vgpreload_memcheck-amd64-linux.so)
==26628==    by 0x40062E: main (alreadyfree.c:12)
==26628==  Address 0x51d9050 is 16 bytes inside a block of size 17 free'd
==26628==    at 0x4C2B200: free (in /usr/lib/valgrind/vgpreload_memcheck-amd64-linux.so)
==26628==    by 0x40061B: main (alreadyfree.c:11)
==26628==
==26628==
==26628== HEAP SUMMARY:
==26628==     in use at exit: 0 bytes in 0 blocks
==26628==   total heap usage: 1 allocs, 1 frees, 17 bytes allocated
==26628==
==26628== All heap blocks were freed -- no leaks are possible
==26628==
==26628== For counts of detected and suppressed errors, rerun with: -v
==26628== ERROR SUMMARY: 17 errors from 2 contexts (suppressed: 0 from 0)
```

Apparently, `strcpy` attempts to access the first and last byte of the destination string, thus causing `valgrind` to identify two invalid writes.

3.13.4 Reading/writing off the end of malloc'd blocks

`valgrind` keeps track of the length of each `malloc()` allocated block to check for attempted access beyond the allocation. Such attempts cause `valgrind` to identify each occurrence appropriately.

Consider the following program.

```
#include <stdlib.h>
#include <string.h>
#define UNUSED __attribute__((unused))

int main(UNUSED int argc, UNUSED char *argv[]) {
    char *s, *str="this is a string";
```

```
    int c, n;

    n = strlen(str);
    s = (char *)malloc(n);      /* no space for 0-byte */
    strcpy(s, str);             /* invalid write error */
    c = s[n];                   /* invalid read error */
    free(s);
    return EXIT_SUCCESS;
}
```

When executed by `valgrind`, the following output results:

```
==26596== Memcheck, a memory error detector
==26596== Copyright (C) 2002-2013, and GNU GPL'd, by Julian Seward et al.
==26596== Using Valgrind-3.10.1 and LibVEX; rerun with -h for copyright info
==26596== Command: ./overrun
==26596==
==26596== Invalid write of size 1
==26596==    at 0x4C2D623: strcpy (in /usr/lib/valgrind/vgpreload_memcheck-amd64-linux.so)
==26596==    by 0x40061F: main (overrun.c:11)
==26596==  Address 0x51d9050 is 0 bytes after a block of size 16 alloc'd
==26596==    at 0x4C29F90: malloc (in /usr/lib/valgrind/vgpreload_memcheck-amd64-linux.so)
==26596==    by 0x400608: main (overrun.c:10)
==26596==
==26596== Invalid read of size 1
==26596==    at 0x40062D: main (overrun.c:12)
==26596==  Address 0x51d9050 is 0 bytes after a block of size 16 alloc'd
==26596==    at 0x4C29F90: malloc (in /usr/lib/valgrind/vgpreload_memcheck-amd64-linux.so)
==26596==    by 0x400608: main (overrun.c:10)
==26596==
==26596==
==26596== HEAP SUMMARY:
==26596==     in use at exit: 0 bytes in 0 blocks
==26596==   total heap usage: 1 allocs, 1 frees, 16 bytes allocated
==26596==
==26596== All heap blocks were freed -- no leaks are possible
==26596==
==26596== For counts of detected and suppressed errors, rerun with: -v
==26596== ERROR SUMMARY: 2 errors from 2 contexts (suppressed: 0 from 0)
```

This program shows the typical cause of these overrun problems – forgetting to allocate space for the 0-byte at the end of a string. Another common source of this problem is to allocate an array of n items in a heap memory block, and then attempt to use n as an index into that block, forgetting that the array is indexed by *0 .. n-1*.

3.13.5 Heap allocated memory leaks

`valgrind` keeps track of each `malloc()` allocated block to determine when it is returned to the heap. Attempts to terminate the program when there are still outstanding allocations cause `valgrind` to identify those occurrences.

Consider the following program.

```
#include <stdlib.h>
#include <string.h>
#define UNUSED __attribute__((unused))

int main(UNUSED int argc, UNUSED char *argv[]) {
    char *s, *str="this is a string";
    int c, n;

    n = strlen(str) + 1;
    s = (char *)malloc(n);
    strcpy(s, str);
    return EXIT_SUCCESS;        /* forgot to free heap memory */
}
```

When executed by `valgrind`, the following output results:

```
==26646== Memcheck, a memory error detector
==26646== Copyright (C) 2002-2013, and GNU GPL'd, by Julian Seward et al.
==26646== Using Valgrind-3.10.1 and LibVEX; rerun with -h for copyright info
==26646== Command: ./memleak
==26646==
==26646==
==26646== HEAP SUMMARY:
==26646==     in use at exit: 17 bytes in 1 blocks
==26646==   total heap usage: 1 allocs, 0 frees, 17 bytes allocated
==26646==
==26646== LEAK SUMMARY:
==26646==    definitely lost: 17 bytes in 1 blocks
==26646==    indirectly lost: 0 bytes in 0 blocks
==26646==      possibly lost: 0 bytes in 0 blocks
==26646==    still reachable: 0 bytes in 0 blocks
==26646==         suppressed: 0 bytes in 0 blocks
==26646== Rerun with --leak-check=full to see details of leaked memory
==26646==
==26646== For counts of detected and suppressed errors, rerun with: -v
==26646== ERROR SUMMARY: 0 errors from 0 contexts (suppressed: 0 from 0)
```

If you wish to see details of leaked memory, use the following invocation:

```
$ valgrind --leak-check=full ./prog arguments
```

3.13.6 Memory leaks due to not closing open files

When you open a file using `fopen()`, a heap allocation is performed to hold the state of the open file. You must close each file that you have opened, using `fclose()`, in order to return this heap block, and thus demonstrate good heap memory hygiene.

Consider the following program.

```
#include <stdio.h>
#include <stdlib.h>

#define UNUSED __attribute__((unused))

int main(UNUSED int argc, UNUSED char *argv[]) {
    FILE *fd = fopen("closefailure.c", "r");
    return EXIT_SUCCESS;
}
```

When executed by `valgrind`, the following output results:

```
==10345== Memcheck, a memory error detector
==10345== Copyright (C) 2002-2017, and GNU GPL'd, by Julian Seward et al.
==10345== Using Valgrind-3.14.0 and LibVEX; rerun with -h for copyright info
==10345== Command: ./closefailure
==10345==
==10345==
==10345== HEAP SUMMARY:
==10345==     in use at exit: 552 bytes in 1 blocks
==10345==   total heap usage: 1 allocs, 0 frees, 552 bytes allocated
==10345==
==10345== LEAK SUMMARY:
==10345==    definitely lost: 0 bytes in 0 blocks
==10345==    indirectly lost: 0 bytes in 0 blocks
==10345==      possibly lost: 0 bytes in 0 blocks
==10345==    still reachable: 552 bytes in 1 blocks
==10345==         suppressed: 0 bytes in 0 blocks
==10345== Rerun with --leak-check=full to see details of leaked memory
==10345==
==10345== For counts of detected and suppressed errors, rerun with: -v
==10345== ERROR SUMMARY: 0 errors from 0 contexts (suppressed: 0 from 0)
```

3.13.7 Mismatched use of malloc vs free

`valgrind` keeps track of each `malloc()` allocated block to determine when it is returned to the heap. Attempts to free memory that is not allocated (e.g. has already been `free()`'ed or is an address that does not reside on the heap) cause `valgrind` to identify those occurrences.

Consider the following program.

```
#include <stdlib.h>
#include <string.h>
#define UNUSED __attribute__((unused))

int main(UNUSED int argc, UNUSED char *argv[]) {
    char *s, *str="this is a string";
    int c, n;
```

```
    n = strlen(str) + 1;
    s = (char *)malloc(n);
    strcpy(s, str);
    free(s);
    free(s);              /* freed a second time */
    return EXIT_SUCCESS;
}
```

When executed by `valgrind`, the following output results:

```
==26612== Memcheck, a memory error detector
==26612== Copyright (C) 2002-2013, and GNU GPL'd, by Julian Seward et al.
==26612== Using Valgrind-3.10.1 and LibVEX; rerun with -h for copyright info
==26612== Command: ./dblfree
==26612==
==26612== Invalid free() / delete / delete[] / realloc()
==26612==    at 0x4C2B200: free (in /usr/lib/valgrind/vgpreload_memcheck-amd64-linux.so)
==26612==    by 0x40063A: main (dblfree.c:13)
==26612==  Address 0x51d9040 is 0 bytes inside a block of size 17 free'd
==26612==    at 0x4C2B200: free (in /usr/lib/valgrind/vgpreload_memcheck-amd64-linux.so)
==26612==    by 0x40062E: main (dblfree.c:12)
==26612==
==26612==
==26612== HEAP SUMMARY:
==26612==     in use at exit: 0 bytes in 0 blocks
==26612==   total heap usage: 1 allocs, 2 frees, 17 bytes allocated
==26612==
==26612== All heap blocks were freed -- no leaks are possible
==26612==
==26612== For counts of detected and suppressed errors, rerun with: -v
==26612== ERROR SUMMARY: 1 errors from 1 contexts (suppressed: 0 from 0)
```

3.13.8 Invoking free on an automatic variable

It is illegal to invoke `free()` on a pointer that was *NOT* allocated from the heap. This is such a heinous transgression that it is caught by `gcc`.

Consider the following program.

```
#include <stdio.h>
#include <stdlib.h>

#define UNUSED __attribute__((unused))

int main(UNUSED int argc, UNUSED char *argv[]) {
    long aVariable = 42L;

    free(&aVariable);
    return EXIT_SUCCESS;
```

```
}
```

When compiled by `gcc`, the following output results:

```
automatic.c: In function `main':
automatic.c:9:5: warning: attempt to free a non-heap object `aVariable'
[-Wfree-nonheap-object]
     free(&aVariable);
     ^~~~~~~~~~~~~~~~
```

3.13.9 General advice

`valgrind` is an enormously useful tool. Nearly every sophisticated C program makes extensive use of the heap; it is **essential** that all memory allocation **and** use errors be eliminated from your programs.

The previous sections have demonstrated how different types of memory misuse manifest themselves in the output from `valgrind`. The *ONLY* time you should be satisfied that you have eliminated all problems with your memory use is if the output from `valgrind` looks like the following dialog.

```
==26596== Memcheck, a memory error detector
==26596== Copyright (C) 2002-2013, and GNU GPL'd, by Julian Seward et al.
==26596== Using Valgrind-3.10.1 and LibVEX; rerun with -h for copyright info
==26596== Command: ./allok
==26596==
==26596== HEAP SUMMARY:
==26596==     in use at exit: 0 bytes in 0 blocks
==26596==   total heap usage: 1 allocs, 1 frees, 16 bytes allocated
==26596==
==26596== All heap blocks were freed -- no leaks are possible
==26596==
==26596== For counts of detected and suppressed errors, rerun with: -v
==26596== ERROR SUMMARY: 0 errors from 0 contexts (suppressed: 0 from 0)
```

Chapter 4

Abstract Data Types

This book assumes that you have previously learned about classes and their use to construct your own complex data types in Python, Java, or C++. This chapter describes how to construct such complex data types using the C programming language; the equivalent to a class is called an abstract data type, and the equivalent to an object is termed an abstract data type instance.

4.1 Brief Review of Object-Oriented Programming

Object-oriented programming [1] (OOP) is a programming paradigm based on the concept of *objects*, which can contain data and references to code that operates on that data; the data is in the form of fields (often known as attributes or properties), and the code is in the form of procedures or functions (often known as methods).

A feature of objects is that an object's methods can access (termed *accessor* methods) and modify (termed *mutator* methods) the data fields of itself (objects have a notion of *this* or *self*). In OOP, programs are designed by constructing them out of objects that interact with one another. OOP programming languages are diverse, but the most popular ones are class-based, meaning that objects are instances of classes; the type of such an object is the class from which it is instantiated.

Many of the most widely used OOP languages (C++, Java, Python) are multi-paradigm, in that they support object-oriented programming to a greater or lesser degree in combination with imperative, procedural programming; the remainder of this section will focus on these three particular multi-paradigm languages.

[1] Much of the discussion in this section is derived from `https://en.wikipedia.org/wiki/Object-oriented_programming`

4.1.1 Encapsulation

A class that does not allow calling code to directly access internal object data, restricting access to object data through method invocation **only**, provides a strong form of abstraction or information hiding known as *encapsulation*. Some languages (Java, for example) let classes enforce access restrictions explicitly, for example denoting internal data with the *private* keyword and designating data intended for use by code outside the class with the *public* keyword. Methods may also be designated public, private, or intermediate levels such as *protected* (which allows access from the same class and its subclasses, but not objects of a different class). In other languages (like Python) this is enforced only by convention (for example, private methods may have names that start with an underscore). Encapsulation prevents external code from being concerned with the internal workings of an object. This facilitates code refactoring, for example allowing the author of the class to change how objects of that class represent their data internally without changing any external code (as long as "public" method calls continue to work the same way). It also encourages programmers to put all the code that is concerned with a certain set of data in the same class, which organizes it for easy comprehension by other programmers.

4.1.2 Class specification

Each multi-paradigm language supports the definition of functions that act as *constructors*; each constructor yields an object reference to a class instance of a particular type. After invoking a constructor to obtain an object reference, the programmer then uses the object reference to invoke public methods defined for that class instance; depending upon the language's support for encapsulation, the programmer may be able to use the reference to directly access attributes of the class instance, as well.

A class specification, sometimes also referred to as a *template* for instances of that class, enables the programmer to specify the following:

- the name (type) of the class; if the language supports inheritance, it will also enable the programmer to indicate the parent class[es] from which the current class is derived;
- the names, types, and, if supported, encapsulation of attributes for objects of that type; and
- the signatures and implementations for methods of that type.

4.1.3 Pure virtual classes (aka abstract classes)

As you can see, class specifications are a mixture of specification **and** implementation. Some OOP languages support *pure virtual classes*[2]; in such classes, the attribute component of the class specification is empty and the method component has the method

[2] Also known as *abstract classes*.

signatures **only**; such a class specification simply indicates the methods that must be supported by any non-virtual class that inherits from the pure virtual class. An example of pure virtual classes is the use of *interfaces* in Java).

4.1.4 An example

Suppose we need to write a program that can read data about students from a comma-separated value file that has been redirected to standard input. We need to create a `Person` instance for each line, and store those object references in an array for subsequent processing.

Each line of the file has the following form:

```
Last name,First name,UOID,Duckid,Primary major
```

Appendix A shows the main program and the class file needed to create a program that meets these requirements using Python, Java, and C++. You should look at the implementation for the OOP language with which you are familiar and make sure you understand why that implementation meets the requirements.

4.2 What are Abstract Data Types?

In computer science, an *abstract data type (ADT)* is a mathematical model for a data type, where a data type is defined by its behavior (semantics) from the point of view of a user of the data, specifically in terms of possible values, possible operations on data of this type, and the behavior of these operations. This contrasts with data structures, which are concrete representations of data, and are the point of view of an implementer, not a user.

Formally, an ADT may be defined as a "class of objects whose logical behavior is defined by a set of values and a set of operations".[3] ADTs are a theoretical concept in computer science, used in the design and analysis of algorithms, data structures, and software systems, and do *not* correspond to specific features of computer languages - i.e., mainstream computer languages do not directly support formally-specified ADTs. However, various language features, such as abstract base classes, correspond to certain aspects of ADTs. ADTs were first proposed by Liskov and Zilles in 1974, as part of the CLU language.

[3]This is analogous to an algebraic structure in mathematics.

4.3 How do they compare to objects?

Since an ADT is defined by its behavior (the methods it supports and the results of invoking those methods), it acts like an implementation of a pure virtual class/abstract base class as described in Section 4.1. As with all classes, an ADT must support one or more constructor functions for creating an ADT instance and a set of methods that one can invoke on an instance.

Since C is not object-oriented, our approach to ADTs consists of two parts:

- we define the behavior of an ADT through a header file which defines function prototypes for one or more constructor functions, defines function prototypes for the methods, and describes the actions performed when one invokes one of these methods; a program that wishes to use instances of a particular ADT will `#include` the corresponding header file; and
- **an** implementation of an ADT is provided through a source file; when the user's program creates instances of an ADT and invokes methods on those instances, the user must link an implementation into their program. For the ADTs discussed in the book, the user's code must be linked to an implementation contained in the ADT library; for ADTs that you implement yourself, you must specify the .o file that results from compiling your implementation in the link command for your program.

It is important to note that the implementation of the ADT is hidden from the calling code - i.e., any object attributes are completely encapsulated; the header file provides the "contract" between the user and the implementation. That is why we have indicated **an** when discussing the implementation above. One of the strengths of ADTs is that there can be multiple implementations of the abstract type; these different implementations may have different characteristics in terms of space and time complexity. We will cover this in more detail later in the book.

4.4 A well-structured approach to ADTs in C

This section describes a well-structured approach to constructing and using ADTs in C. It is not the only way to do it, but it provides similar syntax and structure to that provided by object-oriented languages such as Java, C++, and Python.

Every ADT will have one [or more] constructor function[s]; when invoked, a constructor will return a pointer to a data structure in which private data elements are stored, and which contains function pointers to all of the methods defined in the ADT. Since the data elements are private (to the user), alternative implementations of an ADT are readily supported.

4.4.1 Alternative implementations behind an interface

Let's look back at the header and source files for `isSubString()` in the last chapter.

issubstring.h

```
#include <stdbool.h>
bool isSubString(const char *needle, const char *haystack);
```

issubstring.c

```
#include "issubstring.h"
#include <string.h>

bool isSubString(const char *needle, const char *haystack) {
    return (strstr(haystack, needle) != NULL);
}
```

We defined the function prototype for `isSubString()` in the header file; any program that wishes to use the function must call it according to that prototype, and must link to an object file resulting from compilation of an implementation.

We could have implemented `isSubString()` differently, as in

issubstring.c (alternative version)

```
#include "issubstring.h"
#include <string.h>

bool isSubString(const char *needle, const char *haystack) {
    int nl = strlen(needle);
    int hl = strlen(haystack);
    int i;

    for (i = 0; i <= (hl - nl); i++)
        if (strncmp(needle, haystack+i, nl) == 0)
            return true;
    return false;
}
```

Our main program **has not changed** - it simply calls `isSubString()` knowing that the implementation conforms to the syntax and semantics defined in the header file. In fact, the object file to link to is probably contained in a library, and you are completely unable to see the source code for the function - e.g., implementations for `strlen()` or `getopt()`.

Thus we can see that specifying the prototype for one or more functions in a header file already gives us the support we need to be able to use different implementations of those functions.

4.4.2 Dispatch table basics

If you think about classes in Python, when you define a class (we'll refer to it as `TheClass`), you have to define an `__init__()` method which is called when your code invokes the constructor, `TheClass()`; assume we have done so, and assigned the return value from the constructor to a variable named `tc`.

Suppose `TheClass` also defines methods named `a()` and `b()`; if you want to invoke `a()` on `tc`, you invoke it as `tc.a()`. A similar syntax is used to invoke `b()`.

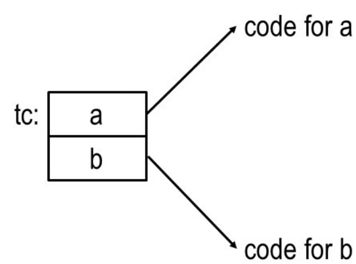
In a sense, when we define `TheClass`, we define a global function `TheClass()`, and an instance of the class contains function pointers to `a()` and `b()`, so that they can be invoked from `tc`. A data structure that contains function pointers is often called a *dispatch table*; the dispatch table for this simple Python example is shown below.

```
class TheClass:
    def __init__(self, arguments):
        # statements to initialize `self'

    def a(self):
        # statements to implement fxn

    def b(self):
        # statements to implement fxn

tc = TheClass()
```



In Python, when you invoke `tc.a()`, the interpreter actually rewrites the call to a global function, `TheClass.a()`, passing `tc` to `TheClass.a()` as the first argument, `self`. This is needed, since the code in `TheClass.a()` may need to access instance-specific data items that are stored in `tc` in order to do its work.

In a similar fashion, each C ADT will have one [or more] constructor function[s], each of which returns a pointer to a `struct` that has:

- a `void *` pointer to another struct in which the instance-specific data is kept; and
- a function pointer for each method defined for the ADT.

Let's assume that we have a C implementation of `TheClass`. There will be a header file, `theclass.h`, that defines the default constructor function prototype and the structure that is the dispatch table.

The default constructor function prototype has the following signature:

```
typedef struct theClass TheClass;  /* synonym for struct theClass */
const TheClass *TheClass_create(/* arguments needed */);
```

We first declare that `TheClass` is a synonym for `struct theClass`.[4] Do not worry, we will define `struct theClass` next. Note that we have declared that the pointer returned by the constructor has the `const` attribute. This means that the compiler can help prevent the user from modifying the fields in the structure which represents an instance of `TheClass`.

Next we need to define `struct theClass`.

```
/* now define the dispatch table */
struct theClass {
    /* the private data of the instance */
    void *self;

    /* function pointer to method a() */
    void (*a)(const TheClass *tc);

    /* function pointer to method b() */
    void (*b)(const TheClass *tc);
};
```

This states that `TheClass_create()` will return a pointer to an instance of this structure; the `self` member points at the private data of the instance, and the remaining members of the structure are function pointers to member functions.

How would a user program create an instance of `TheClass` and use it?

```
#include "theclass.h"

const TheClass *tc = TheClass_create(/* arguments */);

tc->a(tc);
tc->b(tc);
```

Having to specify the `tc` twice seems a bit repetitive, but we do not have something like the Python interpreter rewriting our statements for us. Additionally, this looks a bit like the invocation of an external object in C++, except for having to provide *self* in each method call.

4.4.3 The interface (header file)

The previous section showed parts of the header file for `TheClass`. Here it is in its entirety.

[4] See section 3.7.5 to remind yourself why we might do this.

```
#ifndef _THECLASS_H_
#define _THECLASS_H_

typedef struct theClass TheClass;  /* synonym for struct theClass */
const TheClass *TheClass_create(/* arguments needed */);

/* now define the dispatch table */
struct theClass {
    /* the private data of the instance */
    void *self;

    /* function pointer to method a() */
    void (*a)(const TheClass *tc);

    /* function pointer to method b() */
    void (*b)(const TheClass *tc);
};

#endif /* _THECLASS_H_ */
```

Let's enumerate the contents again:

- `#ifndef ... #define ... #endif` wrapper
  this enables you to `#include` this header file wherever it makes sense in your source code and other header files *without* having to worry if the compile of a single source file will somehow `#include` the file more than once, thus attempting to redefine function signatures and structure declarations;
- `typedef struct theClass TheClass;`
  this simply establishes `TheClass` as a synonym for `struct theClass` so `TheClass` can be used in the signatures that follow;
- `const TheClass *TheClass_create(/* arguments needed */);`
  this is the function prototype for the constructor; `/* arguments needed */` simply indicates that each ADT's default constructor will be defined to take the appropriate ADT-specific arguments in order for the constructor to create an ADT instance; if successful, the constructor returns a pointer to the dispatch table for the ADT instance; if unsuccessful, it returns `NULL`;
- `struct theClass { ... };`
  the structure declaration defines the members of the dispatch table; in particular,
  - `void *self;`
    defines a pointer to a structure that contains the instance-specific data; it is a `void *` to hide the shape and contents of that structure, thus enabling different implementations of the ADT to be used, since the caller has no dependency upon the implementation-dependent data;
  - `void (*a)(const TheClass *tc);`
    `void (*b)(const TheClass *tc);`
    for each method, a function pointer member of the dispatch table is defined

with the appropriate signature; each such method must have a first argument of type `const TheClass *` - i.e., the dispatch table structure returned from the constructor.

4.4.3.1 Mandatory method[s] in an ADT interface

Some object-oriented languages, such as Python, advise that one provide some standard methods in your class if you want it to be "pythonic". These include `__str__()` which is called whenever a programmer invokes `str()` on your object, `__iter__()` to return an iterator over your object, `__getitem__()` if your object can naturally be indexed, and many others.

A constructor for an ADT will have to allocate the instance-specific data structure *and* the dispatch table from the heap. Since C is not garbage-collected, we are going to mandate that *every* ADT interface must define a method of the following form:

```
/* destroys the TheClass instance */
void (*destroy)(const TheClass *tc);
```

The implementation of this method must free all heap memory that was allocated to implement the class instance: the dispatch table, the instance-specific structure `self`, *and* any other heap memory that was allocated and pointed to by `self`.

4.4.3.2 Mandatory method[s] in the ADT interface of a container

Later in the book, we will see that many of our data structures act as containers for user-inserted data. Sometimes the data inserted by the user are simple data type instances, such as integers or floating point numbers; at other times, the data inserted are pointers to heap-allocated storage.

The `destroy()` method described in the previous section is able to return any heap-allocated memory created and used by the ADT instance. Unfortunately, if a container still possesses any of the user-inserted data, the implementation of the `destroy()` method does not know whether it has to return those data items to the heap, and if so, how it should do so. How can we provide this information (whether it needs to return the items and how to do so) to the ADT implementation?

Recall from section 3.6.9.2 that we can pass pointers to functions as arguments when we call another C function. At the time when we create an ADT instance, by calling a constructor, we can provide a pointer to a function (which we will refer to as `freeValue()`) that the `destroy()` method implementation can invoke on each element that is still in the container; in essence, we are delegating to the ADT implementation the responsibility to return our heap-allocated data, if any remain in the container, to the heap.

What about the situation when we are only storing simple data types, such as integers or floating point numbers, in our container? We need some way to tell the `destroy()` method implementation that it should *not* attempt to return any remaining elements to the heap. We can do this by specifying `doNothing` as the "function pointer" to use in our call to a constructor.

This is exactly like the `apply()` function that was presented in section 3.6.9.2, except that instead of supplying an array of values to which `freeValue()` is applied, the container implementation will apply the function to each of the values remaining in the container.

Container ADTs will also define and implement several other mandatory methods, shown below.

```
/* create a new container instance using the same implementation and
/* and freeValue() function pointer as the
 * container upon which the method has been invoked;
 * return NULL if error creating the new container */
const TheClass *(*create)(const TheClass *adt);

/* clear container; any remaining items in the container must
 * be processed as in destroy()
 * empty container upon return */
void (*clear)(const TheClass *tc);

/* returns the number of elements in the container */
long (*size)(const TheClass *tc);

/* returns true if the container is empty, false if not */
bool (*isEmpty)(const TheClass *tc);

/* returns array of void * pointers to elements;
   # of elements returned in *len; NULL if heap failure */
void **(*toArray)(const TheClass *tc, long *len);

/* return iterator over the container, NULL if heap failure */
const Iterator *(*itCreate)(const TheClass *tc);
```

Let's provide more explanation for each of these methods.

- `const TheClass *(*create)(const TheClass *adt);`
  Many of the containers that we will encounter later in the book can have multiple implementations; the different implementations may have different space and/or runtime complexities. If you already possess a pointer to the dispatch table for a particular container type, the `create()` method enables you to create another instance of that container type that will use the same implementation AND the same `freeValue()` function.

- `void (*clear)(const TheClass *tc);`
  Instead of destroying the ADT instance, this method simply purges all elements from the container, leaving the container in the same state as it was immediately after invoking the constructor. The `freeValue()` specified when the ADT instance was constructed is applied to any remaining values in the container, as for the `destroy()` method.

- `long (*size)(const TheClass *tc);`
  This method acts like the `len()` built-in Python function - it returns the number of elements in the container.

- `bool (*isEmpty)(const TheClass *tc);`
  This method returns `true/false` if the container is/is-not empty. This method is not strictly needed, since it provides the same information as the following expression: `tc->size(tc) == 0L`

- `void **(*toArray)(const TheClass *tc, long *len);`
  This method allocates an array of `void *` pointers long enough to point to each of the elements in the container, and copies the element pointers into the array; the number of elements in the array are returned in `*len`. If there were memory allocation failures, `NULL` is returned. After the programmer has finished using the array of pointers, the programmer **MUST** return the array to the heap using `free()`, as in:

```
void **array;
long len;

array = tc->toArray(tc, &len);
/* use the array */
free(array);
```

- `const Iterator *(*itCreate)(const TheClass *tc);`
  This method, similar to the `__iter__()` method in Python, returns an iterator ADT instance; such a method, which returns an instance of another ADT, is called a *factory method*. Upon receipt of an iterator instance, the programmer can traverse the container using the following pseudo-code:

```
const Iterator *it;
void *v;

it = tc->itCreate(tc);

while (it->hasNext(it)) {
    (void) it->next(it, &v);
    /* suitably cast v and use the value so obtained */
}
it->destroy(it);
```

> The use of iterators to traverse a container *without* knowledge of its exact structure is excellent software engineering practice, and should be used in preference to the `toArray()` method. `toArray()` is required when the user needs to access all of the items randomly - e.g., to sort them.

4.4.3.3 A brief digression on iterators

In computer programming, an *iterator* is an object that enables a programmer to traverse a container.[5] The primary purpose of an iterator is to enable a user to process each element in a container while isolating the user from the internal structure of the container.

There is usually a natural order in which the iterator should sequence its way through a container, depending upon the type of container being traversed. For each of the data structures described in the remainder of the book, we will discuss the appropriate natural order, which will manifest itself in the iterator factory method implementation.

4.4.3.4 The `Iterator` ADT

The observant reader will have noted that the `itCreate()` *factory* method returns an ADT instance of type `Iterator`. Here is the header file for that ADT.

```
#ifndef _ITERATOR_H_
#define _ITERATOR_H_

/* BSD Header removed to conserve space */

#include "ADTs/ADTdefs.h"

/* interface definition for generic iterator
 *
 * patterned roughly after Java 6 Iterator class
 */

typedef struct iterator Iterator; /* forward reference */

/* creates an iterator from the supplied arguments; it is for use by the
 * iterator factory methods in ADTs
 *
 * NB - iterator assumes responsibility for elements[] if create is successful
 * i.e. it_destroy will free the array of pointers
 *
 * returns pointer to iterator if successful, NULL otherwise
 */
const Iterator *Iterator_create(long size, void **elements);
```

[5] `https://en.wikipedia.org/wiki/Iterator`

```
/* now define struct iterator */
struct iterator {
    /* the private data of the iterator */
    void *self;

    /* returns true/false if the iterator has a next element */
    bool (*hasNext)(const Iterator *self);

    /* returns the next element from the iterator in `*element'
     *
     * returns true if successful, false if unsuccessful (no next element)
     */
    bool (*next)(const Iterator *self, void **element);

    /* destroys the iterator */
    void (*destroy)(const Iterator *self);
};

#endif /* _ITERATOR_H_ */
```

The `#include "ADTs/ADTdefs.h"` performs a standard set of file includes (for example, `<stdbool.h>`) and macro definitions needed by ADT implementations described in the book. Now let's see how we implement the `Iterator` ADT.

4.4.4 The implementation (source file)

Given the header file for an ADT, an implementation must do the following:

- determine what instance-specific information is required in `self`;
- define the `struct` that will hold this information;
- provide implementations of each of the defined methods;
- implement the constructor, which must do the following:
  - allocate an instance of the dispatch table; if an allocation failure, return NULL;
  - allocate an instance of `self`; if an allocation failure, free up the dispatch table and return NULL;
  - fill in the members of `self`; if any of those fields are allocated from the heap, and if any of those allocations fail, it must free all allocations to that point, and return NULL;
  - store the address of `self` into the dispatch table;
  - store the function pointers for the methods in the dispatch table; and
  - return the dispatch table as the return value of the constructor.

4.4.4.1 `Iterator` implementation

We will use a particularly simple `Iterator` implementation that works for all containers. For this implementation, each instance requires three data items:

- an array of pointers to the elements of the container;
- the number of pointers in that array; and
- an array index which represents the next item to return to the user.

Thus we need the following `struct` definition in the implementation:

```
typedef struct it_data {
    long next;
    long size;
    void *elements[];
} ItData;
```

Now we need to implement each method.

`hasNext()` Let's start with the `hasNext()` method.

```
static bool it_hasNext(const Iterator *it) {
    ItData *itd = (ItData *)(it->self);
    return (itd->next < itd->size);
}
```

Let's discuss each line in turn.

- `static bool it_hasNext(const Iterator *it) {`
  This function conforms to the function signature for the `hasNext()` method; we have declared it to be a static function, since we do not want programs to be able to call this function directly, only through the dispatch table.
- `ItData *itd = (ItData *)(it->self);`
  This statement declares a variable of type `ItData *`, and casts the `self` member of the dispatch table from `void *` to `ItData *`, storing it in `itd`. This is essential, as code cannot dereference a `void *` pointer, so we must cast it back to its original type (`ItData *`) in order to access the instance-specific data.
- `return (itd->next < itd->size);`
  If `next` is less than `size`, the condition will yield a true value; if not, it yields false; regardless, this is exactly what needs to be the return value of the method.

While this is quite succinct code, by now you should understand why it works correctly, and begin to appreciate the elegance of such code.

`next()` While the `hasNext()` method merely needed to consult the values in the instance-specific structure, `next()` needs to consult and modify the values. Here is the code for this method.

```
static bool it_next(const Iterator *it, void **element) {
    ItData *itd = (ItData *)(it->self);
    bool status = (itd->next < itd->size);
    if (status)
        *element = itd->elements[itd->next++];
    return status;
}
```

Let's discuss each line in turn.

- `static bool it_next(const Iterator *it, void **element) {`
  This function conforms to the function signature for the `next()` method; we have declared it to be a static function, since we do not want programs to be able to call this function directly, only through the dispatch table. This function passes the next data item back through `*element`, returning `true/false` as the function value if there *was* a next element.

  Given the existence of `hasNext()`, why do we have to do it this way? There is another standard pattern for using iterators, captured by the following pseudocode:

  ```
  const Iterator *it;
  void *v;

  it = tc->itCreate(tc);

  while (it->next(it, &v)) {
      /* suitably cast v and use the value so obtained */
  }
  it->destroy(it);
  ```

  Since it is relatively easy to support both usage patterns, it was felt that our `Iterator` ADT should do so. The author prefers the `while has, fetch and do` approach, since this maps to more language and library systems; you are encouraged to use that structure.
- `ItData *itd = (ItData *)(it->self);`
  Same as for the `hasNext()` method.
- `bool status = (itd->next < itd->size);`
  Since we are going to have to return whether there was another element, `status` captures whether this is the case.
- `if (status)`
  We only proceed if `status` is true.
- `*element = itd->elements[itd->next++];`
  This causes the element at `itd->next` to be copied into `*element`, incrementing `itd->next` after the assignment has been made.
- `return status;`
  Return the success/failure of the call.

You may have noticed in the code on page 159 that we have indicated `(void) it->next(it, &v);`. This is the way to indicate in the code that we are explicitly ignoring the return value, since we have invoked `hasNext()` before calling `next()`. Such explicit indication is similar to our use of `UNUSED` to flag variables and function parameters that we are not using *on purpose*.

`destroy()` The final method defined for an `Iterator` ADT instance is the `destroy()` method. One normally only writes this code after one has written the constructor, since the `destroy()` method must return all heap-allocated storage created by the constructor in the reverse order to the constructor. The iterator itself is particularly simple in terms of heap storage - just the dispatch vector and the instance-specific data. A careful reader of the header file will have noticed the following statement:

```
iterator assumes responsibility for elements[] if create is successful
- i.e., destroy() will free the array of pointers;
```

thus, the `destroy()` method must also return the array of `void *` pointers.

Here is the code.

```
static void it_destroy(const Iterator *it) {
    ItData *itd = (ItData *)(it->self);
    free(itd->elements);
    free(itd);
    free((void *)it);
}
```

The only thing that may be considered unusual in this code is the need to cast `it` to a `void *` in the call to `free()`. Normally this would not be required. In this case, since `it` is `const`, we need to perform the cast to change the attribute for `it` from `const` to `non-const`, thus avoiding an error message from the compiler.

`Iterator_create()` The constructor for an `Iterator` is as straight-forward as was the `destroy()` method, just in reverse. As before, we'll show the code before we give a line-by-line description of what is going on.

```
static Iterator template = {NULL, it_hasNext, it_next, it_destroy};

const Iterator *Iterator_create(long size, void **elements) {
    Iterator *it = (Iterator *)malloc(sizeof(Iterator));

    if (it != NULL) {
        ItData *itd = (ItData *)malloc(sizeof(ItData));
        if (itd != NULL) {
            itd->next = 0L;
            itd->size = size;
            itd->elements = elements;
            *it = template;
            it->self = itd;
        } else {
            free(it);
            it = NULL;
        }
    }
    return it;
}
```

Let's discuss each line in turn.

- `static Iterator template = {NULL, it_hasNext, it_next, it_destroy};`
  Every time the constructor is called, it creates an `Iterator` on the heap, and then assigns `self`, and function pointers for `hasNext()`, `next()`, and `destroy()` to the newly-allocated structure. By creating this template, we can perform the method assignments by simply doing a copy of the template into the newly-allocated structure.
- `const Iterator *Iterator_create(long size, void **elements) {`
  This is the signature for the constructor. The `itCreate()` factory methods in container ADTs will call this method after creating an array of `void *` pointers of length `size`. Note that we have *NOT* flagged the constructor as `static`, since we *DO* want user code to be able to call this function, so it must be global.
- `Iterator *it = (Iterator *)malloc(sizeof(Iterator));`
  This uses `malloc()` to allocate a structure of the correct size, cast it to the correct type, and assign it to a pointer variable of the correct type.
- `if (it != NULL) {`
  We only carry on with the function if `it` is not `NULL`. If it is `NULL`, we pick up at the bottom of the block in the scope of this if statement, which performs a `return it` - thus if `it` is `NULL`, we return `NULL` as per the specification.
- `ItData *itd = (ItData *)malloc(sizeof(ItData));`
  Now allocate the instance-specific data structure from the heap.
- ```
  if (itd != NULL) {
      itd->next = 0L;
      itd->size = size;
  ```
  ```

```
itd->elements = elements;
*it = template;
it->self = itd;
```

With a successful allocation of `itd`, fill in the `next`, `size`, and `elements` members of `itd`; copy `template` into the dispatch table structure on the heap; finally, replace the `self` member of the dispatch table with a pointer to the instance-specific structure.

> ⚠ These last two assignments must be done in this order, since copying the template leaves the `self` field with a value of `NULL`.

- `} else {`
  ```
  free(it);
  it = NULL;
  ```
  The allocation for `itd` failed, so we need to return the storage for `it` to the heap, and set `it` to `NULL`.
- `return it;`
  Return the `Iterator` to the caller, or `NULL` if there were memory allocation errors.

4.5 Back to our Student example

It is informative at this point to return to the discussion in section 4.1.4 and to build a C version of the programs in Appendix A using an ADT for a Student. If you have not reviewed the implementations in that Appendix, you should do it now to better understand why the C implementation using an ADT does **exactly** what each of those implementations do.

4.5.1 The header file for our Student ADT - `student.h`

```
#if !defined(_STUDENT_H_)
#define _STUDENT_H_
#include <stdbool.h>
#include <stdio.h>

typedef struct student Student;

const Student *Student_create(char *last, char *first, char *uoid,
                              char *duckid, char *primaryMajor);
struct student {
    void *self;                 /* instance data */
    void (*destroy)(const Student *s); /* delete the student instance */
    char *(*lastName)(const Student *s);/* obtain last name from instance */
    char *(*firstName)(const Student *s); /* obtain first name */
    char *(*UOID)(const Student *s); /* obtain 95 number */
    char *(*duckid)(const Student *s); /* obtain duckid */
    char *(*primaryMajor)(const Student *s); /* obtain primary Major */
    bool (*setMajor)(const Student *s, char *major); /* set primary Major */
```

```
    void (*print)(const Student *s, FILE *f); /* print student as CSV on f */
};
#endif /* _STUDENT_H_ */
```

Just as we saw with the header file for the Iterator ADT, the header file has appropriate `#if !defined(_STUDENT_H_)` and `#define _STUDENT_H_` statements at the top of the file, and ends with `#endif /* _STUDENT_H_ */`; this enables this header file to be included multiple times during the compilation of a single source file without causing compiler errors.

Note that for this example, we did not need all of the definitions provided in `ADTs\ADTdefs.h`, so we have simply included the standard header files needed for the signatures: `<stdbool.h>` and `<stdio.h>`.

Again, as we saw for the Iterator ADT, we define a synonym for `struct student` and define the function signature for `Student_create`.

As indicated above, every ADT must support a `destroy()` method, and this is shown in the header file; also shown in the header file are the signatures for all of the required methods for a Student instance.

4.5.2 The source file for our Student ADT - `student.c`

```
#include "student.h"
#include <stdlib.h>
#include <string.h>

typedef struct instanceData {
    char *lastName;
    char *firstName;
    char *UOID;
    char *duckid;
    char *primaryMajor;
} InstanceData;

/* destroy the student instance, returning all heap-allocated storage */
static void student_destroy(const Student *s) {
    InstanceData *self = (InstanceData *)s->self;

    free(self->lastName); free(self->firstName); free(self->UOID);
    free(self->duckid); free(self->primaryMajor); free(self);
    free((void *)s);
}

/* return last name from instance */
static char *student_lastName(const Student *s) {
    InstanceData *self = (InstanceData *)s->self;
```

```
    return (self->lastName);
}

/* return first name from instance */
static char *student_firstName(const Student *s) {
    InstanceData *self = (InstanceData *)s->self;
    return (self->firstName);
}

/* return 95 number from instance */
static char *student_UOID(const Student *s) {
    InstanceData *self = (InstanceData *)s->self;
    return (self->UOID);
}

/* return duckid (your UO email address w/o @uoregon.edu) from instance */
static char *student_duckid(const Student *s) {
    InstanceData *self = (InstanceData *)s->self;
    return (self->duckid);
}

/* return primary Major from instance */
static char *student_primaryMajor(const Student *s) {
    InstanceData *self = (InstanceData *)s->self;
    return (self->primaryMajor);
}

/* set primary Major from instance; returns true if successful, false if not */
static bool student_setMajor(const Student *s, char *major) {
    InstanceData *self = (InstanceData *)s->self;
    char *newMajor = strdup(major);
    bool status = (newMajor != NULL);
    if (status) {
        free(self->primaryMajor);
        self->primaryMajor = newMajor;
    }
    return status;
}

/* print 'Last name,First name,UOID,Duckid,Primary major' on a line by itself
 * on the open file `f' */
static void student_print(const Student *s, FILE *f) {
    InstanceData *self = (InstanceData *)s->self;
    fprintf(f, "%s,%s,%s,%s,%s\n", self->lastName, self->firstName,
            self->UOID, self->duckid, self->primaryMajor);
}

static Student template = {
    NULL, student_destroy, student_lastName, student_firstName, student_UOID,
    student_duckid, student_primaryMajor, student_setMajor, student_print
};
```

```
/* create Student instance from the arguments; returns pointer to the dispatch
 * table if successful, NULL if not */
const Student *Student_create(char *last, char *first, char *uoid,
                              char *duckid, char *primaryMajor) {
    Student *s = (Student *)malloc(sizeof(Student));
    if (s != NULL) {
        InstanceData *self = (InstanceData *)malloc(sizeof(InstanceData));
        if (self != NULL) {
            bool status = true;
            status = status && ((self->lastName = strdup(last)) != NULL);
            status = status && ((self->firstName = strdup(first)) != NULL);
            status = status && ((self->UOID = strdup(uoid)) != NULL);
            status = status && ((self->duckid = strdup(duckid)) != NULL);
            status = status &&
                     ((self->primaryMajor = strdup(primaryMajor)) != NULL);
            if (status) {
                *s = template;
                s->self = self;
            } else {
                free(self->lastName); free(self->firstName); free(self->UOID);
                free(self->duckid); free(self->primaryMajor); free(self);
                free(s);
                s = NULL;
            }
        } else {
            free(s);
            s = NULL;
        }
    }
    return s;
}
```

The source file starts off by including `student.h`; this guarantees that the implemented functions conform to the signatures in the header file.

Next it defines the structure of the instance data for each Student. In our case, that structure simply has pointers to the five pieces of information associated with a student. A pointer to the instance data is stored in the `self` member of the dispatch table. Note that the first line of each method implementation has the form

```
InstanceData *self = (InstanceData *)s->self;
```

Since the `self` member is `void *` to hide the data from calling code, it must be cast back to its true type before a method can access or modify elements in the instance data.

In this implementation, I have chosen to duplicate the five pieces of data provided in the constructor call. Thus, the `destroy()` method has to free those strings before freeing the self structure and the dispatch table.

The accessor functions are straightforward, simply returning the pointer to the relevant strings in the instance data.

The mutator function, `setMajor()`, first has to duplicate the `major` argument on the heap; if that is successful, it frees the current value of `primaryMajor`, then sets it to point to the string on the heap.

The `print()` method is straightforward use of `fprintf()`.

The constructor has the same structure as that for an Iterator: 1) allocate the dispatch table on the heap; 2) allocate the self structure on the heap; and 3) allocate any additional heap memory. The sequence of `status = status && (...);` statements enables us to allocate the heap storage in straightline code, while still keeping track if any of those allocations failed; if any did fail, then we can free all of the pointers in the self structure (note that if `free()` is invoked on a pointer that is `NULL`, it gracefully returns).

4.5.3 Source code for the main program - `main.c`

```
#include "student.h"
#include <stdio.h>
#include <stdlib.h>
#include <string.h>

#define UNUSED __attribute__((unused))
#define INITIAL_SIZE 64

typedef struct student_array {
    int size, next;
    const Student **array;
} StudentArray;

bool addToArray(StudentArray *students, const Student *student) {
    bool status = (students->next < students->size);
    if (! status) { /* try to grow the array */
        int newSize = 2 * students->size;
        size_t nBytes = newSize * sizeof(const Student *);
        const Student **tmp =
                      (const Student **)realloc(students->array, nBytes);
        if (tmp != NULL) {
            students->array = tmp;
            students->size *= 2;
            status = true;
        }
    }
    if (status)
        students->array[students->next++] = student;
    return status;
}

void split(char *buf, char **last, char **first, char **uoid, char **duckid,
           char **major) {
```

```
    *last = strtok(buf, ",\n");
    *first = strtok(NULL, ",\n");
    *uoid = strtok(NULL, ",\n");
    *duckid = strtok(NULL, ",\n");
    *major = strtok(NULL, ",\n");
}

int main(UNUSED int argc, UNUSED char *argv[]) {
    char buf[BUFSIZ];
    StudentArray students = {INITIAL_SIZE, 0,
           (const Student **)malloc(INITIAL_SIZE * sizeof(const Student *))};
    long i = 0L;
    long nStudents = 0L;

    if (students.array == NULL) {
        fprintf(stderr, "Error allocating array on heap\n");
        return EXIT_FAILURE;
    }
    while (fgets(buf, BUFSIZ, stdin) != NULL) {
        char *last, *first, *uoid, *duckid, *major;
        const Student *s;
        split(buf, &last, &first, &uoid, &duckid, &major);
        s = Student_create(last, first, uoid, duckid, major);
        if (! addToArray(&students, s)) {
            fprintf(stderr, "Cannot extend array\n");
            return EXIT_FAILURE;
        }
    }
    nStudents = students.next;
/* now print out the data in reverse order */
    for (i = nStudents - 1; i >= 0L; i--) {
        students.array[i]->print(students.array[i], stdout);
        students.array[i]->destroy(students.array[i]);
    }
    free(students.array);
    return EXIT_SUCCESS;
}
```

Unlike the three object-oriented languages shown in Appendix A, C does not provide an extensible array data type; therefore, for this program we have to build it. First we define a `StudentArray` structure type. The function `addToArray` grows the array if it is full. Finally, `main()` has to declare an instance of such an array and appropriately initialize it.

As with C++, C does not provide a standard `split()` function. Thus we define `split()`, using the `strtok()` function defined in `<string.h>`.

As for the actual program logic in `main()` we read each line, split out the five fields from each line, create a Student instance from those fields, and add that instance to the StudentArray. Then we traverse the array from last to first, printing each student instance and then invoking the `destroy` method on each instance.

To compile and execute this program, do the following:

```
$ #cd to the directory in which student.h, student.c, and main.c are stored
$ gcc -o main -W -Wall main.c student.c
$ ./main
```

4.6 A container example - an ArrayList

We saw in the previous section that we had to construct an extensible array in order to implement the main program using the Student ADT instances. Therefore, let's create a container ADT for an extensible array to simplify not only our Student program, but all programs that require a dynamic array container.

We saw in Section 3.3.3 that C supports arrays of other data types. One must declare the type of element that can be stored at each index in the array, as well as the number of elements that can be stored in that array. There is no ability at runtime to query an array for its size, nor can the array grow/shrink as one uses it. Thus, we can see that, while one can create arrays, the programmer must remember several pieces of management information in order to effectively use the array.

An *ArrayList* ADT supports dynamic arrays that can grow as needed. We will first implement an ArrayList of long integers; this will enable us to become familiar with building a container ADT. After we have a working implementation of an ArrayList of long integers, we will show the changes necessary to support ArrayLists of arbitrary types.

4.6.1 Methods on an ArrayList

Obviously, we should be able to retrieve an element at a legal index into the array, and should be able to store an element at a legal index; otherwise, an ArrayList would not be a superset of a C array. Here are some other methods that would be useful in an ArrayList; we would like:

- a constructor in order to create a new ArrayList;
- a method to be able to destroy an ArrayList after we are finished with it;
- a method that enables us to append a new element to the ArrayList; if there is no more room in the ArrayList for the new element, we would like it to grow to accommodate the new element; appending the element has the side effect of incrementing the length of the ArrayList;
- a method to clear all elements from the ArrayList, thus making it empty, just as it is after invocation of the constructor;
- a method to retrieve the element at a particular index (legal indices are 0 .. length-1);

- a method to insert an element at a particular index; all current elements from that index onwards are shifted one position to the right; if there is no more room in the ArrayList for the new element, we would like it to grow to accommodate the new element; inserting the element has the side effect of incrementing the length of the ArrayList;
- a method to remove the element at a particular index; all current elements beyond that index are shifted one position to the left; removing the element has the side effect of decrementing the length of the ArrayList;
- a method to set the element at a particular, currently-occupied index; and
- a method to return the current number of elements in the ArrayList.

A word about "growing the ArrayList to accommodate new elements" - this is likely to require that a new call to `malloc()` or `realloc()` is made to increase the size of a C array managed by the ArrayList; this means that the perceived running time for a call to the `add` method, for example, can be different from one call to the next, since it will be slower if the method invocation causes a call to `realloc()` as compared to an invocation when there is a free slot in the C array. This difference in running time could be crucial if an ArrayList is being used by code that is performing some soft realtime processing (e.g., reading out an mp3-encoded track). Thus, an ArrayList ADT typically includes the following additional methods:

- the constructor enables the user to specify an initial capacity when creating a new ArrayList;
- a method to ensure that an ArrayList has capacity to accept a known number of elements; if not, it is grown by this call to avoid dynamic growth during calls to append or insert new elements; and
- a method to trim excess capacity from the ArrayList.

Finally, we mentioned earlier in this chapter that there are a standard set of methods that we want all container ADTs to support:

- a method that returns true if an ArrayList is empty;
- a method to return an Iterator over the ArrayList; and
- a method to return a dynamically-allocated C array that points to each element in the container.

It may seem odd to provide the last method since we are requiring each container to provide a factory method that returns an Iterator over the elements of the container. In fact, one needs to have an array of the elements available for certain types of algorithms, such as sorting the elements. These algorithms depend upon being able to randomly access the elements in the container; this is not achievable using the iterator. Since the array is heap allocated, the programmer MUST remember to free the array when finished with it.

4.6.2 An ArrayList of long integers

First let's look at an ArrayList of long integers. The next subsection presents the header file for the ArrayListLong ADT interface. The subsequent subsection presents an implementation for this interface.

4.6.2.1 The header file for the ArrayListLong ADT

This section provides the header file for the ArrayListLong ADT interface. First we present the entire header file; each method is then discussed separately.

```
#ifndef _ARRAYLISTLONG_H_
#define _ARRAYLISTLONG_H_

#include "ADTs/ADTdefs.h"
#include "ADTs/iterator.h"                  /* needed for factory method */

typedef struct arraylistlong ArrayListLong;  /* synonym for struct */
const ArrayListLong *ArrayListLong_create(long capacity);
struct arraylistlong {
    void *self;
    void (*destroy)(const ArrayListLong *al);
    bool (*add)(const ArrayListLong *al, long element);
    void (*clear)(const ArrayListLong *al);
    bool (*ensureCapacity)(const ArrayListLong *al, long minCapacity);
    bool (*get)(const ArrayListLong *al, long index, long *element);
    bool (*insert)(const ArrayListLong *al, long index, long element);
    bool (*isEmpty)(const ArrayListLong *al);
    bool (*remove)(const ArrayListLong *al, long index);
    bool (*set)(const ArrayListLong *al, long index, long element);
    long (*size)(const ArrayListLong *al);
    long *(*toArray)(const ArrayListLong *al, long *len);
    bool (*trimToSize)(const ArrayListLong *al);
    const Iterator *(*itCreate)(const ArrayListLong *al);
};
#endif /* _ARRAYLISTLONG_H_ */
```

The following discusses each function/method in terms of functionality provided and constraints on function arguments.

- `const ArrayListLong *ArrayListLong_create(long capacity);`
  This creates an ArrayList of long integers; if `capacity > 0`, the initial capacity of the list is `capacity`, otherwise a default capacity is used. Note that we do *not* have a `freeValue()` argument to the constructor, since we can only add long integers to such an ArrayList, and as such, there is no heap memory associated with each element to return.
- `void (*destroy)(const ArrayListLong *al);`
  Destroys the ArrayList of long integers.

- `bool (*add)(const ArrayListLong *al, long element);`
  Appends `element` to the ArrayList of long integers; dynamically grows the list if more capacity is needed; increments the length of the list by 1; returns `true` if successful, `false` if there were errors (could not allocate more space).
- `void (*clear)(const ArrayListLong *al);`
  Clears all elements from the ArrayList of long integers; upon return, the list is empty.
- `bool (*ensureCapacity)(const ArrayListLong *al, long minCapacity);`
  Ensure that the ArrayList of long integers can hold at least `minCapacity` elements; if not, the buffer is grown to handle that many elements; returns `true` if successful, `false` if not (`realloc` failure).
- `bool (*get)(const ArrayListLong *al, long index, long *element);`
  Returns the element at the specified `index` in the ArrayList of long integers; the value is returned in `*element`. The method returns `true` if successful, `false` if no element at that position.
- `bool (*insert)(const ArrayListLong *al, long index, long element);`
  Inserts `element` at the specified `index` in the ArrayList of integers; all current elements from `index` are shifted one position to the right; dynamically grows the list if more capacity is needed; increments the length of the list by 1; returns `true` if successful, `false` if there were errors (could not allocate more space).
- `bool (*isEmpty)(const ArrayListLong *al);`
  Returns `true` if ArrayList of long integers is empty, `false` if it is not.
- `bool (*remove)(const ArrayListLong *al, long index);`
  Removes the element from `index`; all other elements from `[index + 1, size)` are shifted down one position. Returns `true` if successful, `false` if the position at `index` was unoccupied.
- `bool (*set)(const ArrayListLong *al, long index, long element);`
  Replaces the element at `index` with `element`. Returns `true` if successful, `false` if the position at `index` was unoccupied.
- `long (*size)(const ArrayListLong *al);`
  Returns the number of elements in the ArrayList of long integers.
- `long *(*toArray)(const ArrayListLong *al, long *len);`
  Returns an array containing all of the elements of the ArrayList of long integers in the proper sequence `[0..size-1]`; returns the length of the array in `*len`. Returns NULL if unable to allocate array of long integers; the caller is responsible for freeing the array when finished with it.
- `bool (*trimToSize)(const ArrayListLong *al);`
  Trims the capacity of the ArrayList of long integers to be the current size. Returns `true` if successful, `false` if failure (allocation failure).
- `const Iterator *(*itCreate)(const ArrayListLong *al);`
  Creates a generic iterator to the ArrayList of long integers. Returns a pointer to the Iterator or NULL if failure.

4.6.2.2 The implementation file for the ArrayListLong ADT

We will break up the implementation into bitesize pieces to make it easier to understand.

The preliminaries

```
/* implementation for array list of long integers */

#include "arraylistlong.h"
#include <stdlib.h>

#define DEFAULT_CAPACITY 10L

typedef struct al_data {
    long capacity;
    long size;
    long *theArray;
} AlData;
```

Obviously, we must `#include` the header file to make sure that each method implementation satisfies the signature defined in the header file. We establish the default capacity as `10`. We also define the structure for the instance-specific data; it consists of the size of the allocated array (`capacity`), the number of elements that are stored in the array (`size`), and a pointer to the C array allocated on the heap (`theArray`).

The `destroy()` and `clear()` methods

```
static void al_destroy(const ArrayListLong *al) {
    AlData *ald = (AlData *)(al->self);
    free(ald->theArray);         /* free array of long integers */
    free(ald);                   /* free AlData structure */
    free((void *)al);            /* free the dispatch table */
}

static void al_clear(const ArrayListLong *al) {
    AlData *ald = (AlData *)(al->self);
    ald->size = 0L;
}
```

The `destroy()` method first frees up the C array of long integers that was allocated from the heap. It then frees up the structure that contained the instance-specific data. Finally, it frees up the dispatch table.

The `clear()` method simply sets the `size` member of the instance-specific structure to 0, indicating that the ArrayList of long integers is empty.

The `add()`, `insert()`, `remove()`, and `set()` methods

```
static bool al_add(const ArrayListLong *al, long element) {
    AlData *ald = (AlData *)(al->self);
    bool status = (ald->capacity > ald->size);

    if (! status) { /* need to reallocate */
        size_t nbytes = 2 * ald->capacity * sizeof(long);
        long *tmp = (long *)realloc(ald->theArray, nbytes);
        if (tmp != NULL) {
            status = true;
            ald->theArray = tmp;
            ald->capacity *= 2;
        }
    }
    if (status)
        ald->theArray[ald->size++] = element;
    return status;
}

static bool al_insert(const ArrayListLong *al, long index, long element) {
    AlData *ald = (AlData *)(al->self);
    bool status = true;                     /* assume success */

    if (index < 0 || index > ald->size)
        return false;                       /* 0 <= index <= size */
    if (ald->capacity <= ald->size) {   /* need to reallocate */
        size_t nbytes = 2 * ald->capacity * sizeof(long);
        long *tmp = (long *)realloc(ald->theArray, nbytes);
        if (tmp == NULL)
            status = false;                 /* allocation failure */
        else {
            ald->theArray = tmp;
            ald->capacity *= 2;
        }
    }
    if (status) {
        long j;
        for (j = ald->size; j > index; j--)       /* slide items up */
            ald->theArray[j] = ald->theArray[j-1];
        ald->theArray[index] = element;
        ald->size++;
    }
    return status;
}

static bool al_remove(const ArrayListLong *al, long index) {
    AlData *ald = (AlData *)(al->self);
    bool status = (index >= 0L && index < ald->size);
    long j;

    if (status) {
        for (j = index + 1; j < ald->size; j++) /* slide items down */
```

```
            ald->theArray[index++] = ald->theArray[j];
        ald->size--;
    }
    return status;
}

static bool al_set(const ArrayListLong *al, long index, long element) {
    AlData *ald = (AlData *)(al->self);
    bool status = (index >= 0L && index < ald->size);

    if (status)
        ald->theArray[index] = element;
    return status;
}
```

These are the mutator methods on an ArrayList of long integers. Both `add()` and `insert()` must check to see if the C array of integers has been exhausted, and if so, invoke `realloc()` to allocate a larger C array; at each reallocation, the capacity of the C array is doubled. `insert()`, `remove()`, and `set()` must check to see if the index that was passed in the argument list is legal (0 <= `i` < `size` for `remove()` and `set()`, and 0 <= `i` <= `size` for `insert()`). For `insert()`, we need to move all of the data in `[i, size)` up one location in order to insert `element` into the `i`th location. For `remove()`, we need to move all of the data in `(i, size)` down one location. Each of these methods returns `true/false` if the method was successful/unsuccessful.

The `get()`, `isEmpty()`, `size()`, `ensureCapacity()`, and `trimToSize()` methods

```
bool al_get(const ArrayListLong *al, long index, long *element) {
    AlData *ald = (AlData *)(al->self);
    bool status = (index >= 0L && index < ald->size);

    if (status)
        *element = ald->theArray[index];
    return status;
}

static bool al_isEmpty(const ArrayListLong *al) {
    AlData *ald = (AlData *)(al->self);
    return (ald->size == 0L);
}

static long al_size(const ArrayListLong *al) {
    AlData *ald = (AlData *)(al->self);
    return ald->size;
}

static bool al_ensureCapacity(const ArrayListLong *al, long minCapacity) {
    AlData *ald = (AlData *)(al->self);
    bool status = true;                        /* assume success */
```

```
    if (ald->capacity < minCapacity) {     /* must extend */
        long *tmp = (long *)realloc(ald->theArray, minCapacity * sizeof(long));
        if (tmp == NULL)
            status = false;                    /* allocation failure */
        else {
            ald->theArray = tmp;
            ald->capacity = minCapacity;
        }
    }
    return status;
}

static bool al_trimToSize(const ArrayListLong *al) {
    AlData *ald = (AlData *)al->self;
    bool status = false;                        /* assume failure */

    long *tmp = (long *)realloc(ald->theArray, ald->size * sizeof(long));
    if (tmp != NULL) {
        status = true;
        ald->theArray = tmp;
        ald->capacity = ald->size;
    }
    return status;
}
```

`isEmpty()` and `size()` simply return a value based upon the `size` member of the instance-specific struct. `get()` simply checks that the specified index is legal, and if so, returns the value stored there in `*element`, returning `true/false` if the index was legal/illegal. `ensureCapacity()` and `trimToSize()` simply use `realloc()` appropriately to provide the requested functionality, returning `true` if the reallocation was successful, `false` if not.

The `toArray()` and `itCreate()` methods

```
/*
 * helper function that duplicates the array of long integers on the heap
 *
 * returns pointer to duplicate array or NULL if malloc failure
 */
static long *arraydupl(AlData *ald) {
    long *tmp = NULL;
    if (ald->size > 0L) {
        size_t nbytes = ald->size * sizeof(long);
        tmp = (long *)malloc(nbytes);
        if (tmp != NULL) {
            long i;

            for (i = 0; i < ald->size; i++)
                tmp[i] = ald->theArray[i];
```

```
        }
    }
    return tmp;
}

static long *al_toArray(const ArrayListLong *al, long *len) {
    AlData *ald = (AlData *)al->self;
    long *tmp = arraydupl(ald);

    if (tmp != NULL)
        *len = ald->size;
    return tmp;
}

static const Iterator *al_itCreate(const ArrayListLong *al) {
    AlData *ald = (AlData *)al->self;
    const Iterator *it = NULL;
    long *tmp = arraydupl(ald);

    if (tmp != NULL) {
        it = Iterator_create(ald->size, (void **)tmp);
        if (it == NULL)
            free(tmp);
    }
    return it;
}
```

Both `toArray()` and `itCreate()` need to allocate an array of long integers on the heap, so we first define a helper function, `arraydupl()`, that performs this function, returning the allocated array of integers as its function value. The two methods each invoke this helper function; if that call is successful, each then proceeds to complete its functionality.

`itCreate()` invokes the `Iterator` constructor to obtain an interator; since the generic iterator is defined to take an array of `void *` pointers, we have to cast the pointer to the integer array to `void **` when we call the constructor.

The `ArrayListLong` constructor

```
static ArrayListLong template = {
    NULL, al_destroy, al_add, al_clear, al_ensureCapacity, al_get, al_insert,
    al_isEmpty, al_remove, al_set, al_size, al_toArray, al_trimToSize,
    al_itCreate
};

const ArrayListLong *ArrayListLong_create(long capacity) {
    ArrayListLong *al = (ArrayListLong *)malloc(sizeof(ArrayListLong));

    if (al != NULL) {
        AlData *ald = (AlData *)malloc(sizeof(AlData));
        if (ald != NULL) {
```

```
            long cap = (capacity <= 0) ? DEFAULT_CAPACITY : capacity;
            long *array = (long *) malloc(cap * sizeof(long));

            if (array != NULL) {
                ald->capacity = cap;
                ald->size = 0L;
                ald->theArray = array;
                *al = template;
                al->self = ald;
            } else {
                free(ald);
                free(al);
                al = NULL;
            }
        } else {
            free(al);
            al = NULL;
        }
    }
    return al;
}
```

As with the `Iterator` implementation, we create a static template for the dispatch table so we can initialize the dispatch table by copying the template `struct` for each new `ArrayListLong` instance. The logic in the constructor is straightforward:

1. allocate a new dispatch table;
2. if that was successful, allocate the instance-specific data structure;
3. if that was successful, allocate the initial long integer C array from the heap; its capacity is either the value passed in the argument to the constructor or the default capacity;
4. initialize the members of the instance-specific data structure, and the dispatch table.

If all heap allocations were successful, return the pointer to the dispatch table. If any of the heap allocations failed, free any previous allocations that were successful, and return NULL.

4.6.3 A generic ArrayList

While the preceding ADT provides a very functional interface to an ArrayList of long integers, would we have to implement another ADT for an ArrayList of doubles? Or an ArrayList of structures? Or an ArrayList of ArrayLists? We need a way to make our data structures generic - i.e., work with all types of data.

You will recall that all pointer types in C can be cast to `void *` and back again without loss of information. In fact, the implementation for the ArrayListLong ADT has taken advantage of this with respect to the `self` member in the dispatch table; it is declared as a `void *`, yet in the constructor a legitimate pointer is assigned to `self`. In each of the methods, the first statement is a cast to convert `self` to a pointer to the instance-specific data type. We will take advantage of `void *` to make our container data structures generic.

If we review the functions of an ArrayList from Section 4.6.1, we can see that the functionality provided should work for all types of items. Obviously, methods to add or retrieve items from the ArrayList (`add()`, `get()`, `insert()`, and `set()`) will need to have different signatures than those in the ArrayListLong ADT. Additionally, we expect that the data stored in an ArrayList instance may be allocated from the heap, so the constructor must take a `freeValue()` function pointer which will be applied whenever `destroy()`, `clear()`, `remove()`, and `set()` are invoked.

4.6.3.1 Header file for a generic ArrayList

```
#ifndef _ARRAYLIST_H_
#define _ARRAYLIST_H_

/* BSD header removed to conserve space */

#include "ADTs/ADTdefs.h"
#include "ADTs/iterator.h"                  /* needed for factory method */

/* interface definition for generic arraylist implementation
 *
 * patterned roughly after Java 6 ArrayList generic class
 */

typedef struct arraylist ArrayList;     /* forward reference */

#define DEFAULT_ARRAYLIST_CAPACITY 50L

/* create an arraylist with the specified capacity; if capacity == 0, a
 * default initial capacity (50 elements) is used
 *
 * freeValue is a function pointer that will be called by
 * destroy(), clear(), remove(), and set() on each relevant entry/entries
 * in the ArrayList
 *
 * returns a pointer to the array list, or NULL if there are malloc() errors
 */
const ArrayList *ArrayList_create(long capacity, void (*freeValue)(void *e));

/* now define the dispatch table */
struct arraylist {
/* the private data of the array list */
    void *self;
```

```
/* destroys the arraylist;
 * applies constructor-specified freeValue to each element in the arraylist
 * the storage associated with the arraylist is then returned to the heap
 */
    void (*destroy)(const ArrayList *al);

/* appends `element' to the arraylist; if no more room in the list, it is
 * dynamically resized
 *
 * returns true if successful, false if unsuccessful (malloc errors)
 *
 */
    bool (*add)(const ArrayList *al, void *element);

/* clears all elements from the arraylist;
 * applies constructor-specified freeValue to each element in the arraylist
 * any storage associated with each element in the arraylist is then
 * returned to the heap
 *
 * upon return, the arraylist will be empty
 */
    void (*clear)(const ArrayList *al);

/* ensures that the arraylist can hold at least `minCapacity' elements
 *
 * returns true if successful, false if unsuccessful (malloc failure)
 */
    bool (*ensureCapacity)(const ArrayList *al, long minCapacity);

/* returns the element at the specified position in this list in `*element'
 *
 * returns true if successful, false if no element at that position
 */
    bool (*get)(const ArrayList *al, long index, void **element);

/* inserts `element' at the specified position in the arraylist;
 * all elements from `i' onwards are shifted one position to the right;
 * if no more room in the list, it is dynamically resized;
 * if the current size of the list is N, legal values of i are in the
 * interval [0, N]
 *
 * returns true if successful, false if unsuccessful (malloc errors)
 */
    bool (*insert)(const ArrayList *al, long index, void *element);

/* returns true if arraylist is empty, false if it is not */
    bool (*isEmpty)(const ArrayList *al);

/* removes the `i'th element from the list
 * all elements from [i+1, size-1] are shifted down one position
 * applies constructor-specified freeValue to the removed element
```

```
 *
 * returns true if successful, false if `i'th position was not occupied
 */
    bool (*remove)(const ArrayList *al, long index);

/* relaces the `i'th element of the arraylist with `element';
 * applies constructor-specified freeValue to the replaced element
 *
 * returns true if successful
 * returns false if `i'th position not currently occupied
 */
    bool (*set)(const ArrayList *al, long index, void *element);

/* returns the number of elements in the arraylist */
    long (*size)(const ArrayList *al);

/* returns an array containing all of the elements of the list in
 * proper sequence (from first to last element); returns the length of
 * the list in `*len'
 *
 * returns pointer to void * array of elements, or NULL if malloc failure
 *
 * NB - the caller is responsible for freeing the void * array when finished
 *      with it
 */
    void **(*toArray)(const ArrayList *al, long *len);

/* trims the capacity of the arraylist to be the list's current size
 *
 * returns true if successful, false if failure (malloc errors)
 */
    bool (*trimToSize)(const ArrayList *al);

/* create generic iterator to this arraylist
 *
 * returns pointer to the Iterator or NULL if failure
 */
    const Iterator *(*itCreate)(const ArrayList *al);
};

#endif /* _ARRAYLIST_H_ */
```

Changes to the ArrayListLong interface are as follows:

- `const ArrayList *ArrayList_create(long capacity, void (*freeV)(void *e));`
  The constructor must be invoked with a `freeV()` function pointer; that function will be applied to each relevant entry/entries in the ArrayList by the implementations of `destroy()`, `clear()`, `remove()`, and `set()`.
- `bool (*add)(const ArrayList *al, void *element);`
  `bool (*get)(const ArrayList *al, long index, void **element);`
  `bool (*insert)(const ArrayList *al, long index, void *element);`

`bool (*remove)(const ArrayList *al, long index);`
`bool (*set)(const ArrayList *al, long index, void *element);`
`element` is everywhere declared a `void *`.

- `void **(*toArray)(const ArrayList *al, long *len);`
  `toArray()` returns an array of `void *` pointers.
- `const Iterator *(*itCreate)(const ArrayList *al);`
  `itCreate()` creates a generic iterator over the ArrayList.

4.6.3.2 Implementation for the generic ArrayList

The implementation of the generic ArrayList is shown in section B.2.

Besides the obvious conversion from `long` to `void *`, the only addition to the implementation is the definition of a static function `purge()` that traverses the current elements in the arraylist, calling `self->freeValue()` on each element; this function is used by both `destroy()` and `clear()` methods.

4.6.3.3 Storing integers and floating point numbers in a generic ArrayList

The method signatures for `add()`, `get()`, `insert()`, `remove()`, and `set()` are all in terms of `void *` values or pointers. How might one use the generic ArrayList to store integers or floating point numbers?

It should be apparent from the source code in section B.2 that the ArrayList ADT stores `void *` pointers for each of the elements. If integer or floating point values can be stored in the same amount of memory that a `void *` occupies, then we can use the generic ArrayList through the use of casts. As seen in the table in Section 3.3.2, a `void *` occupies 8 bytes in your Debian Linux image, as does a `long int` and a `double`.

For other integer types, by assigning to a `long` or an `unsigned long`, one can then cast the value to a `void *`. For `float` values, assign it to a `double`, and then cast the value to a `void *`. In general, this will will work for all scalar types *except* the C `long double` type.

> ⚠ Casting to a `void *` will **not** change the data, it simply tells the compiler to treat the 8-byte quantity as a `void *` for the purposes of matching the method signature.

For retrieval methods, such as `get()`, a corresponding cast must be performed to retrieve the original value from the ADT.

The following table summarizes the required casts needed for `add()` and `get()` for different integer and floating point data types. For all of these entries, the following declarations hold:

long l;	**unsigned long ul;**	**char c;**	**unsigned char uc;**
short s;	**unsigned short us;**	**int i;**	**unsigned int ui;**
long long ll;	**unsigned long long ull;**	**double d;**	**float f;**

Data type	add()	get()
signed char	al->add(al, (void *)(long)c);	al->get(al, index, (void **)&l); c = (char)l;
unsigned char	al->add(al, (void *)(unsigned long)uc);	al->get(al, index, (void **)&ul); uc = (unsigned char)ul;
signed short	al->add(al, (void *)(long)s);	al->get(al, index, (void **)&l); s = (short)l;
unsigned short	al->add(al, (void *)(unsigned long)us);	al->get(al, index, (void **)&ul); us = (unsigned short)ul;
signed int	al->add(al, (void *)(long)i);	al->get(al, index, (void **)&l); i = (int)l;
unsigned int	al->add(al, (void *)(unsigned long)ui);	al->get(al, index, (void **)&ul); us = (unsigned int)ul;
signed long	al->add(al, (void *)l);	al->get(al, index, (void **)&l);
unsigned long	al->add(al, (void *)ul);	al->get(al, index, (void **)&ul);
signed long long	al->add(al, (void *)ll);	al->get(al, index, (void **)&ll);
unsigned long long	al->add(al, (void *)ull);	al->get(al, index, (void **)&ull);
float	al->add(al, (void *)(double)f);	al->get(al, index, (void **)&d); f = (float)d;
double	al->add(al, (void *)d);	al->get(al, index, (void **)&d);

The following program, `testal.c`, shows how we can use this to store long integers. The program does not do anything particularly useful except show how to use the generic ADT with scalar types.

Note that when we invoke the constructor, we specify `doNothing` as the `freeValue()` function pointer, so that `destroy()` will not try to return any elements to the heap, since the elements stored in the `ArrayList` are *not* allocated from the heap.

```
#include "ADTs/arraylist.h"
#include <string.h>
#include <stdlib.h>
#include <stdio.h>

#define UNUSED __attribute__((unused))
#define NINTEGERS 256

int main(UNUSED int argc, UNUSED char *argv[]) {
    const ArrayList *al;
    long index;

    if ((al = ArrayList_create(0L, doNothing)) == NULL) {
        fprintf(stderr, "Unable to create ArrayList to hold long integers\n");
        return EXIT_FAILURE;
    }
```

```
    for (index = 0L; index < NINTEGERS; index++)
        if (!al->add(al, ADT_VALUE(index))) {
            fprintf(stderr, "Unable to append %ld to ArrayList", index);
            al->destroy(al);
            return EXIT_FAILURE;
        }
    for (index = 0; index < al->size(al); index++) {
        long value;
        if (!al->get(al, index, ADT_ADDRESS(&value))) {
            fprintf(stderr, "Unable to retrieve item at index %ld\n", index);
            al->destroy(al);
            return EXIT_FAILURE;
        }
        printf("%8ld", value);
        if ((index % 8) == 7)
            printf("\n");
    }
    al->destroy(al);
    return EXIT_SUCCESS;
}
```

Exercise 4.1. Build and test this program.

4.7 Some macros to make programming method calls easier

Suppose you have created an ArrayList to hold characters. In such a case, you would have the following declarations at the top of `main()`

```
long lc;
const ArrayList *list = ArrayList_create(0L, doNothing);
```

This creates an ArrayList with a default size and indicates that we are going to store basic data types (in this case, characters), so nothing needs to be done to any elements that remain in the ArrayList if the `destroy()` method is invoked. The declaration of `lc` is to provide a long integer into which we can read values from the ArrayList, as we shall see later.

Now suppose that we wish to add `'a'` to the ArrayList. To do so, we need a statement like the following:

```
list->add(list, (void *)(long)'a');
```

What is happening in the second argument to `add()`?

- As you will remember from chapter 3, `'a'` is an 8-bit integer;

- `(long)'a'` converts the 8-bit integer to a 64-bit integer;
- `(void *)(long)'a'` indicates to the compiler that for the purposes of this call, the 64-bit integer should be considered a pointer that cannot be dereferenced.

Some of you may find it difficult to become accustomed to using the `void *` casts when invoking methods on a generic ADT. For situations like the above, where we are providing a value to be stored in a generic container, we have provided the macro `ADT_VALUE()` which can be used as follows:

```
list->add(list, ADT_VALUE((long)'a'));
```

We still need to cast `'a'` to a long integer (the argument to the macro), but the macro name explicitly indicates that it is a value being added to the ArrayList.

Since `list` was empty before we invoked `add()`, this means that the value at index `0L` will be a 64-bit integer that is the value of `'a'`. How do we retrieve values from the ArrayList?

Functions that retrieve values from a container require that you provide the **address** of a variable to receive the value, since the return value of the method indicates `true/false` if the retrieval was successful. Let's suppose that we wish to retrieve the character that is at index `0L` from `list`. It will require a statement as follows:

```
list->get(list, 0L, (void **)&lc);
```

What is happening in the third argument to `get()`?

- `&lc` is the address of the long integer variable declared earlier;
- `(void **)&lc` indicates to the compiler that for the purposes of this call, the address provided should be considered the address of a `void *` variable.

For situations like the above, where we are retrieving a value from a generic container, we have provided the macro `ADT_ADDRESS()` which can be used as follows:

```
list->get(list, 0L, ADT_ADDRESS(&lc));
```

After such a call, `(char)lc` will yield the 8-bit value that we started with.

Note that the argument to `ADT_ADDRESS()` **must be the address of a variable in the calling function that occupies 64 bits**, while the argument to `ADT_VALUE()` simply has to be an expression that yields a value that occupies 64 bits.

4.8 Revisit the Student program using the generic ArrayList

Now that we have an extensible array ADT, we can modify the main program shown in section 4.5.3 to use it; this will make it look much more like the main programs for the three object-oriented languages shown in Appendix A.

```
#include "student.h"
#include "ADTs/arraylist.h"
#include <stdio.h>
#include <stdlib.h>
#include <string.h>

#define UNUSED __attribute__((unused))

void split(char *buf, char **last, char **first, char **uoid, char **duckid,
           char **major) {
    *last = strtok(buf, ",\n");
    *first = strtok(NULL, ",\n");
    *uoid = strtok(NULL, ",\n");
    *duckid = strtok(NULL, ",\n");
    *major = strtok(NULL, ",\n");
}

void freeStudent(void *x) {
    const Student *student = (const Student *)x;
    student->destroy(student);
}

int main(UNUSED int argc, UNUSED char *argv[]) {
    char buf[BUFSIZ];
    const ArrayList *students = ArrayList_create(0L, freeStudent);
    long i;
    long nStudents = 0L;

    if (students == NULL) {
        fprintf(stderr, "Error creating ArrayList of Student instances\n");
        return EXIT_FAILURE;
    }
    while (fgets(buf, BUFSIZ, stdin) != NULL) {
        char *last, *first, *uoid, *duckid, *major;
        const Student *s;
        split(buf, &last, &first, &uoid, &duckid, &major);
        s = Student_create(last, first, uoid, duckid, major);
        if (! students->add(students, ADT_VALUE(s))) {
            fprintf(stderr, "Cannot extend array\n");
            return EXIT_FAILURE;
        }
    }
```

```
    nStudents = students->size(students);
/* now print out the data in reverse order */
    for (i = nStudents - 1; i >= 0L; i--) {
        const Student *s;
        (void)students->get(students, i, ADT_ADDRESS(&s));
        s->print(s, stdout);
    }
    students->destroy(students);

    return EXIT_SUCCESS;
}
```

Note that we have added `#include "ADTs/arraylist.h"` at the top of the file; this enables the program to use the constructor and methods of an ArrayList. The struct definition for `StudentArray` has been removed, as has the `addToArray()` function. A function named `freeStudent` has been added; this function will be called for each element in the ArrayList when its `destroy()` method is invoked.

`main()` has been modified to invoke `ArrayList_create()` to create the ArrayList; note that we have provided `freeStudent` as the second argument to the constructor call.

The body of `main()` is significantly simplified, simply adding each Student instance to the ArrayList while reading standard input, then using the `get()` method to fetch the Student instance from the ArrayList in order to invoke the `print()` method on it. Note that we have used the two macros described above to make the methods calls a little more understandable.

Finally, the `destroy()` method is invoked on the ArrayList; that will cause `freeStudent()` to be invoked on each Student instance in the list, which invokes the `destroy()` method on the Student instance.

To compile and execute this program, do the following:

```
$ #cd to the directory in which student.h, student.c, and mainAL.c are stored
$ gcc -o mainAL -W -Wall -I/usr/local/include main.c student.c /usr/local/lib/libADTs.a
$ ./mainAL
```

Exercise 4.2. Build and test this program as described.

4.9 Where are the ADT header files and the library?

Now that we have at least one ADT that we may wish to use[6], we have to decide where to put the header files. We also need to determine where to place the library containing the ADT object files so we can link our programs to the ADT implementations.

[6] We actually have two, `ArrayList` and `Iterator`.

You may recall that in Chapter 2 we discussed the `/usr/local` branch of the file system as a place to store site-specific programs. When we add site-specific header files and libraries, we will place these in that branch, as well.

We will use `/usr/local/include` as a place to store header files and `/usr/local/lib` as a place to store additional libraries. Let's look at the contents of `/usr/local/include`:

```
$ ls -p /usr/local/include
ADTs/
```

As you can see, it contains a single directory named `ADTs`. Let's look at its contents:

```
$ ls /usr/local/include/ADTs
arraydeque.h  deque.h          llistcskmap.h     lliststack.h  stringADT.h
arraylist.h   hashcskmap.h     llistdeque.h      map.h
arrayqueue.h  hashmap.h        llistmap.h        prioqueue.h
arraystack.h  heapprioqueue.h  llistprioqueue.h  queue.h
cskmap.h      iterator.h       llistqueue.h      stack.h
```

We have seen `arraylist.h` and `iterator.h` earlier in this chapter and the remaining header files will be introduced in later chapters in the book.

How do you access these header files from your source code? We need to add another standard option to `CFLAGS` in the makefile to make sure that `gcc` knows to also look in `/usr/local/include/ADTs` for files specified in `#include` directives. The appropriate `CFLAGS` definition now becomes:

```
CFLAGS=-W -Wall -I/usr/local/include
```

The `-Idir` directive adds the directory `dir` to the head of the list of directories to be searched for header files.

A source file that wishes to access `/usr/local/include/ADTs/arraylist.h`, for example, would have the following `#include` directive at the top of the source file:

```
#include "ADTs/arraylist.h"
```

assuming that `CFLAGS` is defined as above.

You may wonder why we do not specify `-I/usr/local/include/ADTs` in `CFLAGS`, and simply `#include "arraylist.h"`. This would certainly work. It is common for there to be many local packages of header files, each in their own sub-directory of `/usr/local/include`. For programs that need to access two or more of these local packages, by specifying `#include "package/file.h"` in the source code, and by specifying `-I/usr/local/include"` in `CFLAGS`, we only require one `-Idir` directive in `CFLAGS` **and** our source code is more self-documenting, since we are indicating the `package` from which `file.h` is being included.

After compiling your source files, how do we link to the appropriate implementations of the ADTs? Before we describe this in detail, we first need a diversion regarding how one links to one of the standard system libraries.

Let's look at a simple program that computes the square root of each of the arguments passed to the program, `sqroot.c`:

```
#include <stdio.h>
#include <math.h>
#include <stdlib.h>

int main(int argc, char *argv[]) {
    double d;
    int i;

    for (i = 1; i < argc; i++) {
        sscanf(argv[i], "%lf", &d);
        printf("sqrt(%s) = %.4f\n", argv[i], sqrt(d));
    }
    return EXIT_SUCCESS;
}
```

We have included `<math.h>` in order to access the square root function, which has the following signature:

```
double sqrt(double x);
```

For each argument, we use `sscanf()` to convert the string to a double precision floating point number, and then invoke `sqrt()` on that number to complete the printed line. Here is an example of the output of `sqroot`:

```
$ ./sqroot 0.09 1 25 169 1e6
sqrt(0.09) = 0.3000
sqrt(1) = 1.0000
sqrt(25) = 5.0000
sqrt(169) = 13.0000
sqrt(1e6) = 1000.0000
```

The implementations of functions defined in `<math.h>` are stored in `/usr/lib`; there are two types of library implementation: those that end in `.a` are static libraries, and those that end in `.so` are shared object libraries, which is the Linux equivalent of a dynamically loadable library. The file containing the implementations of `sqrt()` and other mathematical functions is either `libm.a` or `libm.so` in the directory `/usr/lib`. One links to that library by specifying `-lm` in the `gcc` command that produces your executable file. By convention, all library filenames start with "lib", and the `-l` flag to `gcc` requires that the initial "lib" in the filename be dropped and that the `.a` or `.so` be dropped, as well. Here is a makefile to build `sqroot`.

```
CFLAGS=-W -Wall
OBJECTS=sqroot.o
LIBRARIES=-lm

sqroot: sqroot.o
        gcc -o sqroot $^ $(LIBRARIES)

sqroot.o: sqroot.c

clean:
        rm -f sqroot $(OBJECTS)
```

When `gcc` sees a `-lname` argument, by default it will look for it in the standard library location, `/usr/lib`; this is what it has done in the makefile for `sqroot`, looking for `libm.a` or `libm.so` in `/usr/lib`. One can add additional directories in which `gcc` will look for library arguments using a `-Ldir` option; any directory specified in this way will be searched *before* the standard library location is searched. If more than one `-Ldir` is specified, they are searched from left to right for each library, with the standard library location searched last.

Since a `-Ldir` argument is associated with linking, it is inappropriate to include it in `CFLAGS`, and most Linux programmers define an additional variable, `LDFLAGS`, that is expanded in each of the commands used to link object files to produce a program.

The following example will bring this all together.

The source file `testal.c` on page 186 includes `"ADTs/arraylist.h"` and creates one or more array lists, invoking methods on them that are defined in the header file. The actual path for the header file is `/usr/local/include/ADTs/arraylist.h`, and the library containing the array list implementation is `/usr/local/lib/libADTs.a`. The following Makefile will build `testal`.

```
CFLAGS=-W -Wall -I/usr/local/include
LDFLAGS=-L/usr/local/lib
OBJECTS=testal.o
LIBRARIES=-lADTs

testal: $(OBJECTS)
        gcc $(LDFLAGS) -o testal $^ $(LIBRARIES)

testal.o: testal.c

clean:
        rm -f $(OBJECTS) testal
```

Data Structures

This section starts off with a discussion of complexity metrics for data structures, in general, and big O notation, in particular. It also describes how one can empirically measure the runtime performance of an implementation.

It then proceeds to describe the interfaces, and make the interfaces concrete using the previously described implementation approach, for ADTs of the following types:

- stacks;
- queues;
- linked lists;
- deques;
- priority queues;
- searching and sorting;
- maps; and
- heaps.

The interface header files for the above ADTs are stored in `/usr/local/include/ADTs` in the Arch Linux virtual machine. A static library of the implementations is stored in `/usr/local/lib/libADTs.a`. Man pages exist for each of the ADTs, both implementation-independent and implementation-specific; all are stored in section `3adt` of the manual. Consult

```
man 3adt Intro
```

for an introduction to the system and a list of all of the man pages available.

Chapter 5

Complexity metrics and runtime analysis

A *data structure* is a systematic way to organize and access data; an *algorithm* is a step-by-step procedure for performing a task. As a computer scientist, we are interested in "good" data structures and algorithms. How do we determine if a particular data structure or algorithm is good?

The generally accepted measure of "goodness" is the running time of algorithms and data structure methods; another measure that is sometimes important is the amount of memory consumed. Running time is a natural measure of "goodness", since we would like our programs to run as quickly as possible while delivering the correct results.

It is generally the case that an algorithm's or a data structure method's running time increases with the size of its input. The running time is also dependent upon the computer hardware and its software environment. If we keep the hardware and its software environment fixed, we can compare the running time of different algorithms and data structure methods to determine the relationship between the running time and the size of its input.

5.1 How do we measure running time?

If an algorithm or a data structure method has been implemented, we can empirically measure the running time by executing it on various test inputs, reporting the elapsed time to process each test input. If the only difference between the test inputs is the number of values, these measurements give us an idea of running time as a functions of the number of inputs, $\tau(n)$.

5.1.1 Measurement at the shell level

Linux supplies a program, `/usr/bin/time`, which will execute a program and report various measurements concerning the resources consumed by the program. Let's assume that we have a file named `verylargefile`, that it has `12,480,100` lines, each line has a single word, and the total number of characters is `111,148,500`. Let's use `wc` on the file to count the lines, words, and characters, and use `/usr/bin/time` to determine the resource utilization of `wc`.

```
$ /usr/bin/time wc verylargefile
 12480100  12480100 111148500 verylargefile
1.59user 0.03system 0:01.63elapsed 99%CPU (0avgtext+0avgdata 429468
maxresident)k 0inputs+0output (1760major+0minor)pagefaults 0 swaps
```

As you can see, `/usr/bin/time` not only tells us the amount of time spent in the user program, time spent in the kernel while the program was running, and total elapsed time, it also gives us other information about resources used by the program. If we just want to see the timing information, we can provide `/usr/bin/time` with a format string indicating what information we want and in what format:

```
$ fmt='real    %E\nuser    %Us\nsys     %Ss'
$ /usr/bin/time -f "$fmt" wc verylargefile
 12480100  12480100 111148500 verylargefile
real    0:01.58
user    1.54s
sys     0.01s
```

This is certainly more tractable; fortunately, `/usr/bin/time` looks for the `TIME` environment variable; if found, it uses that as its format string.

```
$ export TIME='real    %E\nuser    %Us\nsys     %Ss'
$ /usr/bin/time wc verylargefile
 12480100  12480100 111148500 verylargefile
real    0:01.58
user    1.54s
sys     0.01s
```

Why do we keep specifying the full pathname to `/usr/bin/time`? `bash` has a built-in `time` command, which looks like this:

```
$ time wc verylargefile
 12480100  12480100 111148500 verylargefile

real    0m1.618s
user    0m1.531s
sys     0m0.062s
```

While this looks like exactly what we want, we will see that shell built-ins do not respect some of the I/O redirection commands that we wish to use. When the shell is resolving a command, if it finds a built-in, it will *not* search for the command along the search path. This is unfortunate when the program we want to run has an identical name to a built-in. Fortunately, we can indicate to the shell that it should *not* look for a built-in simply by prefixing a backslash to the name of the command, as in

```
$ \time wc verylargefile
 12480100  12480100 111148500 verylargefile
real    0:01.58
user    1.53s
sys     0.03s
```

Now let's get back to I/O redirection. `/usr/bin/time` writes the timing and other resource usage information on standard error. How might we cause that information to be stored in a file?

```
$ \time wc verylargefile
 12480100  12480100 111148500 verylargefile
real    0:01.58
user    1.53s
sys     0.03s
$ \time wc verylargefile >wc.out
real    0:01.61
user    1.57s
sys     0.01s
$ \time wc verylargefile >wc.out 2>time.out
$ cat time.out
real    0:01.58
user    1.53s
sys     0.03s
```

As we saw in chapter 2, the construction `2>`*filename* (no spaces are allowed between the `2` and the `>`) directs the standard error output into the file.

Note that standard output or standard error output from shell built-in's, like `time`, do not abide by the output redirection commands. For example,

```
$ time wc verylargefile >wc.out 2>&1

real    0m1.618s
user    0m1.531s
sys     0m0.062s
```

We see that despite indicating that standard error should be merged with standard output on `wc.out`, the built-in `time` still wrote the timing information on the **shell**'s standard error, the terminal. This is why we prefer to use `/usr/bin/time`, since it is a separate process and abides by any output redirection that has been specified.

If we are going to use `/usr/bin/time` to perform comparative measurements of an algorithm with different input sizes, then reporting the user and system times would appear to be superfluous. Thus, specifying `TIME="%e"` would appear to be most appropriate, as it will cause `/usr/bin/time` to report the elapsed time in seconds on standard error output. Thus, if you had a number of files with different numbers of lines, each line consisting of a single word and a newline, one could capture the performance of `wc` as a function of number of lines using the following `for` loop in `bash`:

```
$ export TIME="%e"
$ ls f*
f10 f100 f1000 f10000 f100000 f1000000 f10000000
$ for n in 10 100 1000 10000 100000 1000000 10000000; do
>     echo -n "$n," 1>&2
>     \time wc "f$n" >/dev/null
> done 2>time.out
$ cat time.out
10,0.01
100,0.01
1000,0.01
10000,0.01
100000,0.02
1000000,0.13
10000000,1.27
```

There are several things about this `for` loop that may seem new to you.

- The invocation of `ls` is simply to show you the filenames with different numbers of lines.
- We are used to seeing the `"$ "` prompt from `bash`; when `bash` is reading your command *and* it is obvious that the command is continuing on the next line of input, the secondary prompt, `"> "` is issued on the line. These two prompts are actually defined as environment variables, `PS1` and `PS2`.
- We have used the `-n` flag to `echo`, which tells it to *not* output a newline after outputting its arguments; we have also used `1>&2` to force `echo`'s output onto standard error.

- While it is not new, we used variable expansion within a quoted string (`"f$n"`) to generate the appropriate filename; note that variable expansion *does not* work if you use apostrophes (`'`) to delineate your quoted string.
- We redirected standard output for `time`, and for `wc` since it is a child process, to `/dev/null`. `/dev/null` is a pseudo-device in Linux that simply acts as a sink for information written to it. By doing this redirection, we prevent huge amounts of data being written to the terminal, which could skew the elapsed runtime for `wc`.
- And, finally, we redirected standard error output for the entire `for` loop.

Note that the data is written in the form of comma-separated values, which can be processed by a large number of statistical and graphical packages.

What have we determined from this experiment?

- `/usr/bin/time` enables us to measure the performance of a program.
- Through use of the `TIME` environment variable we can tailor the output from `time`.
- Exploitation of features in `bash` and `echo` enable us to output the performance data in any way we would like.
- 1 second granularity (well, yes, it does give us hundredths of a second) does not give us much insight into the performance if we do not have enough data to keep the processor busy for a significant amount of time (cf. the performance numbers for 10, 100, 1000, and 10000 lines are all 0.01 seconds).
- The elapsed time reported by `time` also includes the time to start up the program, and to tear down the program; thus the number reported is actually something like $overhead + \tau(n)$.

5.1.2 Measurement via source code instrumentation

If your performance analysis needs require elimination of the process overhead, and better precision than hundredths of a second, then you will need to insert instrumentation into your source code. Doing so is straightforward.

Linux provides a system call, `gettimeofday()`, which returns the current time of day as a struct consisting of two integers:

- `tv_sec` - the number of seconds
- `tv.usec` - the number of microseconds

since a fixed time in the past. The following code shows how one would obtain the current time of day using this function.

```
#include <sys/time.h>

struct timeval tm;

(void)gettimeofday(&tm, NULL);
```

Armed with this function, we can now provide the instrumentation needed to time a function. Suppose the function to be timed is `f()`. Then the following code segment will display the elapsed time in milliseconds.

```
#include <sys/time.h>
#include <stdio.h>

struct timeval t1, t2;
long long musecs;

(void)gettimeofday(&t1, NULL);
f(); /* invoke the function to be timed */
(void)gettimeofday(&t2, NULL);
musecs = 1000000 * (t2.tv_sec - t1.tv_sec) + (t2.tv_usec - t1.tv_usec);
fprintf(stderr, "%Ld.%03d\n", musecs / 1000, (int)(musecs % 1000));
```

As with our use of the `for` loop earlier, we are exploiting some previously unexercised features.

- We declare a `long long` integer for the number of microseconds; since there are `1,000,000` microseconds in a second, and a 32-bit, unsigned integer can only count up to 4 billion, we would overflow `musecs` after `~4000` seconds; this is not very much time, so we are better off guaranteeing that we have 64 bits of precision.
- You might think you need some conditional logic to handle the computation of `musecs` if `t2.tv_usec < t1.tv_usec`. This is not the case, as the first part of the computation has over counted based upon the difference of the `tv_sec` members, and the negative number that results from the difference of the `tv_usec` members merely compensates for that.
- The format string to `fprintf()` is probably more complex than anything you have written to date. Let's deconstruct it to be sure that you understand what it implies.
  - `%Ld` - indicates that the argument to be formatted is a `long long` integer; that is what we get by dividing `musecs` by `1000`.
  - `%03d` - indicates that the argument to be formatted is an `int`, and that it should be formatted in an output field 3 characters wide, and use leading `0`'s if needed to pad out to 3 characters wide; this gives us a decimal expression for the number of milliseconds.
  - Note the cast to type `int` of the modulus operation on `musecs`; we know that the value will be in the range `[0 .. 1000)`, so this fits in an `int`, and guarantees that it fits in a 3 character wide field.

5.2 Is measuring running time sufficient?

While useful, there are limitations to using experimentally measured running times to characterize algorithms:

- Just as with using test cases to test the correctness of your code, the performance characterization is only as good as the completeness of the set of test inputs. The most important test input (i.e., one that causes worst-case behavior) may have been omitted.
- Since the measured runtimes depend upon the hardware and software environment of the system upon which the measurements are performed, we will be unable to compare performance measured on one system with that measured on a different system.
- Finally, a complete implementation of the algorithm or data structure method is required to measure the performance experimentally.

The computer science community has devised a standard approach to analyzing the performance of an algorithm or data structure method that does not depend upon performing experiments. This approach associates with each algorithm a function, $f(n)$, that characterizes the running time of the algorithm as a function of the input size, n. For example, the running time for one algorithm may take twice as long when it processes twice as many items; for such an algorithm, we say "the algorithm runs in time proportional to n", or is "linear in n". The running time for another algorithm may take 4 times as long when the number of items doubles; in this case, we say "the algorithm runs in time proportional to n^2", or is "quadratic in n".

What does it mean to say that "the algorithm runs in time proportional to n"? If we were to experimentally measure the performance of an implementation of the algorithm on *any* input of size n, the measured performance would never exceed kn, where k is a constant that depends upon the hardware and software environment upon which the experiments were conducted.

More importantly, if we have two implementations of an algorithm, one of which is linear in n, and the other is quadratic in n, you would prefer the first to the second, since the linear algorithm will perform much better as the number of items grows larger.

5.3 The most prevalent performance functions, $f(n)$

There are a large number of functions, $f(n)$, that have been found to characterize algorithms. In this section, we discuss only the most prevalent functions that we use to characterize the algorithms and data structure methods in the remainder of the text book.

5.3.1 Constant in n

There are actually some algorithms and data structure methods where the running time does not depend upon the number of items, n, at all. In this case, we write the function as

$$f(n) = k,$$

where k is a fixed constant. Let's look at a simple example.

```
struct array {
    long size;
    int *buffer;
};

long arraySize(struct array *a) {
    return a->size;
}

int main(int argc, char *argv[]) {
    int buf[] = {0, 1, 2, 3, 4, 5, 6, 7, 8, 9};
    struct array myArray = { 10, buf};
    long theSize = arraySize(&myArray);
    return 0;
}
```

Everytime `arraySize()` is called, it simply returns the `size` member of the argument. Even though a `struct array` could contain arrays of varying sizes, the time required to compute the return for `arraySize()` is constant.

5.3.2 Linear in n

We have already introduced this type of function,

$$f(n) = n.$$

We will encounter this type of function whenever an algorithm or method has to perform a single operation on each of n items. Let's look at a simple example.

```
double sumOfSquares(double theArray[], long size) {
    double answer = 0.0;
    int i;

    for (i = 0; i < size; i++)
        answer += theArray[i] * theArray[i];
    return answer;
}
```

For each element of the array, this function generates the square of that element, and adds this value to `answer`. Thus, we will perform the loop `size` times; the running time will be some constant cost for function entry and return plus another constant times the number of elements in the array - i.e.,

$$k_{overhead} + k_{product+addition} n,$$

which shows that the running time is linear in the number of items.

5.3.3 Quadratic in n

We've previously touched on this type of function, as well,

$$f(n) = n^2.$$

We often encounter this type of function when an algorithm or method has nested loops. Consider the following example.

```
#include <stdio.h>

void bubble(int theArray[], long size) {
    long i, j;

    for (i = size - 2; i >= 0; i--)
        for (j = 0; j <= i; j++)
            if (theArray[j] > theArray[j+1]) {
                int t = theArray[j];
                theArray[j] = theArray[j+1];
                theArray[j+1] = t;
            }
}

void print(int theArray[], long size) {
    long i;

    for (i = 0; i < size; i++)
        printf("%s%d", ((i == 0) ? "" : ","), theArray[i]);
    printf("\n");
}

int main(int argc, char *argv[]) {
    int theArray[] = {0, 9, 1, 8, 2, 7, 3, 6, 4, 5};

    print(theArray, 10);
    bubble(theArray, 10);
    print(theArray, 10);
}
```

If we compile, link, and execute this program, the following output results:

```
0,9,1,8,2,7,3,6,4,5
0,1,2,3,4,5,6,7,8,9
```

In other words, `bubble()` sorts the array of integers in place. We will discuss sorting algorithms in a later chapter, but let's look at the complexity for `bubble()`:

- The outer loop is executed `size-1` times.
- For each value of `i` in the outer loop, we execute the inner loop `size-i-1` times.
- For each value of `j` in the inner loop, we compare two adjacent values in the array, and if the `j`th value is greater than the `j+1`st value, we swap the values. In this way, the largest item "bubbles" to the end of the array on each iteration of the outer loop.

The running time for the outer loop is linear in n, since it depends upon `size`. The running time for the inner loop is also linear in n, since it too depends upon `size`. Thus, the running time for `bubble()` is quadratic in n.

5.3.4 Logarithmic in n

There are a number of algorithms for which the performance varies as the logarithm of n:

$$f(n) = \log_b n,$$

where $b > 1$ is a constant, and is called the base. $\log_b n$ grows much more slowly than n. In computer science, b is usually 2.

Suppose that you are storing a number of integers, with no duplicates, in an array. One of the functions that you would typically need is to determine if a particular integer of interest is in the array. The signature for this function is

```
bool contains(int theArray[], long size, int value);
```

An implementation of `contains()` that makes no assumptions about how the elements of the array are ordered would look like this.

```
bool contains(int theArray[], long size, int value) {
    long i;

    for (i = 0; i < size; i++)
        if (theArray[i] == value)
            return true;
    return false;
}
```

Since no assumptions are made regarding the ordering of elements in the array, we have to do a linear search to see if the array contains `value`. By now, it should be clear that this implementation has complexity linear in n.

If we guarantee that the array is sorted at all times, can we do better? You were most likely introduced to the notion of binary search in your previous computer science courses. The following is an implementation of `contains()` that assumes that the array is sorted.

```
bool contains(int theArray[], long size, int value) {
    long lBound = 0, uBound = size - 1, midPoint;

    while (lBound <= uBound) {
        midPoint = lBound + (uBound - lBound) / 2
        if (theArray[midPoint] == value)
            return true;
        if (theArray[midPoint] < value)
            lBound = midPoint + 1;
        else
            uBound = midPoint - 1;
    }
    return false;
}
```

Binary search works on the principle of divide and conquer; at each iteration through the array, the number of items under consideration is $\frac{1}{2}$ the number on the previous iteration. If `value` is not contained in the array, then we will perform $\log_2 n$ iterations before returning `false`. Thus, the complexity is $\log_2 n$.

5.3.5 Loglinear in n

There are a number of algorithms for which a straightforward implementation is quadratic in n, but for which one can provide an implementation exhibiting

$$f(n) = n \log_b n$$

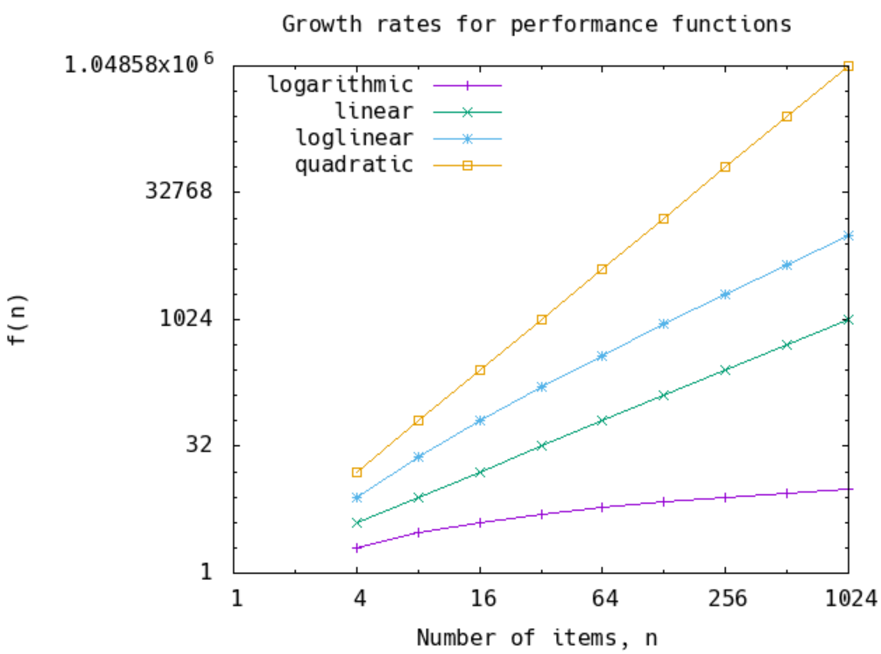
performance behavior. This function grows a little faster than linear, but much more slowly than quadratic. We will encounter this when discussing sorting algorithms, and examples will be provided at that time.

5.3.6 Summary of these performance functions

If we assume that $b = 2$ for logarithmic and loglinear, let's see how these functions grow as a function of n.

n	$\log n$	n	$n \log n$	n^2
4	2	4	8	16
8	3	8	24	64
16	4	16	64	256
32	5	32	160	1,024
64	6	64	384	4,096
128	7	128	896	16,384
256	8	256	2,048	65,536
512	9	512	4,608	262,144
1,024	10	1,024	10,240	1,048,576

The growth rates of these functions are shown graphically below.



Note that this is a log-log graph.

From this data, it should be clear that if one has four different implementations of an algorithm, one being logarithmic, one linear, one loglinear, and one quadratic, then the logarithmic implementation is preferred over the linear implementation, linear preferred over loglinear, and loglinear preferred over the quadratic. This "preference" is transitive, as well.

5.4 Asymptotic notation - the big O

We could spend a significant amount of time determining the running time cost for each basic operation of an algorithm or method. It should come as no surprise that if the running time grows very rapidly, knowing how many instructions one performs for each element simply determines a constant that multiplies the rapidly growing running time function; that function will dominate the runtime performance. Thus, if we can characterize how an algorithm or method relates to our basis set of running time functions, we will understand its asymptotic behavior - i.e., for large n.

Big O notation is a mathematical notation that describes the limiting behavior of a function when the argument tends toward a particular value or infinity. It is a member of a family of notations invented by Paul Bachmann, Edmund Landau, and others, collectively called *Bachmann-Landau notation*.

For our purposes, big O notation is used to classify algorithms or methods according to how the running time grows as the input size grows. Thus, big O notation characterizes functions according to their growth rates - different functions with the same growth rate may be represented using the same O notation.

The letter O is used because the growth rate of a function is also referred to as *order of the function*.

Let $f(n)$ and $g(n)$ be functions mapping non-negative integers to real numbers - i.e., number of input items to running time. We say that $f(n)$ is $O(g(n))$ if there is a real constant $k > 0$ and an integer constant $n_0 \geq 1$ such that

$$f(n) \leq kg(n), for\ n \geq n_0.$$

As you can see, $O(g(n))$ defines an upper bound for $f(n)$. Thus, if the running time is linear in n, we can describe its complexity as $O(n)$. We could equally well describe its complexity as $O(n^2)$, since kn^2 will certainly be an upper bound for our running time, which only grows linearly in n. We say that $O(n)$ is a *tight* upper bound for $f(n)$, and that $O(n^2)$ is a *loose* upper bound for $f(n)$.

In typical usage, the formal definition of O notation is not used directly; rather, the O notation for a function $f(n)$ is derived by the following simplification rules:

1. if $f(n)$ is a sum of several terms, if there is one with the largest growth rate, it can be kept, and all others omitted; and
2. if $f(n)$ is a product of several factors, any constants (i.e., terms in the product that do not depend upon n) can be omitted.

Let's look at a number of examples.

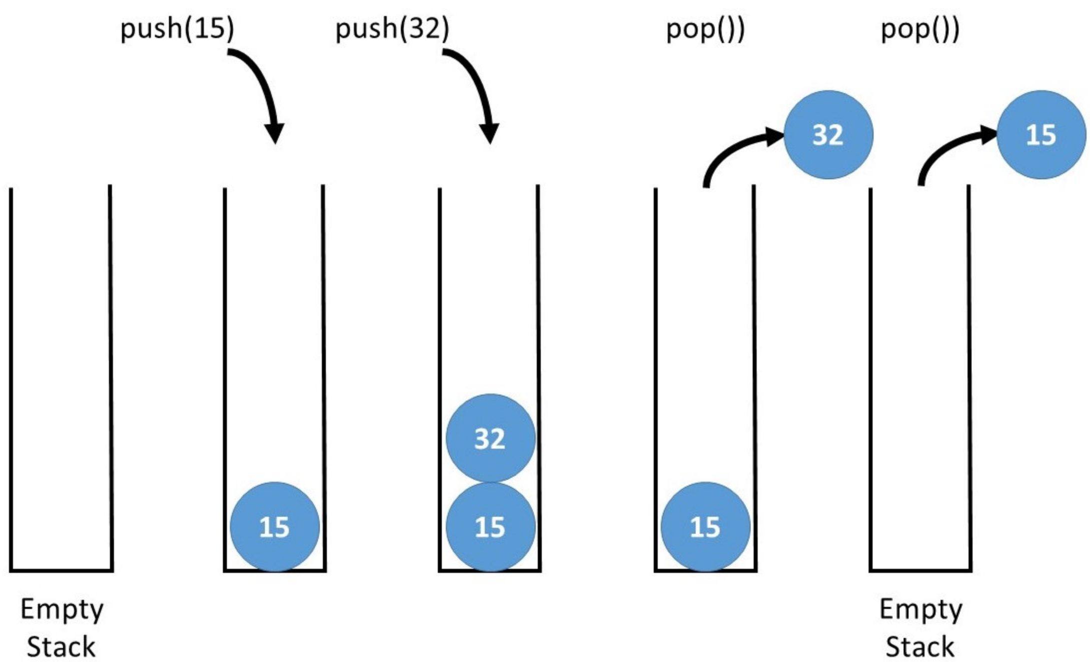
- If $f(n) = 5n - 3$, it is $O(n)$ - i.e., its growth is linear. — By rule 1 above, $5n - 3$ reduces to $5n$; by rule 2 above, $5n$ reduces to n; thus, $f(n)$ is $O(n)$.
- If $f(n) = 8n^4 - 4n^2 + 42$, it is $O(n^4)$ - i.e., its growth is quartic. — By rule 1 above, $8n^4 - 4n^2 + 42$ reduces to $8n^4$; by rule 2 above, $8n^4$ reduces to n^4; thus, $f(n)$ is $O(n^4)$.
- If $f(n) = 11n \log n + 23n - 5$, it is $O(n \log n)$ - i.e., its growth is loglinear. — By rule

1 above, $11n \log n + 23n - 5$ reduces to $11n \log n$; by rule 2 above, $11n \log n$ reduces to $n \log n$; thus, $f(n)$ is $O(n \log n)$.

Chapter 6

Stacks

A *stack* is an object container that conforms to the *last in, first out* discipline: one may *push* an element onto the stack, and one may *pop* the most recently added element from the stack; usually, one may also *peek* at the most recently added element without removing it from the stack.



Why call it a stack? Consider the analogy of a set of rectangular physical objects (pieces of paper) "stacked" on top of each other; it is easy to add ("push") another such object on the top of the stack, and it is easy to remove ("pop") the top element from the stack. Attempting to remove an element that is not at the top of the stack is much more difficult.

A stack can have bounded capacity; if a `push()` method is invoked when the stack is full, an exception is raised; as you have probably already deduced, an exception is raised if a `pop()` or a `peek()` operation is invoked on an empty stack, as well. It is often more useful to the programmer if the stack has unbounded capacity; of course, it's not truly unbounded, simply an attempt is made to grow the stack when is it full, much as we did with our ArrayList implementation (see section 4.6.2.2).

6.1 A stack of long integers

As we did with ArrayLists, first let's look at how one would define and implement a stack of long integers. We will first implement it as a bounded stack, then show the changes required to make it unbounded.

6.1.1 The interface specification

```
#ifndef _STACKLONG_H_
#define _STACKLONG_H_

#include "ADTs/ADTdefs.h"

typedef struct stacklong StackLong;            /* forward reference */
const StackLong *StackLong_create(long capacity);
struct stacklong {
    void *self;
    void (*destroy)(const StackLong *st);
    void (*clear)(const StackLong *st);
    bool (*push)(const StackLong *st, long element);
    bool (*pop)(const StackLong *st, long *element);
    bool (*peek)(const StackLong *st, long *element);
    long (*size)(const StackLong *st);
    bool (*isEmpty)(const StackLong *st);
};

#endif /* _STACKLONG_H_ */
```

By now, the general structure of the interface should be familiar. When we are first introducing a new data structure focused on long integers, we will dispense with the `toArray()` and `itCreate()` methods to simplify the presentation. We will reintroduce them when we introduce the generic version.

The semantics of the constructor and the methods are as follows:

- `const StackLong *StackLong_create(long capacity);`
  create a new instance of a Stack of long integers that can hold `capacity` elements; returns a pointer to the dispatch table, or `NULL` if there were heap-allocation errors;
- `void (*destroy)(const StackLong *st);`
  destroy the Stack of long integers; all heap-allocated memory is returned;

- `void (*clear)(const StackLong *st);`
  purge all elements from the stack; upon return, the stack is empty;
- `bool (*push)(const StackLong *st, long element);`
  push `element` onto the stack; if the stack cannot accommodate the new element (it is full), the function return is false/0; otherwise, the function return is true/1;
- `bool (*pop)(const StackLong *st, long *element);`
  remove the element at the top of the stack, returning it in `*element`; if the stack has no elements, the function return is false/0; otherwise, the function return is true/1;
- `bool (*peek)(const StackLong *st, long *element);`
  return the element at the top of the stack in `*element` *without* removing it from the stack; if the stack has no elements, the function return is false/0; otherwise, the function return is true/1;
- `long (*size)(const StackLong *st);`
  return the number of elements in the stack; and
- `bool (*isEmpty)(const StackLong *st);`
  return true/1 if the stack is empty, false/0 otherwise.

6.1.2 The implementation

6.1.2.1 The preliminaries

As with the ArrayList implementation, the secret to an efficient and successful implementation is in the choice of the instance-specific data structure.

```
#include "stacklong.h"
#include <stdlib.h>

typedef struct st_data {
    long capacity;
    long next;
    long *theArray;
} StData;
```

`next` is an index into `theArray[]` where the next `push()` will store the element. The top element on the stack is always found at `theArray[next-1]`. `capacity` indicates the number of elements that can be pushed onto the stack before overflow would occur (remember, this is a bounded stack).

6.1.2.2 The constructor

This looks very similar to the constructor for ArrayListLong. Allocate a dispatch table from the heap, allocate an instance-specific data structure from the heap, allocate an array of longs from the heap. If all allocations are successful, initialize the instance-specific data structure and dispatch table, and return to the caller. If any heap-allocation failures occur, free up any successful heap-allocations prior to the failure and return `NULL`.

```
static StackLong template = {
    NULL, st_destroy, st_clear, st_push, st_pop, st_peek, st_size, st_isEmpty
};

const StackLong *StackLong_create(long capacity) {
    StackLong *st = (StackLong *)malloc(sizeof(StackLong));

    if (st != NULL) {
        StData *std = (StData *)malloc(sizeof(StData));

        if (std != NULL) {
            long *array = (long *)malloc(capacity * sizeof(long));;

            if (array != NULL) {
                std->capacity = capacity;
                std->next = 0L;
                std->theArray = array;
                *st = template;
                st->self = std;
            } else {
                free(std);
                free(st);
                st = NULL;
            }
        } else {
            free(st);
            st = NULL;
        }
    }
    return st;
}
```

6.1.2.3 `destroy()` and `clear()`

`destroy()` frees the heap-allocated memory in the reverse order to the constructor. `clear()` simply resets `next` to 0, indicating that the stack is empty.

```
static void st_destroy(const StackLong *st) {
    StData *std = (StData *)st->self;

    free(std->theArray);        /* free array of longs */
    free(std);                  /* free structure with instance data */
    free((void *)st);           /* free dispatch table */
}

static void st_clear(const StackLong *st) {
    StData *std = (StData *)st->self;
```

```
    std->next = 0L;
}
```

6.1.2.4 push(), pop(), and peek()

`push()` checks to see if there is room on the stack for another element; if so, it stores it into `theArray[next]`, increments `next`, and returns 1 as the function value; if not, it returns 0 as the function value.

`pop()` checks to see if `next > 0`; if so, the value of `theArray[next-1]` is stored into `*element`, `next` is decremented, and 1 is returned as the function value; if not, 0 is returned as the function value.

`peek()` checks to see if `next > 0`; if so, the value of `theArray[next-1]` is stored into `*element` and 1 is returned as the function value; if not, 0 is returned as the function value.

```
static bool st_push(const StackLong *st, long element) {
    StData *std = (StData *)st->self;
    bool status = (std->next < std->capacity);

    if (status)
        std->theArray[std->next++] = element;
    return status;
}

static bool st_pop(const StackLong *st, long *element) {
    StData *std = (StData *)st->self;
    bool status = (std->next > 0L);

    if (status) {
        *element = std->theArray[--std->next];
    }
    return status;
}

static bool st_peek(const StackLong *st, long *element) {
    StData *std = (StData *)st->self;
    bool status = (std->next > 0L);

    if (status) {
        *element = std->theArray[std->next - 1];
    }
    return status;
}
```

6.1.2.5 size() and isEmpty()

Since arrays in C are 0-based, the call to `size()` simply returns the current value of `next`. Likewise, `isEmpty()` simply returns `next == 0L`.

```
static long st_size(const StackLong *st) {
    StData *std = (StData *)st->self;

    return std->next;
}

static bool st_isEmpty(const StackLong *st) {
    StData *std = (StData *)st->self;

    return (std->next == 0L);
}
```

6.1.3 Complexity of the constructor and methods

Now let's characterize the running time complexity of each of the methods. In the characterizations below, we will use n to mean the number of elements in the array that are occupied; this is stored in the `next` member of the instance-specific data structure for the stack.

- `StackLong_create()` - when this function is called, there are no elements in the Stack; we perform three calls to `malloc()`.
  We have no insight into the implementation of `malloc()`, so we do not know its complexity as a function of the number of bytes requested. Most heap allocation systems are extremely efficient at finding a memory block of the required size; buddy heaps have a complexity of $O(\log m)$, where m is the number of memory blocks that it uses. It is impossible to correlate m with n, thus for for `malloc()` and `free()` we will assume a complexity of $O(1)$.
  Thus, the complexity for the constructor is $O(1)$.
- `push()` - this method simply checks to see that `next < capacity`, and if true, stores the element in the array at that index and increments `next`. This is independent of the number of elements currently in the stack, thus the complexity for `push()` is $O(1)$.
- `pop()` - this method simply checks to see that `next > 0`, and if true, stores the element at `next-1` in the pointer argument and decrements `next`. This is independent of the number of elements currently in the stack, thus the complexity for `pop()` is $O(1)$.
- `peek()` - this method simply checks to see that `next > 0`, and if true, stores the element at `next-1` in the pointer argument. This is independent of the number of elements currently in the stack, thus the complexity for `peek()` is $O(1)$.
- `destroy()` - when this function is called, we perform three calls to `free()`, which as we have explained above, we consider $O(1)$ for the purposes of this discussion. Thus,

the complexity for `destroy()` is $O(1)$.

- `clear()` - this function simply sets `next` to 0. This is independent of the number of elements currently in the stack, thus the complexity for `clear()` is $O(1)$.
- `size()` - this function simply returns the value of `next`. This is independent of the number of elements currently in the stack, thus the complexity for `size()` is $O(1)$.
- `isEmpty()` - this function simply returns the value of `next == 0L`. This is independent of the number of elements currently in the stack, thus the complexity for `size()` is $O(1)$.

From this discussion, we can see that for a bounded Stack of long integers, the constructor and *all* of the methods are $O(1)$. Thus, if your problem needs a bounded container exhibiting *last in, first out* functionality, you cannot do better than a stack that is implemented using an array.

6.1.4 Changes needed to make the stack unbounded

6.1.4.1 The interface

No change is required to the signatures for the constructor or the methods, although the semantics for the value of `capacity` in the constructor is slightly different. If `capacity == 0L`, this tells the implementation to use a default stack size for the initial array. This default capacity should be `#define`'d in the header file, as in

```
#define DEFAULT_CAPACITY 50
```

6.1.4.2 The instance-specific data structure

The array of long integers will need to be made larger if `push()` is invoked when the current stack is already full. The implementation can choose to simply double the size of the array whenever this occurs - this leads to exponential growth of the array. Alternatively, the implementation can choose to grow the array by a constant increment each time, leading to linear growth of the array. If linear growth is chosen, the increment can be a defined constant for all stacks, or it can be a stack-specific value, usually dependent upon the initial capacity specified in the constructor.

If a stack-specific linear growth increment is to be used, then an additional member must be added to `StData`, typically called `increment`. It will look as follows:

```
typedef struct st_data {
    long capacity;
    long next;
    long increment;
    long *theArray;
```

```
} StData;
```

The changes below will double the size of the array each time it must grow, meaning that we do *not* need to add the increment field to `StData`.

6.1.4.3 `destroy()`, `clear()`, `pop()`, `peek()`, `size()`, and `isEmpty()`

No change required, since none of these methods can cause the array of longs to have to grow.

6.1.4.4 The constructor

After successful allocation of the instance-specific struct, we need to determine the initial capacity of the stack. The following code replaces the lines from "`if(std != NULL) {`" up to the first line consisting of "`} else {`".

```
if (std != NULL) {
    long cap;
    long *array = NULL;

    cap = (capacity <= 0L) ? DEFAULT_CAPACITY : capacity;
    array = (long *)malloc(cap * sizeof(long));
    if (array != NULL) {
        std->capacity = cap;
        std->next = 0L;
        std->theArray = array;
        *st = template;
        std->self = std;
    } else {
```

6.1.4.5 `push()`

The implementation for `push()` in section 6.1.2.4 does nothing if `next >= capacity`. The following code will grow the array when it is full, and should simply be inserted above the "`if (status)`" line in the previous implementation.

```
if (! status) {          /* need to reallocate */
    size_t nbytes = 2 * std->capacity * sizeof(long);
    long *tmp = (long *)realloc(std->theArray, nbytes);

    if (tmp != NULL) {
```

```
        status = true;
        std->theArray = tmp;
        std->capacity *= 2;
    }
}
```

6.1.5 Complexity for unbounded stack

Section 6.1.3 described the complexity for the constructor and methods for a bounded stack; as you will recall, all methods and the constructor were $O(1)$ complexity.

Only the `push()` method changed for the unbounded stack. We, therefore, need to analyze the complexity for `push()` to see if it has changed.

If `next` $<$ `capacity`, the code performs identically as for the bounded stack, and is therefore $O(1)$. If the stack at the current `capacity` is full, then we invoke `realloc()` to grow the array. A successful call to `realloc()` performs two actions:

- it allocates a chunk of memory of the requested larger size; and
- if that is successful, it copies the contents of the old chunk into the new chunk and frees the old chunk, returning a pointer to the new chunk as the function return.

Similar to our previous discussion, we consider the allocation of the new chunk of memory to be $O(1)$. The time required to copy contents from old to new chunk is dependent upon the size of the old chunk, which is linear in the number of stack entries; therefore, when this resizing takes place, the complexity of that call to `push()` is $O(n)$.

Thus, the worst-case complexity for `push()` is $O(n)$.[1]

6.2 A generic stack

The following show the header and implementation files for a stack in which `void *` elements are stored. We have also included the `create()`, `toArray()`, and `itCreate()` methods, and the constructor has a `freeValue()` argument. As described for the generic `ArrayList`, one can use the generic `Stack` to store scalar types through appropriate casts of those types.

As promised, we need to discuss the appropriate order in which elements of a stack should be returned by a sequence of calls to the iterator returned by `itCreate()`. The natural order for a stack is from the top to the bottom of the stack. The implementation for `itCreate()` orders the elements in the iterator such that the elements are delivered in this

[1] In your next course on algorithms and data structures, you will learn about *amortized complexity*, which is an approach to evaluate the complexity for methods like `push()` that exhibit such a mix of complexities. Given our choice to double the size of the array, the amortized complexity for `push()` is $O(1)$.

natural order.

6.2.1 Implementation-independent generic `Stack` interface

```
#ifndef _STACK_H_
#define _STACK_H_

/* BSD Header removed to conserve space */

/*
 * interface definition for generic stack
 *
 * patterned roughly after Java 6 Stack interface
 */

#include "ADTs/ADTdefs.h"
#include "ADTs/iterator.h"                   /* needed for factory method */

typedef struct stack Stack;                /* forward reference */

/*
 * this function signature is provided as the default constructor for
 * any Stack implementation
 *
 * freeValue is a function pointer that will be called by
 * destroy() and clear() on each entry in the Stack
 *
 * returns a pointer to the stack instance, or NULL if errors
 */
const Stack *Stack_create(void (*freeValue)(void *e));

/*
 * dispatch table for a generic stack
 */
struct stack {
/*
 * the private data of the stack
 */
    void *self;

/*
 * create a new stack using the same implementation as the stack upon which
 * the method has been invoked; returns NULL if error creating the new stack
 */
    const Stack *(*create)(const Stack *st);

/*
 * destroys the stack;
 * applies constructor-specified freeValue to each element in the stack
```

```
 * the storage associated with the stack is then returned to the heap
 */
   void (*destroy)(const Stack *st);

/*
 * clears all elements from the stack;
 * applies constructor-specified freeValue to each element in the stack
 * the stack is then re-initialized
 *
 * upon return, the stack is empty
 */
   void (*clear)(const Stack *st);

/*
 * pushes `element' onto the stack; if no more room in the stack, it is
 * dynamically resized
 *
 * returns true if successful, false if unsuccessful (malloc errors)
 */
   bool (*push)(const Stack *st, void *element);

/*
 * pops the element at the top of the stack into `*element'
 *
 * returns true if successful, false if stack was empty
 */
   bool (*pop)(const Stack *st, void **element);

/*
 * peeks at the top element of the stack without removing it;
 * returned in `*element'
 *
 * return true if successful, false if stack was empty
 */
   bool (*peek)(const Stack *st, void **element);

/*
 * returns the number of elements in the stack
 */
   long (*size)(const Stack *st);

/*
 * returns true if the stack is empty, false if not
 */
   bool (*isEmpty)(const Stack *st);

/*
 * returns an array containing all of the elements of the stack in
 * proper sequence (from top to bottom element); returns the length of the
 * array in `*len'
 *
```

```
 * returns pointer to array of void * elements, or NULL if malloc failure
 *
 * The array of void * pointers is allocated on the heap, so must be returned
 * by a call to free() when the caller has finished using it.
 */
    void **(*toArray)(const Stack *st, long *len);

/*
 * creates generic iterator to this stack;
 * successive next calls return elements in the proper sequence (top to bottom)
 *
 * returns pointer to the Iterator or NULL if malloc failure
 */
    const Iterator *(*itCreate)(const Stack *st);
};

#endif /* _STACK_H_ */
```

6.2.2 Array-based implementation for a generic `Stack`

As discussed in Section 4.3, there can be multiple implementations of an ADT. Different implementations will typically use different low-level data structures in the `self` structure. For example, for `StackLong`, we used an array of long integers, and `next` was an index into the array where the next long integer would be pushed.

Another common implementation technique for a `Stack` is to use a linked list, as described in Chapter 8. How would you explicitly indicate that you wanted a `Stack` implemented using an array if both implementations are available in the library? You need an implementation-specific constructor to do so; since all implementations need to implement the default constructor, one cannot guarantee which implementation will be linked to your program if you use the the default constructor defined in the `Stack` interface.

For container ADTs that can have different implementations, one normally provides an additional interface header file which has the signature for the implementation-specific constructor and also indicates that the implementation has to conform to the implementation-independent interface. In this case, we define an additional interface for an `ArrayStack`, as shown in the following header file, `ADTs/arraystack.h`.

```
#ifndef _ARRAYSTACK_H_
#define _ARRAYSTACK_H_

/* BSD Header removed to conserve space */

/*
 * constructor for an array-based stack
 *
 * implements the methods defined in stack.h
```

```
 */

#include "ADTs/ADTdefs.h"
#include "ADTs/stack.h"

#define DEFAULT_STACK_CAPACITY 50L

/*
 * create an array-based stack with the specified capacity;
 * if capacity == 0L, a default initial capacity (50 elements) is used
 *
 * freeValue is a function pointer that will be called by
 * destroy() and clear() on each entry in the Stack
 *
 * returns a pointer to the stack, or NULL if there are malloc() errors
 */
const Stack *ArrayStack(long capacity, void (*freeValue)(void *e));

#endif /* _ARRAYSTACK_H_ */
```

The first thing this header file does is `#include` the generic `Stack` interface. By including this file, the common dispatch table structure for stacks is defined, as well as the signature for the default constructor.

The implementation of an `ArrayStack` must implement the default constructor, `Stack_create()`, as well as the `ArrayStack` constructor, `ArrayStack()`.

A program that wishes to create a `Stack` can use either the default constructor (if you do not care how the `Stack` is implemented) or the `ArrayStack` constructor (if you wish to guarantee that it is implemented using an array). Sample invocations are shown in the following table.

⚠ These invocations assume that non-heap-allocated elements are pushed onto the `Stack`; obviously, if you were creating a `Stack` onto which heap-allocated elements are pushed, then a different `freeValue()` function pointer would replace the occurrences of `doNothing`.

Default constructor	ArrayStack constructor

`#include ¨ADTs/stack.h¨`
 	
`const Stack *st = Stack_create(doNothing);`
	`#include ¨ADTs/arraystack.h¨`
	
	`const Stack *st = ArrayStack(0L, doNothing);`

The `ArrayStack` implementation is shown in section B.3.

If you review the implementation in section B.3, you will see that there are three functions in the implementation that can create a new `Stack`:

- `static const Stack *st_create(const Stack *st);`
- `const Stack *ArrayStack(long capacity, void (*freeValue)(void *e));`

- `const Stack *Stack_create(void(*freeValue)(void *e));`

The first function above is the implementation of the `create()` method; this can be used to create a new stack when one already has a stack in your possession. The new stack so created will use the same implementation and `freeValue()` function as the stack in your possession.

The second function above creates a new array-based stack of the specified capacity (or the default capacity if `capacity <= 0L`).

The third function above implements the default constructor, so it uses the default capacity.

Exercise 6.1. Exercise the generic `Stack` implementation
Write a C program that takes a single command-line argument, which is a filename. The input file contains instructions for stack operations. The first line of the input file is an integer $0 \leq N \leq 10^4$ giving the number of instructions that will follow. Each of the following N lines contains an instruction. The possible instructions are:

- `push X`, where $-10^5 \leq X \leq 10^5$ is an integer. For this instruction, push X onto the stack. There is no output.
- `pop`: pop the top element of the stack. Print the removed element. If the stack was empty, output *StackError*.
- `print`: print the contents of the stack, with each pair of elements separated by a single space, starting at the top (the element that would be removed by a pop). If the stack is empty, output *Empty*. The stack must be in the same state after it has been printed as it was before it was printed.

The print action is *not* a method in the ADT, but a function that uses the ADT methods to access the elements of the stack. Instead, you should write a `printStack` function that takes a stack as an argument and accomplishes the print action using only the methods on the `Stack` ADT. You may *not* use the `toArray()` or `itCreate()` methods in your `printStack` implementation. You can, of course, use other aspects of C in the implementation of the print function.
All output should be to standard output. Each piece of output should be separated by a newline.
Example input and output are shown in the following table.

Input	Output
`7`	*no output*
`print`	`Empty`
`push 1`	*no output*
`push 2`	*no output*
`print`	`2 1`
`pop`	`2`
`pop`	`1`
`pop`	`StackError`

Exercise 6.2. Evaluation of postfix expressions
We are used to seeing algebraic expressions using infix notation - i.e., binary operators (such as +, -, *, and /) are sandwiched between their operands. In order to be able to express the

usual precedence relationships (* and / have higher precedence than + and -) we have to use parentheses in the expression to avoid incorrect evaluation: for example, `8 + 3 * 5 + 1` evaluates to 24, while `(8 + 3) * (5 + 1)` evaluates to 66.
We can also express algebraic expressions using postfix notation - i.e., binary operators come after their two operands. The postfix expression for the parenthesized infix expression above becomes
`8 3 + 5 1 + *`.
We can use a stack to evaluate postfix expressions.

1. Create a stack to store values.
2. Scan the given expression and do the following for every scanned element:
   - If the element is a number, push it onto the stack.
   - If the element is an operator, pop two elements from the stack, evaluate the operator, and push the result back onto the stack.
3. When all elements of the expression have been scanned and processed, the number on the stack is the final result.

For example, consider the expression `2 3 1 * + 9 -`.

- Scan '2'; since it is a number, push it onto the stack; stack contains '2'.
- Scan '3'; since it is a number, push it onto the stack; stack contains '3 2'.
- Scan '1'; since it is a number, push it onto the stack; stack contains '1 3 2'.
- Scan '*'; since it is an operator, pop '1' into `v2`, pop '3' into `v1`, push `v1 * v2` onto the stack; stack contains '3 2'.
- Scan '+'; since it is an operator, pop '3' into `v2`, pop '2' into `v1`, push `v1 + v2` onto the stack; stack contains '5'.
- Scan '9': since it is a number, push '9' onto the stack; stack contains '9 5'.
- Scan '-': since it is an operator, pop '9' into `v2`, pop '5' into `v1`, push `v1 - v2` onto the stack; stack contains '-4'.
- Since there are no more items to scan, the element at the top of the stack (-4) is the value of the expression.

Write a C program that uses the generic version of a stack. The program takes a single command argument, which is an input filename. The format of the input file is as follows:

- A line consisting of a positive integer $0 \leq N \leq 10^5$; N is the number of expression lines to follow.
- N expression lines in postfix format.

You are to evaluate each expression, printing the result of each evaluation on a separate line on standard output.

Exercise 6.3. Check for balanced parentheses in an expression
Given an expression string, call it `exp`, write a program to examine whether the pairs and the orders of '{', '}', '[', ']', '(', ')' are correct. For example, if `exp` = "[()]{}{[()()]()}", the program should determine that it is correctly formed, whereas if it is "[(])", it should determine that it is incorrectly formed.
Write a C program that uses the generic version of a stack. The program takes a single command argument, which is an input filename. The format of the input file is as follows:

- A line consisting of a positive integer $0 \leq N \leq 10^5$; N is the number of expression lines to follow.
- N expression lines consisting of the characters "{}[]()".

You are to check each expression for balance and order; if it is correctly formed, print 'True' (without the apostrophes) on a single line on standard output; if not, print 'False' (without the apostrophes) on a single line on standard output.

Exercise 6.4. Reverse a number using a stack
Given a number, write a C program that reverses this number using the generic version of a stack. The reverse of 12345 is 54321, whereas the reverse of -12345 is -54321.
The program takes a single command argument, which is an input filename. The format of the input file is as follows:

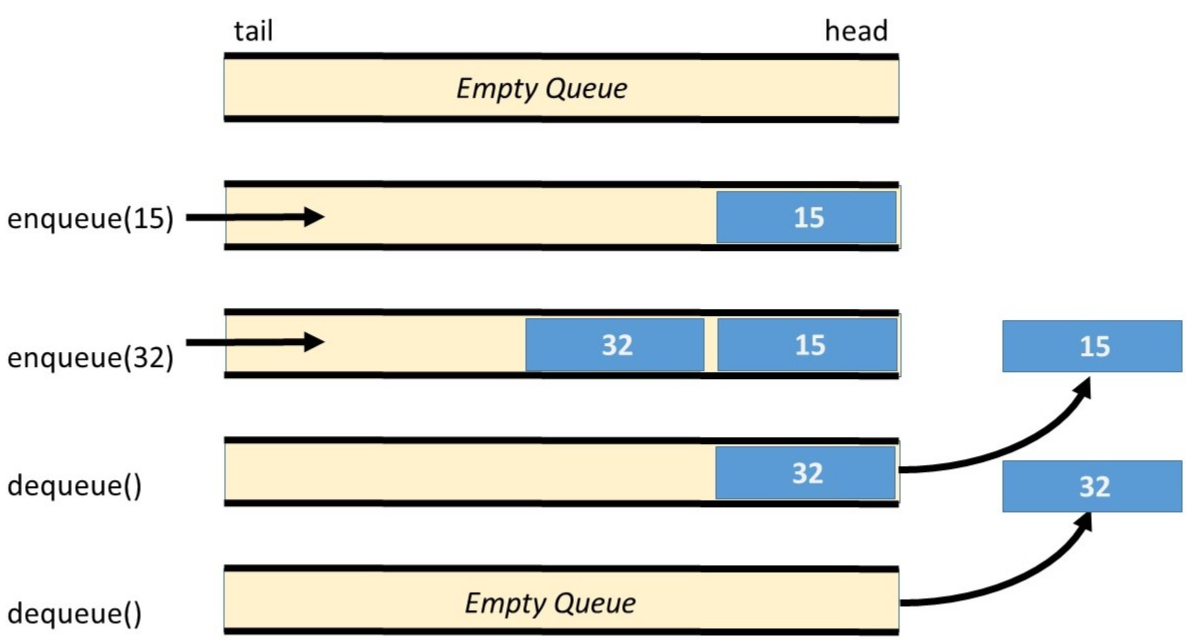
- A line consisting of a positive integer $0 \leq N \leq 10^5$; N is the number of integer lines to follow.
- N lines, each consisting of an integer $i, -10^9 \leq i \leq 10^9$.

You are to read each integer, and print the reverse representation on a single line on standard output. Note that there are to be no leading zeroes on the reversed representation - i.e., if asked to reverse 100, the output is 1, not 001.

Chapter 7

Queues

A *queue* is an object container that conforms to the *first in, first out* discipline: there is a notion of the head and tail of the queue, elements may be added to the tail of the queue (*enqueue*), and removed from the head of the queue (*dequeue*). Once a new element is added to the queue, all elements that were added before it must be removed before the new element is removed. There is also usually a *front* method, returning the element at the head of the queue without dequeuing it.



Why call it a queue? Whenever there is a fixed number of points of service, and more requests needing service than there are points of service, one will typically queue. Examples abound in every day life: at the DMV, at the bakery, buying tickets to see a movie, ... Individuals line up, awaiting their turn to be served, in the order in which they entered the queue. A queue data structure maintains this arrival sequence by forcing additions at the tail of the queue and removals from the head of the queue.

A queue can have bounded capacity; if an `enqueue()` method is invoked when the queue is full, an exception is raised; as with a stack, an exception is raised if a `dequeue()` or a `front()` method is invoked on an empty queue, as well. It is often more useful to the programmer if the queue has unbounded capacity; of course, it's not truly unbounded, simply an attempt is made to grow the queue when is it full, much as we did with our Stack implementation.

In this section, we will show how to create a queue using an array. It is also common to implement a queue using a linked list, which we will explore in a later chapter.

7.1 A queue of long integers

As we did with Stacks, first let's look at how one would define and implement a queue of long integers. We will first implement it as a bounded queue, then show the changes required to make it unbounded.

How are we going to use an array to implement our queue? We could structure our `dequeue()` method so that we always return the element at index 0; if we did so, after removing the value at index 0, we would have to copy each of the other elements down one position. Such a method will have $O(n)$ running time complexity. Since a Queue has localized addition and removal (as did a Stack), we would like an implementation that exhibited $O(1)$ complexity on removal. How might we do this?

We can avoid moving the other elements of the queue if we keep track of two indices into the array: `in`, which is the next index into which an element can be stored (therefore, is the "tail" of the queue); and `out`, which is the next index from which an element can be retrieved (therefore, is the "head" of the queue). Obviously, whenever we `enqueue()` a new element, we need to increment `in`. What happens if we reach the end of the array?

If we treat the array as a circular buffer, then after storing a new element at the last index in the array, instead of simply incrementing `in`, we increment *modulo* the size of the array. That is, if `N` is the size of the array, when we invoke `enqueue()`, we increment `in` as

```
in = (in + 1) % N;
```

We would do a similar increment for `out` after a successful `dequeue()`. We also have to keep track of the number of elements in the queue to prevent one index from overtaking the other. We shall see this in the implementation.

7.1.1 The interface specification

```
#ifndef _QUEUELONG_H_
#define _QUEUELONG_H_

#include "ADTs/ADTdefs.h"

typedef struct queuelong QueueLong;        /* forward reference */
const QueueLong *QueueLong_create(long capacity);
struct queuelong {
    void *self;
    void (*destroy)(const QueueLong *ql);
    void (*clear)(const QueueLong *ql);
    bool (*enqueue)(const QueueLong *ql, long element);
    bool (*front)(const QueueLong *ql, long *element);
    bool (*dequeue)(const QueueLong *ql, long *element);
    long (*size)(const QueueLong *ql);
    bool (*isEmpty)(const QueueLong *ql);
};

#endif /* _QUEUELONG_H_ */
```

The semantics of the constructor and the methods are as follows:

- `const QueueLong *QueueLong_create(long capacity);`
  create a new instance of a Queue of long integers that can hold `capacity` elements; returns a pointer to the dispatch table, or `NULL` if there were heap-allocation errors;
- `void (*destroy)(const QueueLong *ql);`
  destroy the Queue of long integers; all heap-allocated memory is returned;
- `void (*clear)(const QueueLong *ql);`
  purge all elements from the Queue; upon return, the queue is empty;
- `bool (*enqueue)(const QueueLong *ql, long element);`
  add `element` to the tail of the queue; if the queue cannot accommodate the new element (it is full), the method returns false/0; otherwise, it returns true/1;
- `bool (*front)(const QueueLong *ql, long *element);`
  return the element at the head of the queue in `*element` *without* removing it from the queue; if the queue has no elements, the method returns false/0; otherwise it returns true/1;
- `bool (*dequeue)(const QueueLong *ql, long *element);`
  remove the element at the head of the queue, returning it in `*element`; if the queue has no elements, the method returns false/0; otherwise, it returns true/1;
- `long (*size)(const QueueLong *ql);`
  return the number of elements in the queue; and
- `bool (*isEmpty)(const QueueLong *ql);`
  return true/1 if the stack is empty, false/0 otherwise.

7.1.2 The implementation

7.1.2.1 The preliminaries

As with the Stack implementation, the secret to an efficient and successful implementation is the choice of the instance-specific data structure.

```
#include "queuelong.h"
#include <stdlib.h>

typedef struct ql_data {
    long count;      /* number of elements in Q */
    long size;       /* size of array for elements */
    long in;         /* array index for next enqueue */
    long out;        /* array index for next dequeue or front */
    long *buffer;    /* array holding queue elements */
} QlData;
```

`count` is the number of elements in the queue, while `size` is the size of the array holding the queue; if `count == size`, then the queue is full (this is a bounded queue); if `count == 0`, the queue is empty. As we discussed earlier, `in` is the index into which the next `enqueue()` will store an element, and `out` is the index from which the next `dequeue()` or `front()` will retrieve an element.

7.1.2.2 The constructor

This looks very similar to the constructor for StackLong. Allocate a dispatch table from the heap, allocate an instance-specific data structure from the heap, allocate an array of longs from the heap. If all allocations are successful, initialize the instance-specific data structure and dispatch table, and return to the caller. If any heap-allocation failures, free up any heap-allocations prior to the failure and return `NULL`.

```
static QueueLong template = {
    NULL, ql_destroy, ql_clear, ql_enqueue, ql_front, ql_dequeue, ql_size,
    ql_isEmpty
};

const QueueLong *QueueLong_create(long capacity) {
    QueueLong *ql = (QueueLong *)malloc(sizeof(QueueLong));

    if (ql != NULL) {
        QlData *qld = (QlData *)malloc(sizeof(QlData));

        if (qld != NULL) {
            long *tmp;
```

```
            tmp = (long *)malloc(capacity * sizeof(long));
            if (tmp != NULL) {
                qld->count = 0;
                qld->size = capacity;
                qld->in = 0;
                qld->out = 0;
                qld->buffer = tmp;
                *ql = template;
                ql->self = qld;
            } else {
                free(qld);
                free(ql);
                ql = NULL;
            }
        } else {
            free(ql);
            ql = NULL;
        }
    }
    return ql;
}
```

Note that we initialize `in` and `out` to `0`. This can certainly not be a legal situation, or can it? If the queue is full, or the queue is empty, these two indices can be equal (you should work this through yourself). Thus, as we shall see below, `enqueue()`, `dequeue()`, and `front()` must check for full/empty *before* manipulating the indices.

7.1.2.3 `destroy()` and `clear()`

`destroy()` frees the heap-allocated memory in reverse order to the constructor. `clear()` simply resets `count`, `in`, and `out` to `0`, indicating that the queue is empty.

```
static void ql_destroy(const QueueLong *ql) {
    QlData *qld = (QlData *)ql->self;

    free(qld->buffer);
    free(qld);
    free((void *)ql);
}

static void ql_clear(const QueueLong *ql) {
    QlData *qld = (QlData *)ql->self;

    qld->count = 0L;
    qld->in = 0L;
    qld->out = 0L;
}
```

7.1.2.4 enqueue()

`enqueue()` first checks to see if `count < size`; if not, the queue is full, and it returns `false/0`, indicating a failure to queue `element`. Otherwise, it stores `element` in `buffer[in]`, increments `in` modulo `size`, increments `count`, and returns `true/1`, indicating that `element` was successfully queued.

```
static bool ql_enqueue(const QueueLong *ql, long element) {
    QlData *qld = (QlData *)ql->self;
    bool status = (qld->count < qld->size);

    if (status) {
        long i = qld->in;
        qld->buffer[i] = element;
        qld->in = (i + 1) % qld->size;
        qld->count++;
    }
    return status;
}
```

7.1.2.5 front() and dequeue()

The logic for these two methods is identical, except that `front()` does not increment `out` or decrement `count`.

```
static bool ql_front(const QueueLong *ql, long *element) {
    QlData *qld = (QlData *)ql->self;
    bool status = (qld->count > 0);

    if (status)
        *element = qld->buffer[qld->out];
    return status;
}

static bool ql_dequeue(const QueueLong *ql, long *element) {
    QlData *qld = (QlData *)ql->self;
    bool status = (qld->count > 0);

    if (status) {
        long i = qld->out;
        *element = qld->buffer[i];
        qld->out = (i + 1) % qld->size;
        qld->count--;
    }
    return status;
}
```

7.1.2.6 `size()` and `isEmpty()`

These methods perform the obvious manipulations of `count`, returning the result to the caller.

```
static long ql_size(const QueueLong *ql) {
    QlData *qld = (QlData *)ql->self;
    return qld->count;
}

static bool ql_isEmpty(const QueueLong *ql) {
    QlData *qld = (QlData *)ql->self;
    return (qld->count == 0L);
}
```

7.1.3 Complexity of the constructor and methods

As we did with Stacks, let's estimate the complexity of the constructor and each of the methods.

- `QueueLong_create()` - when this function is called, there are no elements in the Queue; we perform three calls to `malloc()`, which, as we have discussed in the Stack chapter, we consider $O(1)$ for the purposes of this discussion. Thus, the complexity for the constructor is $O(1)$.
- `enqueue()` - this method simply checks to see if `count < size`, and if true, stores the element in the array at `in`, increments `in` modulo `size`, and increments `count`. This is independent of the number of elements in the queue, thus the complexity for `enqueue()` is $O(1)$.
- `dequeue()` - this method checks to see if `count > 0`, and if true, retrieves the element in the array at `out`, increments `out` modulo `size`, and decrements `count`. This is independent of the number of elements in the queue, thus the complexity for `dequeue()` is $O(1)$.
- `front()` - this method checks to see if `count > 0`, and if true, retrieves the element in the array at `out`. This is independent of the number of elements in the queue, thus the complexity for `front()` is $O(1)$.
- `destroy()` - when this function is called, we perform three calls to `free()`, which as we have discussed in the Stack section, we consider $O(1)$ for the purposes of this discussion. Thus, the complexity for `destroy()` is $O(1)$.
- `clear()` - this function simply sets `count`, `in`, and `out` to 0. This is independent of the number of elements currently in the queue, thus the complexity for `clear()` is $O(1)$.
- `size()` - this function simply returns the value of `count`. This is independent of the number of elements currently in the queue, thus the complexity for `size()` is $O(1)$.
- `isEmpty()` - this function simply returns the value of `count == 0L`. This is independent of the number of elements currently in the queue, thus the complexity for `size()` is $O(1)$.

From this discussion, we can see that for a bounded Queue of long integers, the constructor and *all* of the methods are $O(1)$. Thus, if your problem needs a bounded container exhibiting *first in, first out* functionality, you cannot do better than a queue that is implemented using an array.

7.1.4 Changes needed to make the queue unbounded

7.1.4.1 The interface

No change is required to the signatures for the constructor or the methods, although the semantics for the value of `capacity` in the constructor is slightly different. If `capacity == 0L`, this tells the implementation to use a default queue size for the initial array. This default capacity should be `#define`'d in the header file, as in

```
#define DEFAULT_CAPACITY 50
```

7.1.4.2 The instance-specific data structure

The array of long integers will need to be made larger if `enqueue()` is invoked when the current queue is already full. The implementation can choose to simply double the size of the array whenever this occurs - this leads to exponential growth of the array. Alternatively, the implementation can choose to grow the array by a constant increment each time, leading to linear growth of the array. If linear growth is chosen, the increment can be a defined constant for all queues, or it can be a queue-specific value, usually dependent upon the initial capacity specified in the constructor.

If a queue-specific linear growth increment is to be used, then an additional member must be added to `QlData`, typically called `increment`. The data structure will look as follows:

```
typedef struct ql_data {
    long count;
    long size;
    long increment;
    long in;
    long out;
    long *buffer;
} QlData;
```

The changes below assume a doubling of the array whenever it needs to grow; thus, there is no need for the `increment` field in `QlData`.

7.1.4.3 `destroy()`, `clear()`, `dequeue()`, `front()`, `size()`, and `isEmpty()`

No change required, since none of these methods can cause the array of longs to have to grow.

7.1.4.4 The constructor

After successful allocation of the instance-specific struct, we need to determine the initial capacity of the queue. The following code replaces the lines from "`if(qld != NULL) {`" up to the first line consisting of "`} else {`".

```
if (qld != NULL) {
    long cap;
    long *tmp = NULL;

    cap = (capacity <= 0L) ? DEFAULT_CAPACITY : capacity;
    tmp = (long *)malloc(cap * sizeof(long));
    if (tmp != NULL) {
        qld->count = 0;
        qld->size = cap;
        qld->in = 0;
        qld->out = 0;
        qld->buffer = tmp;
        *ql = template;
        ql->self = qld;
    } else {
```

7.1.4.5 `enqueue()`

The implementation for `enqueue()` in section 7.1.2.4 does nothing if `count >= size`. The following code will grow the array when it is full, and should simply be inserted above the "`if (status)`" line in the previous implementation.

```
if (! status) {          /* need to reallocate */
    size_t nbytes = 2 * qld->size * sizeof(long);
    long *tmp = (long *)malloc(nbytes);

    if (tmp != NULL) {
        long n = qld->count, i, j;
        status = true;
        for (i = qld->out, j = 0; n > 0; i = (i + 1) % qld->size, j++) {
            tmp[j] = qld->buffer[i];
```

```
            n--;
        }
        free(qld->buffer);
        qld->buffer = tmp;
        qld->size *= 2;
        qld->out = 0L;
        qld->in = qld->count;
    }
}
```

Note that on the occasion when an `enqueue()` invocation causes the queue to be expanded, the running time complexity of that call will be $O(n)$ - why is this so? Since we are using the array as a circular buffer, we may have wrapped around to the beginning of the array; when we grow the array, we need to move the queue of items to the beginning of the larger array in order to continue to use it in this circular fashion.

This is an example where the running time complexity of a method is different for the average case ($O(1)$ for `enqueue()` when not growing the array) and for the worst case ($O(n)$ when we have to grow the array). As long as we do not have to grow the array very often, `enqueue()` can be considered as $O(1)$. After we have introduced linked lists in Chapter 8, you will have an opportunity to implement Stacks and Queues using a linked list, for which the worst case running time complexity for `enqueue()` is $O(1)$, as well.[1]

7.2 A generic queue

The following show the header and implementation files for an unbounded queue in which `void *` elements are queued. We have also included the `create()`, `toArray()`, and `itCreate()` methods, along with a `freeValue()` argument for the constructor.

The appropriate order of elements that should be produced by a sequence of calls to the iterator returned by `itCreate()` should be from the head of the queue to the tail. The implementation of `itCreate()` populates the list of pointers to reflect this natural order.

7.2.1 Implementation-independent generic `Queue` interface

```
#ifndef _QUEUE_H_
#define _QUEUE_H_

/* BSD Header removed to conserve space */

/*
```

[1] As described for unbounded stacks, an unbounded queue will exhibit $O(1)$ amortized complexity if we choose to double the size of the array every time we grow it.

```
 * interface definition for generic FIFO queue
 *
 * patterned roughly after Java 6 Queue interface
 */

#include "ADTs/ADTdefs.h"
#include "ADTs/iterator.h"              /* needed for factory method */

typedef struct queue Queue;        /* forward reference */

/*
 * this function signature is provided as the default constructor for
 * any Queue implementation
 *
 * freeValue is a function pointer that will be called by
 * destroy() and clear() on each entry in the Stack
 *
 * returns a pointer to the stack instance, or NULL if errors
 */
const Queue *Queue_create(void (*freeValue)(void *e));

/*
 * dispatch table for a generic Queue
 */
struct queue {
/*
 * the private data of the queue
 */
    void *self;

/*
 * create a new queue using the same implementation as the queue upon which
 * the method has been invoked; returns NULL if error creating the queue
 */
    const Queue *(*create)(const Queue *q);

/*
 * destroys the queue;
 * applies constructor-specified freeValue to each element in the queue
 * the storage associated with the queue is then returned to the heap
 */
    void (*destroy)(const Queue *q);

/*
 * clears all elements from the queue;
 * applies constructor-specified freeValue to each element in the queue
 * the queue is then re-initialized
 *
 * upon return, the queue is empty
 */
    void (*clear)(const Queue *q);
```

```
/*
 * appends `element' to the end of the queue
 *
 * returns true if successful, false if unsuccesful (malloc failure)
 */
    bool (*enqueue)(const Queue *q, void *element);

/*
 * retrieves, but does not remove, the head of the queue, returning that
 * element in `*element'
 *
 * returns true if successful, false if unsuccessful (queue is empty)
 */
    bool (*front)(const Queue *q, void **element);

/*
 * Retrieves, and removes, the head of the queue, returning that
 * element in `*element'
 *
 * return true if successful, false if not (queue is empty)
 */
    bool (*dequeue)(const Queue *q, void **element);

/*
 * returns the number of elements in the queue
 */
    long (*size)(const Queue *q);

/*
 * returns true if the queue is empty, false if not
 */
    bool (*isEmpty)(const Queue *q);

/*
 * returns an array containing all of the elements of the queue in
 * proper sequence (from first to last element); returns the length of the
 * queue in `*len'
 *
 * returns pointer to array of void * elements, or NULL if malloc failure
 *
 * NB - it is the caller's responsibility to free the void * array when
 *      finished with it
 */
    void **(*toArray)(const Queue *q, long *len);

/*
 * creates an iterator for running through the queue
 *
 * returns pointer to the Iterator or NULL
 */
```

```
    const Iterator *(*itCreate)(const Queue *q);
};

#endif /* _QUEUE_H_ */
```

7.2.2 Implementation for a generic array-based queue

As with a Stack, a Queue can be implemented using an array (as we did for QueueLong), or using a linked list. In order to enable a programmer to select the desired implementation, we need to provide an implementation-dependent constructor, defined in an implementation-dependent interface file. The implementation-dependent interface file and the array-based implementation follow.

Array-based queue include file

```
#ifndef _ARRAYQUEUE_H_
#define _ARRAYQUEUE_H_

/* BSD Header removed to conserve space */

/*
 * constructor for array-based queue
 */

#include "ADTs/ADTdefs.h"
#include "ADTs/queue.h"

#define DEFAULT_QUEUE_CAPACITY 50L

/*
 * create a queue; if capacity is 0L, give it a default capacity (50L)
 *
 * freeValue is a function pointer that will be called by
 * destroy() and clear() on each entry in the Queue
 *
 * returns a pointer to the queue, or NULL if there are malloc() errors
 */
const Queue *ArrayQueue(long capacity, void (*freeValue)(void *e));

#endif /* _ARRAYQUEUE_H_ */
```

Array-based queue implementation The array-based queue implementation is shown in section B.4.

Exercise 7.1. Exercise the generic `Queue` implementation

Write a C program that takes a single command-line argument, which is a filename. The input file contains instructions for queue operations. The first line of the input file is an integer $0 \leq N \leq 10^4$ giving the number of instructions that will follow. Each of the following N lines contains an instruction. The possible instructions are:

- `enqueue X`, where $-10^5 \leq X \leq 10^5$ is an integer. For this instruction, put X on the queue. There is no output.
- `dequeue`: remove the front element of the queue. Print the removed element. If the queue was empty, output *QueueError*.
- `print`: print the contents of the queue, with each pair of elements separated by a single space, starting with the front (the element that would be removed by a dequeue). If the queue is empty, output *Empty*. The queue must be in the same state after it has been printed as it was before it was printed.

The print action is not a method in the ADT, but a function that uses the ADT methods to access the elements of the queue. Instead, you should write a `print_queue` function that takes a queue as an argument and accomplishes the print action using only the methods on the `Queue` ADT. You may *not* use the `toArray()` or `itCreate()` methods in your `print_queue` implementation. You can, of course, use other aspects of C in the implementation of the print function.

All output should be to standard output. Each piece of output should be separated by a newline.

Example input and output are shown in the following table.

Input	Output
`7`	*no output*
`print`	`Empty`
`enqueue 1`	*no output*
`enqueue 2`	*no output*
`print`	`1 2`
`dequeue`	`1`
`dequeue`	`2`
`dequeue`	`QueueError`

Exercise 7.2. Reversing a queue

Given a generic `Queue q`, write a function to reverse `q` *in place* - i.e., when the function returns, `q` will have the elements in reverse order. The signature for your function is

```
void reverse(const Queue *q);
```

Your function may use a `Stack` in order to perform its work.

For example, if the elements in Q are $1, 2, 3, 4, 5$, after calling your function, they should be in the order $5, 4, 3, 2, 1$.

Write a C program that uses your `reverse()` function. The program takes a single command argument, which is an input filename. The format of the input file is as follows:

- A line consisting of a positive integer $0 \leq N \leq 10^5$; N is the number of pairs of lines that follow.
- N pairs of lines; the first line of each pair is the number of elements M, in the queue; the second line contains M space-separated integers; each integer i satisfies $-10^9 \leq i \leq 10^9$.

You are to `enqueue()` each integer into a queue, invoke `reverse()` on that queue, and then print out the elements of the reversed queue, with a single space separating each pair of queue elements, and a newline terminating the line.

For example, the input file consisting of the lines

```
1
5
1 2 3 4 5
```

should yield the following single line of output.

```
5 4 3 2 1
```

Exercise 7.3. Motorcycle tour

There is a closed loop connecting gas stations, each with a single pump. You wish to tour all of the gas stations in the loop.

The stations are numbered 0 through $N - 1$, and since the stations form a loop, you can only travel from station i to station $i + 1(modN)$. Since it takes some amount of gasoline to get from one station to another, it is possible that you could run out of gasoline before completing the cycle.

Two pieces of information are associated with each station:

- the amount of gasoline that particular pump will dispense (in liters); and
- the distance from that station to the next station, in miles.

Initially you have a tank of infinite capacity with *no* gasoline. You can start the tour at any of the stations. Since the motorcycle has an infinite capacity tank, it consumes 1 liter of gasoline for each 10 miles covered. You need to determine the number of the first station at which you can start traveling and complete the loop.

The first line of the input file will be an integer $0 \leq N \leq 10^5$ giving the number of stations. Following will be N lines, each containing two integers $1 \leq L, D \leq 10^9$ separated by a space; the integer L is the number of liters that you will receive at that station, and D is the number of miles to the next station. The output is the lowest numbered station at which you can start your journey and complete the cycle through the loop.

Your solution should have linear time complexity in the number of stations - i.e., $O(N)$. Hint: use a queue to organize the stations into a cycle.

Example input file:

```
4
4 20
1 110
10 30
18 60
```

Example output:

```
2
```

Chapter 8

Linked lists

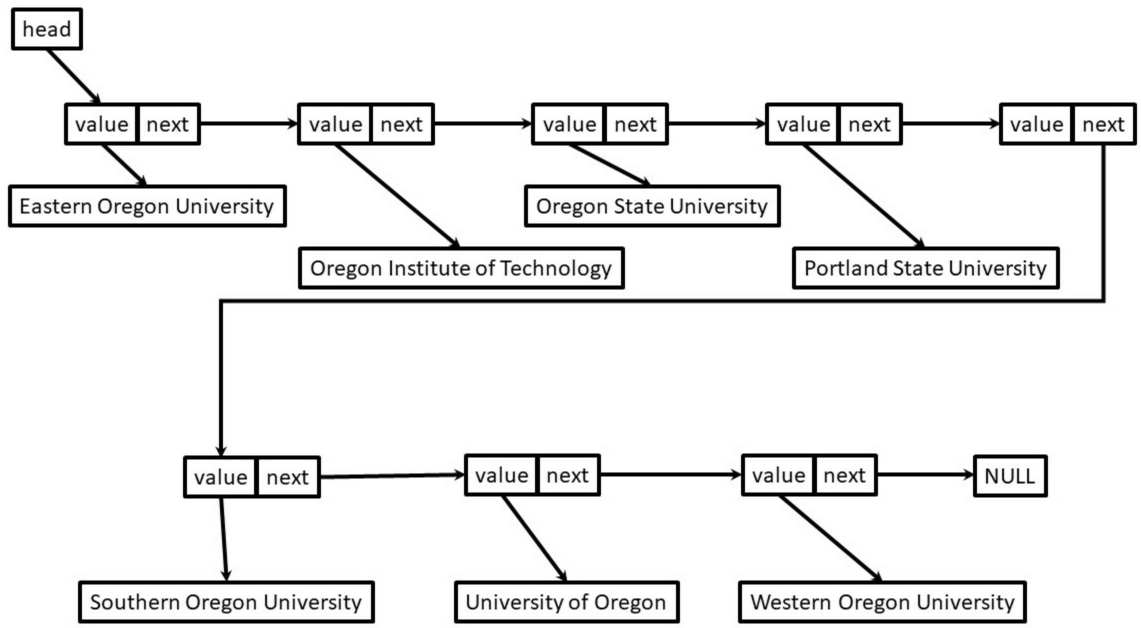
A *linked list* is a linear collection of data elements, in which the linear order is *not* given by their physical placement in memory; instead, each *node* in the list points at the next element in the list. Such a structure enables insertion or removal of elements *without* reallocation or reorganization of the entire structure, since the data items do not need to be stored contiguously in memory.

It is important to note that while a linked list is an implementation of a sequence, it does *not* enable random access to the data, unlike an array.

8.1 General structure

Each node in a linked list consists of a pointer to the next node in the list (or `NULL` if the current node is the last one in the list) and the value that the node contains. The value might be a a basic numeric value, such as 42, or more often, is a pointer to the value (for example, a pointer to a character string or a structure). We also require a pointer to the first element in the list, commonly called the *listhead*.

For example, suppose we wanted to have a linked list of the seven public universities in Oregon. A picture of this list is shown below.



This is an example of a *singly linked* list, since there are only links in the forward direction along the list. We will discuss doubly-linked lists in Chapter 9.

For this linked list, each *node* in the list is a struct with the following members:

```
struct node {
    struct node *next;
    char *value;
};
```

and the variable **head** has the following declaration:

```
struct node *head;
```

The strings for the universities have been allocated on the heap.

What are some things that we can do with such a list? Suppose that we want to print out the names of the universities, one per line. The following code would do the trick:

```
struct node *p;

for (p = head; p != NULL; p = p->next)
    printf("%s\n", p->value);
```

Now suppose that we wish to search the linked list to see if a particular university is contained in the list. Writing a function to search such a list is straightforward:

```
int search(char *university, struct node *theList) {
    struct node *p;

    for (p = theList; p != NULL; p = p->next)
        if (strcmp(p->value, university) == 0)
            return 1;
    return 0;
}
```

Now let's search the list for "Medford College".

```
if (! search("Medford College", head))
    fprintf(stderr, "Medford College not found in list of Universities\n");
```

8.2 Additions/deletions to singly linked lists

Insertion or deletion at the head of a linked list can be done in $O(1)$ running time complexity. Suppose that we wish to add `"Oregon Health Science University"` to the front of the list. First we would have to create a new node using `malloc()`. Then we would have to make a copy of the string on the heap, using `strdup()`. Then we have the new node point to the current node at the head of the list, and then have the `head` variable point at this new node.

```
struct node *new = (struct node *)malloc(sizeof(struct node));
new->value = strdup("Oregon Health Science University");
new->next = head;
head = new;
```

We can see that the amount of work that we have to do is independent of the number of nodes currently in the list, thus $O(1)$. Prove to yourself that this works correctly even if `head == NULL`.

Deletion of the node at the head of the list is similarly straightforward:

```
struct node *p = head;  /* p points to head node */
if (p != NULL) {        /* check that list was not empty */
    head = p->next;     /* head now points to 2nd node */
    free(p->value);     /* free the string */
    free(p);            /* free the node */
}
```

Here we have to explicitly check that the list was not empty; otherwise, we would have attempted to dereference a `NULL` pointer, which would cause our process to terminate with a segmentation violation.

How about additions at the end of the list? Absent any other metadata about the list, our only choice would be to write a loop to "chase pointers" until we found the last node, and then append a new node to form the new tail of the list. The code would be similar to the following:

```
struct node *new = (struct node *)malloc(sizeof(struct node));
new->value = strdup("Oregon Health Science University");
new->next = NULL;
struct node *p = head;

if (p != NULL) {
    while (p->next != NULL)
        p = p->next;
}
if (p != NULL)
    p->next = new;
else
    head = new;
```

This is significantly more complex than addition at the head. We still have to allocate a new node and the string for its value; note that we initialize the `next` field to `NULL`, since that is the required value in that field for the node at the tail of the list. We then have to find the current tail node, which is the next 4 lines of code; note that we have to conditionalize entering the while loop on the list being non-empty. Finally, we have to take different actions depending upon the loop being empty before the addition or not.

The while loop to find the tail node has to touch all of the nodes in the list, thus has an $O(n)$ running time complexity. We can reduce this complexity for additions at the tail by keeping one additional pointer for the list, a pointer to the tail node. Suppose we have a non-empty list, and that `head` points at the head node, and that `tail` points at the tail node. The logic required to add a new node at the tail becomes

```
struct node *new = (struct node *)malloc(sizeof(struct node));
new->value = strdup("Oregon Health Science University");
new->next = NULL;
tail->next = new;  /* previous tail node now points to new tail */
tail = new;        /* tail points to new tail */
```

From our experience to date, since this code does not depend at all on the number of nodes in the list, we can conclude that the running time complexity is $O(1)$.

The previous code assumed that the list was non-empty. If the list was empty, both `head` and `tail` would be `NULL`, and our code for additions at the tail becomes a little more complex to handle the empty list case.

```
struct node *new = (struct node *)malloc(sizeof(struct node));
new->value = strdup("Oregon Health Science University");
new->next = NULL;
if (head == NULL)  /* empty list */
    head = new;
else
    tail->next = new;
tail = new;        /* tail points to new tail */
```

Deletions of nodes anywhere in the list but at the head are $O(n)$ complexity. This is because we need to have a pointer to the node that precedes the node to be deleted. Since the list is singly linked, this means that we must chase pointers through the list, remembering the previous node as well as the current node.

Exercise 8.1. Implement a generic stack using a singly-linked list.
Your implementation, in a file named `lliststack.c`, must conform to the interface defined in `/usr/local/include/ADTs/lliststack.h`.
After you have successfully compiled your linked-list stack implementation, link it to the test program that you wrote for Exercise 6.1 and test it thoroughly.

Exercise 8.2. Implement a generic queue using a singly-linked list.
Your implementation, in a file named `llistqueue.c`, must conform to the interface defined in `/usr/local/include/ADTs/llistqueue.h`.
After you have successfully compiled your linked-list stack implementation, link it to the test program that you wrote for Exercise 7.1 and test it thoroughly.

Chapter 9

Deques - double-ended queues

The singly-linked list implementation of unbounded queues gives us $O(1)$ running time complexity for insertions at the head and tail, and removals at the head; if we wish to remove at the tail, the complexity is $O(n)$. This chapter is concerned with double-ended queues, or *deques* (pronounced "decks"). Deques support $O(1)$ complexity insertion and deletion at both the head and tail of the queue.

9.1 The interface for the Deque ADT

A deque supports insertion and removal from the head and tail of the queue. The interface of a Deque is shown below.

```
#ifndef _DEQUE_H_
#define _DEQUE_H_

/* BSD Header removed to conserve space */

#include "ADTs/ADTdefs.h"
#include "ADTs/iterator.h"                  /* needed for factory method */

typedef struct deque Deque;                 /* forward reference */

/* interface definition for generic deque implementation */

/*
 * this function signature is provided as the default constructor for any
 * Deque implementation
 *
 * freeValue is a function pointer that will be called by
 * destroy() and clear() on each entry in the Deque
 *
```

```
 * returns a pointer to the deque instance, or NULL if errors
 */
const Deque *Deque_create(void (*freeValue)(void *e));

typedef struct deque Deque;             /* forward reference */

/* now define struct deque */
struct deque {
/* the private data for the deque */
    void *self;

/* create a new deque using the same implementation as the deque upon which
 * the method has been invoked; returns NULL if error creating the new deque
 */
    const Deque *(*create)(const Deque *d);

/* destroys the deque;
 * applies constructor-specified freeValue to each element in the deque
 * the storage associated with the deque is then returned to the heap
 */
    void (*destroy)(const Deque *d);

/* clears all elements from the deque;
 * applies constructor-specified freeValue to each element in the deque
 * the deque is then re-initialized
 *
 * upon return, the deque is empty
 */
    void (*clear)(const Deque *d);

/* inserts element at the head of the deque
 *
 * returns true if successful, false if unsuccessful (malloc errors) */
    bool (*insertFirst)(const Deque *d, void *element);

/* inserts element at the tail of the deque
 *
 * returns true if successful, false if unsuccessful (malloc errors) */
    bool (*insertLast)(const Deque *d, void *element);

/* returns the element at the head of the deque in *element; does not remove it
 *
 * returns true if successful, false if the deque is empty */
    bool (*first)(const Deque *d, void **element);

/* returns the element at the tail of the deque in *element; does not remove it
 *
 * returns true if successful, false if the deque is empty */
    bool (*last)(const Deque *d, void **element);

/* removes the element at the head of the deque, returning it in *element
```

```
 *
 * returns true if successful, true if the deque is empty */
    bool (*removeFirst)(const Deque *d, void **element);

/* removes the element at the tail of the deque, returning it in *element
 *
 * returns true if successful, false if the deque is empty */
    bool (*removeLast)(const Deque *d, void **element);

/* returns the number of elements in the deque */
    long (*size)(const Deque *d);

/* returns true if the deque is empty, false if it is not */
    bool (*isEmpty)(const Deque *d);

/* returns an array containing all of the elements of the deque in
 * proper sequence (from head to tail); returns the length of the array
 * in *len
 *
 * returns a pointer to the array of void * elements, or NULL if malloc failure
 *
 * NB - the caller is responsible for freeing the void * array when finished
 * with it */
    void **(*toArray)(const Deque *d, long *len);

/* create generic iterator to this deque
 *
 * returns pointer to the Iterator or NULL if malloc failure */
    const Iterator *(*itCreate)(const Deque *d);
};

#endif /* _DEQUE_H_ */
```

The semantics of the constructor and the methods are as follows:

- `const Deque *Deque_create(void (*freeValue)(void *e));`
  create a new instance of a deque; provide a function pointer to `freeValue()` to be used by `destroy()` and `clear()`; returns a pointer to the dispatch table, or `NULL` if there were heap-allocation errors;
- `const Deque *(*create)(const Deque *d);`
  create a new deque using the same implementation as `d`; uses `d`'s `freeValue()` for the new deque; returns NULL if error creating the new deque;
- `void (*destroy)(const Deque *d);`
  destroy the deque; apply constructor-supplied `freeValue()` to each element; then all heap-allocated memory associated with the deque is freed;
- `void (*clear)(const Deque *d);`
  purge all elements from the deque; apply constructor-supplied `freeValue()` to each element; upon return, the deque is empty;
- `bool (*insertFirst)(const Deque *d, void *element);`
  insert `element` at the head of the deque; if successful, returns true/1; if not

(heap-allocation failure), returns false/0;

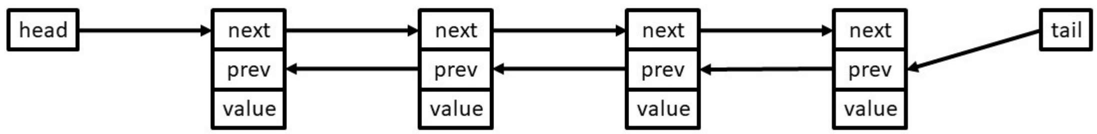
- `bool (*insertLast)(const Deque *d, void *element);`
  insert `element` at the tail of the deque; if successful, returns true/1; if not (heap-allocation failure), returns false/0;
- `bool (*first)(const Deque *d, void **element);`
  return the element at the head of the deque in `*element` *without* removing it from the deque; if the deque has no elements, the function return is false/0; otherwise, it is true/1;
- `bool (*last)(const Deque *d, void **element);`
  return the element at the tail of the deque in `*element` *without* removing it from the deque; if the deque has no elements, the function return is false/0; otherwise, it is true/1;
- `bool (*removeFirst)(const Deque *d, void **element);`
  remove the element at the head of the deque, returning it in `*element`; if the deque has no elements, the function return is false/0; otherwise, it is true/1;
- `bool (*removeLast)(const Deque *d, void **element);`
  remove the element at the tail of the deque, returning it in `*element`; if the deque has no elements, the function return is false/0; otherwise, it is true/1;
- `long (*size)(const Deque *d);`
  return the number of elements in the deque;
- `bool (*isEmpty)(const Deque *d);`
  return true/1 if the deque is empty, false/0 otherwise;
- `void **(*toArray)(const Deque *d, long *len);`
  returns an array containing all of the elements of the deque in proper sequence (from first to last element); returns the length of the array in `*len`; function return is pointer to the array of elements, or NULL if heap-allocation failure; the programmer must `free()` the array when it is no longer needed; and
- `const Iterator *(*itCreate)(const Deque *d);`
  creates an iterator for running through the elements in the deque; returns a pointer to the Iterator or NULL if there were heap-allocation problems.

9.2 The implementation for a generic Deque

We have already seen that when using a singly-linked list to implement a Queue that we need conditional code to handle the case when a removal leaves the Queue empty. Also, if you think about it, it will be difficult to provide an $O(1)$ method for removing the last element in the Queue; this is because we need to know the element just before the last element in order to leave the Queue in a known state.

We could implement the Deque using an array, and this is one of the programming exercises at the end of the chapter. Here, we will discuss the most common way to implement a Deque, using a doubly linked list with a *sentinel*.

9.2.1 What is a doubly linked list?



This figure shows how a doubly-linked list is structured. We still require a pointer to the head of the list, and another pointer to the tail of the list. Each node in the list has two pointers, `next` points to the next node in the list, and `prev` points to the previous node in the list. The last node in the list will have `next == NULL`, and the first node in the list will have `prev == NULL`. In essence, we have two singly linked lists combined into the doubly linked list.

Recall that we already had $O(1)$ removal of the node at the head of a Queue, and with the `tail` pointer, we had $O(1)$ insertion at the tail of a Queue. We already knew from our Queue implementation that we had $O(1)$ insertion at the head of the list. Thus, we need to show that a doubly-linked list exhibits $O(1)$ removal of the node at the tail of a Deque.

The following code fragment shows how we would remove the tail node

```
LLNode *p, *tail;

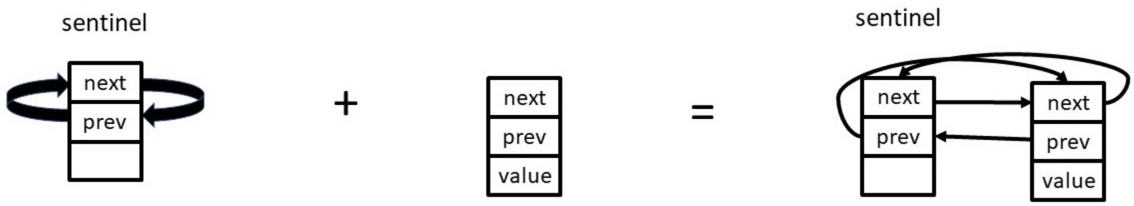
p = tail;                /* p now points to the tail node */
p->prev->next = p->next; /* p's predecessor now points to NULL */
tail = p->prev;          /* tail now points to p's predecessor */
```

None of these actions have anything to do with the number of nodes in the list, therefore this code fragment has $O(1)$ running time complexity.

This code fragment assumed that this was **NOT** a singleton doubly-linked list; this is implicit in assigning a value to `p->prev->next`; if there was only one node in the list, then `p->prev` would be NULL, and attempting to dereference it would lead to a segmentation violation, causing your program to abort. In general, the code to handle removing the last node in the doubly-linked list, or inserting into a singleton doubly-linked list, can be quite complex.

An elegant way to finesse this situation is to create a *sentinel* node. An *empty* doubly-linked list has a single node, the *sentinel*; the `next` field in the sentinel points at itself, the `prev` field points at itself, and its `value` field is not used. Why would this eliminate all of the conditional code?

Consider that we have an empty doubly-linked list and wish to add a node to it. The following figure shows graphically what will happen.



It may be a little easier to understand how we go from left hand side to the right hand side with some code:

```
typedef struct node {
    struct node *next;
    struct node *prev;
    void *value;
} Node;

Node sentinel = {&sentinel, &sentinel, NULL};
Node *p;     /* assume that p points to the node to be added */

p->next = &sentinel;
p->prev = &sentinel;
sentinel.prev = p;
sentinel.next = p;
```

This is just a special case of the following: on insertions, if we have pointers to the two adjacent nodes between which the insertion should occur, then the insertion action takes place as:

```
void link(Node *before, Node *p, Node *after) {
    p->next = after;
    p->prev = before;
    after->prev = p;
    before->next = p;
}
```

To insert at the head,

```
link(&sentinel, p, sentinel.next);
```

while to insert at the tail

```
link(sentinel.prev, p, &sentinel);
```

Removals are equally as straightforward. In general, given a pointer to a node in the doubly-linked list, we can remove it from the list as follows:

```
void unlink(Node *p) {
    p->prev->next = p->next;
    p->next->prev = p->prev;
}
```

To remove the tail node,

```
unlink(sentinel.prev);
```

while to remove the head node,

```
unlink(sentinel.next);
```

9.2.2 The linked list Deque include file

Since a `Deque` can be implemented using a linked list or an array, we also need to provide a constructor that enables the user to explicitly create a `Deque` implemented using a linked list. The following header file is provided in `/usr/local/include/ADTs/llistdeque.h` for that purpose.

```
#ifndef _LLISTDEQUE_H_
#define _LLISTDEQUE_H_

/* BSD Header removed to conserve space */

#include "ADTs/ADTdefs.h"
#include "ADTs/deque.h"

/* constructor for a linked list implementation of a generic deque
 *
 * freeValue is a function pointer that will be called by
 * destroy() and clear() on each entry in the Deque
 *
 * returns a pointer to the deque, or NULL if there are malloc() errors
 */
const Deque *LListDeque(void (*freeValue)(void *e));

#endif /* _LLISTDEQUE_H_ */
```

9.2.3 The Deque implementation using a doubly-linked list with a sentinel

The implementation file for a Deque using a doubly-linked list with a sentinel is shown in section B.5.

Exercise 9.1. Palindrome checker
An interesting problem that can be easily solved using the deque data structure is the classic palindrome problem. A palindrome is a string that reads the same forward and backward; examples include *radar*, *madam*, and *able was I ere I saw elba*. For this problem, you are to write a program that detects palindromes using the generic deque ADT implementation.
Your program takes a single argument, which is the name of a file. The first line of the file consists of a single integer $0 \leq N \leq 10^5$. Each of the following N lines is a string; for each such string (which does not include the trailing `'\n'`), you are to print `YES` if the string *is* a palindrome, and print `NO` if the string is not a palindrome.

Input	Output
3	
radar	YES
murder	NO
able was I ere I saw elba	YES

Exercise 9.2. Implement a deque using an array
Implement an array-based Deque, in a file named `arraydeque.c`, that satisfies the interface defined in `/usr/local/include/ADTs/arraydeque.h`.
Link your solution to the palindrome exercise above to this array-based dequeue implementation. Test it against the test data provided in that exercise.

Run performance tests of your linked-list implementation and your array-based implementation (see Section 5.1.1). Do you see any difference in performance? If so, what could be the cause?

Chapter 10

Priority queues

A *priority queue* is an abstract data type for storing a collection of prioritized elements that supports arbitrary element insertion, but only supports removal of elements in order of priority. The priority associated with an element is usually a numerical value, **with the smallest numerical value connoting highest priority**. We will first show different implementations when the priority is an unsigned long; at the end, we will generalize to arbitrary priorities that support a comparator function.

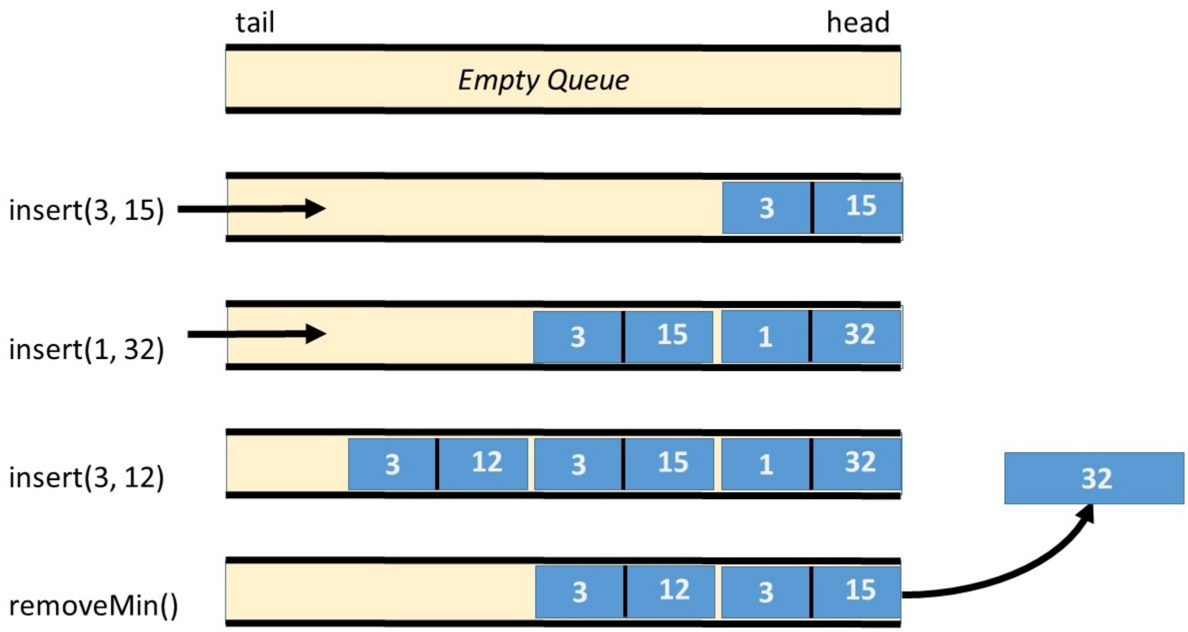
10.1 Priorities and total order relations

A priority queue needs a comparator rule (denoted by $\leq$ below) between priorities (denoted by p_i below) that defines a *total order* relation; this means that it is defined for every pair of priorities, and it must satisfy three properties:

- **reflexive**: $p \leq p$;
- **antisymmetric**: $if\ p_1 \leq p_2\ and\ p_2 \leq p_1, then\ p_1 = p_2$;
- **transitive**: $if\ p_1 \leq p_2\ and\ p_2 \leq p_3,\ then\ p_1 \leq p_3$.

Such a rule defines a linear ordering relationship among a set of priorities; from this we can deduce that if a collection of elements has a total order defined for it, then there is a well-defined notion of a *smallest* priority value (representing the highest priority), $p_{min} \leq p$, for any priority p in the collection. It should be apparent that the normal numeric semantics of $\leq$ provide a total order over integers.

A priority queue is a container of elements, each having an associated priority that is provided at the time that the element is inserted. We will first focus on numeric priorities; later in the chapter, we will generalize to other priority data types.



10.2 The interface for an integer priority queue ADT

```
#ifndef _PRIOQUEUELONG_H_
#define _PRIOQUEUELONG_H_

#include "ADTs/ADTdefs.h"

typedef struct prioqueuelong PrioQueueLong;        /* forward reference */
const PrioQueueLong *PrioQueueLong_create(void (*freeValue)(void *e));
struct prioqueuelong {
    void *self;
    void (*destroy)(const PrioQueueLong *pq);
    void (*clear)(const PrioQueueLong *pq);
    bool (*insert)(const PrioQueueLong *pq, long priority, void *element);
    bool (*min)(const PrioQueueLong *pq, void **element);
    bool (*removeMin)(const PrioQueueLong *pq, void **element);
    long (*size)(const PrioQueueLong *pq);
    bool (*isEmpty)(const PrioQueueLong *pq);
};

#endif /* _PRIOQUEUELONG_H_ */
```

The semantics of the constructor and the methods are as follows:

- `const PrioQueueLong *PrioQueueLong_create(void (*freeValue)(void *e));` create a new instance of a priority queue using longs as a priority; returns a pointer to the dispatch table, or `NULL` if there were heap-allocation errors; `freeValue` is invoked on each element in the priority queue when the `destroy()` and `clear()` methods are invoked;

- `void (*destroy)(const PrioQueueLong *pq);`
  destroy the priority queue; all heap-allocated memory associated with the priority queue is freed;
- `void (*clear)(const PrioQueueLong *pq);`
  purge all elements from the priority queue; upon return, the priority queue is empty;
- `bool (*insert)(const PrioQueueLong *pq, long priority, void *element);`
  insert `element` in the priority queue at the location appropriate to `priority`; if other elements at that priority are already in the queue, this element should be placed after the last such element (FIFO within a priority); returns false/0 if there are heap-allocation problems, true/1 otherwise;
- `bool (*min)(const PrioQueueLong *pq, void **element);`
  returns the `element` with the smallest `priority` in `*element`; function return is true/1 if successful, false/0 if priority queue is empty;
- `bool (*removeMin)(const PrioQueueLong *pq, void **element);`
  returns the `element` with the smallest `priority` in `*element` and removes that element from the priority queue; function return is true/1 if successful, false/0 if priority queue is empty;
- `long (*size)(const PrioQueueLong *pq);`
  returns the number of elements in the priority queue;
- `bool (*isEmpty)(const PrioQueueLong *pq);`
  returns true/1 if the priority queue is empty, false/0 otherwise.

10.3 Implementations for an integer priority queue ADT

There are several possible implementation strategies for a priority queue:

1. implement as an unordered linked list - we always insert a new element at the head of the linked list, but in order to implement `min()` and `removeMin()` we have to scan the entire list to find the smallest priority value; this means that insertions are $O(1)$, but removal is $O(n)$; not a particularly elegant solution, and the worst running time complexity is during removal; we will *not* show the implementation for this approach;
2. implement as an ordered linked list - we always insert a new element at the appropriate place in the list such that the comparator rule holds between adjacent items in the list; if there are already elements in the list with the specified priority, the new element is inserted after those elements (FIFO within a particular priority); removal is always to return the element at the head of the list; thus, insertion is $O(n)$ and removal is $O(1)$; this is a slightly more elegant solution, with worst running time complexity for insertions; we will show this implementation below;
3. if there are a bounded number of priorities, we can implement the priority queue as a set of FIFO queues, one for each priority; insertions are now $O(1)$, and removals are $O(P)$ where P is the number of priorities; for example, the Linux process scheduler supports 140 different process priorities [0..139]; since the number of

priorities never changes, this means that removals are also $O(1)$; this implementation is left as an exercise at the end of the chapter.

4. if there is no bound for the number of priorities, but you would like both insertions and removals to have better running time complexity than $O(n)$, we can use a heap to implement the priority queue; for this implementation, the running time complexity for insertions and removals will be $O(\log n)$; we will introduce heaps in Chapter 13, and provide a full implementation of a generic priority queue using a heap there.

10.3.1 Implementation as an ordered linked list

10.3.1.1 The preliminaries

We've seen all this before: a standard set of includes, macro to obtain address of sentinel node, typedef for linked list node, and definition of the instance-specific data structure.

```
/*
 * implementation for generic priority queue, where priorities are longs
 * implemented as an ordered, doubly-linked list with a sentinel
 */

#include "prioqueuelong.h"
#include <stdlib.h>

#define SENTINEL(p) (&(p)->sentinel)

typedef struct llnode {
    struct llnode *next;
    struct llnode *prev;
    long priority;
    void *element;
} LLNode;

typedef struct pq_data {
    long size;
    LLNode sentinel;
    void (*freeValue)(void *e);
} PqData;
```

10.3.1.2 `destroy()` and `clear()`

Two helper functions, one to apply the constructor-supplied `freeValue()` to each element, the other to free the nodes from the list.

```
/*
 * traverses linked list, calling freeValue on each element
 */
static void purge(PqData *pqd) {
    LLNode *p;

    for (p = pqd->sentinel.next; p != SENTINEL(pqd); p = p->next)
        pqd->freeValue(p->element);
}

/*
 * frees the nodes from the doubly-linked list
 */
static void freeList(PqData *pqd) {
    LLNode *p = pqd->sentinel.next;

    while (p != SENTINEL(pqd)) {
        LLNode *q = p->next;
        free(p);
        p = q;
    }
}

static void pq_destroy(const PrioQueueLong *pq) {
    PqData *pqd = (PqData *)pq->self;
    purge(pqd);
    freeList(pqd);
    free(pqd);
    free((void *)pq);
}

static void pq_clear(const PrioQueueLong *pq) {
    PqData *pqd = (PqData *)pq->self;
    purge(pqd);
    freeList(pqd);
    pqd->size = 0L;
    pqd->sentinel.next = SENTINEL(pqd);
    pqd->sentinel.prev = SENTINEL(pqd);
}
```

10.3.1.3 `insert()`

A helper function to link a new node into the doubly-linked list is defined. The method needs to traverse the entire list each time looking for the correct pair of nodes between which the new node must be inserted.

```
/*
 * link `p` between `before' and `after'
 * must work correctly if `before' and `after' are the same node
 * (i.e. the sentinel)
 */
static void link(LLNode *before, LLNode *p, LLNode *after) {
    p->next = after;
    p->prev = before;
    after->prev = p;
    before->next = p;
}

static bool pq_insert(const PrioQueueLong *pq, long priority, void *element) {
    PqData *pqd = (PqData *)pq->self;
    LLNode *p = (LLNode *)malloc(sizeof(LLNode));
    bool status = (p != NULL);

    if (status) {
        LLNode *q = pqd->sentinel.next;
        while (q != SENTINEL(pqd) && q->priority <= priority)
            q = q->next;
        /* q either points to the sentinel or to the first entry for which
           the priority is larger than our insertion */
        p->priority = priority;
        p->element = element;
        link(q->prev, p, q);
        pqd->size++;
    }
    return status;
}
```

10.3.1.4 min() and removeMin()

`min()` is straightforward. A helper function to unlink a node from the doubly-linked list is defined. With that helper function, `removeMin()` is also straightforward.

```
static bool pq_min(const PrioQueueLong *pq, void **element) {
    PqData *pqd = (PqData *)pq->self;
    LLNode *p = SENTINEL(pqd)->next;
    bool status = (p != SENTINEL(pqd));

    if (status) {
        *element = p->element;
    }
    return status;
}

/*
```

```
 * unlinks the LLNode from the doubly-linked list
 */
static void unlink(LLNode *p) {
    p->prev->next = p->next;
    p->next->prev = p->prev;
}

static bool pq_removeMin(const PrioQueueLong *pq, void **element) {
    PqData *pqd = (PqData *)pq->self;
    LLNode *p = SENTINEL(pqd)->next;
    bool status = (p != SENTINEL(pqd));

    if (status) {
        *element = p->element;
        unlink(p);
        free(p);
        pqd->size--;
    }
    return status;
}
```

10.3.1.5 size() and isEmpty()

The identical implementation to all of our other ADTs.

```
static long pq_size(const PrioQueueLong *pq) {
    PqData *pqd = (PqData *)pq->self;
    return pqd->size;
}

static bool pq_isEmpty(const PrioQueueLong *pq) {
    PqData *pqd = (PqData *)pq->self;
    return (pqd->size == 0L);
}
```

10.3.1.6 The constructor

Again, there should be no surprises here.

```
static PrioQueueLong template = {
    NULL, pq_destroy, pq_clear, pq_insert, pq_min, pq_removeMin, pq_size,
    pq_isEmpty
};

const PrioQueueLong *PrioQueueLong_create(void (*freeValue)(void *e)) {
    PrioQueueLong *pq = (PrioQueueLong *)malloc(sizeof(PrioQueueLong));
```

```
    if (pq != NULL) {
        PqData *pqd = (PqData *)malloc(sizeof(PqData));

        if (pqd != NULL) {
            pqd->size = 0L;
            pqd->sentinel.next = SENTINEL(pqd);
            pqd->sentinel.prev = SENTINEL(pqd);
            pqd->freeValue = freeValue;
            *pq = template;
            pq->self = pqd;
        } else {
            free(pq);
            pq = NULL;
        }
    }
    return pq;
}
```

10.4 Priority queues for arbitrary, ordered data types

All of the examples shown above have assumed long integers represent priorities. In addition, all examples have ignored the `create()`, `toArray()`, and `itCreate()` methods, as well. The purpose of this section is to complete our implementation to address these two deficiencies.

10.4.1 Iteration natural order for a priority queue

With respect to iteration, what would be the natural order of elements returned by successive calls to the iterator? The most natural order would be to deliver elements according to the total ordering provided by the priority values, from smallest to largest. If the priority queue has been implemented using a linked list, we can easily deliver the elements in this natural order by traversing the linked list from head to tail.

10.4.2 Arbitrary priority data types

In order for our priority queues to allow arbitrary data types for the priority, the interface will define the priority values to be of type `void *`, just as we define the element values to be of type `void *`. The user must supply a pointer to a comparison function that given two `void *` priorities, $p1$ and $p2$, returns a value less than 0 if $p1 < p2$, the value 0 if $p1 == p2$, and value greater than 0 if $p1 > p2$.

The constructor for a priority queue takes three arguments:

1. a pointer to a comparison function for the priorities;
2. a pointer to a function that will free a priority; and
3. a pointer to a function that will free a value.

10.4.3 The generic interface

First we will present the entire header file. Then we describe how it differs from the previous interface.

```
#ifndef _PRIOQUEUE_H_
#define _PRIOQUEUE_H_

/* BSD Header removed to conserve space */

#include "ADTs/ADTdefs.h"
#include "ADTs/iterator.h"                      /* needed for factory method */

/* dispatch table structure for generic priority queue */
typedef struct prioqueue PrioQueue;

/* constructor for priority queue
 *
 * cmp is a function pointer to a comparator function between two priorities
 *
 * freePrio is a function pointer that will be called by
 * destroy() and clear() for the priority of each entry in the PrioQueue.
 *
 * freeValue is a function pointer that will be called by
 * destroy() and clear() for the value of each entry in the PrioQueue.
 *
 * returns a pointer to the priority queue, or NULL if malloc errors */
const PrioQueue *PrioQueue_create(int (*cmp)(void*, void*),
                                  void (*freePrio)(void *prio),
                                  void (*freeValue)(void *value)
                                 );

struct prioqueue {
/* the private data for the priority queue */
    void *self;

/* create a new priority queue using the same implementation as the priority
 * queue upon which the method has been invoked; returns NULL if error creating
 * the new priority queue
 */
    const PrioQueue *(*create)(const PrioQueue *pq);

/* destroys the priority queue;
 * applies the constructor-specified freePrio to each element in the prioqueue
 * applies the constructor-specified freeValue to each element in the prioqueue
```

```
 * the storage associated with the priority queue is returned to the heap */
    void (*destroy)(const PrioQueue *pq);

/* clears all elements from the priority queue;
 * applies the constructor-specified freePrio to each element in the prioqueue
 * applies the constructor-specified freeValue to each element in the prioqueue
 * the prioqueue is then re-initialized
 *
 * upon return, the priority queue is empty */
    void (*clear)(const PrioQueue *pq);

/* inserts the element into the priority queue
 *
 * returns true if successful, false if unsuccessful (malloc errors) */
    bool (*insert)(const PrioQueue *pq, void *priority, void *value);

/* returns the minimum element's value *value
 *
 * returns true if successful, false if the priority queue is empty */
    bool (*min)(const PrioQueue *pq, void **value);

/* removes the minimum element of the priority queue
 *
 * returns the value in *value
 * returns the priority in *priority
 *
 * returns true if successful, false if the priority queue is empty */
    bool (*removeMin)(const PrioQueue *pq, void **priority, void **value);

/* returns the number of elements in the priority queue */
    long (*size)(const PrioQueue *pq);

/* returns true if the priority queue is empty, false if it is not */
    bool (*isEmpty)(const PrioQueue *pq);

/* returns an array containing all of the values of the priority queue in
 * proper sequence (smallest priority to largest priority); returns the
 * length of the array in *len
 *
 * returns a pointer to the array of void * values, or NULL if malloc failure
 *
 * NB - the caller is responsible for freeing the void * array when finished
 * with it */
    void **(*toArray)(const PrioQueue *pq, long *len);

/* create generic iterator to this priority queue
 *
 * returns pointer to the Iterator or NULL if malloc failure */
    const Iterator *(*itCreate)(const PrioQueue *pq);
};
```

```
#endif /* _PRIOQUEUE_H_ */
```

How does this differ from the previous interface when we used long integers for priorities?

- The constructor requires a pointer to a comparison function to compare the arbitrary priority values.
- The constructor requires a pointer to a `freePrio` function to free up priorities if they are allocated on the heap.
- A `create()` method has been added to enable the creation of a new priority queue, given a priority queue, guaranteeing that it has the same implementation as the one in hand.
- The `destroy()` and `clear()` methods will apply the `freePrio` function to the priorities associated with any elements remaining in the priority queue.
- The priority argument to `insert()` is a `void *`.
- An additional argument is provided in `removeMin()` in which the priority associated with the element is returned.
- The usual `toArray()` and `itCreate()` methods are defined.

10.4.4 The LinkedList-based constructor interface

This is the LinkedList-based constructor interface.

```
#ifndef _LLISTPRIOQUEUE_H_
#define _LLISTPRIOQUEUE_H_

/* BSD Header removed to conserve space */

#include "ADTs/ADTdefs.h"
#include "ADTs/prioqueue.h"

/* constructor for linked list priority queue */

/* create a priority queue using a singly-linked list
 *
 * cmp is a function pointer to a comparator function between two priorities
 *
 * freePrio is a function pointer that will be called by
 * destroy() and clear() for the priority of each entry in the PrioQueue.
 *
 * freeValue is a function pointer that will be called by
 * destroy() and clear() for the value of each entry in the PrioQueue.
 *
 * returns a pointer to the priority queue, or NULL if malloc errors */
const PrioQueue *LListPrioQueue(int (*cmp)(void*, void*),
                                void (*freePrio)(void *prio),
                                void (*freeValue)(void *value)
                               );
```

```
#endif /* _LLISTPRIOQUEUE_H_ */
```

10.4.5 The LinkedList-based implementation

The ordered linked list implementation for a generic priority queue is shown in section B.6.

10.4.6 A test program to exercise this implementation

The program `pqtest.c` satisfies the following pseudocode:

*define function numcmp(void *p1, void *p2)*

create priority queue pq with numcmp as the constructor argument
while there is another line on standard input
    insert the line into the priority queue, with its line number as the priority
create iterator over the priority queue
while there is another element in the iterator
    fetch that next element
    print the line on standard output
destroy the iterator
destroy the priority queue

This program can then be invoked and tested with `bash` commands of the following form.

```
$ ./pqtest <pqtest.c | diff - pqtest.c
$ valgrind ./pqtest <pqtest.c >/dev/null
```

The first command should yield no output, while the second should show that all heap memory has been used correctly and returned to the heap before the program exits.

The program source is as follows.

```
#include "ADTs/prioqueue.h"
#include <stdio.h>
#include <string.h>
#include <stdlib.h>

#define UNUSED __attribute__((unused))

int numcmp(void *p1, void *p2) {
    return (long)p1 - (long)p2;
}
```

```
int main(UNUSED int argc, UNUSED char *argv[]) {
    const PrioQueue *pq = NULL;
    const Iterator *it = NULL;
    char buf[BUFSIZ];
    long lineno = 1;
    int status = EXIT_FAILURE;

    if ((pq = PrioQueue_create(numcmp, doNothing, free)) == NULL) {
        fprintf(stderr, "Unable to create priority queue\n");
        goto cleanup;
    }
    while (fgets(buf, sizeof buf, stdin) != NULL) {
        if (!pq->insert(pq, ADT_VALUE(lineno), ADT_VALUE((strdup(buf))))) {
            fprintf(stderr, "Error inserting line %ld into priority queue\n",
                    lineno);
            goto cleanup;
        }
        lineno++;
    }
    it = pq->itCreate(pq);
    if (it != NULL) {
        while (it->hasNext(it)) {
            char *s;
            (void)it->next(it, ADT_ADDRESS(&s));
            fputs(s, stdout);
        }
        it->destroy(it);
    } else {
        fprintf(stderr, "Unable to create iterator over priority queue\n");
        goto cleanup;
    }
    status = EXIT_SUCCESS;
cleanup:
    if (pq != NULL)
        pq->destroy(pq);
    return status;
}
```

Exercise 10.1. Prioritizing Requests
You are reviewing log data from a server application with the goal of optimizing the order in which the application processes incoming requests. You want to determine the order in which the requests could have been processed so that the average turnaround time is as small as possible.
The log data has been reduced to just the essential information: the time at which the request arrived and, once scheduled, how long it took to process the request. Once scheduled, a request cannot be preempted. You need to determine the optimal order for processing the requests and output the minimum average turnaround time. The minimum average turnaround time is achieved if at each scheduling opportunity, the request with the smallest service time of the requests that have been received is chosen.
Your program will take a single argument, which is the name of a log file. The first line of

the input file is an integer $0 \leq N \leq 10^5$ giving the number of requests. Each of the following N lines contains a request string having the following format

`ARRIVAL_TIME SERVICE_TIME`

where $0 \leq ARRIVAL\_TIME, SERVICE\_TIME \leq 10^9$ are integers representing the arrival time and service time, respectively. The separator is a single space. The log might be a bit jumbled, so you cannot rely upon the input list being in the order of arrival time.
Assume that the server clock starts at 0 and it cannot process a request having arrival time A until the server clock is at least A - i.e., it cannot process requests that have not yet arrived. Furthermore, if at any moment there are requests waiting to be served, it must serve one of them - i.e., it cannot stall, hoping for better requests.
Output the minimum average response time for the given batch of requests. Truncate your answer to its integer part.

Input	Output
4 0 2 4 5 1 10 3 1	9

Explanation: At server time 0, a request is available to be processed with service time 2. The total turnaround time for the first request is 2. When the server finishes with this request, the server time is 2, and there is one request available to be processed with service time 10. Since this second request arrived at time 1, and it completes it service at time 12, the turnaround time for this request is 11. When the server finishes processing the second request, the server time is 12 and there are two requests waiting.
As indicated above, minimum average turnaround time is achieved if at each scheduling decision, you choose the request (from those that have arrived) with the smallest service time. In this case, we have one request that needs 1 unit of service time, and another that requires 5 units of service time. Choosing the request that arrived at time 3, we service that request, completing it at time 13, with a turnaround time for this request of $13 - 3 = 10$. Finally, the request that arrived at time 4 is scheduled, completing at time 18, with a turnaround time of $18 - 4 = 14$. Thus, the average turnaround time is $(2 + 11 + 10 + 14)/4 = 9.25$, and we print 9 on the output.

Exercise 10.2. As indicated in section 10.3, if there are a bounded number of integer priorities, it is possible to construct a priority queue for which insertion and removal of elements is $O(1)$. This is achieved by using a set of FIFO linked lists, one per priority value. The purpose of this exercise is for you to implement such a priority queue ADT.
Create the following header file, named `"prioqueuelongbounded.h"`:

```
#ifndef _PRIOQUEUELONGBOUNDED_H_
#define _PRIOQUEUELONGBOUNDED_H_

#include "ADTs/ADTdefs.h"

typedef struct prioqueuelongbounded PrioQueueLongBounded;
const PrioQueueLongBounded *PrioQueueLongBounded_create(
    long minP; /* smallest priority value */
    long maxP; /* largest priority value */
    void (*freeValue)(void *e));
struct prioqueuelongbounded {
    void *self;
    void (*destroy)(const PrioQueueLongBounded *pq);
    void (*clear)(const PrioQueueLongBounded *pq);
    bool (*insert)(const PrioQueueLongBounded *pq, long priority,
                   void *element);
    bool (*min)(const PrioQueueLongBounded *pq, void **element);
    bool (*removeMin)(const PrioQueueLongBounded *pq, void **element);
    long (*size)(const PrioQueueLongBounded *pq);
    bool (*isEmpty)(const PrioQueueLongBounded *pq);
};

#endif /* _PRIOQUEUELONGBOUNDED_H_ */
```

Create an implementation for this priority queue in a file named `"prioqueuelongbounded.c"`. Create a test program that exercises your implementation and demonstrate that it is $O(1)$ for insertions and removals.

Chapter 11

Searching and sorting

In the data structures that we have covered so far, the containers were structured in such a way that we did not have to search for the items to return. We had methods such as `pop()` for a Stack, `dequeue()` for a Queue, `removeFirst()` and `removeLast()` for a Deque, and `removeMin()` for a PrioQueue. Searching for an item in a container is a very common operation when constructing an application. This chapter will first remind you of two different types of searching that you will have learned in your previous programming experience: linear and binary search. It will then focus on different types of sorting algorithms and their running time complexities that can be used to support binary search.

11.1 Searching

The basic structured data type provided by C is the array. An array has a declared type and size; the cells that make up the array are allocated in contiguous memory locations. The size of an array is not part of the array, so one must remember the size using another variable. We have seen examples of this for the array-based Stack and Queue implementations.

For the next two subsections, we will assume the following declarations:

```
#define N 32
void *a[N];          /* the array of values in which we search */
void *x;             /* the value for which we are searching */
int size = N;        /* legal indices are [0..N-1] */
/*
 * the following function compares two values, returning <0 | 0 | >0
 * if v1 < v2 | v1 == v2 | v1 > v2, respectively
 */
int cmp(void *v1, void *v2);
```

11.1.1 Linear search

If we do not have any information about how the values are stored in the array, we have to resort to *linear search*. Given `x`, we wish to search the array `a[]` to see if it is contained therein. We will start searching at the beginning of `a[]`.

There are two conditions that terminate the search:

1. the element is found - i.e., `a[i] == x` for some `0 <= i < N`; or
2. the entire array has been searched, and no match was found.

We will write a function that searches the array for a value, returning the index in `a[]` at which `x` was found; if it is not found, we return `-1`.

```
int linearSearch(void *a[], int size, void *x) {
    int i;
    int ans = -1;     /* assume failure */

    for (i = 0; i < size; i++)
        if (cmp(a[i], x) == 0) {
            ans = i;
            break;
        }
    return ans;
}
```

Does this return the correct function values? There are two ways that we end up at the `return ans;` statement:

1. we have encountered an array element `a[i]` that is equal to `x` (as determined by the function `cmp()`); when this occurs, we assign the value of `i` to `ans` and break out of the `for` loop; or
2. `i >= size`, in which case we do not execute the loop; since we initialized `ans` to -1, this is the result that will be returned.

It should be clear that this function has $O(N)$ running time complexity since it has to process some portion of the array; in the worst case, it has to invoke `cmp` on all of the items in the array; in the average case, when searching for an item that *is* in the array, one will invoke `cmp` on half of the items. Thus the complexity of the function depends upon the number of items in the array, yielding $O(N)$ running time complexity.

11.1.2 Binary search

The only way we will be able to improve on the running time complexity is if there is more information about the data to be searched. It is well known that a search can be made much more efficient if the data to be searched is ordered. For example, consider how you use an index in a book; the index is sorted alphabetically, so you can quickly zero in on the topic of interest, and from there go to the pages upon which that topic is discussed. In particular, you do *not* need to linearly search through the index.

So let's assume that our array, `a[]`, is ordered by the comparator function `cmp()`. That is:

$$\forall_{1 \le k < N} \; cmp(a[k-1], a[k]) \le 0$$

Since the array is ordered, we can use a *divide and conquer* approach:

- select a value at random, say `a[m]` for some legal index `m`;
- compare `x` with the selected array element;
- if they are equal, terminate the search;
- if $cmp(a[m], x) < 0$, it means that array elements with indices less than or equal to `m` can be eliminated from the search, and repeat the process with the indices greater than `m`;
- if $cmp(a[m], x) > 0$, then we eliminate indices greater than or equal to `m` from the search, and repeat the process with indices less than `m`;
- since the range of indices that we process reduces each time, we eventually either find the element, or we have no more indices to check.

Let's write a function that searches the array using this algorithm.

```
int binarySearch(void *a[], int size, void *x) {
    int left = 0, right = size - 1;
    int ans = -1;                    /* assume failure */

    while (left <= right) {
        int m = (left + right) / 2;  /* take the midpoint */
        result = cmp(a[m], x);

        if (result == 0) {
            ans = m;
            break;
        } else if (result < 0)
            left = m + 1;
        else
            right = m - 1;
    }
    return ans;
}
```

How does this work? Let's assume the worst case, that `x` is not in `a[]`; we will assume that `x < a[0]`, but the complexity is the same if $a[0] < x < a[N-1]$ and `x` is not in the array. Let's track the values of `left` and `right` through the iterations of the while loop.

iteration	left	right	m
1	0	31	15
2	0	14	7
3	0	6	3
4	0	2	1
5	0	0	0
6	0	-1	

By selecting the midpoint at each iteration, we are reducing the number of elements to search by $\frac{1}{2}$. Such a reduction at each iteration means that we will perform $\log_2 N$ iterations in the worst case. In our case, we had 32 elements in the array, and $\log_2 32$ is 5; in fact, we performed exactly 5 iterations, since the 6th iteration listed above actually fails the `left <= right` condition of the while loop.

We already know from Chapter 5 that $O(\log n)$ grows much more slowly than $O(n)$, so binary search is preferred over linear search if the array being searched is ordered.

11.2 Sorting

Since searching over a sorted array is so much more scalable than over an unsorted array, we now need to discuss various ways to sort an array to enable this more scalable behavior. We will focus on a C function that sorts the array elements in place.

The basic problem we are trying to solve is as follows:

- we have an array of items that need to be ordered;
- we assume that all of the elements fit into the random access memory of the computer; if they do not, then one must resort to external sorting algorithms, which is beyond the scope of this discussion;
- we have a comparator function defined on the items that determines the appropriate ordering of the array elements;
- the array elements may already be ordered, or may be in random order.

Given this set of requirements, we will first look at algorithms that exhibit $O(n^2)$ complexity. Then we will move on to algorithms that exhibit better than $O(n^2)$ complexity.

A sorting algorithm is said to be *stable* if two objects with equal keys appear in the same order in the sorted output as they appear in the unsorted input array. There are some applications for which a stable sorting algorithm is required - e.g., you have multi-column records, and you first sort by column 2, then by column 1, and you want all records that have identical values in column 1 to remain sorted by column 2. We will note those algorithms that are stable by nature in the following sections.

For all of the sort algorithms described in the subsequent subsections, the function prototype for our function is:

```
void sort(void *a[], long size, int (*cmp)(void *v1, void *v2));
```

We will link our sort implementations with the following main program to test it out.

```
#include "sort.h"
#include <stdio.h>
#include <stdlib.h>

void display(void *a[], int size) {
    int i;
    for (i = 0; i < size; i++) {
        long v = (long)a[i];
        printf("%3ld", v);
    }
    printf("\n");
}

int cmp(void *v1, void *v2) {
    long l1 = (long)v1;
    long l2 = (long)v2;
    return (l1 - l2);
}

int main(int argc, char *argv[]) {
    void *a[25];
    int i, j;

    for (i = 1, j = 0; i < argc; i++) {
        long v = atoi(argv[i]);
        a[j++] = (void *)v;
    }
    display(a, j);
    sort(a, (long)j, cmp);
    display(a, j);
    return EXIT_SUCCESS;
}
```

We link `sortmain.o` with the object file from our sort algorithm, and invoke the resulting executable as

```
$ ./program 23 40 15 73 97 11 2 87
```

with the resulting output being

```
 23 40 15 73 97 11  2 87
  2 11 15 23 40 73 87 97
```

11.2.1 Sorting algorithms with $O(n^2)$ complexity

Sorting methods that sort items *in situ* can be classified into three principal categories according to their underlying method:

1. sort by insertion;
2. sort by selection; or
3. sort by exchange.

11.2.1.1 Insertion sort

Insertion sort is typically how bridge players structure their hands after they are dealt. The items are divided into a destination sequence, `a[0]...a[i-1]`, and a source sequence, `a[i]...a[N-1]`. We start with `i = 1`, yielding a destination sequence consisting of `a[0]` (since a single element is obviously sorted), and a source sequence of `a[1]...a[N-1]`. At each step, the `i`$^{\text{th}}$ element of the source sequence is transferred into the appropriate place in the destination sequence, and then `i` is incremented. These steps are repeated until the source sequence is empty, at which point the destination sequence is the entire sorted array.

Here is a C implementation of insertion sort.

```
#include "sort.h"

void sort(void *a[], long size, int (*cmp)(void *v1, void *v2)) {
    long i;

    for (i = 1; i < size; i++) {
        void *x = a[i];
        long j;

        for (j = i - 1; j >= 0 && (*cmp)(a[j], x) > 0; j--)
            a[j+1] = a[j];
        a[j+1] = x;
    }
}
```

Lets look at how the array changes with each iteration over `i` in the insertion sort function.

Input	23	40	15	73	97	11	2	87
i = 1	23	40	15	73	97	11	2	87
i = 2	15	23	40	73	97	11	2	87
i = 3	15	23	40	73	97	11	2	87
i = 4	15	23	40	73	97	11	2	87
i = 5	11	15	23	40	73	97	2	87
i = 6	2	11	15	23	40	73	97	87
i = 7	2	11	15	23	40	73	87	97

Each iteration over `j` checks that `a[j] > x`; thus, if we have duplicates in the initial array, we guarantee that the second identical value will not overtake the first. Thus, **insertion sort is stable**.

The complexity for insertion sort is obviously $O(n^2)$, since the outer for loop (over `i`) is executed `n - 1` times. The inner for loop (over `j`) is executed `i` times; since `i` is a fraction of `n`, this means that we have $O(n^2)$ comparisons and moves.

11.2.1.2 Selection sort

Selection sort is based upon the following approach:

1. select the array element that has the smallest value;
2. exchange it with `a[0]`;
3. repeat with the remaining `n-1` items, then `n-2` items, until only one item, which is the largest, is left.

In some sense, selection is the opposite of insertion; insertion sort considers in each step only the *one* next item of the source sequence and *all* the items of the destination sequence; selection sort considers *all* items of the source sequence to find the one with the smallest value, and then deposits it as the *one* next item of the destination sequence.

Here is a C implementation of selection sort.

```
#include "sort.h"

void sort(void *a[], long size, int (*cmp)(void *v1, void *v2)) {
    long i;

    for (i = 0; i < size - 1; i++) {
        long k = i;
        long j;

        for (j = i + 1; j < size; j++)
            if ((*cmp)(a[j], a[k]) < 0)
                k = j;
        if (k != i) {
            void *x = a[i];
            a[i] = a[k];
            a[k] = x;
        }
    }
}
```

Lets look at how the array changes with each iteration over `i` in the selection sort function.

Input	23	40	15	73	97	11	2	87
i = 0	2	40	15	73	97	11	23	87
i = 1	2	11	15	73	97	40	23	87
i = 2	2	11	15	73	97	40	23	87
i = 3	2	11	15	23	97	40	73	87
i = 4	2	11	15	23	40	97	73	87
i = 5	2	11	15	23	40	73	97	87
i = 6	2	11	15	23	40	73	87	97

Selection sort is *not* stable, since at each step it swaps the current element with the minimum element in the source sequence. If the source sequence had a duplicate of the current element at a location before the index where the minimum element was found, it has inverted the order of the two identical elements, and is thus *not* stable.

The complexity is again $O(n^2)$, since we again have an outer loop that is performed `n-1` times, and an inner loop that is performed a fraction of `n` times, thus yielding $O(n^2)$.

11.2.1.3 Exchange sort

While both insertion and selection sorts performed the exchange of two items, the exchange was not the dominant characteristic of the algorithm. Exchange sort is based on the principle of comparing and exchanging pairs of adjacent items until all items are sorted.

As in selection sort, we make repeated passes over the array, each time "bubbling" the least item of the remaining set to the left end of the subarray under consideration. This method is widely known as *Bubblesort*.

Here is a C implementation of Bubblesort/exchange sort.

```c
#include "sort.h"

void sort(void *a[], long size, int (*cmp)(void *v1, void *v2)) {
    long i;

    for (i = 1; i < size; i++) {
        long j;

        for (j = size - 1; j >= i; j--)
            if ((*cmp)(a[j-1], a[j]) > 0) {
                void *x = a[j-1];
                a[j-1] = a[j];
                a[j] = x;
            }
    }
}
```

Let's look at how the array changes with each iteration over `i` in the exchange sort function.

Input	23	40	15	73	97	11	2	87
i = 1	2	23	40	15	73	97	11	87
i = 2	2	11	23	40	15	73	97	87
i = 3	2	11	15	23	40	73	87	97
i = 4	2	11	15	23	40	73	87	97
i = 5	2	11	15	23	40	73	87	97
i = 6	2	11	15	23	40	73	87	97
i = 7	2	11	15	23	40	73	87	97

Note that the order of the array elements did not change for the last four iterations for the outer loop. Thus, we can improve the implementation by noting in each pass whether any exchanges were made; if not, the algorithm can terminate. This improvement is shown in the following implementation.

```
#include "sort.h"

void sort(void *a[], long size, int (*cmp)(void *v1, void *v2)) {
    long i;
    int nexchange = 1;        /* guarantee that we perform first iteration */

    for (i = 1; i < size && nexchange > 0; i++) {
        long j;

        for (j = size - 1, nexchange = 0; j >= i; j--)
            if ((*cmp)(a[j-1], a[j]) > 0) {
                void *x = a[j-1];
                a[j-1] = a[j];
                a[j] = x;
                nexchange++;
            }
    }
}
```

With these changes, we guarantee that we perform the minimum number of outer loop iterations.

Exchange sort *is* stable, since the pairwise exchanges is driven by $a[j-1] > a[j]$; thus, items with the same values will cluster together in the same order in which they appeared in the input array.

The complexity is $O(n^2)$, since the outer loop is performed `n - 1` times, and the inner loop is performed a fraction of `n` times. The improvement obtained by tracking the number of exchanges in each iteration generally improves the performance, but the complexity remains $O(n^2)$.

There is a particular asymmetry to exchange sort; if there is a small value at the end of the input array, it will bubble into its correct position in a single pass; if there is a very large value at the beginning of the input array, it will only move one location toward its correct position with each iteration. For example, the array

```
11 15 23 40 73 87 97 2
```

is sorted by our improved exchange sort in a single pass, but the array

```
97 2 11 15 23 40 73 87
```

requires 7 passes to sort the array.

Thus, another improvement to exchange sort can be obtained if we alternate the direction (and the nature of the comparison) of consecutive passes. This is left as a programming exercise at the end of the chapter.

11.2.2 Sorting algorithms with better than $O(n^2)$ complexity

As promised, this section will cover versions of insertion, selection, and exchange sort that exhibit better running time complexity than the simple sort algorithms shown previously.

11.2.2.1 Shell sort

The insertion sort presented in Section 11.2.1.1 forces an $O(n^2)$ complexity since you have to shuffle through all of the elements of the destination sequence to find the right place for the next item from the source sequence. This variation of insertion sort requires that we perform insertion sort with different sized strides, starting with a large stride, then processing the array with a smaller stride, ..., until we are left with a stride of 1. While it is not obvious that this will improve the running time complexity, the complexity is always better than $O(n^2)$; depending upon the number of strides chosen and the relationships between the strides, the worst case is $O(n^{5/3})$ and the best case is $O(n[\log(n)]^2)$.[1]

Let's try it on our standard eight item sequence of integers, with strides of 4, 2, and 1.

Input	23	40	15	73	97	11	2	87
after 4-sort	23	11	2	73	97	40	15	87
after 2-sort	2	11	15	40	23	73	97	87
after 1-sort	2	11	15	23	40	73	87	97

[1] Donald E. Knuth, *The Art of Computer Programming, Volume 3, Searching and Sorting*, Addison-Wesley, Boston, MA, ISBN: 978-0-201-89685-5, 1998.

It may seem counterintuitive that several sorting passes, each of which involves all items, reduces the complexity. Note that each sorting step over a chain either involves relatively few items or the items are already quite well-ordered and relatively few rearrangements are required.

While it is clear from the table above that this works when the set of strides are decreasing powers of two, it works even better if the strides are not related in this way. Knuth[2] suggests two reasonable choices for the increments $(h_1, h_2, ..., h_t)$ to be used (with the order reversed):

1, 4, 13, 40, 121, ... i.e., $h_{k-1} = 3h_k + 1$, $h_t = 1$, and $t = \lfloor \log_3 n \rfloor - 1$

1, 3, 7, 15, 31, ... i.e., $h_{k-1} = 2h_k + 1$, $h_t = 1$, and $t = \lfloor \log_2 n \rfloor - 1$

We will use `malloc()` to allocate the appropriate number of strides for the second of the choices above. Here is an implementation of Shell sort.

```
#include "sort.h"
#include <stdlib.h>

static long logb2(long size) {
    long power = 1;         /* overcompensate by 1 */
    unsigned long mask = 1;

    while ((unsigned long)size > mask) {
        mask *= 2;
        power++;
    }
    return power;
}

void sort(void *a[], long size, int (*cmp)(void *v1, void *v2)) {
    long t = logb2(size) - 1;
    long *h = (long *)malloc(t*sizeof(long));
    long i;

    h[t-1] = 1;
    for (i = t - 2; i >= 0; i--)
        h[i] = 2 * h[i+1] + 1;
    for (i = 0; i < t; i++) {
        long stride = h[i];
        long j;
        for (j = stride; j < size; j++) {
            long k;
            for (k = j - stride; k >= 0; k -= stride) {
                if ((*cmp)(a[k+stride], a[k]) >= 0)
                    break;
                else {
```

[2] Donald E. Knuth, ibid.

```
                    void *tmp = a[k];
                    a[k] = a[k+stride];
                    a[k+stride] = tmp;
                }
            }
        }
    }
    free(h);
}
```

Note that since we are exchanging non-adjacent items when the stride is large, we could be changing the order of items that have identical keys. As a result, **shell sort is *not* a stable sort**.

11.2.2.2 Heap sort

The fundamental characteristic of our previous selection sort was, at each step, to scan the source sequence to find the minimum value to exchange with the next item in the destination sequence. Finding the minimum value was $O(n)$, and since we had to do that scan for each index in our array, we ended up with an algorithm that was $O(n^2)$ complexity. If we could reduce the complexity for finding the minimum value in the source sequence, we could reduce the complexity of our sort algorithm.

In Chapter 13 we discuss the heap data structure, which enables us to find the minimum value of a bag of numbers in $O(\log n)$ time. A sorting algorithm that uses a heap, named *heap sort*, will be described in that chapter.

11.2.2.3 Quick sort

We have shown advanced sorting methods based upon the principles of insertion and selection, so it is no surprise that the third improved method is based upon the principle of exchange. Bubblesort exchanged adjacent pairs of items, “bubbling” the smallest remaining value in the source sequence into the next location in the destination sequence. We might expect that if we exchanged pairs of items over large distances, we would see a performance improvement.

Consider the following algorithm: pick any item, `x`, at random - we call this item the *pivot*; scan the array from the left until an item `a[i] > x` is found, and then scan from the right until an item `a[j] < x` is found. Now exchange these two items and continue this “scan and swap” process until the two scans meet somewhere in the middle of the array. The array is now partitioned into a left part with keys less than (or equal to) `x`, and a right part with keys greater than (or equal to) `x`. If we change the relations to $\geq$ and $\leq$, then `x` acts as a sentinel terminating the two scans. This leads us to the following function to partition our array in this way.

```
void partition(void *a[], long size, int (*cmp)(void*, void*)) {
    void *x;
    long i = 0, j = size-1;

    /* select the pivot from a[], assigning it to x */
    while (i <= j) {
        while ((*cmp)(a[i], x) < 0)
            i++;
        while ((*cmp)(x, a[j]) < 0)
            j--;
        if (i <= j) {
            void *y = a[i];
            a[i] = a[j];
            a[j] = y;
            i++;
            j--;
        }
    }
}
```

So, how do we “select the pivot from `a[]`, assigning it to `x`”? Usually we compute the index for the middle element in the array, and use its value for `x`. This works quite well if the items are randomly ordered in the array. This also works very well for arrays that are initially sorted in decreasing value - $\frac{n}{2}$ pairs are swapped around the middle value, and we are done. One could choose `a[0]` or `a[size-1]` as the pivot value; for random initial order, they work well, but if the array is already sorted, it leads to worst case $O(n^2)$ complexity. We will use the middle element for the *pivot*.

Here is a recursive implementation of Quicksort.

```
#include "sort.h"

static void qsort(void *a[], long L, long R, int(*cmp)(void*, void*)) {
    long i = L, j = R;
    void *x = a[(L+R)/2];

    while (i <= j) {
        while ((*cmp)(a[i], x) < 0)
            i++;
        while ((*cmp)(x, a[j]) < 0)
            j--;
        if (i <= j) {
            void *y = a[i];
            a[i] = a[j];
            a[j] = y;
            i++;
            j--;
```

```
        }
    }
    if (L < j)
        qsort(a, L, j, cmp);
    if (i < R)
        qsort(a, i, R, cmp);
}

void sort(void *a[], long size, int (*cmp)(void *v1, void *v2)) {
    qsort(a, 0L, size-1, cmp);
}
```

What is the running time complexity for Quicksort? Since we are doing a "divide and conquer" approach to the exchange of items, as long as we choose a *pivot* that approximately divides the array into two equal sized subarrays at each recursion, we will perform $\log n$ of these recursions. Since we have to compare each item against the pivot, this comparison activity will be $O(n)$. Thus, in the normal case, we expect the complexity to be $O(n \log n)$.

What happens if we make a bad choice for the pivot? For example, if we use `a[0]` as the pivot and the array is initially sorted, we are left with a left partition of a single element, and a right partition with $n-1$ items. The result is that we will recurse to a depth of n, instead of $\log n$, leading to a worst-case performance of $O(n^2)$.

⚠ If the choice of pivot does **not** divide the array into approximately equal-sized subarrays for each partition, Quicksort's complexity degenerates to $O(n^2)$.

We might opt for an iterative Quicksort implementation to avoid the call frame overhead of the recursive implementation. In order to solve this iteratively, we must maintain a list of partitioning requests that have yet to be performed. After each step, two partitioning tasks must be performed; only one of them can be performed in the next iteration, so we must store the other partitioning task away on the list. The tasks on the list must be processed in a *last in, first out* sequence - thus, we must implement a stack representing the partitioning tasks remaining to be performed.

How big should this stack be? Given the worst-case performance for a bad choice of the pivot, we have previously argued that the recursion depth would be `n`, which means that we might need a stack of that size. There is a way out of this - if we always stack the larger of the two subarrays, and process the smaller in the next iteration, it can be shown that the stack need never be larger than $\log n$ in size. We will use `malloc()` to allocate the appropriately sized stack in our iterative Quicksort implementation.

```
#include "sort.h"
#include <stdlib.h>
#include <stdio.h>

typedef struct pStruct {
```

```
    long left;
    long right;
} PStruct;

static long logb2(long size) {
    long power = 1;         /* overcompensate by 1 */
    unsigned long mask = 1;

    while ((unsigned long)size > mask) {
        mask *= 2;
        power++;
    }
    return power;
}

void sort(void *a[], long size, int (*cmp)(void *v1, void *v2)) {
    PStruct *st = (PStruct *)malloc(logb2(size)*sizeof(PStruct));
    int sp = 0;

    st[sp].left = 0;
    st[sp].right = size - 1;
    while (sp >= 0) {
        long L = st[sp].left;
        long R = st[sp].right;
        sp--;
        while (L < R) {
            long i = L;
            long j = R;
            void *x = a[(L+R)/2];
            while (i <= j) {
                while ((*cmp)(a[i], x) < 0)
                    i++;
                while ((*cmp)(x, a[j]) < 0)
                    j--;
                if (i <= j) {
                    void *y = a[i];
                    a[i] = a[j];
                    a[j] = y;
                    i++;
                    j--;
                }
            }
            if ((j - L) < (R - i)) {
                if (i < R) {         /* stack right partition */
                    sp++;
                    st[sp].left = i;
                    st[sp].right = R;
                }
                R = j;               /* continue with left partition */
            } else {
                if (L < j) {         /* stack left partition */
```

```
                    sp++;
                    st[sp].left = L;
                    st[sp].right = j;
                }
                L = i;              /* continue with right partition */
            }
        }
    }
    free(st);                       /* return the stack to the heap */
}
```

Note that since we are exchanging non-adjacent items when we partition a range of items, we could be changing the order of items that have identical keys. As a result, **quick sort is *not* a stable sort**.

11.2.3 Merge sort

In Section 11.2.2, we showed two different advanced sorting algorithms, both of which outperformed the simple sorting algorithms in Section 11.2.1, but *neither* were stable[3]. There are numerous occasions where a stable sorting algorithm is required, and usually at a scale where $O(n^2)$ simply will not work. This section describes *Mergesort*, an algorithm that yields $O(n \log n)$ complexity, but at the cost of $O(n)$ extra storage locations for a scratch array.

Mergesort is another "divide and conquer" algorithm. The algorithm has three steps:

1. **divide**: if the input size is smaller than a certain threshold, solve the problem directly using a straightforward *stable* method and return the solution; otherwise, divide the input data into two or more disjoint subsets;
2. **recurse**: recursively solve the problem for each of the subsets; and
3. **merge**: merge the solutions to the subproblems into a solution to the original problem.

We have our items in an array, `a[]`, and a comparator function that defines a total order over those items. Let's define a sequence `S` as a sub-array of `a[]`, defined by `low` and `high` indices, and which has `n = high - low + 1` items. To sort the `n` items in `S`, our Mergesort algorithm implements the above three steps as follows:

1. if `n` is `0` or `1`, return `S` immediately, as it is already sorted; otherwise (`n >= 2`), divide `S` into two disjoint subsequences, $\mathtt{S}_{\mathtt{low}}$ and $\mathtt{S}_{\mathtt{high}}$; each subsequence contains ~half of the elements of `S`;
2. recursively sort sequences $\mathtt{S}_{\mathtt{low}}$ and $\mathtt{S}_{\mathtt{high}}$;
3. merge the sorted sequences $\mathtt{S}_{\mathtt{low}}$ and $\mathtt{S}_{\mathtt{high}}$ back into `S`.

In order to perform the merge in step 3 above, we need a scratch array of size `n`; the way that we will handle this in our implementation of Mergesort is to use `malloc()` to allocate

[3]Heap sort, which will be shown in Chapter 13, is also not a stable sort

a scratch array of the `size` specified in the call to `sort()`; when merging the two sorted subsequences, defined by `L`, `M`, and `H` indices, `scratch[L..H]` is used. Obviously, after the sort is completed, the scratch array is returned to the heap.

Here is a recursive implementation of Mergesort.

```
#include "sort.h"
#include <stdlib.h>

static void **scratch = NULL;

static void merge(void *a[], long L, long M, long H, int (*cmp)(void*,void*)) {
    long l1 = L, l2 = M + 1, i;

    for (i = L; l1 <= M && l2 <= H; i++) {
        if((*cmp)(a[l1], a[l2]) <= 0)
            scratch[i] = a[l1++];
        else
            scratch[i] = a[l2++];
    }
    while (l1 <= M)
        scratch[i++] = a[l1++];
    while (l2 <= H)
        scratch[i++] = a[l2++];
    for (i = L; i <= H; i++)
        a[i] = scratch[i];
}

static void msort(void *a[], long low, long high, int(*cmp)(void*, void*)) {

    if (low < high) {
        long mid = (low + high) / 2;
        msort(a, low, mid, cmp);
        msort(a, mid+1, high, cmp);
        merge(a, low, mid, high, cmp);
    }
}

void sort(void *a[], long size, int (*cmp)(void *v1, void *v2)) {
    scratch = (void **)malloc(size*sizeof(void *));
    msort(a, 0L, size-1, cmp);
    free(scratch);
}
```

Note that our interpretation of the **divide** step is to keep dividing until the size of the sequence is 0 or 1. A standard adaptation of Mergesort is to define a threshold size for the sequence, say `7`, and to use insertion sort to sort the sequence in place if the size of the sequence is less than that threshold. The following code shows the modified `msort()` along with the definition of the threshold and the code for insertion sort (as already seen in Section 11.2.1.1 but with the name changed to `isort()`.

```
static void isort(void *a[], long size, int (*cmp)(void *v1, void *v2)) {
    long i;

    for (i = 1; i < size; i++) {
        void *x = a[i];
        long j;

        for (j = i - 1; j >= 0 && (*cmp)(a[j], x) > 0; j--)
            a[j+1] = a[j];
        a[j+1] = x;
    }
}

#define THRESHOLD 7
static void msort(void *a[], long low, long high, int(*cmp)(void*, void*)) {
    long size = high - low + 1;

    if (size > THRESHOLD) {
        long mid = (low + high) / 2;
        msort(a, low, mid, cmp);
        msort(a, mid+1, high, cmp);
        merge(a, low, mid, high, cmp);
    } else if (size > 1) {
        isort(a+low, size, cmp);
    }
}
```

Since at each step the range of values is divided into two halves, and since the merge function uses $\leq$ to compare values in the subarrays, and since insertion sort is a stable sort for sizes below the threshold, **merge sort is a stable sort**.

Exercise 11.1. Alternating bubblesort directions
Bubblesort's asymmetry was discussed in Section 11.2.1.3. Modify the bubblesort implementation to alternate directions for each iteration. Be sure to maintain the stability of the modified bubblesort.

Chapter 12

Maps

A *map* stores (key, value) pairs, typically called *entries*. Each key in a map is required to be unique. Thus, the key in an entry is a unique identifier for the entry. You may have already seen maps in your previous courses; in Python, a dictionary is a Map.

The most general type of map allows the keys and the values to be any type of data. A function must exist to enable the Map implementation to determine if two key instances are equal in order to be able to support the uniqueness criterion stated above.

Initially, we will focus on maps for which the keys are C character strings, as these are very common; the function for determining if two keys are equal is `strcmp()`.

The interface will be defined in `"ADTs/cskmap.h"`, and the constructor for creating one of these maps is `CSKMap_create()`. There will be two implementation-dependent constructors, `LListCSKMap()` and `HashCSKMap()`; these are defined in `"ADTs/llistcskmap.h"` and `"ADTs/hashcskmap.h"`, respectively. At the end of the chapter we will show the changes that are required to support maps for which the keys can be any data type.

12.1 The C String Key Map interface

A map is a container for (key, value) pairs. The Map interface for C string keys is defined as follows:

```
#ifndef _CSKMAP_H_
#define _CSKMAP_H_

/* BSD Header removed to conserve space */

#include "ADTs/ADTdefs.h"
#include "ADTs/iterator.h"              /* needed for factory method */
```

```
/* interface definition for C string key map */

typedef struct cskmap CSKMap;             /* forward reference */
typedef struct mentry {
    char *key;
    void *value;
} MEntry;

/*
 * constructor for a CSKMap
 *
 * freeValue() is applied by destroy(), clear(), put(), and remove()
 * to appropriate element[s]
 *
 * returns pointer to dispatch table, or NULL if malloc failures
 */
const CSKMap *CSKMap_create(void (*freeValue)(void *v));

/* now define struct cskmap */
struct cskmap {
/* the private data for the map */
    void *self;

/* create a new map using the same implementation as the map upon which
 * the method has been invoked; returns NULL if error creating the new map
 */
    const CSKMap *(*create)(const CSKMap *m);

/* destroys the map;
 * applies constructor-specified freeValue to each element in the map
 * the storage associated with the map is returned to the heap */
    void (*destroy)(const CSKMap *m);

/* clears all (key,value) pairs from the map;
 * applies constructor-specified freeValue to each element in the map
 * the map is then re-initialized
 *
 * upon return, the map is empty */
    void (*clear)(const CSKMap *m);

/* returns true if key is contained in the map, false if not */
    bool (*containsKey)(const CSKMap *m, char *key);

/* returns the value associated with key in *value; returns true if key was
 * found in the map, false if not */
    bool (*get)(const CSKMap *m, char *key, void **value);

/* puts (key,value) into the map;
 * applies constructor-specified freeValue if there was a previous entry
 *
```

```
 * returns true if (key,value) was successfully stored in the map,
 * false if not */
    bool (*put)(const CSKMap *m, char *key, void *value);

/* puts (key,value) into the map iff the map does not contain a value associated
 * with key
 *
 * returns true if (key,value) was successfully stored in the map,
 * false if not */
    bool (*putUnique)(const CSKMap *m, char *key, void *value);

/* removes the (key,value) pair from the map;
 * applies constructor-specified freeValue to the removed entry
 *
 * returns true if (key,value) was present and removed,
 * false if it was not present */
    bool (*remove)(const CSKMap *m, char *key);

/* returns the number of (key,value) pairs in the map */
    long (*size)(const CSKMap *m);

/* returns true if the map is empty, false if not */
    bool (*isEmpty)(const CSKMap *m);

/* returns an array containing all of the keys in the map; the order is
 * arbitrary; returns the length of the array in *len
 *
 * returns a pointer to the char * array of keys, or NULL if malloc failure
 *
 * NB - the caller is responsible for freeing the char * array when finished
 * with it */
    char **(*keyArray)(const CSKMap *m, long *len);

/* returns an array containing all of the (key,value) pairs in the map;
 * the order is arbitrary; returns the length of the array in *len
 *
 * returns a pointer to the MEntry * array of (k,v) pairs,
 * or NULL if malloc failure
 *
 * NB - the caller is responsible for freeing the MEntry * array when finished
 * with it */
    MEntry **(*entryArray)(const CSKMap *m, long *len);

/* create generic iterator to the map
 *
 * returns pointer to the Iterator or NULL if malloc failure
 *
 * NB - when the next() method on the iterator is called, it returns an
 *      MEntry *
 */
    const Iterator *(*itCreate)(const CSKMap *m);
```

```
};

#endif /* _CSKMAP_H_ */
```

The semantics of the constructor and the methods are as follows:

- `const CSKMap *CSKMap_create(void (*freeV)(void *v));`
  create a new instance of a C string map; `freeV` is a function pointer applied to relevant entries by `destroy()`, `clear()`, `put()`, and `remove()`; returns a pointer to the dispatch table, or `NULL` if there were heap-allocation errors;

- `const CSKMap *(*create)(const CSKMap *m);`
  create a new C string map using the same implementation as the map upon which the method has been invoked; returns NULL if error creating the new map;

- `void (*destroy)(const CSKMap *m);`
  destroy the map; applies constructor-specified `freeV` to each element in the map; then all heap-allocated memory associated with the map is freed;

- `void (*clear)(const CSKMap *m);`
  purge all entries from the map; applies constructor-specified `freeV` to each element in the map; then heap-allocated memory associated with the the entries in the map is freed; upon return, the map is empty;

- `bool (*containsKey)(const CSKMap *m, char *key);`
  returns true/1 if the map has an entry for `key`, false/0 otherwise;

- `bool (*get)(const CSKMap *m, char *key, void **value);`
  returns the value associated with `key` in `*value`; if an entry was found, returns true/1; returns false/0 if no mapping for `key`;

- `bool (*put)(const CSKMap *m, char *key, void *value);`
  associates `value` with `key`; applies constructor-specified `freeV` if there was a previous entry; returns true/1 if successful, false/0 if not;

  > ⚠ If `put()` or `putUnique()` inserts a new (key,value) pair into the map, the implementation must make a copy of the key on the heap.

- `bool (*putUnique)(const CSKMap *m, char *key, void *value);`
  associates `value` with `key`; fails if `key` is already present; returns true/1 if successful, false/0 if not;

- `bool (*remove)(const CSKMap *m, char *key);`
  removes the entry associated with `key` if one exists; applies constructor-specified `freeV` to the removed entry; returns true/1 if successful, false/0 if no entry associated with `key`;

- `long (*size)(const CSKMap *m);`
  return the number of entries in the map;

- `bool (*isEmpty)(const CSKMap *m);`
  return true/1 if the map is empty, false/0 otherwise;

- `char **(*keyArray)(const CSKMap *m, long *len);`
  returns an array containing all of the keys in the map in an arbitrary order; returns the length of the array in `*len`; returns a pointer to the `char *` array of keys, or `NULL` if a heap-allocation failure occurred; **N.B.** the caller is responsible for freeing the `char *` array when finished;

- `MEntry **(*entryArray)(const CSKMap *m, long *len);`
  returns an array containing all of the entries in the map in arbitrary order; returns the length of the array in `*len`; returns a pointer to `MEntry *` array of elements, or `NULL` if a heap-allocation failure occurred; **N.B.** the caller is responsible for freeing the `MEntry *` array when finished;

- `const Iterator *(*itCreate)(const CSKMap *m);`
  creates an iterator for running through the entries in the map; returns a pointer to the Iterator or NULL if there were heap-allocation problems; each invocation of `next()` on the iterator will yield a `MEntry *`.

Note that the header file defines the type of an `MEntry` to enable you to access the key and the value associated with each entry.

12.2 A linked list-based CSKMap implementation

A simplistic approach to implementing a CSKMap would be to store the entries in a linked list. As with our differing implementations of other ADTs, such as stacks and queues, we provide an additional header file, `"ADTs/llistcskmap.h"`, which defines an additional constructor that forces the use of the linked-list CSKMap implementation:

```
const CSKMap *LListCSKMap(void (*freeV)(void *v));
```

Since the interface supports removal of an entry corresponding to an arbitrary `key`, it would be wise to use a doubly-linked list. Let's look at how we would implement `containsKey()`, `get()`, `put()`, `putUnique()`, and `remove()`.

12.2.1 The necessary data structures and a helper function

First, we need to define the node structure in the doubly-linked list. Then, we need to define the instance-specific data structure. These are shown below.

In addition, we will define a helper function that scans the doubly-linked list for an entry matching `key`; if found, it returns its `Node *` address; if not found, it returns `NULL`.

```
typedef struct node {  /* a node in the DLL */
    struct node *next;
    struct node *prev;
    MEntry entry;
} Node;
typedef struct m_data { /* instance-specific data structure */
    long size;
    Node sentinel;
    void (*freeV)(void *v);
} MData;

static Node *findKey(MData *md, char *key) {
    Node *p;

    for (p = md->sentinel.next; p != &(md->sentinel); p = p->next)
        if (strcmp(key, p->entry.key) == 0)
            break;
    return (p != &(md->sentinel)) ? p : NULL;
}
```

12.2.2 `containsKey()`

This method is particularly trivial, given that we have defined `findKey()`.

```
static bool m_containsKey(const CSKMap *m, char *key) {
    MData *md = (MData *)m->self;
    return (findKey(md, key) != NULL);
}
```

12.2.3 `get()`

Armed with `findKey()` defined above, the code for the `get()` method is straightforward.

```
static bool m_get(const CSKMap *m, char *key, void **value) {
    MData *md = (MData *)m->self;
    Node *p = findKey(md, key);
    bool status = (p != NULL);

    if (status)
        *value = p->entry.value;
    return status;
}
```

12.2.4 `put()` and `putUnique()`

These methods differ only in the action they take if a call to `findKey(key)` returns a non-NULL value; for `putUnique()`, it returns a failure indication; for `put()`, it proceeds to replace the current value with the new one; `freeV` is applied to the current value before replacing it. Therefore, we will define a helper function that encapsulates the common logic. We also use the `link()` helper function from the Deque implementation.

```
static bool insertEntry(MData *md, char *key, void *value) {
    Node *p = (Node *)malloc(sizeof(Node));
    bool status = (p != NULL);

    if (status) {
        char *k = strdup(key);
        status = (k != NULL);
        if (status) {
            (p->entry).key = k;
            (p->entry).value = value;
            link(md->sentinel.prev, p, &(md->sentinel));
            md->size++;
        } else {
            free(p);
        }
    }
    return status;
}

static bool m_put(const CSKMap *m, char *key, void *value) {
    MData *md = (MData *)m->self;
    Node *p = findKey(md, key);
    bool status = (p != NULL);

    if (status) {
        md->freeV((p->entry).value);
        (p->entry).value = value;
    } else {
        status = insertEntry(md, key, value);
    }
    return status;
}

static bool m_putUnique(const CSKMap *m, char *key, void *value) {
    MData *md = (MData *)m->self;
    Node *p = findKey(md, key);
    bool status = (p == NULL);
```

```
    if (status)
        status = insertEntry(md, key, value);
    return status;
}
```

Note that when we add a new node to the list that we make a copy of the key on the heap using `strdup()`; you might think that we could just have our entry point to the `key` passed to us by the caller. The caller is under no obligation to maintain that key value at that address over time; in order to implement the map semantics, we must make a copy of the `key`.

12.2.5 `remove()`

Armed with `findKey()`, the implementation of this method is straightforward. Note that we use the `unlink()` function from the Deque implementation here, as well.

```
static bool m_remove(const CSKMap *m, char *key) {
    MData *md = (MData *)m->self;
    Node *p = findKey(m, key);
    bool status = (p != NULL);

    if (status) {
        unlink(p);
        md->size--;
        free(p->entry.key);
        md->freeV((p->entry).value);
        free(p);
    }
    return status;
}
```

12.2.6 Running time complexity of these methods

Since each of these methods invokes `findKey()`, their running time complexities will be the same as that for `findKey()`. `findKey()` searches through each entry in the list, returning if it finds an entry with that `key`, or going through the entire list to determine that no such entry exists. In either situation, `findKey()` has to touch some fraction of the entire list, and it thus has a running time complexity of $O(n)$. If we wish to store a large number of entries in a Map, it will be very costly in running time.

You might think that if we kept the entries in the list sorted by key that it would affect the running time complexity. Unfortunately, it will have no effect on the complexity, since the nodes are not contiguous in memory; if they were, we could use a binary search, reducing the complexity to $O(\log n)$.

12.3 Hash tables to the rescue

We would like a data structure that can be used to implement a map such that each of the essential Map methods are typically $O(1)$ running time complexity; the worst case complexity should certainly be no worse that for a list-based implementation, $O(n)$. A very efficient way to implement a map is to use a *hash table*.

A hash table consists of two components: an array for organizing the storage of (key, value) pairs, and a *hash function*. The hash function, which we will discuss a little later, maps from a `key` to an integer in the range [0..N-1], where N is the size of the array. For a given `key`, `hash(key)` returns an index into the array at which the `value` associated with that `key` is "stored" - i.e., it is either at that index or nearby.

Two types of organizing arrays are commonly used:

- for *open hashing*, the array contains the (key, value) pairs themselves; and
- for *bucket hashing*, the array contains the header of a LIFO linked list of entries with `key`s that hash to that index.

In this textbook, we will use bucket hashing; your next course on data structures and algorithms will expose you to open hashing.

12.3.1 The bucket array

The instance-specific data structure for a hash table consists of an integer `N`, which is the size of the array of listheads, and the array of listheads, often called the *bucket array*. Each element of the array can be thought of as a "bucket" containing all (key, value) pairs for which `hash(key)` returns the index for that cell; the number of array elements is sometimes called the *capacity* of the array.

Given a hash function, an insertion into our hash table requires that we

1. compute the index into the bucket array by invoking the hash function on the key;
2. look at each node in the bucket to see if there is already an entry with the specified key;
3. if so, either replace the value and return true/1 (`put()`) or return false/0 (`putUnique()`);
4. if not, generate a node for insertion at the beginning of the linked list at that index and return true/1.

`containsKey()` and `get()` require that we

1. compute the index into the bucket array by calling the hash function on the key;
2. look at each node in the bucket to see if there is an entry with the specified key;
3. if so, either return true/1 (`containsKey()`) or return true/1 and the corresponding value (`get()`);
4. if not, return false/0.

`remove()` requires that we

1. compute the index into the bucket array by calling the hash function on the key;
2. look at each node in the bucket to see if there is an entry with the specified key; **N.B.** while scanning the linked list of nodes in the bucket, we must remember the previous node in order to be able to remove the matching node from the list;
3. if so, return true/1 after unlinking the matching node and freeing heap-allocated storage;
4. if not, return false/0.

Thus, we can see that the running time complexity for these methods depends heavily upon how well the hash function distributes the `key`s over the N buckets. Let's look at some limiting cases.

- Suppose that `hash(key)` always returns the value 0; in this case, our hash table simply degenerates into a single LIFO linked list. We already know that the running time complexity for these five methods is $O(n)$ for such an implementation. Obviously, such a hash function is not a "good" one.
- Suppose that `N > M` (number of items to be stored in the table). A *perfect* hash function would generate no collisions - i.e., each of the buckets would contain 0 or 1 entry. If we had a perfect hash function, the running time complexity for these five methods would be $O(1)$; this is the goal for which we should strive.
- Even if `M > N`, a "good" hash function would evenly distribute the items over the `N` listheads, such that these five methods would display running time complexity of $O(M/N)$.

It is this last type of hash function that we will explore in the next section.

12.3.2 Hash functions

A "good" hash function is a function that:

- when applied to a `key`, returns a number;
- when applied to `key`s that are *equal*, returns the same number for each;
- when applied to `key`s that are *unequal*, is *very unlikely* to return the same number for each.

When two or more unequal `key`s hash to the same value, this is called a *collision*. Since two or more entries can be in a single bucket, it means that we must store the (key, value) pairs in the bucket, and when looking for a particular `key`, we first hash to the bucket, and then compare our `key` with the `key` stored with each entry in the bucket.

Hash functions are often described as having two phases:

1. mapping the `key` to an unsigned integer, and
2. converting that integer to an index in the range `[0..N-1]`.

Typically, the conversion step is achieved by applying the modulus function (`%`) to the unsigned integer from the first step.

12.3.2.1 Hash functions for character string keys

Since we are focused on Maps for which the keys are character strings, let's look at some different hash functions and how well they distribute keys over the bucket array. Each of the hash functions will conform to the following signature:[1]

```
long hashx(char *key, long N);
```

Summing characters The simplest approach to a hash function for character strings is to simply sum the values of the UTF8 characters in the string.

```
long hash1(char *key, long N) {
    unsigned long sum = 0L;
    char *p;

    for (p = key; *p != '\0'; p++)
        sum += (unsigned long)(*p);
    return (long)(sum % N);
}
```

If `N` is small compared to the sums that are generated, this function should do a reasonable job distributing the keys evenly across the bucket array. If `N` is large compared to the sums that are generated, this function will do a very poor job of key distribution. For example, consider words in a dictionary where all letters are lower case. The UTF8 value for `'a'` is 97, and for `'z'` is 122. A dictionary file on Linux contains 124,801 words, with the average word length being 7.91 characters per word. Assuming 8 characters for the sake of simplicity, the sums generated for these words will fall predominantly in the range of 776 .. 976. If we assume even distribution across the buckets, with 124 thousand words we would probably want 200 thousand buckets; unfortunately, this hash function would put most of the words in a very small number of buckets relative to `N`. Thus, this is not a very good hash function.

[1] We are depending upon a long integer consisting of 8 bytes/64 bits, and the second parameter (`N`) being positive.

Polynomial hashing The previous hash function ignores character order. Perhaps we can do a better job if we can somehow take character order into account.

A character string `s` can be viewed as a tuple of the form

$$(s_0, s_1, ..., s_{m-1})$$

where m is the number of characters in the string.

If we pick a positive integer $a \neq 1$, we can compute an integer representing the string using the following polynomial form:

$$s_0 a^{m-1} + s_1 a^{m-2} + \ldots + s_{m-2} a + s_{m-1}.$$

We can obviously expand this polynomial form into:

$$s_{m-1} + a(s_{m-2} + a(s_{m-3} + \ldots + a(s_2 + a(s_1 + a s_0)) \ldots)).$$

Here is an implementation of a hash function using this polynomial form:

```
#define A 31L
long hash2(char *key, long N) {
    unsigned long sum = 0L;
    char *p;

    for (p = key; *p != '\0'; p++)
        sum = A * sum + (unsigned long)(*p);
    return (long)(sum % N);
}
```

If you think about the bit representation of an integer, multiplying by a positive number tends to move the bits to the left - i.e. to higher order bits; in fact, if `A == 32`, this would correspond exactly to shifting `sum` 5 bits left in memory. Thus, multiplication by `A` mixes more of the summation into higher order bits.

Choice of the value for `A` requires some experimentation. We show the number of collisions that occur as a function of the value of `A` for a dictionary file below.

In general, it is a good idea if `A` and `N` are mutually prime, as this improves the distribution of strings over the bucket array. It is common for `N` to be a power of 2; therefore, one should choose `A` to be a prime number.

Cyclic shift hashing C provides syntactic support for shifting variables by an integer number of bits as described in section 3.3.10. The next type of hash function requires this capability.

Recall that if n is an unsigned integer type, then $n << 2$ shifts the value of n by 2 bits left, equivalent to multiplying n by 4; the vacated low order bits are filled with 0. The two high order bits of n are shifted out of the variable.

Likewise, recall that $n >> 3$ shifts the value of n by 3 bits to the right, equivalent to division by 8; the vacated bits are filled with 0.

Finally, recall that $n \mid 0x11$ sets bits 0 and 4 in n to 1, leaving all others alone.

Armed with these bit operations, we can now define a cyclic shift hash function.

```
#define B 5
unsigned long rotate(unsigned long value) {
    static int bits = 8 * sizeof(unsigned long);
    unsigned long ans = value;

    if (B != 0)
        ans = (value << B) | (value >> (bits - B));
    return ans;
}

long hash3(char *key, long N) {
    unsigned long sum = 0L;
    char *p;

    for (p = key; *p != '\0'; p++)
        sum = rotate(sum) + (unsigned long)*p;
    return (long)(sum % N);
}
```

Once again, our hash function has a free paramenter, `B`, which is the number of bits by which the current sum should be rotated; we will need to tune this value. In the next section we show how the number of collisions varies with the value of `B`.

Performance of these hash functions As described earlier, we have a dictionary file that contains 124,801 words, all in lower case. We have tested the three hash functions on the words in that file, and measured the total number of collisions over all buckets (denoted “total” in the table) as well as statistics on the number of collisions per bucket: maximum, mean, median, and standard deviation. For `hash2()` and `hash3()`, we quote these statistics for different values of `A` and `B`, respectively.

Function	Total	Minimum	Maximum	Mean	Median	Std Dev
hash1	123,237	0	639	78.8	18	128.3
hash2(A=1)	123,237	0	639	78.8	18	128.3
hash2(A=7)	6,072	0	6	0.0522	0	0.261
hash2(A=19)	806	0	2	0.00650	0	0.0812
hash2(A=29)	642	0	1	0.00517	0	0.0717
hash2(A=31)	642	0	1	0.00517	0	0.0717
hash2(A=37)	642	0	1	0.00517	0	0.0717
hash2(A=73)	642	0	1	0.00517	0	0.0717
hash2(A=129)	642	0	1	0.00517	0	0.0717
hash2(A=257)	642	0	1	0.00517	0	0.0717
hash2(A=511)	642	0	1	0.00517	0	0.0717
hash3(B=0)	123,237	0	639	78.8	18	128.3
hash3(B=1)	91,185	0	51	2.71	0	5.21
hash3(B=3)	4,432	0	5	0.0368	0	0.208
hash3(B=5)	642	0	1	0.00517	0	0.0717
hash3(B=7)	642	0	1	0.00517	0	0.0717
hash3(B=9)	655	0	1	0.00528	0	0.0724
hash3(B=13)	1,114	0	3	0.00901	0	0.0972
hash3(B=17)	702	0	2	0.00566	0	0.0752
hash3(B=21)	7,800	0	5	0.0667	0	0.287
hash3(B=25)	821	0	2	0.00662	0	0.0818
hash3(B=29)	642	0	1	0.00517	0	0.0717

Note that the statistics are the same for `hash1()`, `hash2(A=1)`, and `hash3(B=0)`; this is exactly as expected.

Also note that with a file this large, these hash functions cannot achieve fewer than 642 total collisions. The worst case is for `hash1()`, where the largest bucket has 639 entries, and the average number of collisions is 78.8. It is clear that `hash1()` is a very poor choice for a task such as this.

The variation of `hash2()` collision statistics as a function of `A` shows that for even small values of `A`, the maximum drops quite rapidly. By the time that `A = 29`, we have reached the best collision statistics for this set of data; for values of `A` larger than that value, the overall statistics remain the same.

The variation of `hash3()` collision statistics as a function of `B` shows that a value of `B = 5` gives us the same overall statistics as `hash2()` with a value of `A = 31`; not particularly surprising, since rotating left by 5 bits is the same as multiplying by 32. For larger `B` values, the overall statistics become ever so slightly worse.

Given these results, we will use a `hash2()` function in our HashCSKMap implementation, with `A = 31`.

12.3.2.2 Hash functions for integer keys

While the `CSKMap` ADT requires C string keys, you may have a need to use integer keys in the generic Map that we will discuss in the next section.

The simplest hash function we could try if the keys are long integers is as follows:

```
long hash(long key, long N) {
    unsigned long ans = (unsigned long)key;
    return (long)(ans % N);
}
```

- i.e., we simply return the key modulo the number of buckets. This would work, but would not guarantee that you would distribute your entries evenly over the buckets in the hash table.

There has been significant research into high-speed, integer hash functions, particularly focused on implementation of cryptographic hash functions[2]. In fact, an entire book entitled "Hashing in Computer Science: Fifty Years of Slicing and Dicing" by Alan G. Korheim (ISBN-13: 978-0470344736) is devoted to the subject.

Of particular importance for such hash functions is that they exhibit the *Avalanche effect* - i.e., flipping a single bit in the input key should results in all output bits changing with a probability of 0.5[3]. One of the best general purpose hash functions today is MurmurHash3, available at `http://code.google.com/p/smhasher/`. MurmurHash3 uses a sequence of XOR MUL XOR MUL XOR[4] operations on the key. D. Stafford performed a series of tests[5] using the general structure of MurmurHash3 and changed some of the free parameters to see if he could improve on the hash function's conformance to the Avalanche effect.

Here is a slight variation on the best performing version of that hash function.[6]

```
#include <stdint.h>
long hash(long key, long N) {
    uint64_t k = (uint64_t)key;
    k ^= (k >> 30);
    k *= 0xbf58476d1ce435b9;
```

[2] For example, see "High Speed Hashing for Integers and Strings", M Thorup, arXiv:1504.06804v9 [cs.DS], 9 May 2020.

[3] See the discussion at `http://zimbry.blogspot.com/2011/09/better-bit-mixing-improving-on.html` by D. Stafford.

[4] XOR is an exclusive or logical operation on a pair of integers, and MUL is a multiply operation on a pair of integers.

[5] ibid.

[6] The variation is to mask off the sign bit of `k` before performing the mod function in the return. This, inevitably, will reduce the efficacy of the hash function in terms of the avalanche effect, but should be in the noise for most uses with a hash table.

```
    k ^= (k >> 27);
    k *= 0x94d049bb133111eb;
    k ^= (k >> 31);
    return (k & 0x7fffffffffffffff) % N;
}
```

12.4 A hash table-based CSKMap implementation

We provide an additional header file, "ADTs/hashcskmap.h", which defines the following constructor to obtain a hash table CSKMap implementation.

```
const CSKMap *HashCSKMap(long capacity, double loadFactor,
                         void (*freeV)(void *v));
```

A hash table needs to know what size of bucket array to create; it could start with a default size, and then resize when performance required; alternatively, the user could specify a *capacity* argument to the constructor so that the implementation starts out at an appropriate size for the problem at hand. If `capacity` is specified as `0L`, a default capacity is used.

Another performance aspect of a hash table is the ratio of the number of entries in the table divided by the number of buckets - this is usually called the *load factor*. It should be apparent that once the load factor gets large, each bucket is a substantial linked list, and the table performance will suffer. We would like to enable the user to specify a target load factor in the call to the constructor; if an addition to the table causes the current load factor to exceed that target, the bucket array should be made larger, and the entries should be redistributed in the new, larger array. If `loadFactor` is specified as `0.0`, a default value is used.

And, of course, we still require a function pointer to manage the value portion of each entry.

12.4.1 The preliminaries

Besides the usual includes and structure definitions, we also include our version of `hash2()` using `A = 31`.

```
/* BSD Header removed to conserve space */

/*
 * implementation for C string key hashmap
 */

```

```
#include "ADTs/hashcskmap.h"
#include <stdlib.h>
#include <string.h>

#define DEFAULT_CAPACITY 16
#define MAX_CAPACITY 134217728L
#define DEFAULT_LOAD_FACTOR 0.75
#define TRIGGER 100 /* number of changes that will trigger a load check */

typedef struct node {
    struct node *next;
    MEntry entry;
} Node;

typedef struct m_data {
    long size;
    long capacity;
    long changes;
    double load;
    double loadFactor;
    double increment;
    Node **buckets;
    void (*freeValue)(void *v);
} MData;

/*
 * generate hash value from key; value returned in range of 0..N-1
 */
#define SHIFT 31L /* should be prime */
static long hash(char *key, long N) {
    unsigned long ans = 0L;
    char *sp;

    for (sp = key; *sp != '\0'; sp++)
        ans = SHIFT * ans + (unsigned long)*sp;
    return (long)(ans % N);
}
```

We define a default capacity as a small value (16). We also define a maximum capacity beyond which the bucket array will not grow. The default load factor implies that we want to keep the total number of entries in the table at 75% of the number of buckets. There is nothing that stops you from setting the target load factor to a number like 2.0, 10.0, or even larger, if you are working with a very big data set.

The members of the instance-specific data structure keep the following information:

- `size`: as with the other data structures that we have implemented, this data member is the number of entries in the map;
- `capacity`: this is the number of buckets in the hash table;
- `changes`: instead of checking the load factor on every insertion, this data member is a counter for the number of changes since the last load factor check; when it reaches

TRIGGER, the load factor will be checked, the table resized if necessary, and changes is reset to 0;
- load: this is the current load factor of the table underlying the map;
- loadFactor: this is the target load factor for the table;
- increment: this is the amount by which the current load factor increases when a new entry is inserted; load is incremented by this amount for each new insertion;
- buckets: this is the bucket array, an array of pointers to MEntry structures;
- freeV: this is the function pointer provided in the constructor for freeing values.

12.4.2 destroy() and clear()

A helper function is provided to apply freeV() to each entry, and to free the heap-allocated memory associated with each entry. The two methods then use this helper function to implement the required functionality.

```
/*
 * traverses the map, calling freeValue on each entry
 * then frees storage associated with the MEntry structure
 */
static void purge(MData *md) {
    long i;

    for (i = 0L; i < md->capacity; i++) {
        Node *p, *q;
        p = md->buckets[i];
        while (p != NULL) {
            free((p->entry).key);
            md->freeValue((p->entry).value);
            q = p->next;
            free(p);
            p = q;
        }
        md->buckets[i] = NULL;
    }
}

static void m_destroy(const CSKMap *m) {
    MData *md = (MData *)m->self;
    purge(md);
    free(md->buckets);
    free(md);
    free((void *)m);
}

static void m_clear(const CSKMap *m) {
    MData *md = (MData *)m->self;
    purge(md);
    md->size = 0;
```

```
    md->load = 0.0;
    md->changes = 0;
}
```

12.4.3 containsKey() and get()

A helper function is provided to find the entry that corresponds to `key`; if such an entry exists, the bucket index is returned in `*bucket`, and the `MEntry *` for that entry is the function return value. If no such entry exists, `NULL` is the function return value.

```
/*
 * helper function to locate key in a map
 *
 * returns pointer to entry, if found, as function value; NULL if not found
 * returns bucket index in `bucket'
 */
static Node *findKey(MData *md, char *key, long *bucket) {
    long i = hash(key, md->capacity);
    Node *p;

    *bucket = i;
    for (p = md->buckets[i]; p != NULL; p = p->next) {
        if (strcmp((p->entry).key, key) == 0) {
            break;
        }
    }
    return p;
}

static bool m_containsKey(const CSKMap *m, char *key) {
    MData *md = (MData *)m->self;
    long bucket;

    return (findKey(md, key, &bucket) != NULL);
}

static bool m_get(const CSKMap *m, char *key, void **value) {
    MData *md = (MData *)m->self;
    long i;
    Node *p = findKey(md, key, &i);
    bool status = (p != NULL);

    if (status)
        *value = (p->entry).value;
    return status;
}
```

12.4.4 put() and putUnique()

Two helper functions are provided to support these methods:

- `resize()` resizes the hash table. It attempts to double the number of buckets; if doing so takes it over `MAX_CAPACITY`, it limits the size to `MAX_CAPACITY`. If the capacity of the table is already at `MAX_CAPACITY`, it does nothing.
- `insertEntry()` inserts a new (key, value) pair into the bucket corresponding to index `i`. In that function, an `MEntry` is allocated, the `key` is duplicated on the heap and stored in the entry, the value is stored in the entry, and the entry is inserted at the head of that bucket (i.e., the bucket is a LIFO linked list). We also increment the size, increment the current load value, and increment the `changes` variable.

The methods each check if `changes > TRIGGER`, and if so, resize the table if `load > loadFactor`. They each attempt to find an entry corresponding to `key`. `putUnique()` returns an error if an entry is found, while `put()` just replaces the value in that entry. If an entry is not found, both methods invoke the insertion helper function.

```
/*
 * helper function that resizes the hash table
 */
static void resize(MData *md) {
    long N;
    Node *p, *q, **array;
    long i, j;

/* double capacity, unless exceeds max capacity;
 * if already at max capacity, simply return */
    N = 2 * md->capacity;
    if (N > MAX_CAPACITY)
        N = MAX_CAPACITY;
    if (N == md->capacity)
        return;
    array = (Node **)malloc(N * sizeof(Node *));
    if (array == NULL)
        return;
    for (j = 0; j < N; j++)
        array[j] = NULL;
    /*
     * now redistribute the entries into the new set of buckets
     */
    for (i = 0; i < md->capacity; i++) {
        for (p = md->buckets[i]; p != NULL; p = q) {
            q = p->next;
            j = hash((p->entry).key, N);
            p->next = array[j];
            array[j] = p;
        }
    }
```

```
    free(md->buckets);
    md->buckets = array;
    md->capacity = N;
    md->load /= 2.0;
    md->changes = 0;
    md->increment = 1.0 / (double)N;
}

/*
 * helper function to insert new (key, value) into table
 */
static bool insertEntry(MData *md, char *key, void *value, long i) {
    Node *p = (Node *)malloc(sizeof(Node));
    bool status = (p != NULL);

    if (status) {
        char *k = strdup(key);
        if (k != NULL) {
            (p->entry).key = k;
            (p->entry).value = value;
            p->next = md->buckets[i];
            md->buckets[i] = p;
            md->size++;
            md->load += md->increment;
            md->changes++;
        } else {
            free(p);
            status = false;
        }
    }
    return status;
}

static bool m_put(const CSKMap *m, char *key, void *value) {
    MData *md = (MData *)m->self;
    long i;
    Node *p;
    bool status = true;

    if (md->changes > TRIGGER) {
        md->changes = 0;
        if (md->load > md->loadFactor)
            resize(md);
    }
    p = findKey(md, key, &i);
    if (p != NULL) {
        md->freeValue((p->entry).value);
        (p->entry).value = value;
    } else {
        status = insertEntry(md, key, value, i);
    }
```

```
    return status;
}

static bool m_putUnique(const CSKMap *m, char *key, void *value) {
    MData *md = (MData *)m->self;
    long i;
    Node *p;
    bool status = false;

    if (md->changes > TRIGGER) {
        md->changes = 0;
        if (md->load > md->loadFactor)
            resize(md);
    }
    p = findKey(md, key, &i);
    if (p == NULL) {
        status = insertEntry(md, key, value, i);
    }
    return status;
}
```

12.4.5 `remove()`

The method searches for an entry matching the `key`. Then it scans the linked list in that bucket to determine the `MEntry` node that precedes the node being removed; the node is then unlinked from the list. `size` is decremented, `load` is decremented, and `changes` is incremented. Then the key and the entry are returned to the heap.

```
static bool m_remove(const CSKMap *m, char *key) {
    MData *md = (MData *)m->self;
    long i;
    Node *entry = findKey(md, key, &i);
    bool status = (entry != NULL);

    if (status) {
        Node *p, *c;
        /* determine where the entry lives in the singly linked list */
        for (p = NULL, c = md->buckets[i]; c != entry; p = c, c = c->next)
            ;
        if (p == NULL)
            md->buckets[i] = entry->next;
        else
            p->next = entry->next;
        md->size--;
        md->load -= md->increment;
        md->changes++;
        free((entry->entry).key);
        md->freeValue((entry->entry).value);
```

```
        free(entry);
    }
    return status;
}
```

12.4.6 size() and isEmpty()

These methods do the obvious thing with `size`.

```
static long m_size(const CSKMap *m) {
    MData *md = (MData *)m->self;
    return md->size;
}

static bool m_isEmpty(const CSKMap *m) {
    MData *md = (MData *)m->self;
    return (md->size == 0L);
}
```

12.4.7 keyArray()

A helper function allocates an appropriately-sized array of `char *` pointers for the keys that are defined in the map. The method then uses this function to return the array to the caller. **N.B.** the caller must invoke `free()` to return this array to the heap when no longer needed.

```
/*
 * helper function for generating an array of keys from a map
 *
 * returns pointer to the array or NULL if malloc failure
 */
static char **keys(MData *md) {
    char **tmp = NULL;
    if (md->size > 0L) {
        size_t nbytes = md->size * sizeof(char *);
        tmp = (char **)malloc(nbytes);
        if (tmp != NULL) {
            long i, n = 0L;
            for (i = 0L; i < md->capacity; i++) {
                Node *p = md->buckets[i];
                while (p != NULL) {
                    tmp[n++] = (p->entry).key;
                    p = p->next;
                }
            }
```

```
        }
    }
    return tmp;
}

static char **m_keyArray(const CSKMap *m, long *len) {
    MData *md = (MData *)m->self;
    char **tmp = keys(md);

    if (tmp != NULL)
        *len = md->size;
    return tmp;
}
```

12.4.8 entryArray() and itCreate()

A helper function allocates an appropriately-sized array of `MEntry *` pointers for the entries in the map. The methods then use this function to implement their functionality. **N.B.** the caller must invoke `free()` to return the array from `entryArray()` when no longer needed; the `destroy()` method on the iterator returned by `itCreate()` must be invoked when the iterator is no longer needed.

```
/*
 * helper function for generating an array of MEntry * from a map
 *
 * returns pointer to the array or NULL if malloc failure
 */
static MEntry **entries(MData *md) {
    MEntry **tmp = NULL;
    if (md->size > 0L) {
        size_t nbytes = md->size * sizeof(MEntry *);
        tmp = (MEntry **)malloc(nbytes);
        if (tmp != NULL) {
            long i, n = 0L;
            for (i = 0L; i < md->capacity; i++) {
                Node *p = md->buckets[i];
                while (p != NULL) {
                    tmp[n++] = &(p->entry);
                    p = p->next;
                }
            }
        }
    }
    return tmp;
}

static MEntry **m_entryArray(const CSKMap *m, long *len) {
    MData *md = (MData *)m->self;
```

```
    MEntry **tmp = entries(md);

    if (tmp != NULL)
        *len = md->size;
    return tmp;
}

static const Iterator *m_itCreate(const CSKMap *m) {
    MData *md = (MData *)m->self;
    const Iterator *it = NULL;
    void **tmp = (void **)entries(md);

    if (tmp != NULL) {
        it = Iterator_create(md->size, tmp);
        if (it == NULL)
            free(tmp);
    }
    return it;
}
```

12.4.9 The constructor

The usual creation of a template so that we can construct a valid dispatch table at link time. We create a helper function to perform the usual memory allocations for the dispatch table, the instance-specific data structure, and the bucket array; this helper function also has logic to use defaults for the capacity and load factor if nothing is provided by the caller. If all allocations are successful, then the various members of the instance-specific data structure are filled in.

The helper function is followed by implementatins of the `create()` method, `CSKMAP_create()` which uses defaults for the capacity and load factor, and `HashCSKMap()`.

```
static const CSKMap *m_create(const CSKMap *m);

static CSKMap template = {
    NULL, m_create, m_destroy, m_clear, m_containsKey, m_get, m_put,
    m_putUnique, m_remove, m_size, m_isEmpty, m_keyArray, m_entryArray,
    m_itCreate
};

/*
 * helper function to create a new CSKMap dispatch table
 */
static const CSKMap *newCSKMap(long capacity, double loadFactor,
                         void (*freeValue)(void *)) {
    CSKMap *m = (CSKMap *)malloc(sizeof(CSKMap));
    long N;
```

```
    double lf;
    Node **array;
    long i;

    if (m != NULL) {
        MData *md = (MData *)malloc(sizeof(MData));

        if (md != NULL) {
            N = ((capacity > 0) ? capacity : DEFAULT_CAPACITY);
            if (N > MAX_CAPACITY)
                N = MAX_CAPACITY;
            lf = ((loadFactor > 0.000001) ? loadFactor : DEFAULT_LOAD_FACTOR);
            array = (Node **)malloc(N * sizeof(Node *));
            if (array != NULL) {
                md->capacity = N;
                md->loadFactor = lf;
                md->size = 0L;
                md->load = 0.0;
                md->changes = 0L;
                md->increment = 1.0 / (double)N;
                md->freeValue = freeValue;
                md->buckets = array;
                for (i = 0; i < N; i++)
                    array[i] = NULL;
                *m = template;
                m->self = md;
            } else {
                free(md);
                free(m);
                m = NULL;
            }
        } else {
            free(m);
            m = NULL;
        }
    }
    return m;
}

static const CSKMap *m_create(const CSKMap *m) {
    MData *md = (MData *)m->self;

    return newCSKMap(md->capacity, md->loadFactor, md->freeValue);
}

const CSKMap *CSKMap_create(void (*freeValue)(void *v)) {
    return newCSKMap(DEFAULT_CAPACITY, DEFAULT_LOAD_FACTOR, freeValue);
}

const CSKMap *HashCSKMap(long capacity, double loadFactor,
                         void (*freeValue)(void *v)) {
```

```
    return newCSKMap(capacity, loadFactor, freeValue);
}
```

12.5 Maps with generic keys

While the discussion in the preceding sections has restricted keys to character strings, we have all the tools we need to enable the creation and manipulation of maps that support generic keys. Not surprisingly, since keys are now represented as `void *`, the constructors and method signatures are all different.

`"ADTs/map.h"` defines the dispatch table and the MEntry structure. Note that it does not define an implementation-independent constructor. To create a map supporting generic keys, one must invoke an implementation-specific constructor.

First, we will show the relevant header files. Then, we will show the linked list and hash table implementations in their entirety.

12.5.1 Hash function considerations

The move to generic keys, in which a key is represented as a `void *`, requires that the user provide a function pointer to a hash function that conforms to the following signature:[7]

```
long (*hash)(void *key, long N);
```

If the keys are character strings, then you need to define in your code a function like the following:

```
#define SHIFT 31L
long hash(void *key, long N) {
    char *sp = (char *)key;
    unsigned long ans;
    for ( ; *sp != '\0'; sp++)
        ans = SHIFT * ans + (unsigned long)*sp;
    return (long)(ans % N);
}
```

i.e., we have simply used the same hash function we used in our CSKMap implementation, with the additional requirement that we cast the `void *` to a `char *`.

If the keys are long integers, then you need to define in your code a function like the following:

[7] As in our previous discussions of hash functions, those shown in this section depend upon a long integer occupying 8 bytes/64 bits, and the value of `N` being positive.

```
#include <stdint.h>
long hash(void *key, long N) {
    uint64_t k = (uint64_t)key;
    k ^= (k >> 30);
    k *= 0xbf58476d1ce435b9;
    k ^= (k >> 27);
    k *= 0x94d049bb133111eb;
    k ^= (k >> 31);
    return (k & 0x7fffffffffffffff) % N;
}
```

- i.e., it is the code we described previously with a long integer key, except we cast the `void *key` to a `uint64_t`.

12.5.2 The interfaces

12.5.2.1 map.h

```
#ifndef _MAP_H_
#define _MAP_H_

/* BSD Header removed to conserve space */

#include "ADTs/ADTdefs.h"
#include "ADTs/iterator.h"              /* needed for factory method */

/* interface definition for generic map implementation */

typedef struct map Map;             /* forward reference */
typedef struct mentry {
    void *key;
    void *value;
} MEntry;

/* now define struct map */
struct map {
/* the private data for the map */
    void *self;

/* create a new map using the same implementation as the map upon which
 * the method has been invoked; returns NULL if error creating the new map
 */
    const Map *(*create)(const Map *m);

/* destroys the map;
 * applies constructor-specified freeK and freeV to each element in the map
```

```
 * the storage associated with the map is returned to the heap */
    void (*destroy)(const Map *m);

/* clears all (key,value) pairs from the map;
 * applies constructor-specified freeK and freeV to each element in the map
 * the map is then re-initialized
 *
 * upon return, the map is empty */
    void (*clear)(const Map *m);

/* returns true if key is contained in the map, false if not */
    bool (*containsKey)(const Map *m, void *key);

/* returns the value associated with key in *value; returns true if key was
 * found in the map, false if not */
    bool (*get)(const Map *m, void *key, void **value);

/* puts (key,value) into the map;
 * applies constructor-specified freeK and freeV if there was a previous entry
 *
 * returns true if (key,value) was successfully stored in the map,
 * false if not */
    bool (*put)(const Map *m, void *key, void *value);

/* puts (key,value) into the map iff the map does not contain a value associated
 * with key
 *
 * returns true if (key,value) was successfully stored in the map,
 * false if not */
    bool (*putUnique)(const Map *m, void *key, void *value);

/* removes the (key,value) pair from the map;
 * applies constructor-specified freeK and freeV to the removed entry
 *
 * returns true if (key,value) was present and removed,
 * false if it was not present */
    bool (*remove)(const Map *m, void *key);

/* returns the number of (key,value) pairs in the map */
    long (*size)(const Map *m);

/* returns true if the map is empty, false if not */
    bool (*isEmpty)(const Map *m);

/* returns an array containing all of the keys in the map; the order is
 * arbitrary; returns the length of the array in *len
 *
 * returns a pointer to the array of void * keys, or NULL if malloc failure
 *
 * NB - the caller is responsible for freeing the void * array when finished
 * with it */
```

```
    void **(*keyArray)(const Map *m, long *len);

/* returns an array containing all of the (key,value) pairs in the map;
 * the order is arbitrary; returns the length of the array in *len
 *
 * returns a pointer to the MEntry * array of (k,v) pairs,
 * or NULL if malloc failure
 *
 * NB - the caller is responsible for freeing the MEntry * array when finished
 * with it */
    MEntry **(*entryArray)(const Map *m, long *len);

/* create generic iterator to the map
 *
 * returns pointer to the Iterator or NULL if malloc failure
 *
 * NB - when the next() method on the iterator is called, it returns an
 *      MEntry *
 */
    const Iterator *(*itCreate)(const Map *m);
};

#endif /* _MAP_H_ */
```

12.5.2.2 llistmap.h

```
#ifndef _LLISTMAP_H_
#define _LLISTMAP_H_

/* BSD Header removed to conserve space */

#include "ADTs/ADTdefs.h"
#include "ADTs/map.h"

/* constructor for generic linked list map */

/* create a linked list map
 *
 * returns a pointer to the linked list map, or NULL if there are malloc errors
 *
 * the cmp function pointer is applied to a pair of keys, yielding <0 | 0 | >0
 *
 * freeK is a function pointer that will be called by destroy(),
 * clear(), put(), and remove() on keys of relevant entry/entries in the Map
 *
 * freeV is a function pointer that will be called by destroy(),
 * clear(), put(), and remove() on values of relevant entry/entries in the Map
 */
```

```
const Map *LListMap(int (*cmp)(void*, void*), void (*freeK)(void *k),
                    void (*freeV)(void *v));

#endif /* _LLISTMAP_H_ */
```

12.5.2.3 hashmap.h

```
#ifndef _HASHMAP_H_
#define _HASHMAP_H_

/* BSD Header removed to conserve space */

#include "ADTs/ADTdefs.h"
#include "ADTs/map.h"

/* constructor for generic hashmap */

/* create a hashmap
 *
 * returns a pointer to the hashmap, or NULL if there are malloc errors
 *
 * the hash function pointer is applied to a key to yield a bucket index
 *
 * the cmp function pointer is applied to a pair of keys, yielding <0 | 0 | >0
 *
 * freeK is a function pointer that will be called by destroy(),
 * clear(), put(), and remove() on keys of relevant entry/entries in the Map
 *
 * freeV is a function pointer that will be called by destroy(),
 * clear(), put(), and remove() on values of relevant entry/entries in the Map
 */
const Map *HashMap(long capacity, double loadFactor,
                   long (*hash)(void*, long N), int (*cmp)(void*, void*),
                   void (*freeK)(void *k), void (*freeV)(void *v));

#endif /* _HASHMAP_H_ */
```

12.5.3 The implementations

The generic Map implementation using a linked list is shown in B.7.

The generic Map implementation using a hash table is shown in B.8.

12.5.4 An example program using the generic Map interface

Suppose that each line of a file consisted of a keyword, a blank separator, and a string value to associate with that keyword. We need to load each (key, value) pair from the file into a map for some subsequent processing. This section shows how we would do so using the generic Map interface.

```
#include "ADTs/hashmap.h"
#include <string.h>
#include <stdlib.h>
#include <stdio.h>

#define UNUSED __attribute__((unused))

/*
 * need to define the hash and compare functions used by the generic hashmap
 */
#define SHIFT 31L
long hash(void *value, long N) {
    char *sp = (char *)value;
    unsigned long ans;

    for ( ; *sp != '\0'; sp++)
        ans = SHIFT * ans + (unsigned long)*sp;
    return (long)(ans % N);
}

int cmp(void *v1, void *v2) {
    return strcmp((char *)v1, (char *)v2);
}

int main(UNUSED int argc, UNUSED char *argv[]) {
    const Map *m;
    char buf[4096];

    if ((m = HashMap(1024L, 2.0, hash, cmp, free, free)) == NULL) {
        fprintf(stderr, "Unable to create Map to hold (key, value) pairs\n");
        return EXIT_FAILURE;
    }
    while (fgets(buf, sizeof buf, stdin) != NULL) {
        int n = strlen(buf) - 1;
        char *sp, *vp, *kp;
        if (buf[n] == '\n')
            buf[n] = '\0';          /* overwrite newline character */
        sp = strchr(buf, ' ');      /* find the blank */
        *sp++ = '\0';               /* replace with EOS, sp points to value */
        kp = strdup(buf);           /* make a copy on the heap */
        vp = strdup(sp);            /* make a copy on the heap */
        if (! m->putUnique(m, ADT_VALUE(kp), ADT_VALUE(vp))) {
            fprintf(stderr, "%s is not a unique key\n", buf);
```

```
            free(kp);
            free(vp);
        }
    }
    /* code to use the map */
    m->destroy(m);   /* destroy map, each key and value is freed */
    return EXIT_SUCCESS;
}
```

Exercise 12.1. Recall our word frequency problem from Exercise 2.6 on page 40.
You had been asked to determine the frequency of words used in a file.
In that exercise, we solved the problem using a sophisticated pipeline of standard Linux commands.
In this exercise, you are to solve the same problem by writing a program in C, and using some of the ADTs that we have developed during the course of the book.
You are to read each line on standard input. Each line is to be broken up into separate words; as in the previous exercise, a "word" is a sequence of non-whitespace characters, separated from other words by a blank, tab, or end of line.
Your program is to be *case-insensitive* - i.e., "this" and "This" are to be counted as the same word.
After processing the entire file, your program should print the following for each word, one per line:

```
number_of_occurrences the_word
```

In otherwords, the number of occurrences as a decimal integer should be printed first, followed by a single blank character, followed by the word in question, followed by a newline character.
Hint: you should use the stringADT abstract data type to enable you to break each line up into words and to fold words to lower case.
Hint: you should use the CSKmap data type implemented using a hash table to track the number of times each word has been detected in the file.

Exercise 12.2. You want to construct a note by cutting out words from a magazine. First, though, you need to write a computer program that takes a list of words in a magazine and a list of the words you want to use in your note and answers whether it's possible to construct the note from the magazine.
Your program should take a single command-line argument, which will be a filename. The input file consists of exactly three lines. All words will contain only letters.
The first line of the input file is two integers x and y separated by a space, with $1 \leq x, y \leq 10^6$.
The first integer x denotes how many words are in the magazine. The second integer y denotes how many words are in the note.
The second line contains a space-separated list of words in the magazine. The third line contains a space-separated list of the words in the note. The lists are case-sensitive and repetition-sensitive (i.e. the same word can be listed more than once in a list).
Your program should output to stdout the word "YES" if it's possible to construct the note from the magazine or "NO" if it's not possible, followed by a single newline character.
The runtime complexity of your solution should be $O(x + y)$.
Hint: to achieve this runtime, use the CSKMap data type implemented using a hash table
Example inputs and the resulting outputs.

Input	Output

`5 2`
`Hello Cat Dog World Fish`
`Hello World`
	`YES`

`5 2`
`Hello Cat Dog world Fish`
`Hello World`
	`NO`

`5 3`
`Hello Cat Dog World Fish`
`Hello Hello World`
	`NO`

Chapter 13

Heaps

The last data structure that we will introduce is a *heap*. Like an array and a linked list, a heap is a lower-level data structure that we can use to implement high-level data structures and algorithms. In particular, after we have introduced the concept of a heap, we will demonstrate using a heap to implement a priority queue with $\log_2 N$ complexity for insertion and removal, as well as another sort algorithm that demonstrates $N \log_2 N$ complexity.

13.1 What is a heap?

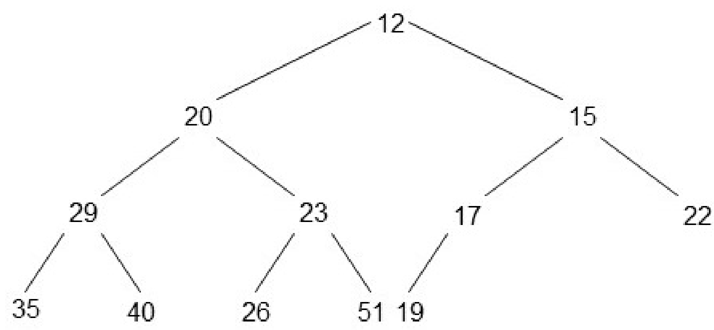
A heap is a data structure for representing an ordered collection of items - just what we need for a priority queue or a sorted set of items. Elements of a heap can be any ordered type.

There are two types of heap, differing only in how the items in the heap are ordered:

- a minHeap - in a minHeap, the items are ordered from smallest to largest; and
- a maxHeap - in a maxHeap, the items are ordered from largest to smallest.

As you might expect, we will use a minHeap to implement a priority queue; it turns out that a maxHeap is the correct version to implement heapsort, shown later in the chapter. The rest of this section uses minHeaps.

For example, here is a minHeap of 12 integers:

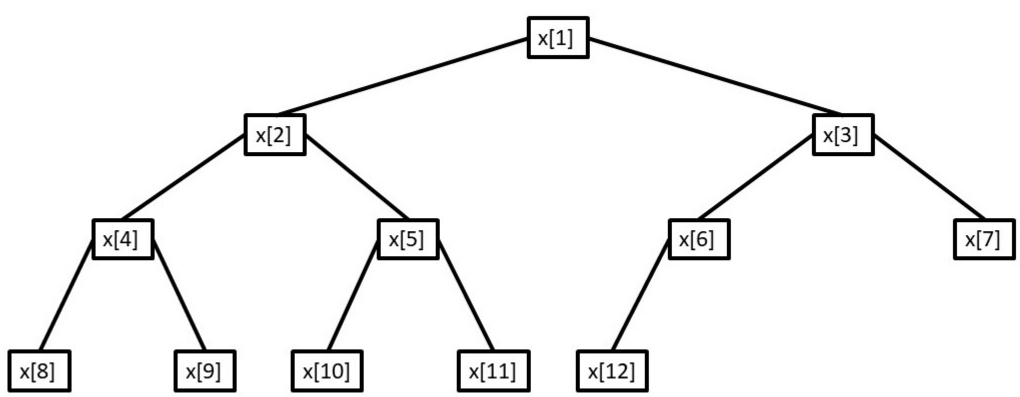


This is an example of a binary tree - i.e., each node has 0, 1, or 2 children. This binary tree is a heap by virtue of two properties:

- *order* - the value at any node is less than or equal to the values of the node's children; this implies that the least element in the bag[1] of numbers is at the root of the tree (12 in this case), but it does *not* say anything about the relative order of the left and right children; and
- *shape* - a heap has its terminal nodes on at most two levels, with those on the bottom level as far left as possible; if it contains N nodes, no node is at a distance of more than $\log_2 N$ levels from the root.

These two properties are restrictive enough to enable us to find the minimum element in a bag[2] of items, but lax enough so that we can efficiently reorganize the structure after inserting or deleting an element.

Despite a heap being a binary tree, there is a *very* efficient way to represent the heap without using pointers - this is because a heap possesses the *shape* property. A 12-element tree with the shape property is represented in a 12-element array $x[1]$ ... $x[12]$ as:



Note that heaps use a 1-based array (we will see why in a few lines); the easiest approach in C is to declare $x[N+1]$ and not use element $x[0]$. In this implicit representation of a

[1] Unlike a set, in which duplicate values are *not* permitted, a bag permits duplicate values.

[2] A bag is also referred to as a multiset.

binary tree with the *shape* property, the root is $x[1]$, its two children are $x[2]$ and $x[3]$, etc. The typical functions on a tree become:

- root = 1
- value(i) = x[i]
- leftchild(i) = 2*i
- rightchild(i) = 2*i + 1
- parent(i) = i / 2 (integer division)

A C declaration for the 12-element tree shown above would be

```
int x[12+1] = {0, 12, 20, 15, 29, 23, 17, 22, 35, 40, 26, 51, 19};
```

Because the shape property is guaranteed by the representation, the name *minHeap* will mean that the value of any node is greater than or equal to the value of its parent. Phrased precisely, the array $x[1]$ ... $x[N]$ has the heap property if

$$\forall_{2\leq i\leq N}\ x[i/2] \leq x[i].$$

This works correctly since integer division rounds down, so 4/2 and 5/2 both yield a parent of 2. We will need to be able to talk about a subarray $x[l]...x[u]$ having the *heap* property, so we will mathematically define $heap(l, u)$ as

$$\forall_{2l\leq i\leq u}\ x[i/2] \leq x[i].$$

13.2 Two critical functions

When we add another element to a heap, assuming that the heap currently occupies $x[1]...x[N-1]$, the easiest thing to do is to place the new element in $x[N]$. Unfortunately, $heap(1, N)$ will most likely not be true. Therefore, we need an efficient algorithm to modify $x[1]...x[N]$ such that $heap(1, N)$ is true. The function that re-establishes the *heap* property is called *siftup*.

The code for `siftup()` is as follows:

```
void siftup(int x[], int n) {
/*
 * preconditions: n > 0 && heap(1, n-1)
 * postcondition: heap(1,n)
 */
    int p, i = n;

    while (i > 1) {
        int tmp;
```

```
        p = i/2;
        if (x[p] <= x[i])
            break;
        tmp = x[p];
        x[p] = x[i];
        x[i] = tmp;
        i = p;
    }
}
```

If $heap(1, N)$ is true, and we remove $x[1]$, we would like to move the $N-1$ remaining elements into $x[1]...x[N-1]$, but we need to re-establish $heap(1, N-1)$. The easiest way to do this is to place $x[N]$ into $x[1]$, and then re-establish $heap(1, N-1)$. The function *siftdown* re-establishes our heap property.

```
void siftdown(int x[], int n) {
/*
 * preconditions: heap(2,n) && n >= 0
 * postcondition: heap(1, n-1)
 */
   int c, i;

    i = 1;
    for (;;) {
        int tmp = x[i];
        c = 2 * i;
        if (c > n)
            break;
        if ((c+1) <= n && x[c+1] < x[c])
            c++;
        if (tmp <= x[c])
            break;
        x[i] = x[c]
        x[c] = tmp;
        i = c;
    }
}
```

Note that `siftup()` and `siftdown()` shown above are correct for re-establishing the heap property of a minHeap. For a maxHeap, these functions should invert the nature of the comparisons.

13.3 Implementing a priority queue using a heap

We are now in a position to implement a priority queue using a minHeap. We can grow the array beyond our original default size when needed. As with the Stack implementation, we will double the size of the array whenever growth is needed.

```
/*
 * implementation for generic priority queue, where priorities are longs
 * implemented using a heap that expands when needed
 */

#include "prioqueuelong.h"
#include <stdlib.h>

#define DEFAULT_HEAP_SIZE 25

typedef struct heapnode {
    long priority;
    void *element;
} HeapNode;

typedef struct pq_data {
    long last;
    long size;
    HeapNode *heap;
    void (*freeValue)(void *e);
} PqData;

/*
 * traverses the heap, calling freeValue on each element
 */
static void purge(PqData *pqd) {
    long i;

    for (i = 1; i <= pqd->last; i++)
        (*pqd->freeValue)(pqd->heap[i].element);
}

static void pq_destroy(const PrioQueueLong *pq) {
    PqData *pqd = (PqData *)pq->self;
    purge(pqd);
    free(pqd->heap);
    free(pqd);
    free((void *)pq);
}

static void pq_clear(const PrioQueueLong *pq) {
    PqData *pqd = (PqData *)pq->self;
    purge(pqd);
    pqd->last = 0L;
```

```
}

/*
 *  the siftup function restores the heap property after adding a new element
 *  preconditions: last > 0 && heap(1,last-1)
 *  postcondition: heap(1,last)
 */
static void siftup(PqData *pqd) {
    int p, i = pqd->last;

    while (i > 1) {
        HeapNode hn;
        p = i / 2;
        if (pqd->heap[p].priority <= pqd->heap[i].priority)
            break;
        hn = pqd->heap[p];
        pqd->heap[p] = pqd->heap[i];
        pqd->heap[i] = hn;
        i = p;
    }
}

static bool pq_insert(const PrioQueueLong *pq, long priority, void *element) {
    PqData *pqd = (PqData *)pq->self;
    long i = pqd->last + 1;
    bool status = (i < pqd->size);

    if (! status) {       /* need to resize the array */
        size_t nbytes = (2 * pqd->size) * sizeof(HeapNode);
        HeapNode *tmp = (HeapNode *)realloc(pqd->heap, nbytes);

        if (tmp != NULL) {
            status = true;
            pqd->heap = tmp;
            pqd->size *= 2;
        }
    }
    if (status) {
        pqd->heap[i].priority = priority;
        pqd->heap[i].element = element;
        pqd->last = i;
        siftup(pqd);
    }
    return status;
}

static bool pq_min(const PrioQueueLong *pq, void **element) {
    PqData *pqd = (PqData *)pq->self;
    bool status = (pqd->last > 0L);

    if (status) {
```

```
        *element = (pqd->heap[1].element);
    }
    return status;
}

/*
 *  the siftdown function restores the heap property after removing
 *  the top element, and replacing it by the previous last element
 *  preconditions: heap(2,last) && last >= 0
 *  postcondition: heap(1,last-1)
 */
static void siftdown(PqData *pqd) {
    int c, i;

    i = 1;
    for(;;) {
        HeapNode hn;
        c = 2 * i;
        if (c > pqd->last)
            break;
        if ((c+1) <= pqd->last && pqd->heap[c+1].priority < pqd->heap[c].priority)
            c++;
        if (pqd->heap[i].priority <= pqd->heap[c].priority)
            break;
        hn = pqd->heap[i];
        pqd->heap[i] = pqd->heap[c];
        pqd->heap[c] = hn;
        i = c;
    }
}

static bool pq_removeMin(const PrioQueueLong *pq, void **element) {
    PqData *pqd = (PqData *)pq->self;
    bool status = (pqd->last > 0L);

    if (status) {
        *element = (pqd->heap[1].element);
        pqd->heap[1] = pqd->heap[pqd->last];
        pqd->last--;
        siftdown(pqd);
    }
    return status;
}

static long pq_size(const PrioQueueLong *pq) {
    PqData *pqd = (PqData *)pq->self;
    return pqd->last;
}

static bool pq_isEmpty(const PrioQueueLong *pq) {
    PqData *pqd = (PqData *)pq->self;
```

```
    return (pqd->last == 0L);
}

static PrioQueueLong template = {
    NULL, pq_destroy, pq_clear, pq_insert, pq_min, pq_removeMin, pq_size,
    pq_isEmpty
};

const PrioQueueLong *PrioQueueLong_create(void (*freeValue)(void *e)) {
    PrioQueueLong *pq = (PrioQueueLong *)malloc(sizeof(PrioQueueLong));

    if (pq != NULL) {
        PqData *pqd = (PqData *)malloc(sizeof(PqData));

        if (pqd != NULL) {
            HeapNode *p = (HeapNode *)malloc(DEFAULT_HEAP_SIZE * sizeof(HeapNode));

            if (p != NULL) {
                pqd->size = DEFAULT_HEAP_SIZE;
                pqd->last = 0L;
                pqd->heap = p;
                pqd->freeValue = freeValue;
                *pq = template;
                pq->self = pqd;
            } else {
                free(pqd);
                free(pq);
                pq = NULL;
            }
        } else {
            free(pq);
            pq = NULL;
        }
    }
    return pq;
}
```

13.4 Priority queues for arbitrary, ordered data types

The example shown above assumed long integers represent priorities. In addition, that example ignored the `create()`, `toArray()`, and `itCreate()` methods, as well. The purpose of this section is to complete our implementation to address these two deficiencies.

13.4.1 Iteration natural order for a priority queue

We previously described that the most natural iteration order would be to deliver elements according to the total ordering provided by the priority values, from smallest to largest. If the priority queue has been implemented using a heap, we have the elements in the order that satisfies the heap property; the only guarantee is that we have the smallest value at index 1 of the heap array.

If we were to simply deliver the elements in index order in the heap array, this would definitely not satisfy this natural order. While we managed to prevent the `insert()` and `removeMin()` methods from being $O(n)$ by using the heap, it appears that the complexity of the `itCreate()` method will be $O(n)$ or worse to construct an iterator that satisfies this natural order. This appears to be a reasonable tradeoff, as we expect to insert and remove entries far more often then we construct an iterator over the priority queue.

How would we go about delivering the elements in the natural order in a heap-based implementation with N elements? We know that the element at index 1 always has the smallest priority value; if we copy that element into the array used by the iterator, replace the value at index 1 by the value at index N, and then perform a `siftdown()`, we can populate an array of pointers according to our total ordering.

⚠ Note that a priority queue naively implemented as a heap would *not* satisfy the requirement that the queue be FIFO within a given priority. To achieve FIFO within a given priority, the implementation maintains a counter of entries inserted into the priority queue, and the total order for elements in the queue is a combination of the priorities provided and the counter; if two elements have the same priority value, their counter values are then compared to yield the value of the comparator.

13.4.2 Arbitrary priority data types

In order for our priority queues to allow arbitrary data types for the priority, the interface will define the priority values to be of type `void *`, just as we define the element values to be of type `void *`. The user must supply a pointer to a comparison function that given two `void *` priorities, $p1$ and $p2$, returns a value less than 0 if $p1 < p2$, the value 0 if $p1 == p2$, and value greater than 0 if $p1 > p2$.

The constructor for a priority queue takes three arguments:

1. a pointer to a comparison function for the priorities;
2. a pointer to a function that will free a priority; and
3. a pointer to a function that will free a value.

All of the comparisons performed in `siftup()` and `siftdown()` will be invocations of the comparison function given the priority values associated with the elements being compared.

Note that if the priority data type is a `struct` or some other complex type, it must be allocated on the heap. Of course, if the priority data type is a `long` or some other basic type that fits in the memory occupied by a `void *`, one can pass the priority as a `(void *)` cast of the basic type.

13.4.3 The generic interface

First we will present the entire header file. Then we describe how it differs from the previous interface.

```
#ifndef _PRIOQUEUE_H_
#define _PRIOQUEUE_H_

/* BSD Header removed to conserve space */

#include "ADTs/ADTdefs.h"
#include "ADTs/iterator.h"                      /* needed for factory method */

/* dispatch table structure for generic priority queue */
typedef struct prioqueue PrioQueue;

/* constructor for priority queue
 *
 * cmp is a function pointer to a comparator function between two priorities
 *
 * freePrio is a function pointer that will be called by
 * destroy() and clear() for the priority of each entry in the PrioQueue.
 *
 * freeValue is a function pointer that will be called by
 * destroy() and clear() for the value of each entry in the PrioQueue.
 *
 * returns a pointer to the priority queue, or NULL if malloc errors */
const PrioQueue *PrioQueue_create(int (*cmp)(void*, void*),
                                  void (*freePrio)(void *prio),
                                  void (*freeValue)(void *value)
                                 );

struct prioqueue {
/* the private data for the priority queue */
    void *self;

/* create a new priority queue using the same implementation as the priority
 * queue upon which the method has been invoked; returns NULL if error creating
 * the new priority queue
 */
    const PrioQueue *(*create)(const PrioQueue *pq);

/* destroys the priority queue;
 * applies the constructor-specified freePrio to each element in the prioqueue
 * applies the constructor-specified freeValue to each element in the prioqueue
 * the storage associated with the priority queue is returned to the heap */
    void (*destroy)(const PrioQueue *pq);

/* clears all elements from the priority queue;
 * applies the constructor-specified freePrio to each element in the prioqueue
```

```
 * applies the constructor-specified freeValue to each element in the prioqueue
 * the prioqueue is then re-initialized
 *
 * upon return, the priority queue is empty */
    void (*clear)(const PrioQueue *pq);

/* inserts the element into the priority queue
 *
 * returns true if successful, false if unsuccessful (malloc errors) */
    bool (*insert)(const PrioQueue *pq, void *priority, void *value);

/* returns the minimum element's value *value
 *
 * returns true if successful, false if the priority queue is empty */
    bool (*min)(const PrioQueue *pq, void **value);

/* removes the minimum element of the priority queue
 *
 * returns the value in *value
 * returns the priority in *priority
 *
 * returns true if successful, false if the priority queue is empty */
    bool (*removeMin)(const PrioQueue *pq, void **priority, void **value);

/* returns the number of elements in the priority queue */
    long (*size)(const PrioQueue *pq);

/* returns true if the priority queue is empty, false if it is not */
    bool (*isEmpty)(const PrioQueue *pq);

/* returns an array containing all of the values of the priority queue in
 * proper sequence (smallest priority to largest priority); returns the
 * length of the array in *len
 *
 * returns a pointer to the array of void * values, or NULL if malloc failure
 *
 * NB - the caller is responsible for freeing the void * array when finished
 * with it */
    void **(*toArray)(const PrioQueue *pq, long *len);

/* create generic iterator to this priority queue
 *
 * returns pointer to the Iterator or NULL if malloc failure */
    const Iterator *(*itCreate)(const PrioQueue *pq);
};

#endif /* _PRIOQUEUE_H_ */
```

How does this differ from the previous interface when we used long integers for priorities?

- The constructor requires a pointer to a comparison function to compare the

arbitrary priority values.
- The constructor requires a pointer to a `freePrio` function to free up priorities if they are allocated on the heap.
- A `create()` method has been added to enable the creation of a new priority queue, given a priority queue, guaranteeing that it has the same implementation as the one in hand.
- The `destroy()` and `clear()` methods will apply the `freePrio` function to the priorities associated with any elements remaining in the priority queue.
- The priority argument to `insert()` is a `void *`.
- An additional argument is provided in `removeMin()` in which the priority associated with the element is returned.
- The usual `toArray()` and `itCreate()` methods are defined.

13.4.4 The Heap-based constructor interface

This is the Heap-based constructor interface.

```
#ifndef _HEAPPRIOQUEUE_H_
#define _HEAPPRIOQUEUE_H_

/* BSD Header removed to conserve space */

#include "ADTs/ADTdefs.h"
#include "ADTs/prioqueue.h"

/* constructor for heap priority queue */

/* create a priority queue using a heap
 *
 * cmp is a function pointer to a comparator function between two priorities
 *
 * freePrio is a function pointer that will be called by
 * destroy() and clear() for the priority of each entry in the PrioQueue.
 *
 * freeValue is a function pointer that will be called by
 * destroy() and clear() for the value of each entry in the PrioQueue.
 *
 * returns a pointer to the priority queue, or NULL if malloc errors */
const PrioQueue *HeapPrioQueue(int (*cmp)(void*, void*),
                               void (*freePrio)(void *prio),
                               void (*freeValue)(void *value)
                              );

#endif /* _HEAPPRIOQUEUE_H_ */
```

13.4.5 The Heap-based implementation

The implementation for a generic priority queue using a minHeap is shown in Section B.9.

Exercise 13.1. Modify `pqtest.c` in Section 10.4.6 to use `HeapPrioQueue()` to create a priority queue, link to the HeapPrioQueue implementation, and then test it out.

13.4.6 Heap sort

The fundamental characteristic of our previous selection sort was, at each step, to scan the source sequence to find the minimum value to exchange with the next item in the destination sequence. Finding the minimum value was $O(n)$, and since we had to do that scan for each index in our array, we ended up with an algorithm that was $O(n^2)$ complexity. If we could reduce the complexity for finding the minimum value in the source sequence, we could reduce the complexity of our sort algorithm.

In Section 13.1 we discuss the heap data structure, which enables us to find the minimum value of a bag of numbers in $O(\log n)$ time. If we can figure out how to use the heap structure while sorting in place, we should end up with an algorithm that is $O(n \log n)$ complexity.

The discussion in Section 13.3 had two functions, `siftup()` for re-establishing the heap property after adding a new element to the array, and `siftdown()` for re-establishing the heap property after removal of the smallest item. In this case, we are presented with an already-populated array, and must establish the heap property for the items that are already there. The logic is similar, but will require some additional machinations in order to make it work; fortunately, the return for this extra effort, $O(n \log n)$ complexity, makes it worth it.

Recall that our heap properties are:

- *order* - the value at any node is less than or equal to the values of the node's children; and
- *shape* - the terminal nodes are on at most two levels, with those on the bottom level as far left as possible.

The first property guarantees that the minimum element of the heap is always the root; thus, if we can move the items in our array such that the heap properties are satisfied, we have $O(1)$ access to the minimum value.

Also recall that if we stored our `N` data items in an array using indices `1..N`, that given a node at index `i`, its left child is at index `2*i`, its right child is at index `2*i + 1`, and its parent is at index `i/2` (using integer division). We are given an array indexed from `0..N-1`, so it will require some additional, straight-forward arithmetic to be able to generate a heap *in situ*.

Suppose that we have an array `b[]` indexed from `1..N`, and consider index `m = N/2 + 1`, where we are using integer division. `b[m]..b[N]` satisfy the heap property already, since no two indices `k` and `l` exist such that `l = 2*k` or `l = 2*k + 1`; these items essentially form the bottom row of the heap.

Now extend the subarray under consideration by one to the left; we need to “sift” this new value into the appropriate place in the subarray `b[m-1]..b[N]` such that the subarray satisfies the heap properties. This sifting is very much like the `siftdown()` helper function in the heap-based implementation of our priority queue ADT in Section 13.2. We continue to extend the array to the left and sift until `b[1]..b[N]` is a heap.

Here is the sift function to establish the heap property for `b[L]..b[R]`.

```
void sift(void *b[], long L, long R, int (*cmp)(void*,void*)) {
    long i = L, j = 2 * L;
    void *x = b[L];

    if (j < R && (*cmp)(b[j+1], b[j]) < 0)
        j++;
    while (j <= R && (*cmp)(b[j], x) < 0) {
        b[i] = b[j];
        b[j] = x;
        i = j;
        j *= 2;
        if (j < R && (*cmp)(b[j+1], b[j]) < 0)
            j++;
    }
}
```

What do we do after we have the entire array satisfying the heap properties? We know that `b[1]` is the minimum value of the array. We can, therefore, swap `b[1]` with `b[N]`, and then call `sift()` to re-establish the heap properties for `b[1]..b[N-1]`. We repeat this until we are left with `b[1]..b[1]`, which obviously satisfies the heap properties.

Unfortunately, this leaves us with our array sorted but in the reverse order to what we expected. If we change the direction of the ordering relations in `sift()`, such that `b[1]` is the largest item in the heap, we will have sorted our array *in situ* from smallest to largest. This yields the following version of `sift()` for 1-based arrays.

```
void sift(void *b[], long L, long R, int (*cmp)(void*,void*)) {
    long i = L, j = 2 * L;
    void *x = b[L];

    if (j < R && (*cmp)(b[j], b[j+1]) < 0)
        j++;
    while (j <= R && (*cmp)(x, b[j]) < 0) {
```

```
        b[i] = b[j];
        b[j] = x;
        i = j;
        j *= 2;
        if (j < R && (*cmp)(b[j], b[j+1]) < 0)
            j++;
    }
}
```

How do we make this work with 0-based arrays? This is actually quite straight-forward. We have the correct logic above if the indices run from `1..N`. Whenever we actually access an element of the array, our index will be too large by `1`. Thus, we define a macro, `ind(val)`, which is invoked whenever we are accessing an element of the array.

The final version of our heapsort is shown in Section B.10.

Have we achieved $O(n \log n)$ complexity? The initial construction of the heap *in situ* requires $\frac{n}{2}$ calls to `sift()`; each call to `sift()` requires a maximum of $\log n$ comparisions and swaps; thus, this part of the algorithm is $O(n \log n)$.[3] The ordering of the array in situ requires n swaps and n calls to `sift()`, which again yields $O(n \log n)$. Since $O(n \log n)$ dominates $O(n)$, the entire algorithm is $O(n \log n)$.

As with the basic selection sort, because we swap values over long distances, both in heap construction and in the assembly of the sorted array, we may invert the order of items that have identical keys. As a result, **heapsort is *not* a stable sorting algorithm**.

[3]It can actually be shown that this heap construction algorithm is $O(n)$, as shown on page 156 of *Introduction to Algorithms, 3e* by Cormen et al.

Appendix A

Object-oriented Examples

This appendix provides C++, Java, and Python examples of the Student class from section 4.1.4.

To refresh your memory, each object/class instance possesses five string attributes:

- *LastName* - the student's surname or last name
- *FirstName* - the student's forename or first name
- *Uoid* - the student's UOID (95 number)
- *Duckid* - the student's duckid (UO email address **without** the @uoregon.edu)
- *PrimaryMajor* - the student's primary major

Each implementation has to provide a constructor that produces a Student instance given five strings: `last`, `first`, `uoid`, `did`, and `major`.

The class has to support the following seven methods:

- `lastName()` - returns the LastName attribute
- `firstName()` - returns the FirstName attribute
- `UOID()` - returns the Uoid attribute
- `duckid()` - returns the Duckid attribute
- `primaryMajor()` - returns the PrimaryMajor attribute
- `setMajor(major)` - sets the PrimaryMajor to major
- `print(stream)` - prints the attributes as a comma-separated line on stream

To exercise the class, we have a main program that conforms to the following pseudocode.

```
create an extensible array
for each line read from standard input
    split line into tokens at ',' characters
    create Student instance from the tokens
    append Student instance to array
for each element in array from last to first
    invoke print(standard output) method on the Student object
```

The following sections provide the source files for the main program and the class for C++, Java, and Python, respectively. Each section will describe any unique aspects associated with that particular language that is reflected in the implementation.

A.1 C++

In C++, we divide the Student class implementation into two files: `student.h` defines the class structure, including which attributes and methods are public and which are private; `student.cpp` provides the method implementations.

There are many ways to provide the `split()` functionality in C++; I have implemented the function using `strdup()` and `strtok()` from `<string.h>`.

The main program uses `std::vector` to store each `Student` object.

To compile and execute this program, do the following:

```
$ #cd to the directory in which student.h, student.cpp, and main.cpp are stored
$ g++ -o main main.cpp student.cpp
$ ./main
```

A.1.1 Source file for the Student class header file - student.h

```
#if !defined(_STUDENT_H_)
#define _STUDENT_H_
#include <ostream>

class Student {

  private:
    std::string LastName, FirstName, Uoid, Duckid, PrimaryMajor;

  public:
```

```
    Student(const std::string &last, const std::string &first,
            const std::string &uoid, const std::string &did,
            const std::string &major);
   ~Student();

    const std::string &lastName();
    const std::string &firstName();
    const std::string &UOID();
    const std::string &duckid();
    const std::string &primaryMajor();
    bool setMajor(const std::string &major);
    void print(std::ostream& f);
};

#endif // _STUDENT_H_
```

A.1.2 Source file for the Student class implementation file - `student.cpp`

```
#include "student.h"
#include <stdlib.h>
#include <ostream>
Student::Student(const std::string &last, const std::string &first,
                 const std::string &uid,  const std::string &did,
                 const std::string &major) {
   LastName = last;
   FirstName = first;
   Uoid = uid;
   Duckid = did;
   PrimaryMajor = major;
}

Student::~Student() {
}

const std::string &Student::lastName() {
    return LastName;
}

const std::string &Student::firstName() {
    return FirstName;
}

const std::string &Student::UOID() {
    return Uoid;
}

const std::string &Student::duckid() {
```

```
    return Duckid;
}

const std::string &Student::primaryMajor() {
    return PrimaryMajor;
}

bool Student::setMajor(const std::string &major) {
    PrimaryMajor = major;
    return true;
}

void Student::print(std::ostream& f) {
    f << LastName << "," << FirstName << "," << Uoid << "," <<
         Duckid << "," << PrimaryMajor << std::endl;
}
```

A.1.3 Source file for the main program - `main.cpp`

```
#include <iostream>
#include <vector>
#include <string.h>
#include <stdlib.h>
#include "student.h"

std::vector<std::string> split(std::string str, std::string delim) {
    std::vector<std::string> tokens;
    char *str_c = strdup(str.c_str());
    char *token = NULL;
    token = strtok(str_c, delim.c_str());
    while (token != NULL) {
        tokens.push_back(std::string(token));
        token = strtok(NULL, delim.c_str());
    }
    free(str_c);
    return tokens;
}

int main() {
    std::vector<Student*> array;
    int i;
    std::string line;
    std::string delims(",\n");
    while(std::getline(std::cin, line)) {
        std::vector<std::string> toks = split(line, delims);
        Student *s = new Student(toks[0], toks[1], toks[2], toks[3], toks[4]);
        array.push_back(s);
    }
```

```
    for (i = array.size() - 1; i >= 0; i--) {
        array[i]->print(std::cout);
        delete array[i];
    }
    return 0;
}
```

A.2 Java

The Java sources are straightforward implementations of the class and the main pseudocode. Since encapsulation is important, the class attributes are flagged as `private`. I have wrapped `System.in` in a `Scanner` in order to read a line at a time. I have used an `ArrayList` to hold the array of `Student` objects. I have used the `split()` method on a `String` twice: first to remove the newline character from the line, then to split the remaining line into comma-separated tokens.

To compile and execute this program, do the following:

```
$ #cd to the directory in which Main.java and Student.java are stored
$ javac -classpath . Student.java
$ javac -classpath . Main.java
$ java -classpath . Main
```

A.2.1 Source file for the Student class - `Student.java`

```
public class Student {
    private String LastName;
    private String FirstName;
    private String Uoid;
    private String Duckid;
    private String PrimaryMajor;

    public Student(String last, String first, String uoid, String did, String major) {
        LastName = last;
        FirstName = first;
        Uoid = uoid;
        Duckid = did;
        PrimaryMajor = major;
    }

    public String lastName() {
        return LastName;
    }
```

```
    public String firstName() {
        return FirstName;
    }

    public String UOID() {
        return Uoid;
    }

    public String duckid() {
        return Duckid;
    }

    public String primaryMajor() {
        return PrimaryMajor;
    }

    public boolean setMajor(String major) {
        PrimaryMajor = major;
        return true;
    }

    public void print(java.io.PrintStream s) {
        s.println(LastName+","+FirstName+","+Uoid+","+Duckid+","+PrimaryMajor);
    }
};
```

A.2.2 Source file for the main program - `Main.java`

```
import java.util.ArrayList;
import java.util.Scanner;

public class Main {
    public static void main(String []args) {
        ArrayList<Student> array = new ArrayList<Student>();
        Scanner stdin = new Scanner(System.in);
        String line;
        int i;

        while(stdin.hasNextLine()) {
            line = stdin.nextLine();
            String[] linesArr = line.split("\\n");
            String[] toks = linesArr[0].split(",");
            Student s = new Student(toks[0], toks[1], toks[2], toks[3], toks[4]);
            array.add(s);
        }
        for (i = array.size() - 1; i >= 0; i--) {
            Student s = array.get(i);
```

```
            s.print(System.out);
        }
    }
};
```

A.3 Python

The Python sources are straightforward implementations of the class and the main pseudocode. I have chosen to write `main.py` as per section D.6; thus, to invoke this program you would:

```
$ #cd to the directory in which main.py and student.py are stored
$ python3 main.py
```

A.3.1 Source file for the Student class - `student.py`

```
class Student:
    def __init__(self, last, first, uoid, did, major):
        self.LastName = last
        self.FirstName = first
        self.Uoid = uoid
        self.Duckid = did
        self.PrimaryMajor = major

    def lastName(self):
        return self.LastName

    def firstName(self):
        return self.FirstName

    def UOID(self):
        return self.Uoid

    def duckid(self):
        return self.Duckid

    def primaryMajor(self):
        return self.PrimaryMajor

    def setMajor(self, major):
        self.PrimaryMajor = major
        return True
```

```
    def print(self, f):
        f.write('{},{},{},{},{}\n'.format(self.LastName, self.FirstName,
                self.Uoid, self.Duckid, self.PrimaryMajor))
```

A.3.2 Source file for the main program - `main.py`

```
from student import *
from sys import stdin, stdout

def main():
    array = []
    for line in stdin:
        toks = line.rstrip().split(',')
        array.append(Student(toks[0], toks[1], toks[2], toks[3], toks[4]))
    for i in range(len(array)-1,-1,-1):
        array[i].print(stdout)

if __name__ == "__main__":
    main()
```

Appendix B

Generic Implementations

This appendix provides the generic implementations for the classes described in the textbook that are in the ADT library.

B.1 iterator.c

```
/* BSD header removed to conserve space */

#include "ADTs/iterator.h"
#include <stdlib.h>

/*
 * implementation for generic iterator
 *
 * patterned roughly after Java 6 Iterator class
 */

typedef struct it_data {
    long next;
    long size;
    void **elements;
} ItData;

static bool it_hasNext(const Iterator *it) {
    ItData *itd = (ItData *)(it->self);
    return (itd->next < itd->size);
}

static bool it_next(const Iterator *it, void **element) {
    ItData *itd = (ItData *)(it->self);
    bool status = (itd->next < itd->size);
    if (status) {
```

```
        *element = itd->elements[itd->next++];
    }
    return status;
}

static void it_destroy(const Iterator *it) {
    ItData *itd = (ItData *)(it->self);
    free(itd->elements);
    free(itd);
    free((void *)it);
}

static Iterator template = {NULL, it_hasNext, it_next, it_destroy};

const Iterator *Iterator_create(long size, void **elements) {
    Iterator *it = (Iterator *)malloc(sizeof(Iterator));

    if (it != NULL) {
        ItData *itd = (ItData *)malloc(sizeof(ItData));
        if (itd != NULL) {
            itd->next = 0L;
            itd->size = size;
            itd->elements = elements;
            *it = template;
            it->self = itd;
        } else {
            free(it);
            it = NULL;
        }
    }
    return it;
}
```

B.2 arraylist.c

```
/* BSD header removed to conserve space */

/*
 * implementation for generic array list
 */

#include "ADTs/arraylist.h"
#include <stdlib.h>

typedef struct al_data {
    long capacity;
    long size;
```

```
    void **theArray;
    void (*freeValue)(void *e);
} AlData;

/*
 * traverses arraylist, calling freeValue on each element
 */
static void purge(AlData *ald) {
    long i;

    for (i = 0L; i < ald->size; i++) {
        ald->freeValue(ald->theArray[i]);    /* free element storage */
        ald->theArray[i] = NULL;
    }
}

static void al_destroy(const ArrayList *al) {
    AlData *ald = (AlData *)(al->self);
    purge(ald);                              /* purge any remaining elements */
    free(ald->theArray);   /* free array of pointers */
    free(ald);                               /* free self structures */
    free((void *)al);   /* free the ArrayList struct */
}

static bool al_add(const ArrayList *al, void *element) {
    AlData *ald = (AlData *)(al->self);
    bool status = (ald->capacity > ald->size);

    if (! status) { /* need to reallocate */
        size_t nbytes = 2 * ald->capacity * sizeof(void *);
        void **tmp = (void **)realloc(ald->theArray, nbytes);
        if (tmp != NULL) {
            status = true;
            ald->theArray = tmp;
            ald->capacity *= 2;
        }
    }
    if (status)
        ald->theArray[ald->size++] = element;
    return status;
}

static void al_clear(const ArrayList *al) {
    AlData *ald = (AlData *)(al->self);
    purge(ald);
    ald->size = 0L;
}

static bool al_ensureCapacity(const ArrayList *al, long minCapacity) {
    AlData *ald = (AlData *)(al->self);
    int status = true;
```

```
    if (ald->capacity < minCapacity) { /* must extend */
        void **tmp = (void **)realloc(ald->theArray,
                                      minCapacity * sizeof(void *));
        if (tmp == NULL)
            status = false; /* allocation failure */
        else {
            ald->theArray = tmp;
            ald->capacity = minCapacity;
        }
    }
    return status;
}

static bool al_get(const ArrayList *al, long index, void **element) {
    AlData *ald = (AlData *)(al->self);
    bool status = (index >= 0L && index < ald->size);

    if (status)
        *element = ald->theArray[index];
    return status;
}

static bool al_insert(const ArrayList *al, long index, void *element) {
    AlData *ald = (AlData *)(al->self);
    bool status = false;

    if (index > ald->size)
        return status; /* 0 <= index <= size */
    if (ald->capacity <= ald->size) { /* need to reallocate */
        size_t nbytes = 2 * ald->capacity * sizeof(void *);
        void **tmp = (void **)realloc(ald->theArray, nbytes);
        if (tmp != NULL) {
            ald->theArray = tmp;
            ald->capacity *= 2;
            status = true;
        }
    }
    if (status) {
        long j;
        for (j = ald->size; j > index; j--) /* slide items up */
            ald->theArray[j] = ald->theArray[j-1];
        ald->theArray[index] = element;
        ald->size++;
    }
    return status;
}

static bool al_isEmpty(const ArrayList *al) {
    AlData *ald = (AlData *)(al->self);
    return (ald->size == 0L);
```

```
}

static bool al_remove(const ArrayList *al, long index) {
    AlData *ald = (AlData *)(al->self);
    bool status = (index >= 0L && index < ald->size);
    long j;

    if (status) {
        void *element = ald->theArray[index];
        for (j = index + 1; j < ald->size; j++)
            ald->theArray[index++] = ald->theArray[j];
        ald->size--;
        ald->freeValue(element);
    }
    return status;
}

static bool al_set(const ArrayList *al, long index, void *element) {
    AlData *ald = (AlData *)(al->self);
    bool status = (index >= 0L && index < ald->size);

    if (status) {
        void *previous = ald->theArray[index];
        ald->theArray[index] = element;
        ald->freeValue(previous);
    }
    return status;
}

static long al_size(const ArrayList *al) {
    AlData *ald = (AlData *)(al->self);
    return ald->size;
}

/*
 * local function that duplicates the array of void * pointers on the heap
 *
 * returns pointer to duplicate array or NULL if malloc failure
 */
static void **arraydupl(AlData *ald) {
    void **tmp = NULL;
    if (ald->size > 0L) {
        size_t nbytes = ald->size * sizeof(void *);
        tmp = (void **)malloc(nbytes);
        if (tmp != NULL) {
            long i;

            for (i = 0; i < ald->size; i++)
                tmp[i] = ald->theArray[i];
        }
    }
```

```
    return tmp;
}

static void **al_toArray(const ArrayList *al, long *len) {
    AlData *ald = (AlData *)al->self;
    void **tmp = arraydupl(ald);

    if (tmp != NULL)
        *len = ald->size;
    return tmp;
}

static bool al_trimToSize(const ArrayList *al) {
    AlData *ald = (AlData *)al->self;
    int status = false;

    void **tmp = (void **)realloc(ald->theArray, ald->size * sizeof(void *));
    if (tmp != NULL) {
        status = true;
        ald->theArray = tmp;
        ald->capacity = ald->size;
    }
    return status;
}

static const Iterator *al_itCreate(const ArrayList *al) {
    AlData *ald = (AlData *)al->self;
    const Iterator *it = NULL;
    void **tmp = arraydupl(ald);

    if (tmp != NULL) {
        it = Iterator_create(ald->size, tmp);
        if (it == NULL)
            free(tmp);
    }
    return it;
}

static ArrayList template = {
    NULL, al_destroy, al_add, al_clear, al_ensureCapacity, al_get, al_insert,
    al_isEmpty, al_remove, al_set, al_size, al_toArray, al_trimToSize,
    al_itCreate
};

const ArrayList *ArrayList_create(long capacity, void (*freeValue)(void *e)) {
    ArrayList *al = (ArrayList *)malloc(sizeof(ArrayList));

    if (al != NULL) {
        AlData *ald = (AlData *)malloc(sizeof(AlData));
        if (ald != NULL) {
            long cap = (capacity <= 0) ? DEFAULT_ARRAYLIST_CAPACITY : capacity;
```

```
            void **array = (void **) malloc(cap * sizeof(void *));

            if (array != NULL) {
                ald->capacity = cap;
                ald->size = 0L;
                ald->theArray = array;
                ald->freeValue = freeValue;
                *al = template;
                al->self = ald;
            } else {
                free(ald);
                free(al);
                al = NULL;
            }
        } else {
            free(al);
            al = NULL;
        }
    }
    return al;
}
```

B.3 arraystack.c

```
/* BSD header removed to conserve space */

/*
 * implementation for array-based generic stack
 */

#include "ADTs/arraystack.h"
#include <stdlib.h>

typedef struct st_data {
    long capacity;
    long next;
    void **theArray;
    void (*freeValue)(void *e);
} StData;

/*
 * local function - traverses stack, applying user-supplied function
 * to each element
 */

static void purge(StData *std) {
    long i;
```

```
    for (i = 0L; i < std->next; i++)
        std->freeValue(std->theArray[i]);       /* free elem storage */
}

static void st_destroy(const Stack *st) {
    StData *std = (StData *)st->self;

    purge(std);                           /* purge remaining elements */
    free(std->theArray);                  /* free array of pointers */
    free(std);                            /* free structure with instance data */
    free((void *)st);                     /* free dispatch table */
}

static void st_clear(const Stack *st) {
    StData *std = (StData *)st->self;

    purge(std);
    std->next = 0L;
}

static bool st_push(const Stack *st, void *element) {
    StData *std = (StData *)st->self;
    bool status = (std->next < std->capacity);

    if (! status) {    /* need to reallocate */
        size_t nbytes = 2 * (std->capacity) * sizeof(void *);
        void **tmp = (void **)realloc(std->theArray, nbytes);

        if (tmp != NULL) {
            status = true;
            std->theArray = tmp;
            std->capacity *= 2;
        }
    }
    if (status)
        std->theArray[std->next++] = element;
    return status;
}

static bool st_pop(const Stack *st, void **element) {
    StData *std = (StData *)st->self;
    bool status = (std->next > 0L);

    if (status)
        *element = std->theArray[--std->next];
    return status;
}

static bool st_peek(const Stack *st, void **element) {
    StData *std = (StData *)st->self;
```

```
    bool status = (std->next > 0L);

    if (status)
        *element = std->theArray[std->next - 1];
    return status;
}

static long st_size(const Stack *st) {
    StData *std = (StData *)st->self;

    return std->next;
}

static bool st_isEmpty(const Stack *st) {
    StData *std = (StData *)st->self;

    return (std->next == 0L);
}

/*
 * local function - duplicates array of void * pointers on the heap
 *
 * returns pointers to duplicate array or NULL if malloc failure
 */
static void **arrayDupl(StData *std) {
    void **tmp = NULL;

    if (std->next > 0L) {
        size_t nbytes = std->next * sizeof(void *);
        tmp = (void **)malloc(nbytes);
        if (tmp != NULL) {
            long i, j = 0L;

            for (i = std->next - 1; i >= 0L; i--)
                tmp[j++] = std->theArray[i];
        }
    }
    return tmp;
}

static void **st_toArray(const Stack *st, long *len) {
    StData *std = (StData *)st->self;
    void **tmp = arrayDupl(std);

    if (tmp != NULL)
        *len = std->next;
    return tmp;
}

static const Iterator *st_itCreate(const Stack *st) {
    StData *std = (StData *)st->self;
```

```
    const Iterator *it = NULL;
    void **tmp = arrayDupl(std);

    if (tmp != NULL) {
        it = Iterator_create(std->next, tmp);
        if (it == NULL)
            free(tmp);
    }
    return it;
}

static const Stack *st_create(const Stack *st);

static Stack template = {
    NULL, st_create, st_destroy, st_clear, st_push, st_pop, st_peek, st_size,
    st_isEmpty, st_toArray, st_itCreate
};

/*
 * helper function to create a new Stack dispatch table
 */
static const Stack *newStack(long capacity, void (*freeValue)(void *e)){
    Stack *st = (Stack *)malloc(sizeof(Stack));

    if (st != NULL) {
        StData *std = (StData *)malloc(sizeof(StData));

        if (std != NULL) {
            long cap;
            void **array = NULL;

            cap = (capacity <= 0L) ? DEFAULT_STACK_CAPACITY : capacity;
            array = (void **)malloc(cap * sizeof(void *));
            if (array != NULL) {
                std->capacity = cap;
                std->next = 0L;
                std->theArray = array;
                std->freeValue = freeValue;
                *st = template;
                st->self = std;
            } else {
                free(std);
                free(st);
                st = NULL;
            }
        } else {
            free(st);
            st = NULL;
        }
    }
    return st;
```

```
}

static const Stack *st_create(const Stack *st) {
    StData *std = (StData *)st->self;

    return newStack(DEFAULT_STACK_CAPACITY, std->freeValue);
}

const Stack *ArrayStack(long capacity, void (*freeValue)(void *e)) {
    return newStack(capacity, freeValue);
}

const Stack *Stack_create(void (*freeValue)(void *e)) {
    return newStack(DEFAULT_STACK_CAPACITY, freeValue);
}
```

B.4 arrayqueue.c

```
/* BSD header removed to conserve space */

/*
 * implementation for array-based generic FIFO queue
 */

#include "ADTs/arrayqueue.h"
#include <stdlib.h>

typedef struct q_data {
    long count;
    long size;
    int in;
    int out;
    void **buffer;
    void (*freeValue)(void *e);
} QData;

static void purge(QData *qd) {
    int i, n;

    for (i = qd->out, n = qd->count; n > 0; i = (i + 1) % qd->size, n--)
        qd->freeValue(qd->buffer[i]);
}

static void q_destroy(const Queue *q) {
    QData *qd = (QData *)q->self;
    purge(qd);
    free(qd->buffer);
```

```
    free(qd);
    free((void *)q);
}

static void q_clear(const Queue *q) {
    QData *qd = (QData *)q->self;

    purge(qd);
    qd->count = 0;
    qd->in = 0;
    qd->out = 0;
}

static bool q_enqueue(const Queue *q, void *element) {
    QData *qd = (QData *)q->self;
    bool status = (qd->count < qd->size);

    if (! status) {          /* need to reallocate */
        size_t nbytes = 2 * (qd->size) * sizeof(void *);
        void **tmp = (void **)malloc(nbytes);

        if (tmp != NULL) {
            long n = qd->count, i, j;
            status = true;

            for (i = qd->out, j = 0; n > 0; i = (i + 1) % qd->size, j++) {
                tmp[j] = qd->buffer[i];
                n--;
            }
            free(qd->buffer);
            qd->buffer = tmp;
            qd->size *= 2;
            qd->out = 0L;
            qd->in = qd->count;
        }
    }
    if (status) {
        int i = qd->in;
        qd->buffer[i] = element;
        qd->in = (i + 1) % qd->size;
        qd->count++;
    }
    return status;
}

static bool q_front(const Queue *q, void **element) {
    QData *qd = (QData *)q->self;
    bool status = (qd->count > 0L);

    if (status)
        *element = qd->buffer[qd->out];
```

```
    return status;
}

static bool q_dequeue(const Queue *q, void **element) {
    QData *qd = (QData *)q->self;
    bool status = (qd->count > 0L);

    if (status) {
        int i = qd->out;
        *element = qd->buffer[i];
        qd->out = (i + 1) % qd->size;
        qd->count--;
    }
    return status;
}

static long q_size(const Queue *q) {
    QData *qd = (QData *)q->self;
    return qd->count;
}

static bool q_isEmpty(const Queue *q) {
    QData *qd = (QData *)q->self;
    return (qd->count == 0L);
}

static void **genArray(QData *qd) {
    void **tmp = NULL;

    if (qd->count > 0L) {
        tmp = (void **)malloc(qd->count * sizeof(void *));
        if (tmp != NULL) {
            int i, j, n;

            n = qd->count;
            for (i = qd->out, j = 0; n > 0; i = (i+1) % qd->size, j++, n--) {
                tmp[j] = qd->buffer[i];
            }
        }
    }
    return tmp;
}

static void **q_toArray(const Queue *q, long *len) {
    QData *qd = (QData *)q->self;
    void **tmp = genArray(qd);

    if (tmp != NULL)
        *len = qd->count;
    return tmp;
}
```

```
static const Iterator *q_itCreate(const Queue *q) {
    QData *qd = (QData *)q->self;
    const Iterator *it = NULL;
    void **tmp = genArray(qd);

    if (tmp != NULL) {
        it = Iterator_create(qd->count, tmp);
        if (it == NULL)
            free(tmp);
    }
    return it;
}

static const Queue *q_create(const Queue *q);

static Queue template = {
    NULL, q_create, q_destroy, q_clear, q_enqueue, q_front, q_dequeue, q_size,
    q_isEmpty, q_toArray, q_itCreate
};

/*
 * helper function to create a new Queue dispatch table
 */
static const Queue *newQueue(long capacity, void (*freeValue)(void *e)) {
    Queue *q = (Queue *)malloc(sizeof(Queue));

    if (q != NULL) {
        QData *qd = (QData *)malloc(sizeof(QData));

        if (qd != NULL) {
            long cap;
            void **tmp;

            cap = (capacity <= 0L) ? DEFAULT_QUEUE_CAPACITY : capacity;
            tmp = (void **)malloc(cap * sizeof(void *));
            if (tmp != NULL) {
                qd->count = 0;
                qd->size = cap;
                qd->in = 0;
                qd->out = 0;
                qd->buffer = tmp;
                qd->freeValue = freeValue;
                *q = template;
                q->self = qd;
            } else {
                free(qd);
                free(q);
                q = NULL;
            }
        } else {
```

```
            free(q);
            q = NULL;
        }
    }
    return q;
}

static const Queue *q_create(const Queue *q) {
    QData *qd = (QData *)q->self;

    return newQueue(DEFAULT_QUEUE_CAPACITY, qd->freeValue);
}

const Queue *ArrayQueue(long capacity, void (*freeValue)(void *e)) {
    return newQueue(capacity, freeValue);
}

const Queue *Queue_create(void (*freeValue)(void *e)) {
    return newQueue(DEFAULT_QUEUE_CAPACITY, freeValue);
}
```

B.5 llistdeque.c

```
/* BSD header removed to conserve space */

/*
 * implementation for generic deque using a linked list with a sentinel
 */

#include "ADTs/llistdeque.h"
#include <stdlib.h>

#define SENTINEL(p) (&(p)->sentinel)

typedef struct llnode {
    struct llnode *next;
    struct llnode *prev;
    void *element;
} LLNode;

typedef struct d_data {
    long size;
    LLNode sentinel;
    void (*freeValue)(void *e);
} DData;

/*
```

```
 * link `p' between `before' and `after'
 * must work correctly if `before' and `after' are the same node
 * (i.e. the sentinel)
 */
static void link(LLNode *before, LLNode *p, LLNode *after) {
    p->next = after;
    p->prev = before;
    after->prev = p;
    before->next = p;
}

/*
 * unlinks the LLNode from the doubly-linked list
 */
static void unlink(LLNode *p) {
    p->prev->next = p->next;
    p->next->prev = p->prev;
}

/*
 * traverses linked list, calling freeValue on each element
 */
static void purge(DData *dd) {
    LLNode *p;

    for (p = dd->sentinel.next; p != SENTINEL(dd); p = p->next)
        dd->freeValue(p->element);
}

/*
 * frees the nodes from the doubly-linked list
 */
static void freeList(DData *dd) {
    LLNode *p = dd->sentinel.next;

    while (p != SENTINEL(dd)) {
        LLNode *q = p->next;
        free(p);
        p = q;
    }
}

static void d_destroy(const Deque *d) {
    DData *dd = (DData *)d->self;
    purge(dd);
    freeList(dd);
    free(dd);
    free((void *)d);
}

static void d_clear(const Deque *d) {
```

```
    DData *dd = (DData *)d->self;
    purge(dd);
    freeList(dd);
    dd->size = 0L;
    dd->sentinel.next = SENTINEL(dd);
    dd->sentinel.prev = SENTINEL(dd);
}

static bool d_insertFirst(const Deque *d, void *element) {
    DData *dd = (DData *)d->self;
    LLNode *p = (LLNode *)malloc(sizeof(LLNode));
    bool status = (p != NULL);

    if (status) {
        p->element = element;
        link(SENTINEL(dd), p, SENTINEL(dd)->next);
        dd->size++;
    }
    return status;
}

static bool d_insertLast(const Deque *d, void *element) {
    DData *dd = (DData *)d->self;
    LLNode *p = (LLNode *)malloc(sizeof(LLNode));
    bool status = (p != NULL);

    if (status) {
        p->element = element;
        link(SENTINEL(dd)->prev, p, SENTINEL(dd));
        dd->size++;
    }
    return status;
}

static bool d_first(const Deque *d, void **element) {
    DData *dd = (DData *)d->self;
    LLNode *p = SENTINEL(dd)->next;
    bool status = (p != SENTINEL(dd));

    if (status)
        *element = p->element;
    return status;
}

static bool d_last(const Deque *d, void **element) {
    DData *dd = (DData *)d->self;
    LLNode *p = SENTINEL(dd)->prev;
    bool status = (p != SENTINEL(dd));

    if (status)
        *element = p->element;
```

```
    return status;
}

static bool d_removeFirst(const Deque *d, void **element) {
    DData *dd = (DData *)d->self;
    LLNode *p = SENTINEL(dd)->next;
    bool status = (p != SENTINEL(dd));

    if (status) {
        *element = p->element;
        unlink(p);
        free(p);
        dd->size--;
    }
    return status;
}

static bool d_removeLast(const Deque *d, void **element) {
    DData *dd = (DData *)d->self;
    LLNode *p = SENTINEL(dd)->prev;
    bool status = (p != SENTINEL(dd));

    if (status) {
        *element = p->element;
        unlink(p);
        free(p);
        dd->size--;
    }
    return status;
}

static long d_size(const Deque *d) {
    DData *dd = (DData *)d->self;
    return dd->size;
}

static bool d_isEmpty(const Deque *d) {
    DData *dd = (DData *)d->self;
    return (dd->size == 0L);
}

/*
 * helper function to generate array of element values on the heap
 *
 * returns pointer to array or NULL if malloc failure
 */
static void **genArray(DData *dd) {
    void **tmp = NULL;
    if (dd->size > 0L) {
        size_t nbytes = dd->size * sizeof(void *);
        tmp = (void **)malloc(nbytes);
```

```
        if (tmp != NULL) {
            long i;
            LLNode *p;
            for (i = 0, p = SENTINEL(dd)->next; i < dd->size; i++, p = p->next)
                tmp[i] = p->element;
        }
    }
    return tmp;
}

static void **d_toArray(const Deque *d, long *len) {
    DData *dd = (DData *)d->self;
    void **tmp = genArray(dd);

    if (tmp != NULL)
        *len = dd->size;
    return tmp;
}

static const Iterator *d_itCreate(const Deque *d) {
    DData *dd = (DData *)d->self;
    const Iterator *it = NULL;
    void **tmp = genArray(dd);

    if (tmp != NULL) {
        it = Iterator_create(dd->size, tmp);
        if (it == NULL)
            free(tmp);
    }
    return it;
}

static const Deque *d_create(const Deque *d);

static Deque template = {
    NULL, d_create, d_destroy, d_clear, d_insertFirst, d_insertLast, d_first,
    d_last, d_removeFirst, d_removeLast, d_size, d_isEmpty, d_toArray,
    d_itCreate
};

/*
 * helper function to create a new Deque dispatch table
 */
static const Deque *newDeque(void (*freeValue)(void *e)) {
    Deque *d = (Deque *)malloc(sizeof(Deque));

    if (d != NULL) {
        DData *dd = (DData *)malloc(sizeof(DData));
        if (dd != NULL) {
            dd->size = 0L;
            dd->sentinel.next = SENTINEL(dd);
```

```
            dd->sentinel.prev = SENTINEL(dd);
            dd->freeValue = freeValue;
            *d = template;
            d->self = dd;
        } else {
            free(d);
            d = NULL;
        }
    }
    return d;
}

static const Deque *d_create(const Deque *d) {
    DData *dd = (DData *)d->self;

    return newDeque(dd->freeValue);
}

const Deque *LListDeque(void (*freeValue)(void *e)) {
    return newDeque(freeValue);
}

const Deque *Deque_create(void (*freeValue)(void *e)) {
    return newDeque(freeValue);
}
```

B.6 llistprioqueue.c

```
/* BSD header removed to conserve space */

/*
 * implementation for generic priority queue, for generic priorities
 * implemented using a singly-linked list, element sorted by priority
 */

#include "ADTs/llistprioqueue.h"
#include <stdlib.h>

typedef struct pqnode {
    struct pqnode *next;
    void *priority;
    void *value;
} PQNode;

typedef struct pq_data {
    int (*cmp)(void *p1, void *p2);
    long size;
```

```
    PQNode *head;
    PQNode *tail;
    void (*freePrio)(void *p);
    void (*freeValue)(void *v);
} PqData;

/*
 * traverses the list, calling freeP on each priority and freeV on each entry
 */
static void purge(PqData *pqd) {
    PQNode *p;

    for (p = pqd->head; p != NULL; p = p->next) {
        pqd->freePrio(p->priority);
        pqd->freeValue(p->value);
    }
}

/*
 * traverses the list, freeing nodes in the list
 */
static void freeList(PqData *pqd) {
    PQNode *p, *q = NULL;

    for (p = pqd->head; p != NULL; p = q) {
        q = p->next;
        free(p);
    }
}

static void pq_destroy(const PrioQueue *pq) {
    PqData *pqd = (PqData *)pq->self;
    purge(pqd);
    freeList(pqd);
    free(pqd);
    free((void *)pq);
}

static void pq_clear(const PrioQueue *pq) {
    PqData *pqd = (PqData *)pq->self;
    purge(pqd);
    freeList(pqd);
    pqd->head = pqd->tail = NULL;
    pqd->size = 0L;
}

static bool pq_insert(const PrioQueue *pq, void *priority, void *value) {
    PqData *pqd = (PqData *)pq->self;
    PQNode *new = (PQNode *)malloc(sizeof(PQNode));
    bool status = (new != NULL);
```

```
    if (status) {
        PQNode *prev = NULL, *next;
        new->next = NULL;
        new->priority = priority;
        new->value = value;
        for (next = pqd->head; next != NULL; prev = next, next = next->next)
            if (pqd->cmp(priority, next->priority) < 0)
                break;
/*
 * when we reach this point, the following situations can be true:
 *      prev==NULL, next==NULL: linked list was empty
 *      prev==NULL, next!=NULL: insert new at head
 *      prev!=NULL, next!=NULL: insert new between prev and next
 *      prev!=NULL, next==NULL: insert new at tail
 */
        if (prev == NULL)
            if (next == NULL) {
                pqd->head = new;
                pqd->tail = new;
            } else {
                new->next = pqd->head;
                pqd->head = new;
            }
        else
            if (next == NULL) {
                prev->next = new;
                pqd->tail = new;
            } else {
                new->next = next;
                prev->next = new;
            }
        pqd->size++;
    }
    return status;
}

static bool pq_min(const PrioQueue *pq, void **value) {
    PqData *pqd = (PqData *)pq->self;
    bool status = (pqd->size > 0L);

    if (status)
        *value = pqd->head->value;
    return status;
}

static bool pq_removeMin(const PrioQueue *pq, void **priority, void **value) {
    PqData *pqd = (PqData *)pq->self;
    bool status = (pqd->size > 0L);

    if (status) {
        PQNode *p = pqd->head;
```

```
        if ((pqd->head = p->next) == NULL)
            pqd->tail = NULL;
        *priority = p->priority;
        *value = p->value;
        pqd->size--;
        free(p);
    }
    return status;
}

static long pq_size(const PrioQueue *pq) {
    PqData *pqd = (PqData *)pq->self;
    return pqd->size;
}

static bool pq_isEmpty(const PrioQueue *pq) {
    PqData *pqd = (PqData *)pq->self;
    return (pqd->size == 0L);
}

/*
 * helper function to generate array of void *'s for toArray and itCreate
 */
static void **genArray(PqData *pqd) {
    void **theArray = NULL;
    if (pqd->size >0L) {
        theArray = (void **)malloc(pqd->size*sizeof(void *));
        if (theArray != NULL) {
            long i = 0L;
            PQNode *p;
            for (p = pqd->head; p != NULL; p = p->next)
                theArray[i++] = p->value;
        }
    }
    return theArray;
}

static void **pq_toArray(const PrioQueue *pq, long *len) {
    PqData *pqd = (PqData *)pq->self;
    void **tmp = genArray(pqd);
    if (tmp != NULL)
        *len = pqd->size;
    return tmp;
}

static const Iterator *pq_itCreate(const PrioQueue *pq) {
    PqData *pqd =(PqData *)pq->self;
    const Iterator *it = NULL;
    void **tmp = genArray(pqd);
    if (tmp != NULL) {
        it = Iterator_create(pqd->size, tmp);
```

```
        if (it == NULL)
            free(tmp);
    }
    return it;
}

static const PrioQueue *pq_create(const PrioQueue *pq);

static PrioQueue template = {
    NULL, pq_create, pq_destroy, pq_clear, pq_insert, pq_min, pq_removeMin,
    pq_size, pq_isEmpty, pq_toArray, pq_itCreate
};

/*
 * helper function to create a new Priority Queue dispatch table
 */
static const PrioQueue *newPrioQueue(int (*cmp)(void*,void*),
                                     void (*freeP)(void*),
                                     void (*freeV)(void*)) {
    PrioQueue *pq = (PrioQueue *)malloc(sizeof(PrioQueue));

    if (pq != NULL) {
        PqData *pqd = (PqData *)malloc(sizeof(PqData));

        if (pqd != NULL) {
            pqd->cmp = cmp;
            pqd->size = 0L;
            pqd->head = NULL;
            pqd->tail = NULL;
            pqd->freePrio = freeP;
            pqd->freeValue = freeV;
            *pq = template;
            pq->self = pqd;
        } else {
            free(pq);
            pq = NULL;
        }
    }
    return pq;
}

static const PrioQueue *pq_create(const PrioQueue *pq) {
    PqData *pqd = (PqData *)pq->self;

    return newPrioQueue(pqd->cmp, pqd->freePrio, pqd->freeValue);
}

const PrioQueue *LListPrioQueue(int (*cmp)(void *p1, void *p2),
                                void (*freePrio)(void *prio),
                                void (*freeValue)(void *value)) {
    return newPrioQueue(cmp, freePrio, freeValue);
```

```
}

const PrioQueue *PrioQueue_create(int (*cmp)(void *p1, void *p2),
                                  void (*freePrio)(void *prio),
                                  void (*freeValue)(void *value)) {
    return newPrioQueue(cmp, freePrio, freeValue);
}
```

B.7 llistmap.c

```
/* BSD header removed to conserve space */

/*
 * implementation for generic linked list map
 */

#include "ADTs/llistmap.h"
#include <stdlib.h>

typedef struct node {
    struct node *next;
    struct node *prev;
    MEntry entry;
} Node;

typedef struct m_data {
    int (*cmp)(void *, void *);
    long size;
    Node sentinel;
    void (*freeK)(void *k);
    void (*freeV)(void *v);
} MData;

/*
 * traverses the map, calling freeK and freeV on each entry
 * then frees storage associated with the Node structure
 */
static void purge(MData *md) {
    Node *p, *q = NULL;

    for (p = md->sentinel.next; p != &(md->sentinel); p = q) {
        md->freeK((p->entry).key);
        md->freeV((p->entry).value);
        q = p->next;
        free(p);
    }
}
```

```
static void m_destroy(const Map *m) {
    MData *md = (MData *)m->self;
    purge(md);
    free(md);
    free((void *)m);
}

static void m_clear(const Map *m) {
    MData *md = (MData *)m->self;
    purge(md);
    md->size = 0L;
    md->sentinel.next = md->sentinel.prev = &(md->sentinel);
}

/*
 * local function to locate key in a map
 *
 * returns pointer to entry, if found, as function value; NULL if not found
 */
static Node *findKey(MData *md, void *key) {
    Node *p;

    for (p = md->sentinel.next; p != &(md->sentinel); p = p->next) {
        if (md->cmp((p->entry).key, key) == 0) {
            break;
        }
    }
    return (p != &(md->sentinel)) ? p : NULL;
}

static bool m_containsKey(const Map *m, void *key) {
    MData *md = (MData *)m->self;

    return (findKey(md, key) != NULL);
}

static bool m_get(const Map *m, void *key, void **value) {
    MData *md = (MData *)m->self;
    Node *p = findKey(md, key);
    bool status = (p != NULL);

    if (status)
        *value = (p->entry).value;
    return status;
}

/*
 * helper function to link `p' between `before' and `after'
 */
static void link(Node *before, Node *p, Node *after) {
```

```
    p->next = after;
    p->prev = before;
    after->prev = p;
    before->next = p;
}

/*
 * helper function to insert new (key, value) into table
 */
static bool insertEntry(MData *md, void *key, void *value) {
    Node *p = (Node *)malloc(sizeof(Node));
    int status = (p != NULL);

    if (status) {
        (p->entry).key = key;
        (p->entry).value = value;
        link(md->sentinel.prev, p, &(md->sentinel));
        md->size++;
    }
    return status;
}

static bool m_put(const Map *m, void *key, void *value) {
    MData *md = (MData *)m->self;
    Node *p = findKey(md, key);
    bool status = (p != NULL);

    if (status) {
        md->freeK((p->entry).key);
        md->freeV((p->entry).value);
        (p->entry).key = key;
        (p->entry).value = value;
    } else {
        status = insertEntry(md, key, value);
    }
    return status;
}

static bool m_putUnique(const Map *m, void *key, void *value) {
    MData *md = (MData *)m->self;
    Node *p = findKey(md, key);
    bool status = (p == NULL);

    if (status) {
        status = insertEntry(md, key, value);
    }
    return status;
}

/*
 * unlinks `p' from the doubly-linked list
```

```
 */
static void unlink(Node *p) {
    p->prev->next = p->next;
    p->next->prev = p->prev;
}

static bool m_remove(const Map *m, void *key) {
    MData *md = (MData *)m->self;
    Node *p = findKey(md, key);
    bool status = (p != NULL);

    if (status) {
        unlink(p);
        md->size--;
        md->freeK((p->entry).key);
        md->freeV((p->entry).value);
        free(p);
    }
    return status;
}

static long m_size(const Map *m) {
    MData *md = (MData *)m->self;
    return md->size;
}

static bool m_isEmpty(const Map *m) {
    MData *md = (MData *)m->self;
    return (md->size == 0L);
}

/*
 * helper function for generating an array of keys from a map
 *
 * returns pointer to the array or NULL if malloc failure
 */
static void **keys(MData *md) {
    void **tmp = NULL;
    if (md->size > 0L) {
        size_t nbytes = md->size * sizeof(void *);
        tmp = (void **)malloc(nbytes);
        if (tmp != NULL) {
            long n = 0L;
            Node *p;
            for (p = md->sentinel.next; p != &(md->sentinel); p = p->next)
                tmp[n++] = (p->entry).key;
        }
    }
    return tmp;
}
```

```
static void **m_keyArray(const Map *m, long *len) {
    MData *md = (MData *)m->self;
    void **tmp = keys(md);

    if (tmp != NULL)
        *len = md->size;
    return tmp;
}

/*
 * helper function for generating an array of MEntry * from a map
 *
 * returns pointer to the array or NULL if malloc failure
 */
static MEntry **entries(MData *md) {
    MEntry **tmp = NULL;
    if (md->size > 0L) {
        size_t nbytes = md->size * sizeof(MEntry *);
        tmp = (MEntry **)malloc(nbytes);
        if (tmp != NULL) {
            long n = 0L;
            Node *p;
            for (p = md->sentinel.next; p != &(md->sentinel); p = p->next)
                tmp[n++] = &(p->entry);
        }
    }
    return tmp;
}

static MEntry **m_entryArray(const Map *m, long *len) {
    MData *md = (MData *)m->self;
    MEntry **tmp = entries(md);

    if (tmp != NULL)
        *len = md->size;
    return tmp;
}

static const Iterator *m_itCreate(const Map *m) {
    MData *md = (MData *)m->self;
    const Iterator *it = NULL;
    void **tmp = (void **)entries(md);

    if (tmp != NULL) {
        it = Iterator_create(md->size, tmp);
        if (it == NULL)
            free(tmp);
    }
    return it;
}
```

```
static const Map *m_create(const Map *m);

static Map template = {
    NULL, m_create, m_destroy, m_clear, m_containsKey, m_get, m_put,
    m_putUnique, m_remove, m_size, m_isEmpty, m_keyArray, m_entryArray,
    m_itCreate
};

/*
 * helper function to create a new Map dispatch table
 */
static const Map *newMap(int (*cmp)(void*, void*), void (*freeK)(void*),
                         void (*freeV)(void *)) {
    Map *m = (Map *)malloc(sizeof(Map));

    if (m != NULL) {
        MData *md = (MData *)malloc(sizeof(MData));

        if (md != NULL) {
            md->size = 0L;
            md->sentinel.next = md->sentinel.prev = &(md->sentinel);
            md->cmp = cmp;
            md->freeK = freeK;
            md->freeV = freeV;
            *m = template;
            m->self = md;
        } else {
            free(m);
            m = NULL;
        }
    }
    return m;
}

static const Map *m_create(const Map *m) {
    MData *md = (MData *)m->self;

    return newMap(md->cmp, md->freeK, md->freeV);
}

const Map *LListMap(int (*cmp)(void*, void*), void (*freeK)(void *k),
                    void (*freeV)(void *v)) {
    return newMap(cmp, freeK, freeV);
}
```

B.8 hashmap.c

```
/* BSD header removed to conserve space */

/*
 * implementation for generic hashmap
 */

#include "ADTs/hashmap.h"
#include <stdlib.h>

#define DEFAULT_CAPACITY 16
#define MAX_CAPACITY 134217728L
#define DEFAULT_LOAD_FACTOR 0.75
#define TRIGGER 100 /* number of changes that will trigger a load check */

typedef struct node {
    struct node *next;
    MEntry entry;
} Node;

typedef struct m_data {
    long (*hash)(void *, long N);
    int (*cmp)(void *, void *);
    long size;
    long capacity;
    long changes;
    double load;
    double loadFactor;
    double increment;
    Node **buckets;
    void (*freeK)(void *k);
    void (*freeV)(void *v);
} MData;

/*
 * traverses the map, calling freeK and freeV on each entry
 * then frees storage associated with the MEntry structure
 */
static void purge(MData *md) {
    long i;

    for (i = 0L; i < md->capacity; i++) {
        Node *p, *q;
        p = md->buckets[i];
        while (p != NULL) {
            md->freeK((p->entry).key);
            md->freeV((p->entry).value);
            q = p->next;
            free(p);
```

```
            p = q;
        }
        md->buckets[i] = NULL;
    }
}

static void m_destroy(const Map *m) {
    MData *md = (MData *)m->self;
    purge(md);
    free(md->buckets);
    free(md);
    free((void *)m);
}

static void m_clear(const Map *m) {
    MData *md = (MData *)m->self;
    purge(md);
    md->size = 0;
    md->load = 0.0;
    md->changes = 0;
}

/*
 * local function to locate key in a map
 *
 * returns pointer to entry, if found, as function value; NULL if not found
 * returns bucket index in `bucket'
 */
static Node *findKey(MData *md, void *key, long *bucket) {
    long i = md->hash(key, md->capacity);
    Node *p;

    *bucket = i;
    for (p = md->buckets[i]; p != NULL; p = p->next) {
        if (md->cmp((p->entry).key, key) == 0) {
            break;
        }
    }
    return p;
}

static bool m_containsKey(const Map *m, void *key) {
    MData *md = (MData *)m->self;
    long bucket;

    return (findKey(md, key, &bucket) != NULL);
}

static bool m_get(const Map *m, void *key, void **value) {
    MData *md = (MData *)m->self;
    long i;
```

```
    Node *p = findKey(md, key, &i);
    bool status = (p != NULL);

    if (status)
        *value = (p->entry).value;
    return status;
}

/*
 * helper function that resizes the hash table
 */
static void resize(MData *md) {
    int N;
    Node *p, *q, **array;
    long i, j;

    N = 2 * md->capacity;
    if (N > MAX_CAPACITY)
        N = MAX_CAPACITY;
    if (N == md->capacity)
        return;
    array = (Node **)malloc(N * sizeof(Node *));
    if (array == NULL)
        return;
    for (j = 0; j < N; j++)
        array[j] = NULL;
    /*
     * now redistribute the entries into the new set of buckets
     */
    for (i = 0; i < md->capacity; i++) {
        for (p = md->buckets[i]; p != NULL; p = q) {
            q = p->next;
            j = md->hash((p->entry).key, N);
            p->next = array[j];
            array[j] = p;
        }
    }
    free(md->buckets);
    md->buckets = array;
    md->capacity = N;
    md->load /= 2.0;
    md->changes = 0;
    md->increment = 1.0 / (double)N;
}

/*
 * helper function to insert new (key, value) into table
 */
static bool insertEntry(MData *md, void *key, void *value, long i) {
    Node *p = (Node *)malloc(sizeof(Node));
    bool status = (p != NULL);
```

```
    if (status) {
        (p->entry).key = key;
        (p->entry).value = value;
        p->next = md->buckets[i];
        md->buckets[i] = p;
        md->size++;
        md->load += md->increment;
        md->changes++;
    }
    return status;
}

static bool m_put(const Map *m, void *key, void *value) {
    MData *md = (MData *)m->self;
    long i;
    Node *p;
    int status = false;

    if (md->changes > TRIGGER) {
        md->changes = 0;
        if (md->load > md->loadFactor)
            resize(md);
    }
    p = findKey(md, key, &i);
    if (p != NULL) {
        md->freeK((p->entry).key);
        md->freeV((p->entry).value);
        (p->entry).key = key;
        (p->entry).value = value;
        status = true;
    } else {
        status = insertEntry(md, key, value, i);
    }
    return status;
}

static bool m_putUnique(const Map *m, void *key, void *value) {
    MData *md = (MData *)m->self;
    long i;
    Node *p;
    int status = false;

    if (md->changes > TRIGGER) {
        md->changes = 0;
        if (md->load > md->loadFactor)
            resize(md);
    }
    p = findKey(md, key, &i);
    if (p == NULL) {
        status = insertEntry(md, key, value, i);
```

```
    }
    return status;
}

static bool m_remove(const Map *m, void *key) {
    MData *md = (MData *)m->self;
    long i;
    Node *entry = findKey(md, key, &i);
    int status = (entry != NULL);

    if (status) {
        Node *p, *c;
        /* determine where the entry lives in the singly linked list */
        for (p = NULL, c = md->buckets[i]; c != entry; p = c, c = c->next)
            ;
        if (p == NULL)
            md->buckets[i] = entry->next;
        else
            p->next = entry->next;
        md->size--;
        md->load -= md->increment;
        md->changes++;
        md->freeK((entry->entry).key);
        md->freeV((entry->entry).value);
        free(entry);
    }
    return status;
}

static long m_size(const Map *m) {
    MData *md = (MData *)m->self;
    return md->size;
}

static bool m_isEmpty(const Map *m) {
    MData *md = (MData *)m->self;
    return (md->size == 0L);
}

/*
 * helper function for generating an array of keys from a map
 *
 * returns pointer to the array or NULL if malloc failure
 */
static void **keys(MData *md) {
    void **tmp = NULL;
    if (md->size > 0L) {
        size_t nbytes = md->size * sizeof(void *);
        tmp = (void **)malloc(nbytes);
        if (tmp != NULL) {
            long i, n = 0L;
```

```
            for (i = 0L; i < md->capacity; i++) {
                Node *p = md->buckets[i];
                while (p != NULL) {
                    tmp[n++] = (p->entry).key;
                    p = p->next;
                }
            }
        }
    }
    return tmp;
}

static void **m_keyArray(const Map *m, long *len) {
    MData *md = (MData *)m->self;
    void **tmp = keys(md);

    if (tmp != NULL)
        *len = md->size;
    return tmp;
}

/*
 * helper function for generating an array of MEntry * from a map
 *
 * returns pointer to the array or NULL if malloc failure
 */
static MEntry **entries(MData *md) {
    MEntry **tmp = NULL;
    if (md->size > 0L) {
        size_t nbytes = md->size * sizeof(MEntry *);
        tmp = (MEntry **)malloc(nbytes);
        if (tmp != NULL) {
            long i, n = 0L;
            for (i = 0L; i < md->capacity; i++) {
                Node *p = md->buckets[i];
                while (p != NULL) {
                    tmp[n++] = &(p->entry);
                    p = p->next;
                }
            }
        }
    }
    return tmp;
}

static MEntry **m_entryArray(const Map *m, long *len) {
    MData *md = (MData *)m->self;
    MEntry **tmp = entries(md);

    if (tmp != NULL)
        *len = md->size;
```

```
    return tmp;
}

static const Iterator *m_itCreate(const Map *m) {
    MData *md = (MData *)m->self;
    const Iterator *it = NULL;
    void **tmp = (void **)entries(md);

    if (tmp != NULL) {
        it = Iterator_create(md->size, tmp);
        if (it == NULL)
            free(tmp);
    }
    return it;
}

static const Map *m_create(const Map *m);

static Map template = {
    NULL, m_create, m_destroy, m_clear, m_containsKey, m_get, m_put,
    m_putUnique, m_remove, m_size, m_isEmpty, m_keyArray, m_entryArray,
    m_itCreate
};

/*
 * helper function to create a new Map dispatch table
 */
static const Map *newMap(long capacity, double loadFactor,
                         long (*hash)(void*,long), int (*cmp)(void*, void*),
                         void (*freeK)(void*), void (*freeV)(void *)) {
    Map *m = (Map *)malloc(sizeof(Map));
    long N;
    double lf;
    Node **array;
    long i;

    if (m != NULL) {
        MData *md = (MData *)malloc(sizeof(MData));

        if (md != NULL) {
            N = ((capacity > 0) ? capacity : DEFAULT_CAPACITY);
            N = (N > MAX_CAPACITY) ? MAX_CAPACITY : N;
            lf = ((loadFactor > 0.000001) ? loadFactor : DEFAULT_LOAD_FACTOR);
            array = (Node **)malloc(N * sizeof(Node *));
            if (array != NULL) {
                md->capacity = N; md->size = 0L; md->changes = 0L;
                md->loadFactor = lf; md->load = 0.0;
                md->increment = 1.0 / (double)N;
                md->hash = hash; md->cmp = cmp;
                md->freeK = freeK;
                md->freeV = freeV;
```

```
                md->buckets = array;
                for (i = 0; i < N; i++)
                    array[i] = NULL;
                *m = template;
                m->self = md;
            } else {
                free(md); free(m); m = NULL;
            }
        } else {
            free(m); m = NULL;
        }
    }
    return m;
}

static const Map *m_create(const Map *m) {
    MData *md = (MData *)m->self;

    return newMap(md->capacity, md->loadFactor, md->hash, md->cmp,
                  md->freeK, md->freeV);
}

const Map *HashMap(long capacity, double loadFactor,
                   long (*hash)(void*, long), int (*cmp)(void*, void*),
                   void (*freeK)(void *k), void (*freeV)(void *v)) {

    return newMap(capacity, loadFactor, hash, cmp, freeK, freeV);
}
```

B.9 heapprioqueue.c

```
/* BSD header removed to conserve space */

/*
 * implementation for generic priority queue, for generic priorities
 * implemented using a heap that expands when needed
 */

#include "ADTs/heapprioqueue.h"
#include <stdlib.h>

#define DEFAULT_HEAP_SIZE 25

typedef struct pqentry {
    void *priority;
    void *value;
    long sequenceNo;
```

```
} PQEntry;

typedef struct pq_data {
    int (*cmp)(void *p1, void *p2);
    long sequenceNo;
    long last;
    long size;
    PQEntry *heap;
    void (*freePrio)(void *p);
    void (*freeValue)(void *v);
} PqData;

/*
 * helper function to perform comparisons
 *
 * in order to guarantee FIFO, we first compare priorities using cmp() - if
 * that yields 0, then we return the difference in sequenceNo values
 */
static int realCmp(PqData *pqd, PQEntry *p1, PQEntry *p2) {
    int ans;
    if ((ans = pqd->cmp(p1->priority, p2->priority)) == 0)
        ans =  (int)(p1->sequenceNo - p2->sequenceNo);
    return ans;
}

/*
 * traverses the heap, calling freeP on each priority and freeV on each entry
 */
static void purge(PqData *pqd) {
    long i;

    for (i = 1; i <= pqd->last; i++) {
        pqd->freePrio(pqd->heap[i].priority);
        pqd->freeValue(pqd->heap[i].value);
    }
}

static void pq_destroy(const PrioQueue *pq) {
    PqData *pqd = (PqData *)pq->self;
    purge(pqd);
    free(pqd->heap);
    free(pqd);
    free((void *)pq);
}

static void pq_clear(const PrioQueue *pq) {
    PqData *pqd = (PqData *)pq->self;
    purge(pqd);
    pqd->last = 0L;
}
```

```
/*
 *  the siftup function restores the heap property after adding a new entry
 *  preconditions: last > 0 && heap(1,last-1)
 *  postcondition: heap(1,last)
 */
static void siftup(PqData *pqd) {
    long p, i = pqd->last;

    while (i > 1) {
        PQEntry hn;
        p = i / 2;
        if (realCmp(pqd, &(pqd->heap[p]), &(pqd->heap[i])) <= 0)
            break;
        hn = pqd->heap[p];
        pqd->heap[p] = pqd->heap[i];
        pqd->heap[i] = hn;
        i = p;
    }
}

static bool pq_insert(const PrioQueue *pq, void *priority, void *value) {
    PqData *pqd = (PqData *)pq->self;
    long i = pqd->last + 1;
    bool status = (i < pqd->size);

    if (! status) {       /* need to resize the array */
        size_t nbytes = (2 * pqd->size) * sizeof(PQEntry);
        PQEntry *tmp = (PQEntry *)realloc(pqd->heap, nbytes);

        if (tmp != NULL) {
            status = true;
            pqd->heap = tmp;
            pqd->size *= 2;
        }
    }
    if (status) {
        pqd->heap[i].priority = priority;
        pqd->heap[i].value = value;
        pqd->heap[i].sequenceNo = pqd->sequenceNo++;
        pqd->last = i;
        siftup(pqd);
    }
    return status;
}

static bool pq_min(const PrioQueue *pq, void **value) {
    PqData *pqd = (PqData *)pq->self;
    bool status = (pqd->last > 0L);

    if (status)
        *value = (pqd->heap[1].value);
```

```
    return status;
}

/*
 *  the siftdown function restores the heap property after removing
 *  the top element, and replacing it by the previous last element
 *  preconditions: heap(2,last) && last >= 0
 *  postcondition: heap(1,last-1)
 */
static void siftdown(PqData *pqd) {
    long c, i;

    i = 1;
    for(;;) {
        PQEntry hn;
        c = 2 * i;
        if (c > pqd->last)
            break;
        if ((c+1) <= pqd->last &&
            realCmp(pqd, &(pqd->heap[c+1]), &(pqd->heap[c])) < 0)
            c++;
        if (realCmp(pqd, &(pqd->heap[i]), &(pqd->heap[c])) <= 0)
            break;
        hn = pqd->heap[i];
        pqd->heap[i] = pqd->heap[c];
        pqd->heap[c] = hn;
        i = c;
    }
}

static bool pq_removeMin(const PrioQueue *pq, void **priority, void **value) {
    PqData *pqd = (PqData *)pq->self;
    bool status = (pqd->last > 0L);

    if (status) {
        *priority = (pqd->heap[1].priority);
        *value = (pqd->heap[1].value);
        pqd->heap[1] = pqd->heap[pqd->last];
        pqd->last--;
        siftdown(pqd);
    }
    return status;
}

static long pq_size(const PrioQueue *pq) {
    PqData *pqd = (PqData *)pq->self;
    return pqd->last;
}

static bool pq_isEmpty(const PrioQueue *pq) {
    PqData *pqd = (PqData *)pq->self;
```

```
    return (pqd->last == 0L);
}

/*
 * helper function to generate array of void *'s for toArray and itCreate
 */
static void **genArray(PqData *pqd) {
    void **theArray = NULL;
    if (pqd->last >0L) {
        PqData npqd = *pqd;
        PQEntry *tmp = (PQEntry *)malloc((pqd->last+1)*sizeof(PQEntry));
        if (tmp != NULL) {
            long i;
            theArray = (void **)malloc(pqd->last*sizeof(void *));
            if (theArray != NULL) {
                for (i = 0; i < pqd->last + 1; i++)  /* copy the heap */
                    tmp[i] = pqd->heap[i];
                npqd.heap = tmp;
                /* copy min element into theArray, swap first with last
                   and siftdown */
                for (i = 0; i < pqd->last; i++) {
                    theArray[i] = tmp[1].value;
                    tmp[1] = tmp[npqd.last--];
                    siftdown(&npqd);
                }
            }
            free(tmp);
        }
    }
    return theArray;
}

static void **pq_toArray(const PrioQueue *pq, long *len) {
    PqData *pqd = (PqData *)pq->self;
    void **tmp = genArray(pqd);
    if (tmp != NULL)
        *len = pqd->last;
    return tmp;
}

static const Iterator *pq_itCreate(const PrioQueue *pq) {
    PqData *pqd =(PqData *)pq->self;
    const Iterator *it = NULL;
    void **tmp = genArray(pqd);
    if (tmp != NULL) {
        it = Iterator_create(pqd->last, tmp);
        if (it == NULL)
            free(tmp);
    }
    return it;
}
```

```
static const PrioQueue *pq_create(const PrioQueue *pq);

static PrioQueue template = {
    NULL, pq_create, pq_destroy, pq_clear, pq_insert, pq_min, pq_removeMin,
    pq_size, pq_isEmpty, pq_toArray, pq_itCreate
};

/*
 * helper function to create a new Priority Queue dispatch table
 */
static const PrioQueue *newPrioQueue(int (*cmp)(void*, void*),
                                     void (*freeP)(void*),
                                     void (*freeV)(void*)) {
    PrioQueue *pq = (PrioQueue *)malloc(sizeof(PrioQueue));

    if (pq != NULL) {
        PqData *pqd = (PqData *)malloc(sizeof(PqData));

        if (pqd != NULL) {
            PQEntry *p = (PQEntry *)malloc(DEFAULT_HEAP_SIZE * sizeof(PQEntry));

            if (p != NULL) {
                pqd->cmp = cmp;
                pqd->sequenceNo = 0L;
                pqd->size = DEFAULT_HEAP_SIZE;
                pqd->last = 0L;
                pqd->heap = p;
                pqd->freePrio = freeP;
                pqd->freeValue = freeV;
                *pq = template;
                pq->self = pqd;
            } else {
                free(pqd);
                free(pq);
                pq = NULL;
            }
        } else {
            free(pq);
            pq = NULL;
        }
    }
    return pq;
}

static const PrioQueue *pq_create(const PrioQueue *pq) {
    PqData *pqd = (PqData *)pq->self;

    return newPrioQueue(pqd->cmp, pqd->freePrio, pqd->freeValue);
}
```

```
const PrioQueue *HeapPrioQueue(int (*cmp)(void *p1, void *p2),
                               void (*freePrio)(void *prio),
                               void (*freeValue)(void *value)) {
    return newPrioQueue(cmp, freePrio, freeValue);
}

const PrioQueue *PrioQueue_create(int (*cmp)(void *p1, void *p2),
                                  void (*freePrio)(void *prio),
                                  void (*freeValue)(void *value)) {
    return newPrioQueue(cmp, freePrio, freeValue);
}
```

B.10 heapsort.c

```
#include "sort.h"

#define ind(val) ((val)-1)    /* macro to compute correct index */

static void sift(void *a[], long L, long R, int(*cmp)(void*,void*)) {
    long i = L, j = 2 * L;
    void *x = a[ind(L)];

    if (j < R && (*cmp)(a[ind(j)], a[ind(j+1)]) < 0)
        j++;
    while (j <= R && (*cmp)(x, a[ind(j)]) < 0) {
        a[ind(i)] = a[ind(j)];
        a[ind(j)] = x;
        i = j;
        j *= 2;
        if (j < R && (*cmp)(a[ind(j)], a[ind(j+1)]) < 0)
            j++;
    }
}

void sort(void *a[], long size, int(*cmp)(void *v1, void *v2)) {
    long L = size / 2 + 1, R = size;

    while (L > 1) {
        L--;
        sift(a, L, R, cmp);
    }
    while (R > 1) {
        void *x = a[ind(1)];
        a[ind(1)] = a[ind(R)];
        a[ind(R)] = x;
        R--;
        sift(a, L, R, cmp);
```

```
        }
    }
```

Appendix C

A Mutable String ADT

Let's design and implement a mutable String ADT. As we learned in chapter 3, character strings in C are simply arrays of type `char`, with one character per array element. The end of the string is encoded as an element with the null value, `'\0'`. In order to manipulate these strings, one must use the functions defined in <string.h>.

Our mutable String ADT provides much of the functionality found in <string.h> and <ctype.h>. A mutable string is a sequence that can be indexed from 0 to N-1, where N is the length of the String. These are the methods that we would like to have on a String:

- obviously, our constructor should convert a C string into a String;
- return a new String which is a copy of an existing String;
- return a new String that is a slice of an existing String;
- destroy a String;
- append a C string to a String;
- assign a new character to a particular index in a String;
- insert a C string into a String before a particular index;
- convert all uppercase letters in the String to lowercase;
- remove all leading whitespace in the String;
- remove a character at a particular index;
- replace all occurrences of one C string by another C string in the String;
- remove all trailing whitespace in the String;
- remove all leading and trailing whitespace from a String;
- translates all characters in a specific equivalence class to a different character;
- convert all lowercase letters in the String to uppercase;
- compare two Strings, returning <0 | 0 | >0 if first < second | first == second | first > second, respectively;
- return true/false if a String contains a particular C string;
- return true/false if a String ends with a particular C string;
- returns the character at a particular index in the String;
- return the index into a String where a particular C string first matches, -1 if does not match;

- returns true if the string has at least one character and all characters are alphanumeric, false otherwise;
- returns true if the String has at least one character and all characters are digits, false otherwise;
- returns true if the String has at least one character and all characters are lowercase, false otherwise;
- returns true if the String has at least one character and all characters are whitespace, false otherwise;
- returns true if the String has at least one character and all characters are uppercase, false otherwise;
- return the length of the String;
- return the index into a String where a particular C string last matches, -1 if does not match;
- return true/false if a String starts with a particular C string;
- return true/false if a String contains a particular C string;
- splits a String into words; and
- convert a String into a C string.

C.1 The header file

We already have a header file named `string.h`, which defines the `str*()` functions for manipulating C strings. On Linux, since the filenames are case-sensitive, we could name our header file `String.h`, and not have any conflict. Some operating systems, such as Windows, have case-insensitive filenames. There is nothing in our ADT implementations that will not work on Windows, or any other system that supports the 1989 version (or later) of the C standard and has case-insensitive filenames. To maximize the utility of this ADT, we will name the header file `stringADT.h`, and the implementation `stringADT.c`.

```
#ifndef _STRINGADT_H_
#define _STRINGADT_H_

/* BSD header removed to conserve space */

/*
 * interface definition for Mutable String ADT
 *
 * patterned roughly after Python 3 string class with inclusion of
 * append(), clear(), insert(), remove(), replace(), translate()
 */

#include "ADTs/ADTdefs.h"
#include "ADTs/arraylist.h"

typedef struct string String; /* forward reference */

/*
```

```
 * creates a String from the supplied argument
 *
 * returns pointer to String if successful, NULL otherwise
 */
const String *String_create(char *str);

/*
 * now define dispatch table
 */
struct string {
/*
 * the private data of the String
 */
    void *self;

/*
 * return copy of `str'
 * returns pointer to new String if successful, NULL otherwise (heap errors)
 */
    const String *(*copy)(const String *str);

/*
 * returns new String that is a slice of `str'
 *
 * if end = 0, the last index of the slice is str->length(str)
 *
 * if `begin' or `end' are illegal, NULL is returned
 * otherwise, a new String is returned with a copy of the specified characters
 */
    const String *(*slice)(const String *str, int begin, int end);

/*
 * destroys the String
 */
    void (*destroy)(const String *str);

/*
 * append `suffix' to `str'
 * returns true if successful, false if not (heap error)
 */
    bool (*append)(const String *str, char *suffix);

/*
 * assign `chr' into `str[index]';
 * legal values of `index' are 0 .. str->len(str) - 1
 * if `index' is outside of legal range, return false; otherwise, return true
 */
    bool (*assign)(const String *str, int chr, int index);

/*
 * clear the characters from the string; equivalent to String_create("")
```

```
 * without creating a new dispatch table
 */
    void (*clear)(const String *str);
/*
 * insert `substr' into `str' before index `index';
 * legal values of `index' are 0 .. str->len(str)
 * if `index' is outside of legal range, return false; otherwise, return true
 */
    bool (*insert)(const String *str, char *substr, int index);

/*
 * converts all uppercase letters in `str' to lowercase
 */
    void (*lower)(const String *str);

/*
 * removes all leading whitespace in `str'
 */
    void (*lStrip)(const String *str);

/*
 * remove character at `index';
 * legal values of `index' are 0 .. str->len(str)-1
 * if `index' is outside of legal range, return false; otherwise, return true
 */
    bool (*remove)(const String *str, int index);

/*
 * replaces all occurrences of `old' in `str' with `new'
 * returns true if successful, false if not (heap error)
 */
    bool (*replace)(const String *str, char *old, char *new);

/*
 * removes all trailing whitespace in `str'
 */
    void (*rStrip)(const String *str);

/*
 * performs both lStrip() and rStrip() on `str'
 */
    void (*strip)(const String *str);

/*
 * translates all characters in `class' to `chr'
 */
    void (*translate)(const String *str, char *class, int chr);

/*
 * converts all lowercase letters in `str' to uppercase
 */
```

```
    void (*upper)(const String *str);

/*
 * return true if `substr' is contained in `str'; false if not
 */
    bool (*contains)(const String *str, char *substr);
/*
 * compare `str' with `other'; return <0|0|>0 if str < other |
 * str == other | str > other, respectively
 */
    int (*compare)(const String *str, const String *other);

/*
 * returns true if str->slice(str, begin, end) ends with `suffix'
 * if end = 0, the last index of the slice is str->length(str)
 * returns false if it does not
 */
    bool (*endsWith)(const String *str, char *suffix, int begin, int end);

/*
 * value of `str[index]' is returned in `*chr';
 * legal values of `index' are 0 .. str->len(str) - 1
 * if `index' is outside of legal range, return false; otherwise, return true
 */
    bool (*get)(const String *str, int index, int *chr);

/*
 * returns index if str->slice(str, begin, end) contains `substr'
 * if end = 0, the last index of the slice is str->length(str)
 * returns -1 if it does not
 */
    int (*index)(const String *str, char *substr, int begin, int end);

/*
 * returns true if `str' has at least 1 character and all characters are
 * alphanumeric
 * returns false otherwise
 */
    bool (*isAlpha)(const String *str);

/*
 * returns true if `str' has at least 1 character and all characters are digits
 * returns false otherwise
 */
    bool (*isDigit)(const String *str);

/*
 * returns true if `str' has at least 1 character and all characters are
 * lowercase
 * returns false otherwise
 */
```

```
    bool (*isLower)(const String *str);

/*
 * returns true if `str' has at least 1 character and all characters are
 * whitespace
 * returns false otherwise
 */
    bool (*isSpace)(const String *str);

/*
 * returns true if `str' has at least 1 character and all characters are
 * uppercase
 * returns false otherwise
 */
    bool (*isUpper)(const String *str);

/*
 * returns the length of `str'
 * returns 0 otherwise
 */
    int (*len)(const String *str);

/*
 * same as index(), but search backwards in `str'
 */
    int (*rindex)(const String *str, char *substr, int begin, int end);

/*
 * splits the string into a list of strings, returning an ArrayList, which
 * can be manipulated by the caller
 *
 * The sep argument is a C string with the characters used to split the string;
 * if it is "", runs of 1 or more white space characters separate words; if
 * it is not "", then the exact sequence of characters is used to separate words
 *
 * the words and the ArrayList are allocated on the heap, so the caller
 * must invoke the destroy() method on the ArrayList when finished to avoid
 * memory leaks
 *
 * returns NULL if memory allocation failure or NO WORDS IN THE String
 */
    const ArrayList *(*split)(const String *str, char *sep);

/*
 * returns true/false if str->slice(str, begin, end) starts with `prefix'
 * if end = 0, the last index of the slice is str->length(str)
 */
    bool (*startsWith)(const String *str, char *prefix, int begin, int end);

/*
 * returns a char * to the contents of the string
```

```
 */
    char *(*convert)(const String *str);
};

#endif /* _STRINGADT_H_ */
```

Note that we have `#include`'d `ADTs/arraylist.h` at the top of the `.h` file; we need this so that the `split` method can return an instance of an `ArrayList`.

Besides the constructor, `String_create()`, which converts a C string into a `String`, we have two methods that create new `String`'s: `copy()` performs a deep copy of the `String` upon which it is invoked, and `slice()`, which performs a deep copy of the subrange of the `String` upon which it is invoked, as specified by [`begin`, `end`). `destroy()` destroys instances of `String`'s.

`append()`, `assign()`, `insert()`, `lower()`, `lStrip()`, `remove()`, `replace()`, `rStrip()`, `strip()`, `translate()`, and `upper()` modify the contents of the string, either by adding characters, deleting characters, or replacing characters.

`compare()`, `contains()`, `endsWith()`, `get()`, `index()`, `isAlpha()`, `isDigit()`, `isLower()`, `isSpace()`, `isUpper()`, `len()`, `rindex()`, `split()`, and `startsWith()` tell you things about the `String` itself, as well as in relation to C strings and other `String`'s.

Note that `split()` returns an instance of an `ArrayList`, with each element in the list being a pointer to a C string; after one has used the elements of the `ArrayList`, one must destroy it with a call of the form

```
al->destroy(al);
```

Finally, `convert()` provides a C string that is the equivalent set of characters that currently make up the `String`.

C.2 The source file

The implementation for a String has several similarities to our implementation of `ArrayList`. To be sure, it has several string-specific methods, but since `ArrayList` implements a sequence of elements, while `StringADT` implements a sequence of characters, it is not unexpected that there will be similarities between common portions of the implementations.

In fact, one might wonder if we shouldn't implement a `StringADT` as an implementation using an `ArrayList`. Such reuse would normally be encouraged if it were not for the fact that strings are used so heavily in C applications. This demands that the `StringADT` implementation be as performant (in both space and running time) as possible. Additionally, you will have noted that when the `ArrayList` implementation needed to grow the buffer, it always doubled it in size; normal dynamic manipulations of a string are in much smaller increments, and growing the buffer by linear increments is preferred over doubling the buffer. Thus, the implementation will encapsulate a normal C array, not an instance of an `ArrayList`.

As we did with `ArrayList`, we will show the implementation in pieces to facilitate understanding. First, let's discuss how to represent a `String`.

Since we are likely to be using functions in `<string.h>` and `<ctype.h>` to assist us in the implementation, we probably want to store the characters that make up a string as an array of `char`, and at all times this array is terminated by `'\0'`. This choice makes the implementation of the `convert()` method particularly easy, as we simply return the address of this array to the caller.

Since so many of the methods modify the `String`, either adding or removing characters, we will need to keep track of how large the character array is (how big a chunk of memory was allocated); we will also keep track of the current length of the string in that array. Of course, we could just invoke `strlen()` on that buffer whenever we needed to know the length, but it is much more efficient to keep track of the length, and avoid the runtime cost to calculate the length.

Most of the method implementations are very straightforward.

C.2.1 The preliminaries

```
/*
 * implementation for String ADT
 */
#include "ADTs/stringADT.h"
#include <string.h>
#include <ctype.h>
#include <stdlib.h>

/*
 * member data for String instance
 */
typedef struct St_data {
    int length;
    int size;
    char *buf;
} StData;

#define INCREMENT 1024 /* if we ever have to grow the string, do it
                          by this increment except for replace() */
```

As always with an ADT, the implementation must include the corresponding interface definition, thus assuring that we have the correct function signatures in the implementation. We include `<string.h>`, `<ctype.h>`, and `<stdlib.h>`, as we will need functions and definitions from those header files in the implementation. Finally, we define an `INCREMENT` size; whenever we need to add things to the character array, if we need more capacity, then we `realloc()` the buffer to be `size + INCREMENT`, except for resizing due to the `replace()` method.

You may wonder why we do not `#include "ADTs/arraylist.h"` - we have included `ADTs/stringADT.h`, which itself includes `ADTs/arraylist.h`, so there is no need to explicitly include it here. Explicit inclusion here would not cause a problem, since `ADTs/arraylist.h` contains an `#ifndef ... #define ... #endif` around the actual definitions, and the 2nd inclusion would not be processed beyone the check to see that `_ARRAYLIST_H_` is already defined.

C.2.2 The manager methods

C.2.2.1 `slice_copy()`

Both `copy()` and `slice()` require that we duplicate part or all of the character array on the heap. This helper function is used by both of those implementations to perform that duplication.

```
/*
 * helper function that creates a copy of buf[begin]..buf[end], inclusive,
 * on the heap
 *
 * assumes that begin and end are legal indices into buf
 *
 * returns pointer to the copy, or NULL if malloc() failure
 */
static char *slice_copy(char *buf, int begin, int end) {
    int size = end - begin + 1 + 1; /* +1 for '\0' */
    char *p;

    if ((p = (char *)malloc(size)) != NULL) {
        int i, j;

        for (i = begin, j = 0; i <= end; i++, j++)
            p[j] = buf[i];
        p[j] = '\0';
    }
    return p;
}
```

C.2.2.2 `copy()`

Most of the complexity in `copy()` is to recover from heap allocation failure. Note that we copy the dispatch table for `str` into the dispatch table for the copy; this initializes all of the function pointers, and all we have to do is cause the `self` member to point to the copy of the string.

```
static const String *st_copy(const String *str) {
    StData *std = (StData *)str->self;
    String *nstr = (String *)malloc(sizeof(String));

    if (nstr != NULL) {
        StData *nstd = (StData *)malloc(sizeof(StData));

        if (nstd != NULL) {
            nstd->buf = slice_copy(std->buf, 0, std->length - 1);
            if (nstd->buf != NULL) {
                nstd->length = std->length;
                nstd->size = std->size;
                *nstr = *str;
                nstr->self = nstd;
            } else {
                free(nstd);
                free(nstr);
                nstr = NULL;
            }
        } else {
            free(nstr);
            nstr = NULL;
        }
    }
    return nstr;
}
```

C.2.2.3 `slice()`

This code is very similar to that for `copy()`. Again, most of the complexity is handling heap allocation failures. Note that we copy the dispatch table for `str` into the dispatch table for the copy; this initializes all of the function pointers, and all we have to do is cause the `self` member to point to the copy of the slice.

```
static const String *st_slice(const String *str, int begin, int end) {
    StData *std = (StData *)str->self;
    String *nstr = NULL;

    if (end == 0)
        end = std->length;
    if (begin >= 0 && end <= std->length && begin < end) {
        nstr = (String *)malloc(sizeof(String));
        if (nstr != NULL) {
            StData *nstd = (StData *)malloc(sizeof(StData));

            if (nstd != NULL) {
```

```
                nstd->buf = slice_copy(std->buf, begin, end - 1);
                if (nstd->buf != NULL) {
                    nstd->length = strlen(nstd->buf);
                    nstd->size = nstd->length + 1;
                    *nstr = *str;
                    nstr->self = nstd;
                } else {
                    free(nstd);
                    free(nstr);
                    nstr = NULL;
                }
            } else {
                free(nstr);
                nstr = NULL;
            }
        }
    }
    return nstr;
}
```

C.2.2.4 `destroy()`

This method is quite straightforward: we need to return the buffer to the heap, then the `StData` instance, and then the dispatch table.

```
static void st_destroy(const String *str) {
    StData *std = (StData *)str->self;

    free(std->buf);
    free(std);
    free((void *)str);
}
```

C.2.3 The mutator methods

C.2.3.1 `append()`

This method appends the contents of the C string `suffix` to our `String` instance. If addition of the contents would overflow the character array, the array is extended using `realloc()` from `<string.h>`. Returns true/1 is successful, false if heap error.

```
static bool st_append(const String *str, char *suffix) {
    StData *std = (StData *)str->self;
    int n = strlen(suffix);
```

```
    if ((std->length + n + 1) > std->size) {
        int nsize = std->size + ((n > INCREMENT) ? n : INCREMENT);
        char *p = (char *)realloc(std->buf, nsize);

        if (p == NULL)
            return false;
        std->buf = p;
        std->size = nsize;
    }
    strcpy(std->buf+std->length, suffix);
    std->length = strlen(std->buf);
    return true;
}
```

C.2.3.2 `assign()`

This method assigns a new character `chr` to the `String` at `index`; the previous character at that location is overwritten; the return value is true/1 if `index` was legal (between 0 and length-1, inclusive), false/0 otherwise. If you want to append a character at `index` length, you have to use `append()` above.

```
static bool st_assign(const String *str, int chr, int index) {
    StData *std = (StData *)str->self;
    bool status = (index >= 0 && index < std->length);

    if (status)
        std->buf[index] = chr;
    return status;
}
```

C.2.3.3 `clear()`

This method sets the length of the `String` to 0; it is equivalent to invoking the constructor with an argument of `""`.

```
static void st_clear(const String *str) {
    StData *std = (StData *)str->self;

    std->length = 0;
    std->buf[0] = '\0';
}
```

C.2.3.4 `insert()`

This method inserts the C string `substr` into the `String` before `index`; the return value is true/1 if `index` was legal (between 0 and length, inclusive), false/0 otherwise. If the insertion would overflow the character buffer, the buffer is extended using `realloc()`.

```
static bool st_insert(const String *str, char *substr, int index) {
    StData *std = (StData *)str->self;
    int n = strlen(substr);
    int i, j;

    if (index < 0 || index > std->length)
        return false;
    if ((std->length + n + 1) > std->size) {
        int nsize = std->size + ((n > INCREMENT) ? n : INCREMENT);
        char *p = (char *)realloc(std->buf, nsize);

        if (p == NULL)
            return false;
        std->buf = p;
        std->size = nsize;
    }
    for (i = std->length, j = std->length + n; i >= index; i--, j--)
        std->buf[j] = std->buf[i];
    for (i = 0, j = index; i < n; i++, j++)
        std->buf[j] = substr[i];
    std->length += n;
    return true;
}
```

C.2.3.5 `lower()`

This method converts all uppercase characters in the `String` to lowercase.

```
static void st_lower(const String *str) {
    StData *std = (StData *)str->self;
    int i;

    for (i = 0; i < std->length; i++)
        std->buf[i] = tolower(std->buf[i]);
}
```

C.2.3.6 `lStrip()`

This method removes all leading whitespace from the `String`.

```
static void st_lStrip(const String *str) {
    StData *std = (StData *)str->self;
    int i, j;

    for (i = 0; i < std->length; i++)
        if (! isspace(std->buf[i]))
            break;
    for (j = 0; i < std->length; i++, j++)
        std->buf[j] = std->buf[i];
    std->buf[j] = '\0';
    std->length = strlen(std->buf);
}
```

C.2.3.7 `remove()`

This method removes the character at `index` from the `String`. If `index` is legal, the return value is true/1; otherwise, it is false/0.

```
static bool st_remove(const String *str, int index) {
    StData *std = (StData *)str->self;
    bool status = (index >= 0 && index < std->length);
    int i, j;

    if (status) {
        for (j = index, i = index + 1; i < std->length; i++, j++)
            std->buf[j] = std->buf[i];
        std->buf[j] = '\0';
        std->length--;
    }
    return status;
}
```

C.2.3.8 `replace()`

This method replaces all occurrences of `old` in the `String` by `new`. If this would cause the buffer to overflow, it is extended. The extension logic is to calculate the worst case number of times `old` can appear in the string (e.g., if `old` is "my", and the `String` is `10` characters long, then the worst case is if the string is "mymymymymy" - length of `String` divided by length of `old`, rounded up to the nearest whole number; this is `nold` in the code). Then, the length of the `String` after the replacement, in the worst case, is current length plus `nold` times the difference in lengths of the `old` and `new` strings. Returns true/1 if successful, false/0 if there are heap errors.

```
static bool st_replace(const String *str, char *old, char *new) {
    StData *std = (StData *)str->self;
    int oldlen = strlen(old);
    int newlen = strlen(new);
    int nold, size;
    char *nbuf;
    bool status = false; /* assume malloc() fails */

    nold = ((std->length) / oldlen) + 1; /* worst case # of matches */
    size = std->size - nold * oldlen + nold * newlen;
    if (size < std->size)
        size = std->size;
    nbuf = (char *)malloc(size);
    if (nbuf != NULL) {
        int i, j;
        i = 0;
        j = 0;
        while (i < std->length) {
            if (strncmp(std->buf+i, old, oldlen) == 0) {
                strncpy(nbuf+j, new, newlen);
                j += newlen;
                i += oldlen;
            } else {
                nbuf[j++] = std->buf[i++];
            }
        }
        nbuf[j] = '\0';
        free(std->buf);
        std->buf = nbuf;
        std->length = j;
        std->size = size;
        status = true;
    }
    return status;
}
```

C.2.3.9 `rStrip()`

This method removes all trailing whitespace from the `String`.

```
static void st_rStrip(const String *str) {
    StData *std = (StData *)str->self;
    int i;

    for (i = std->length - 1; i >= 0; i--)
        if (! isspace(std->buf[i]))
            break;
    std->buf[i+1] = '\0';
```

```
    std->length = strlen(std->buf);
}
```

C.2.3.10 `strip()`

This method removes all leading and trailing whitespace from the `String`.

```
static void st_strip(const String *str) {

    st_lStrip(str);
    st_rStrip(str);
}
```

C.2.3.11 `translate()`

This method replaces each character in the `String` that is a member of the equivalence class `class` by `chr`. The equivalence class names are identical to those used by the `tr` command provided by Linux. They are shown in the following table.

Equivalence class	Description
`"[:alnum:]"`	all letters and digits
`"[:alpha:]"`	all letters
`"[:blank:]"`	all horizontal white space
`"[:cntrl:]"`	all control characters
`"[:digit:]"`	all digits
`"[:graph:]"`	all printable characters, not including space
`"[:lower:]"`	all lower case letters
`"[:print:]"`	all printable characters, including space
`"[:punct:]"`	all punctuation characters
`"[:space:]"`	all horizontal or vertical white space
`"[:upper:]"`	all upper case letters
`"[:xdigit:]"`	all hexadecimal digits

```
static struct class_func {
    char *class;
    int (*func)(int ch);
} classFuncs[] = {
    {"[:alnum:]", isalnum}, {"[:alpha:]", isalpha}, {"[:blank:]", isblank},
    {"[:cntrl:]", iscntrl}, {"[:digit:]", isdigit}, {"[:graph:]", isgraph},
    {"[:lower:]", islower}, {"[:print:]", isprint}, {"[:punct:]", ispunct},
    {"[:space:]", isspace}, {"[:upper:]", isupper}, {"[:xdigit:]", isxdigit},
    {NULL, NULL}
};
```

```
static void st_translate(const String *str, char *class, int chr) {
    StData *std = (StData *)str->self;
    int (*fxn)(int) = NULL;
    int i;

    for (i = 0; classFuncs[i].class != NULL; i++)
        if (strcmp(class, classFuncs[i].class) == 0) {
            fxn = classFuncs[i].func;
            break;
        }
    if (fxn == NULL)
        return;
    for (i = 0; i < std->length; i++)
        if ((*fxn)(std->buf[i]))
            std->buf[i] = chr;
}
```

C.2.3.12 `upper()`

This method converts all lowercase characters in the `String` to uppercase.

```
static void st_upper(const String *str) {
    StData *std = (StData *)str->self;
    int i;

    for (i = 0; i < std->length; i++)
        std->buf[i] = toupper(std->buf[i]);
}
```

C.2.4 The accessor methods

C.2.4.1 `compare()`

This method compares two `String`'s; it returns a value < 0 if `str < other`, returns 0 if `str == other`, and returns a value > 0 if `str > other`.

```
static int st_compare(const String *str, const String *other) {
    StData *std = (StData *)str->self;
    StData *otd = (StData *)other->self;

    return strcmp(std->buf, otd->buf);
}
```

C.2.4.2 `contains()`

This method returns true/1 if the `String` contains `substr`, false/0 if it does not.

```
static int st_contains(const String *str, char *substr) {
    StData *std = (StData *)str->self;
    return (strstr(std->buf, substr) != NULL);
}
```

C.2.4.3 `endsWith()`

This method returns true/1 if the slice `str[begin:end]` "ends with" the characters in `suffix`; if `end == 0`, it means that the ending index is the length of `str`. To simply check if `str` "ends with" `suffix`, specify both `begin` and `end` as 0. If it does not end with `suffix`, return false/0.

```
static bool st_endsWith(const String *str, char *suffix, int begin, int end) {
    StData *std = (StData *)str->self;
    int nchars, suflen;
    bool status = false;

    if (end == 0)
        end = std->length;
    nchars = end - begin;
    suflen = strlen(suffix);
    if (nchars >= suflen) {
        if (strncmp(suffix, std->buf + end - suflen, suflen) == 0)
            status = true;
    }
    return status;
}
```

C.2.4.4 `get()`

The value of `str[index]` is returned in `*chr`; legal values of `index` are `0 .. str->len(str) - `̀. Returns false/0 if index out of range, true/1 otherwise.

```
static bool st_get(const String *str, int index, int *chr) {
    StData *std = (StData *)str->self;
    bool status = (index >= 0 && index < std->length);

    if (status)
        *chr = std->buf[index];
    return status;
}
```

C.2.4.5 `index()`

This method returns the index in `str[begin:end]` at which the first match to `substr` occurs. If there is no match, it returns -1.

```
static int st_index(const String *str, char *substr, int begin, int end) {
    StData *std = (StData *)str->self;
    int n = strlen(substr);
    int i, j;

    if (end == 0)
        end = std->length;
    for (i = begin, j = end - begin; i < end && j >= n; i++, j--)
        if (strncmp(std->buf + i, substr, n) == 0)
            return i;
    return -1;
}
```

C.2.4.6 `isAlpha()`, `isDigit()`, `isLower()`, `isSpace()`, and `isUpper()`

These methods require that `str` have at least one character; the methods returns true/1 if all of the characters in `str` are alphanumeric, digits, lowercase, whitespace, or uppercase, respectively; they return false/0 if not, respectively.

```
static bool st_isAlpha(const String *str) {
    StData *std = (StData *)str->self;
    int i;

    if (std->length > 0) {
        for (i = 0; i < std->length; i++)
            if (! isalpha(std->buf[i]))
                return false;
        return true;
    }
    return false;
}

static bool st_isDigit(const String *str) {
    StData *std = (StData *)str->self;
    int i;

    if (std->length > 0) {
        for (i = 0; i < std->length; i++)
            if (! isdigit(std->buf[i]))
                return false;
        return true;
    }
```

```
    return false;
}

static bool st_isLower(const String *str) {
    StData *std = (StData *)str->self;
    int i;

    if (std->length > 0) {
        for (i = 0; i < std->length; i++)
            if (! islower(std->buf[i]))
                return false;
        return true;
    }
    return false;
}

static bool st_isSpace(const String *str) {
    StData *std = (StData *)str->self;
    int i;

    if (std->length > 0) {
        for (i = 0; i < std->length; i++)
            if (! isspace(std->buf[i]))
                return false;
        return true;
    }
    return false;
}

static bool st_isUpper(const String *str) {
    StData *std = (StData *)str->self;
    int i;

    if (std->length > 0) {
        for (i = 0; i < std->length; i++)
            if (! isupper(std->buf[i]))
                return false;
        return true;
    }
    return false;
}
```

C.2.4.7 `len()`

This method returns the number of characters in `str`.

```
static int st_len(const String *str) {
    StData *std = (StData *)str->self;
```

```
    return std->length;
}
```

C.2.4.8 `rindex()`

This method returns the index in `str[begin:end]` at which the last match to `substr` occurs. If there is no match, it returns -1.

```
static int st_rindex(const String *str, char *substr, int begin, int end) {
    StData *std = (StData *)str->self;
    int n = strlen(substr);
    int i, j;

    if (end == 0)
        end = std->length;
    for (i = end - n, j = end - begin; i >= begin && j >= n; i--, j--)
        if (strncmp(std->buf + i, substr, n) == 0)
            return i;
    return -1;
}
```

C.2.4.9 `split()`

This method splits the String at occurrences of the C string `sep`. If `sep == ""`, then words are separated by horizontal white space characters; if not the empty string, then words are separated by `sep`.

We need several helper functions to support the `split` method.

`st_split_pat` handles the situation when `sep` is not the empty C string. It allocates each word on the heap, storing pointers to them in the `elems` argument. The function return is the number of words stored in `elems`.

```
/*
 * splits the string s at occurrences of sep, malloc'ing the words on
 * the heap and storing the pointers in elems[]; returns the number of words
 * placed in elems[], 0 if malloc() errors
 */
static long st_split_pat(char *s, char *sep, char *elems[]) {
    long i, j;
    int n = strlen(sep);
    char *p, *q, *t, buf[4096];

    i = 0;
    p = s;
```

```
    while (*p != '\0') {
        q = strstr(p, sep);
        t = buf;
        if (q == NULL) {      /* not found, copy rest of s into buf */
            while ((*t++ = *p++) != '\0')
                ;
            p--;              /* went one position too far */
        } else {
            while (p != q)
                *t++ = *p++;
            *t = '\0';
            p += n;           /* point at first character past sep */
        }
        if ((t = strdup(buf)) == NULL)
            goto cleanup;
        elems[i++] = t;
    }
    return i;
cleanup:
    for (j = 0; j < i; j++)
        free(elems[j]);
    return 0;
}
```

The following function returns the index into `buf` at which the character `c` was found. If not found, it returns -1. This function is needed when we are fetching words when `sep` is the empty string.

```
static int skipchr(char buf[], char c) {
    int i;

    for (i = 0; buf[i] != '\0'; i++)
        if (buf[i] == c)
            return i;
    return -1;
}
```

The following function fetches the next white-space separated word from `buf` starting at index `i`, and returns the starting index for the next word; if there was no next word, -1 is returned.

```
static char *whitespace = " \t\n";
static int getword(char buf[], int i, char word[]) {
    char *p;
    int j = i;

    while (skipchr(whitespace, buf[j]) != -1)
        j++;
    if (buf[j] == '\0')
```

```
        return -1;
    p = word;
    while (buf[j] != '\0') {
        if (strchr(whitespace, buf[j]) != NULL)
            break;
        *p++ = buf[j];
        j++;
    }
    *p = '\0';
    return j;
}
```

This function is similar to `st_split_pat` above, except it uses white space characters to separate words.

```
static long st_split_white(char *s, char *elems[]) {
    int i, k;
    long j;
    char buf[4096];

    i = 0;
    j = 0;
    for (i = 0; (k = getword(s, i, buf)) != -1; i = k) {
        char *t = strdup(buf);
        if (t == NULL)
            goto cleanup;
        elems[j++] = t;
    }
    return j;
cleanup:
    for (j--; j >= 0; j--)
        free(elems[j]);
    return 0;
}
```

Finally, the implementation of the `split` method. This implementation is retricted to `String`'s that have no more than 1000 words.

```
static const ArrayList *st_split(const String *str, char *sep) {
    const ArrayList *al = NULL;
    char *elems[1000];        /* can't handle more than 1000 words */
    char *s = str->convert(str);
    long i, n;

    /*
     * note - if sep == "", leading and trailing white space characters are
     * ignored
     */
```

```
    if (sep[0] != '\0')
        n = st_split_pat(s, sep, elems);
    else
        n = st_split_white(s, elems);
    if (n > 0) {
        al = ArrayList_create(n, free);
        if (al != NULL) {
            for (i = 0; i < n; i++)
                (void) al->add(al, elems[i]);
        } else {
            for (i = 0; i < n; i++)
                free(elems[i]);
            al = NULL;
        }
    }
    return al;
}
```

C.2.4.10 startsWith()

This method returns true/1 if the slice `str[begin:end]` "starts with" the characters in `prefix`; if `end == 0`, it means that the ending index is the length of `str`. To simply check if `str` "starts with" `prefix`, specify both `begin` and `end` as 0. It returns false/0 if it does not start with `prefix`.

```
static bool st_startsWith(const String *str, char *prefix, int begin, int end) {
    StData *std = (StData *)str->self;
    int nchars, prelen;
    bool status = false;

    if (end == 0)
        end = std->length;
    nchars = end - begin;
    prelen = strlen(prefix);
    if (nchars >= prelen) {
        if (strncmp(prefix, std->buf + begin, prelen) == 0)
            status = true;
    }
    return status;
}
```

C.2.5 The miscellaneous methods

C.2.5.1 convert()

This method returns a C string representation of `str`.

```
static char *st_convert(const String *str) {
    StData *std = (StData *)str->self;

    return std->buf;
}
```

C.2.6 The constructor

C.2.6.1 The template `String` structure

As with the `Iterator` implementation, we create a template for the dispatch table. It is important to note that the function pointers in the initialization of the template **MUST** be in exactly the same order as the definition for `struct string` in the header file. If they are not in the same order, in the best case the compiler will complain because the function pointer you have specified in a particular place does not match the appropriate method's function prototype; in the worst case, it does match the prototype, but delivers the wrong functionality.

```
static String template = {
    NULL, st_copy, st_slice, st_destroy, st_append, st_assign, st_clear,
    st_insert, st_lower, st_lStrip, st_remove, st_replace, st_rStrip, st_strip,
    st_translate, st_upper, st_compare, st_contains, st_endsWith, st_get,
    st_index, st_isAlpha, st_isDigit, st_isLower, st_isSpace, st_isUpper,
    st_len, st_rindex, st_split, st_startsWith, st_convert
};
```

C.2.6.2 `String_create()`

As with the `copy()` and `slice()` methods, most of the complexity is in handling possible heap allocation failures. You should find the code straightforward to understand.

```
const String *String_create(char *str) {
    String *st = (String *)malloc(sizeof(String));

    if (st != NULL) {
        StData *std = (StData *)malloc(sizeof(StData));

        if (std != NULL) {
            std->length = strlen(str); /* length of str */
            std->size = std->length + 1; /* account for '\0' */
            std->buf = (char *)malloc(std->size);
            if (std->buf != NULL) {
                strcpy(std->buf, str);
                *st = template;
```

```
                st->self = std;
            } else {
                free(std);
                free(st);
                st = NULL;
            }
        } else {
            free(st);
            st = NULL;
        }
    }
    return st;
}
```

Appendix D

A review of Python Programming on Linux

Why review Python? Since we assume you are comfortable with Python, it is often easiest to acquire a new programming language by being able to compare and contrast it with a language that you already understand. Thus, this chapter will focus on the primary elements of Python to enable comparison with C.

Note that we are focused on Python v3.* - all examples and code fragments follow that language standard.

Python is one of many languages that enables one to program a computer that implements the von Neumann model or architecture; nearly all computational devices conform to this architecture. Appendix E provides a description of this architecture if you need a refresher.

D.1 Built-in Types

With most languages, one distinguishes between three different kinds of data types:

- built-in primitive types;
- built-in structured types; and
- programmer-defined structured types.

This section is devoted to the built-in types; programmer-defined structured types will be covered in a later section.

D.1.1 Built-in primitive types

Python provides the following built-in primitive types:

- the *integer* type (`int`) is used to represent the set of values `{..., -3, -2, -1, 0, 1, 2, 3, ...}`;
- the *floating point* type (`float`) is used to represent real numbers; the numbers are stored as a mantissa and an exponent (scientific notation); in most cases, the representation is an approximation of the actual real number due to the number of bits devoted to the mantissa and exponent;
- the *boolean* type (`bool`) represents the truth values `True` and `False`.

Python also defines a *complex* type to represent complex numbers; since C does not have a built-in equivalent to that type, we will ignore it going forward.

The following operators are defined on the numeric types:

`x + y`	sum of x and y
`x - y`	difference of x and y
`x * y`	product of x and y
`x / y`	quotient of x and y
`x // y`	integer division (floored quotient of x and y)
`x % y`	remainder of (x // y)
`-x`	x negated
`+x`	x unchanged
`abs(x)`	absolute value/magnitude of x
`int(x)`	x converted to integer
`float(x)`	x converted to floating point
`x ** y`	x to the power y

The following comparison operators, when used with numeric types, generate boolean values:

`x < y`	x is strictly less than y
`x <= y`	x is less than or equal to y
`x > y`	x is strictly greater than y
`x >= y`	x is greater than or equal to y
`x == y`	x is equal to y
`x != y`	x is not equal to y

Boolean values can be combined using the usual boolean operators:

`x or y`	if x is `False`, then y, else x	y is only evaluated if x is `False`
`x and y`	if x is `False`, then x, else y	y is only evaluated if x is `True`
`not x`	if x is `False`, then `True`, else `False`	has lower priority than non-Boolean operators, so `not a == b` is interpreted as `not (a == b)`

D.1.1.1 Effective use of boolean variables

While the above tables indicate how to generate and combine boolean values, it is important to understand how to use booleans to simplify your code. Consider having to write the following function:

```
def contains(st, subst, invert):
    """
    if invert is False, returns True if subst is contained in st
                        returns False if subst is not contained in st
    if invert is True, returns False if subst is contained in st
                       returns True if subst is not contained in st
    """
```

Seems simple enough. A novice programmer would probably write the following implementation.

```
def contains(st, subst, invert):
    if invert:
        matches = subst not in st
    else:
        matches = subst in st
    return matches
```

This certainly works, but lets take advantage of boolean operations.

```
def contains(st, subst, invert):
    # assume invert is False
    matches = subst in st
    if invert:
        matches = not matches
    return matches
```

This produces the same results, but let's the reader see a more linear version of the code; assume that `invert == False` to generate the original value for `matches`; invert the value of `matches` if `invert == True`.

While one can quibble with the efficacy of this approach if only a single boolean drives the functionality, consider the case when two booleans must be considered.

```
def contains(st, subst, invert, case_insensitive):
    """
    if case_insensitive is False, see if subst is contained in st
    if case_insensitive is True, see if subst.lower() is contained in st.lower()
    if invert is False, returns True if containment is True, False otherwise
    if invert is True, returns False if containment is True, False otherwise
    """
```

The natural approach to this for a novice programmer is a nested set of if statements.

```
def contains(st, subst, invert, case_insensitive):
    if case_insensitive:
        if invert:
            matches = subst.lower() not in st.lower()
        else:
            matches = subst.lower() in st.lower()
    else:
        if invert:
            matches = subst not in st
        else:
            matches = subst in st
    return matches
```

While this certainly works, it is very hard to get right for two booleans; can you imagine how hard it is for three or four?

As with our previous improved solution, we will linearize this code to make it less error prone and more understandable.

```
def contains(st, subst, invert, case_insensitive):
    # set up needle and haystack based upon case_insensitive
    if case_insensitive:
        needle = subst.lower()
        haystack = st.lower()
    else:
        needle = subst
        haystack = st
    # assume invert is false
    matches = needle in haystack
    if invert:
        matches = not matches
    return matches
```

This linearization has enabled separation of concerns (case sensitivity versus inverted test) into separate portions of the code; the reduced complexity substantially enhances our ability to reason about and achieve correct behavior.

This is not to say that `if ... else` constructs should not be used; we are simply saying that deeply nested `if ... else` constructs are difficult to code and get right, usually entail substantial duplication of code, and are difficult for an observer of your code to understand. Linearizing your code, using boolean variables and temporary storage, usually leads to cleaner, more understandable, less error-prone solutions.

D.1.2 Built-in structured types

Python has a rich collection of built-in structured types; many of these built-in types are implementations of some of the data structures we will be covering later in the textbook. For the time being, the only built-in structured type that has a loose equivalence to C is the `list` type and its correspondence to the array structured type of C. Even then, the only true correspondence is the use of `[i]` as an index into the list/array, to access the element of the list/array at index `i`, with the origin index being `0`.

Python also includes a built-in *string* type (`str`), which is an immutable sequence of Unicode code points. Elements of the string can be accessed by indexing, but the character at an index cannot be changed.

D.2 Functions

A function is a parameterized block of reusable code that typically performs a single action. Functions help you write code that is more modular and enables code reuse.

You define functions using the *def* keyword, followed by the name of the function, followed by function arguments inside of parentheses, followed by a ':'. The code block for the function is indented. Finally, a *return* statement can be used to exit the function; an optional expression following the *return* causes the value of that expression to be returned to the caller.

For example, we can define a function `square()` that will return its argument raised to the power of 2.

```
def square(x):
    return x * x
```

Python supports the concept of functions as first class objects with the following properties:

- a function is an instance of the type Object;

- you can store a function in a variable;
- you can pass a function as a parameter to another function;
- you can return a function from a function; and
- you can store functions in data structures such as lists, dictionaries, ...

One typical use of functions as first class objects is to provide a function that will apply a function argument to data supplied in other arguments. Let's consider the following example:

```
>>> def double(v):
...     return 2 * v
...
>>> def square(v):
...     return v * v
...
>>> def apply(func, lst):
...     l = []
...     for v in lst:
...         l.append(func(v))
...     return l
...
>>> L = [1, 3, 5, 7,9]
>>> apply(double, L)
[2, 6, 10, 14, 18]
>>> apply(square, L)
[1, 9, 25, 49, 81]
```

Functions as first class objects are quite important when programming sophisticated classes, libraries, and applications. As we shall see, functions are first class entities in C, as well, and we use them in the interfaces and implementations of abstract data types.

D.3 Variables, Block Structure, and Scoping

D.3.1 Variables

Variables are named memory locations; you can assign a value to a location, and you can later access the value stored in that location. Python imposes three rules on the characters that make up a variable name:

- a variable name must start with a letter or an underscore;
- the remaining characters of the variable name may consist of letters, numbers, and underscores; and
- variable names are case sensitive.

You can assign a value to a variable, and reference its value, using the following syntax:

```
my_variable = 42
print('The meaning of life, the universe, and everything is', my_variable)
```

The print command will print out the string argument, a space, and the string representation of `my_variable` on the standard output.

You do not have to declare variable names, or the type of data that a variable can hold. The first line above caused `my_variable` to come into existence, and assigned `42` to it.

D.3.2 Block Structure

A Python program is constructed from code blocks.[1] A *block* is a piece of Python program text that is executed as a unit. The following are blocks: a module, a function body, and a class definition. Additionally, a script file (a file given as standard input to the interpreter or specified as a command line argument to the interpreter) is a code block.

Names refer to objects. Names are introduced by name binding operations.

The following constructs bind names: formal parameters to functions, `import` statements, class and function definitions (these bind the class or function name in the defining block), and targets that are identifiers (variable names) if occurring in an assignment, a `for` loop header, or after `as` in a `with` statement or `except` clause. An `import` statement of the form `from ... import *` binds all names defined in the imported module, except those that begin with an underscore.

If a name is bound in a block, it is a local variable of that block, unless declared as `nonlocal` or `global`. If a name is bound at the module level, it is a global variable. If a variable is used in a code block but not defined there, it is a *free variable*.

Each occurrence of a name in the program text refers to the *binding* of that name established by the following name resolution rules.

D.3.3 Scoping

A *scope* defines the visibility of a name within a block. If a local variable is defined in a block, its scope includes that block. If the definition occurs in a function block, the scope extends to any blocks contained within the defining one, unless a contained block introduces a different binding for the name.

When a name is used in a code block, it is resolved using the nearest enclosing scope. The set of all such scopes visible to a code block is called the block's *environment*.

[1] Most of the material in this section is derived from the Python Reference Model, `https://docs.python.org/3/reference/executionmodel.html`, section 4 entitled “Execution model”.

If a name binding operation occurs anywhere within a code block, all uses of the name within the block are treated as references to the current block.

The namespace for a module is automatically created the first time a module is imported. The main module for a script is always called `__main__`.

D.4 User-defined types

Python enables the creation of user-defined types through the use of classes. Python classes provide all the standard features of Object-Oriented Programming: the class inheritance mechanism allows multiple base classes, a derived class can override any methods of its base class or classes, and a method can call the method of a base class with the same name. Objects can contain arbitrary amounts and kinds of data.

Class members (including the data members) are *public*; even the name-mangling provided for member names that start with `__` doesn't truly hide those members from direct access by the user.

Since data members are public, there is no need to define methods in a class (other than the constructor), as the data members can be accessed/modified directly by the application. Such "classes" act like records or structures in other languages.

There are two common relationships between a pair of classes:

- class1 *is-a* class2 - this relationship is based upon inheritance, where class2 is the parent of class1; and
- class1 *has-a* class2 - this relationship is based upon composition, where class1 possesses instance variables (attributes in Python parlance) that are references to class2 objects.

While the *is-a* relationship is very powerful, the C programming language does not support inheritance. The Abstract Data Type approach to building data types described later in the book can exploit the *has-a* relationship between our ADTs and other, simpler ADTs.

D.4.1 Function Annotations

PEP 3107[2] defines a syntax for adding arbitrary metadata annotations to Python functions. These annotations have the following attributes:

- function annotations, both for parameters and return values, are completely optional;

[2] `https://www.python.org/dev/peps/pep-3107/`

- function annotations are nothing more than a way of associating arbitrary Python expressions with various parts of a function signature at compile-time; and
- Python does not attach *any* particular meaning or significance to annotations.

The syntax for function annotations take the form of optional expressions that follow the parameter name, as in:

```
def foo(a: expression, b: expression = 5):
    . . .
```

In pseudo-grammar, parameters now look like `identifier [: expression] [= expression]` - i.e., annotations always precede a parameter's default value and both annotations and default values are optional. Similar to the use of equal signs to indicate a default value, colons are used to mark annotations.

The syntax for the type of a function's return value is as follows:

```
def sum() -> expression:
    . . .
```

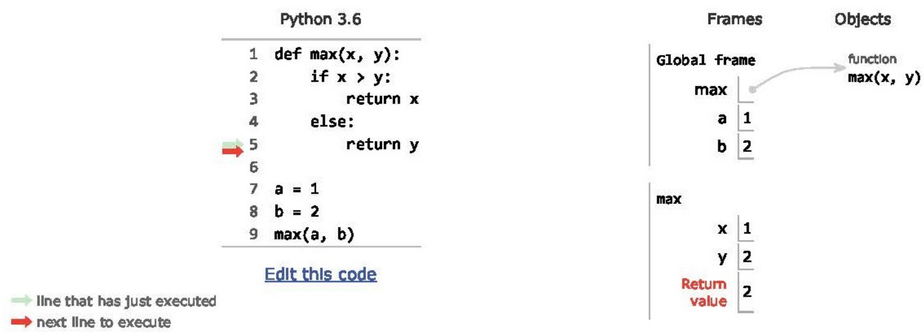
That is, the parameter list can now be followed by a literal `->` and a Python expression.

Why are we introducing function annotations here? Even though they are optional, it provides a mechanism for indicating in the function signature the types of the parameters and return values for functions and methods. Even though this is typically documented in the function/method docstring, the proximity of the annotations to the parameters in the function definition are a benefit to someone reading your code. And, as we shall see, such type information is required by languages such as C.

D.5 Modeling Storage in Python

A Python program in execution consists of the following:

- a global space, consisting of global variables, modules, and functions; the data in the global space lasts until the Python interpreter exits;
- a function call stack, which holds function call parameters, any local variables created by the function, and the location to return to when the function is done; the data in a call frame lasts until the function issues a `return` statement (or falls off the end of the function, which causes an implicit return); and
- a heap, where objects are stored, and which are accessed indirectly through variable names.



You may have used Python Tutor `http://www.pythontutor.com/` to visualize your Python programs as they execute; it shows the global space and call frames immediately to the right of the source listing, with the heap shown to the right of the global space and call frames. The figure above shows a screen shot from Python Tutor for a simple program; the heap is labelled as "Objects", while the global space and call frames are displayed under the "Frames" label.

You may be wondering why we are introducing these concepts at this juncture. The discerning reader will have noted that this memory model explicitly supports the scoping rules described in section D.3.3. It also explicitly has a heap that can be used for object storage, and a call stack on which local variables can be created and which go out of scope when a function returns to the caller. The exact same memory model holds for C with one major difference; while Python keeps track of references to heap memory, and recovers such memory when there are no more variables that reference it, C does *not* track such use; this requires that a C programmer must explicitly manage heap memory in their programs.

D.6 Scripts - invoking Python programs from the command line

We will be building executable programs from C source files that can be invoked by typing commands to `bash`. Since we assume that your Python experience has primarily been using an IDE, at this juncture we need to discuss how one invokes a Python program from the command line, accessing the arguments provided by the shell.

D.6.1 A simple example

There are a number of infinite series expressions for π. One in particular is

$$\pi \;=\; \sqrt{12}\,\sum_{i=0}^{\infty}\frac{(-1)^i}{((2i+1)\;3^i)}$$

Let's write a Python program, `approx_pi.py`, that approximates π by truncating this sum after a fixed number of terms; this fixed number is provided as an argument to the program. Besides computing the approximation, the program also indicates the percentage error of the approximation relative to the value from `math.pi`.

```
"""
approx_pi.py:  Approximate pi by truncating infinite series
"""
import math          # needed for sqrt(), fabs() and pi
from sys import argv # needed to access arguments

def approx_pi(terms:int) -> float:
    """
    Generate an approximation to pi by truncating infinite series
    args: terms: number of terms from the infinite series
    returns: approximate value of pi
    """
    sum = 0.0
    for i in range(terms):
        sum += (-1)**i/((2*i+1)*3**i)
    return math.sqrt(12) * sum

def main() -> None:
    argc = len(argv)
    if argc == 2:
        terms = int(argv[1])
        pi = approx_pi(terms)
        diff = math.fabs(pi - math.pi)
        print('pi[{}] = {}, error = {:.5%}'.format(terms, pi, diff/math.pi))
    else:
        print("usage: python3 approx_pi.py terms")

if __name__ == "__main__":
    main()
```

What are the main points to note in this simple program?

- We need to import `argv` from `sys` in order to access arguments passed by the shell.[3]
- `argv` is simply a list of strings; `argv[0]` is the name of the script that was invoked (`approx_pi.py` in this case); thus, `argv[1]` is the number of terms in the summation to use.
- If the script is invoked as `python3 approx_pi.py 5`, then the global variable `__name__` has the string value `"__main__"`; if this is the case, then the script invokes `main()`, causing it to obtain the argument and invoke `approx_pi()`; if another

[3] To be sure, there are better ways to obtain arguments, for example using `argparse` in Python; we have focused on `sys.argv` due to its similarity to argument access in C.

program has `import`ed `approx_pi`, then the functions will be defined, but `main()` will not be invoked.

Thus, this is the way to write a module so that it can be invoked directly by the shell, and can also be `import`ed by other modules.[4]

D.6.2 Executing the example

How do we go about executing `approx_pi.py`? `python3` is the Python interpreter program accessible from `bash`. To invoke our script to compute the value of π using the first 5 terms in the infinite series, we do the following.

```
$ python3 approx_pi.py 5
pi[5] = 3.1426047456630846, error = 0.03222%
```

As described in the previous section, the Python interpreter makes the string `approx_pi.py` available as `sys.argv[0]`, and the string `5` available as `sys.argv[1]` for use by the script.

Let's see how well the approximation works as the number of terms varies from 1 to 9.

```
$ for n in 1 2 3 4 5 6 7 8 9; do
> python3 approx_pi.py $n
> done
pi[1] = 3.4641016151377544, error = 10.26578%
pi[2] = 3.0792014356780038, error = 1.98597%
pi[3] = 3.156181471569954, error = 0.46438%
pi[4] = 3.1378528915956805, error = 0.11904%
pi[5] = 3.1426047456630846, error = 0.03222%
pi[6] = 3.141308785462883, error = 0.00904%
pi[7] = 3.1416743126988376, error = 0.00260%
pi[8] = 3.141568715941784, error = 0.00076%
pi[9] = 3.141599773811506, error = 0.00023%
```

Exercise D.1. Write a python script named `echo.py`, which does the same thing as the `echo` program on Linux. It must use function annotations and conform to the structure shown in Section D.6.1.

Test your script as follows:

```
$ echo some number of arguments >echo.out
$ python3 echo.py some number of arguments | diff - echo.out
```

[4]If one simply wanted to write a module that would *always* be invoked from the shell, one could dispense with the test of `__name__` and the definition of `main()`; use of the structure described above prevents premature optimization of your Python code and is more similar to the structure of a C program.

If you have implemented the script correctly, there should be no output from `diff`.
□

D.7 File I/O, and standard input, output, and error

D.7.1 File I/O

Besides accessing command arguments, your Python program will invariably need to read data from files, and write data to files. Python defines a built-in `File` class; an object of that class is returned whenever you invoke the built-in `open()` function. `open()` is used in the following ways:

- open an existing file for reading: `fr = open(filename, 'r')`
- open a file for writing: `fw = open(filename, 'w')`
- open a file for writing at the end: `fw = open(filename, 'a')`

In the latter two cases, if `filename` does not already exist, it is created.

⚠ **If an existing filename is opened at 'w' access, its contents are overwritten.**

Once a file is open for reading, one can either read a fixed number of characters (`fr.read(size)`), the entire file (`fr.read()`), or a single line (`fr.readline()`); the return value from these calls is the string that was read.

⚠ **While you *can* read the entire file into a string, it is almost NEVER the right thing to do! You need to consider what your program is doing, and use character-at-a-time (fr.read(1)) or line-at-a-time (fr.readline()) I/O.**

Once a file is open for writing, one can write a string to the file (`fw.write(string)`); if you wish to write data that is not already a string, you must convert it to a string before calling `write()` using the `str()` built-in function. The return value from the `write()` call is the number of characters written.

Calls to `print()` generate `write()` calls on standard output, described in the next section.

D.7.2 Standard input, output, and error

When your Python program comes to life, three of these File objects have already been created for you:

- `sys.stdin` - standard input
- `sys.stdout` - standard output
- `sys.stderr` - standard error output

⚠ **It is important to realize that these file objects represent *already-opened files* - i.e., you can start using them immediately; in particular, they are *not* the names of files that can be used as the first argument to `open()`.**

As you can see, these objects are available from the `sys` module. `sys.stdin` has been opened for reading, while `sys.stdout` and `sys.stderr` have been opened for writing. By default, reading from `sys.stdin` causes characters to be read from the keyboard. Of course, if standard input has been redirected in the shell, as in

```
$ python3 xyz.py <file.data
```

calls to `sys.stdin.readline()` will read from `file.data`.

In a similar fashion, writing to `sys.stdout` or `sys.stderr` causes characters to be written to the terminal window, unless standard output (and/or standard error output) have been redirected in the shell, as in

```
$ python3 xyz.py >file.data
```

calls to `sys.stdout.write()` will write to `file.data`.

D.7.3 The `format()` method on Strings

While the built-in `print()` function enables you to print to standard output, it places a space between each pair of arguments, and always writes a newline character at the end. When one is printing out the results of a computation, one often needs to have sophisticated control over the precision, field widths, left or right justification, and a variety of additional parameters with respect to how the output appears to the user. As of Python version 3, the String class supports a `format()` method to give you control over the output parameters. The following introduces this capability; for more details, see the documentation at
`https://docs.python.org/3.4/library/string.html#string-formatting`.

The general form of an invocation of the format method is as follows:

```
str = 'A string template with replacement fields'.format(arguments)
```

where each “replacement field” is surrounded by curly braces `{}`. Here is an example:

```
print('{} + {} = {}'.format(2, 3, 2+3))
```

which causes the following to be printed out on standard output:

```
2 + 3 = 5
```

So far, this is not very impressive, just replacing each occurrence of `{}` with the string representation of the next argument to the method. The magic is with regards to the "format_spec" that you can place inside of the braces.

What are permissible replacement field contents?

```
replacement_field ::= '{' [':' format_spec] '}'
format_spec ::= [[fill] align] [width] [.precision] [type]
fill ::= <any character other than '{' or '}'>
align ::= '<' | '^' | '>'
width ::= INTEGER
precision ::= INTEGER
type ::= 'd' | 'e' | 'f' | 's' | '%'
```

What does this mean? Let's start with *type* - 'd' means format the integer argument as a decimal integer; 'e' means format the floating point argument in exponent notation; 'f' means format the floating point argument as a fixed-point number; 's' means format the string argument as a string; and `'%'` means format the floating point argument as a percentage (i.e., fixed-point representation of the argument times 100, with a trailing `%` after the number.

width indicates the number of characters that should be allocated to the formatted argument.

precision indicates the number of digits to the right of the representation of floating point arguments.

align indicates how the formatted argument should be aligned in the specified width - `'>'` means right-aligned, `'<'` means left-aligned, and `'^'` means centered.

If *fill* is specified, that character is used to achieve the requested alignment; the default fill character is `' '`.

Here are some examples showing these things in use:

```
>>> '{:0<10s}'.format('abc')    # left justify, 10-chr field, fill with '0'
'abc0000000'
>>> '{:0>10d}'.format(23)       # right justify, 10-chr field, fill with '0'
'0000000023'
>>> '{:-^10.2f'.format(1.234)   # center, 10-chr field, fill with '-'
'---1.23---'
>>> '{:>12.4e}'.format(3.141592)# right justify, 12-chr field, fill with ' '
'  3.1416e+00'
>>> '{:10.4%}'.format(0.1234567)# right justify, 10-chr field, fill with ' '
'  12.3456%'
```

Exercise D.2. Write a python script `sgrep.py` that implements the default behavior of `grep`, where the pattern argument is a simple string. Your script should support the default behavior (if no file arguments are provided, print lines from standard input containing the pattern), should process multiple files, in which case matching lines from a file are prefixed by “filename: ”, where filename is replaced by the name of the file.

As in the previous exercise, you must use function annotations and conform to the program structure described in Section D.6.1.

Devise and apply a set of tests enabling you to compare your script’s functionality with `grep`’s.
□

Appendix E

The von Neumann Architecture

This appendix describes the von Neumann architecture, to which nearly all computational devices conform.

E.1 Early history of electronic computers

In 1937, Alan Turing published a paper [1] that presented the notion of a universal machine, later termed the Turing machine, capable of computing anything that is computable. Immediately following the publication of this paper, several individuals worldwide explored how to translate the idealized Turing machine to workable electronic implementations.

A number of these electronic implementations were based upon the concept of a *stored-program computer*, in which the instructions that the computer executes are stored in electronic memory. The data upon which the instructions act are also stored in electronic memory.

John von Neumann

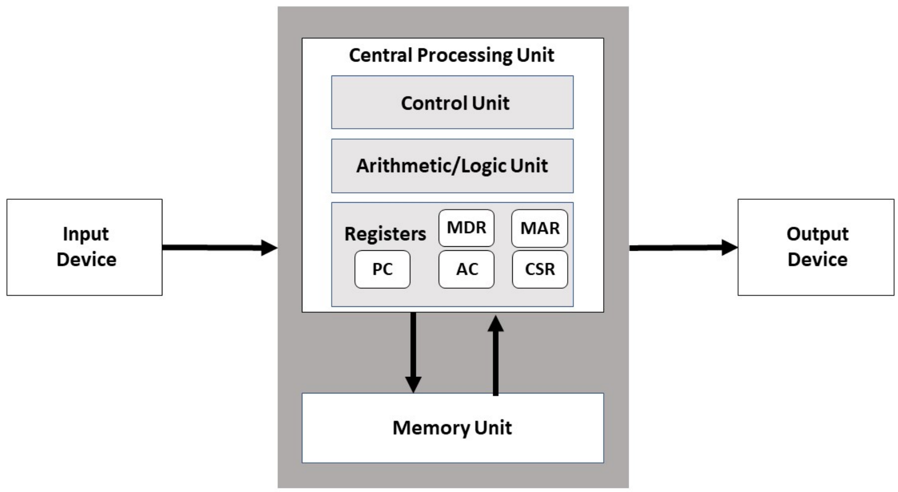
John von Neumann, who was a mathematician involved in the EDVAC project at the University of Pennsylvania, documented an architecture in which the data and instructions are both stored in the electronic memory in the same address space.[2] This architecture is the basis of nearly all modern computational devices, and is known as the von Neumann architecture since he documented it, despite the architecture having been invented by J. Presper Eckert and John Mauchly at the University of Pennsylvania.

[1] A. M. Turing, "On Computable Numbers, with an Application to the Entscheidungsproblem," Proceedings of the London Mathematical Society, Volume s2-42, Issue 1, pp. 230-265, 1937.

[2] John von Neumann, "First Draft of a Report on the EDVAC," `https://sites.google.com/site/michaeldgodfrey/vonneumann/vnedvac.pdf?attredirects=0&d=1`.

E.2 The von Neumann architecture

The architecture described in von Neumann's draft report consisted of six components shown in the following diagram:



1. a processing unit that contains an arithmetic logic unit (ALU) and processor registers;
2. a control unit that contains an instruction register and a program counter;
3. random access memory in which data and instructions are stored;
4. persistent data storage (the persistent store can be considered an input and an output mechanism in the figure);
5. input mechanisms; and
6. output mechanisms.

Now let's look at each of these components in more detail.

E.2.1 Memory Unit

The Memory Unit, also known as RAM (Random Access Memory), is an array of fixed size cells. Each cell is associated with an address - the array index. Each cell has two important characteristics:

- its address (i.e., index into the array); and
- its contents (what's stored in the cell).

In the early days, there was significant experimentation in the size of each of the cells. Today, the number of bits in a cell is standardized to 8 (one byte). This means that the contents of each cell is in the range $[0, 2^8)$.

There was also significant experimentation in the number of bits used to represent a cell address - i.e. what is the range of indices into the cell array? If N bits is used for a cell address, this implies that 2^N cells can be addressed - in other words, legal indices into the memory array are in the range $[0, 2^N)$. Today, computers are usually built where $N = 64$ or $N = 32$. For custom, embedded applications, smaller values of N are sometimes chosen.

Here are some common memory attributes that you will encounter:

- memory sizes
  - kilobyte (KB) = 2^{10} = 1,024 bytes ~ 1 thousand
  - megabyte (MB) = 2^{20} = 1,048,576 bytes ~ 1 million
  - gigabyte (GB) = 2^{30} = 1,073,741,824 bytes ~ 1 billion
- memory access time (read from/write to memory)
  50-75 nanoseconds (1 nsec = 10^{-9} seconds)
- RAM is volatile - i.e., it only maintains the cells' contents when power is on; if you lose power, all of the cell contents are lost

Two operations are permitted on memory:

- fetch(address)
  - fetch a copy of the contents of the addressed memory cell
  - this is non-destructive to the cell - i.e., it continues to retain that value
- store(address, value)
  - store the specific value into the addressed memory cell
  - this is destructive to the cell - i.e., it overwrites the previous cell contents

The processor requires 2 registers in order to implement fetch() and store(). These are shown in the figure as MAR (Memory Address Register) and MDR (Memory Data Register). These registers are connected to underlying circuitry such that fetch() and store() are implemented as follows:

- fetch(address)
  - load “address” into the MAR
  - the content of the memory cell at “address” is placed in the MDR
- store(address, value)
  - load “value” into the MDR
  - load “address” into the MAR
  - the content of the memory cell at “address” is replaced by the contents of the MDR

E.2.2 Arithmetic/Logic Unit

The ALU (Arithmetic/Logic Unit) performs mathematical operations (+, - *, /, ...) and logic operations(==, !=, >, >=, <, <=, and, or, not, ...). The ALU consists of:

- circuits to perform the arithmetic/logic operations,
- registers (fast storage units) to store intermediate computational results,
- a special register (the Control Status Register) that stores the status of the last instruction and can be queried by instructions, and
- a bus that connects the registers to the circuits.

Early von Neumann systems had few general purpose registers (the figure above shows an accumulator (AC) as the only general purpose register; current systems can have many 10s or 100s of general purpose registers for storing intermediate results. One of the primary responsibilities of optimizing compilers is to use registers effectively to speed up computations; it is not uncommon for the time to access RAM to be 30-50 times slower than accessing a register.

E.2.3 Control Unit

As discussed above, the instructions to execute are stored in memory. The program counter register, PC, always contains the address in memory of the next instruction to fetch and execute.

The task of the control unit is to execute programs by repeatedly:

- fetch from memory the instruction at the address stored in the PC register; after the fetch completes, the value of the PC is changed to the address of the succeeding instruction in memory;
- decode the instruction - i.e. determine which ALU operation should be performed upon which operands;
- execute the instruction by issuing appropriate signals to the ALU, memory, and I/O subsystems; and
- continue until the decoded instruction is `HALT`.

Each processor defines how an instruction is structured in terms of operation code and operands. A compiler for your language will map from statements in that language into the corresponding sequence of instructions for the processor. These instructions are typically called *machine language instructions*.

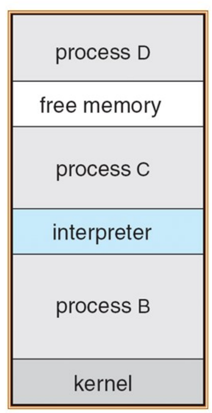
E.2.4 Input/Output Devices

Usually a processor is connected via an I/O bus to a variety of input and output devices. Early systems had explicit input and output instructions executed by the control unit to bring data into memory or write data back out from memory. Modern systems have the CPU and input/output devices connected to a common bus so that devices can write to/from memory without CPU interference - this is referred to as *direct memory access*, or DMA for short.

The 6^{th} component of the von Neumann architecture, persistent data storage, is provided by devices that store information persistently (i.e., do not need to be powered to maintain the stored information), and can provide the data to the CPU as an input device and can receive the data from the CPU as an output device. Modern systems use solid-state drives (SSDs) and hard disk drives (HDDs) upon which a file system has been installed to enable users to store persistent information.

E.3 A process in memory

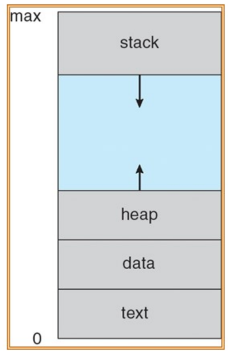
When you are running programs on a typical operating system on your hardware, the **physical** memory is typically allocated as shown in the following figure.[3]



A particular process's (e.g., process D above) **logical** memory is typically laid out in its physical memory partition as shown in the following figure.[4]

[3]This is a purposely simplistic representation, as a process may be stored in discontinuous chunks. You will learn about that in your course on operating systems. This simplistic representation is sufficient to motivate the remainder of the discussion.

[4]Again, this is somewhat simplistic, as a process can consist of many segments, and the segments need not be contiguous in the logical memory space.



The segments shown above contain the following:

- text - this segment contains instructions that are executed by the processor;
- data - this segment contains global data, both initialized and uninitialized;
- heap - this segment is used to allocate data items as the program does its work; the arrow indicates that this segment will grow larger toward higher logical addresses when needed by the program; and
- stack - this segment is used for function call frames and storage for non-global data; the arrow indicates that this segment will grow larger toward lower logical addresses when needed by the program.

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