While these notes may be a useful reference and provide alternate examples for some of the material, they do not cover exactly the same material as the current version of the course. In particular, the current version of the course now specifically covers some C++ 11 and C++ 14 concepts that are not discussed in these notes. There will also be other differences, and the emphasis on some concepts will be different.

As a result, these notes are <u>not</u> an adequate substitute for attending lectures.

School of Computer Science

CS 246
Object-Oriented Software Development

Course Notes* Spring 2016

https://www.student.cs.uwaterloo.ca/~cs246

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Outline

Introduction to basic UNIX software development tools and object-oriented programming in C++ to facilitate designing, coding, debugging, testing, and documenting of medium-sized programs. Students learn to read a specification and design software to implement it. Important skills are selecting appropriate data structures and control structures, writing reusable code, reusing existing code, understanding basic performance issues, developing debugging skills, and learning to test a program.

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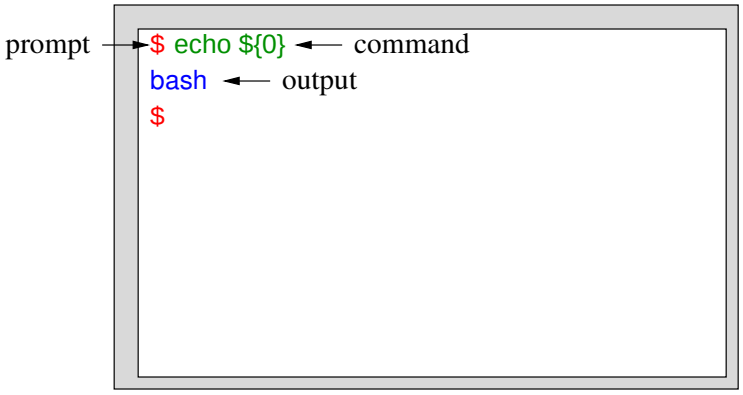
1 Shell

- Computer interaction requires mechanisms to display information and perform operations.
- Two main approaches are graphical and command line.
- **Graphical user interface** (GUI) (desktop):
  - icons represent actions (programs) and data (files),
  - click on icon launches (starts) a program or displays data,
  - program may pop up a dialog box for arguments to affect its execution.
- **Command-line interface** (shell):
  - text strings access programs (commands) and data (file names),
  - command typed after a prompt in an interactive area to start it,
  - arguments follow the command to affect its execution.
- Graphical interface easy for simple tasks, but seldom programmable for complex operations.
- Command-line interface harder for simple tasks (more typing), but allows programming.
- Many systems provide both.
- **Shell** is a program that reads commands and interprets them.
- Provide a simple programming-language with *string* variables and few statements.
- Unix shells falls into two basic camps: **sh** (**ksh**, **bash**) and **csh** (**tcsh**), each with slightly different syntax and semantics.
- Focus on **bash** with some tcsh.
- **Terminal** or **xterm** area (window) is where shell runs.



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- Command line begins with (customizable) **prompt**: $ (sh) or % (csh).
- Command typed after prompt ***not*** executed until **Enter**/Return key pressed.

```
$ dateEnter                          # print current date
Thu Aug 20 08:44:27 EDT 2016
$ whoamiEnter                        # print userid
jfdoe
$ echo Hi There!Enter                # print any string
Hi There!
```

- Command comment begins with hash (#) and continues to end of line.

```
$ # comment text ... does nothing
$
```

- Multiple commands on command line separated by semi-colon.

```
$ date ; whoami ; echo Hi There!     # 3 commands
Sat Dec 19 07:36:17 EST 2016
jfdoe
Hi There!
```

- Commands can be edited on the command line (not sh):

```
$ data ; Whoami ;  cho Hi There!
```

  - position cursor, , with ◁ and ▷ arrow keys,
  - type new characters before cursor,
  - remove characters before cursor with backspace/delete key,
  - press Enter at any point to execute modified command.

- Arrow keys △/▽ move forward/backward through command history (see Section 1.3, p. 7).

```
$ △    $ echo Hi There! △   $ whoami △   $ date ▽   $ whoamiEnter
jfdoe
```

  - press Enter to re-execute a command.
  - often go back to previous command, edit it, and execute new command.

- Tab key auto-completes partial command/file names (see Section 1.1).

```
$ ectab              # cause completion of command name to echo
$ echo q1tab         # cause completion of file name to q1x.C
```

  - if completion is ambiguous (i.e., more than one),
  - press tab again to print all completions,
  - and type more characters to uniquely identify the name.

```
$ datab # beep (maybe)          $ datab # completions
                                dash  date
$ dattab # add "t"              $ dateEnter # execute
```

- Most commands have **options**, specified with a minus followed by one or more characters, which affect how the command operates.

```
$ uname -m          # machine type
x86_64
$ uname -s          # operating system
Linux
$ uname -a          # all system information
Linux ubuntu1204-006 3.13.0-57-generic #95~precise1-Ubuntu SMP
```

- Options are normally processed left to right; one option may cancel another.
- ***No standardization for command option names and syntax.***
- Shell/command terminates with **exit**.

```
$ exit              # exit shell and terminal
```

  - when the login shell terminates ⇒ sign off computer (logout).

- Shell operation returns an **exit status** via optional integer N (return code).

  exit *[N]*

  - exit status defaults to zero if unspecified, which usually means success.
  - *[N]* is in range 0-255
    - larger values are truncated (256 ⇒ 0, 257 ⇒ 1, etc.),
    - negative values (if allowed) become unsigned (-1 ⇒ 255).
  - Exit status can be read after execution (see page 24) and used to control further execution (see page 30).

1.1 File System

- Shell commands interact extensively with the **file system**.
- Files are containers for data stored on persistent storage (usually disk).
- File names organized in N-ary tree: directories are vertexes, files are leaves.
- Information is stored at specific locations in the hierarchy.

```
/               root of local file system
    bin             basic system commands
    lib             system libraries
    usr
        bin             more system commands
        lib             more system libraries
        include         system include files, .h files
    tmp             system temporary files
    home or u       user files
        jfdoe           home directory
            .,  . .         current, parent directory
            .bashrc, .emacs, .login,...  hidden files
            cs246           course files
                a1      assignment 1 files
                        q1x.C, q2y.h, q2y.cc, q3z.cpp
        other users
```

- Directory named "/" is the root of the file system (Windows uses "\").
- bin, lib, usr, include : system commands, system library and include files.
- tmp : temporary files created by commands (***shared among all users***).
- home or u : user files are located in this directory.
- Directory for a particular user (**jfdoe**) is called their **home directory**.
- Shell special character "~" (tilde) expands to user's home directory.

```
~/cs246/a1/q1x.C        # => /u/jfdoe/cs246/a1/q1x.C
```

- ***Every*** directory contains 2 special directories:
  - "." points to current directory.

```
./cs246/a1/q1x.C        # => /u/jfdoe/cs246/a1/q1x.C
```

  - ". ." points to parent directory above the current directory.

```
. ./. ./usr/include/limits.h # => /usr/include/limits.h
```

- **Hidden file**s contain administrative information and start with "." (dot).
- Each file has a unique path-name referenced with an absolute pathname.
- **Absolute pathname** is a list of all the directory names from the root to the file name separated by the forward slash character "/".

```
/u/jfdoe/cs246/a1/q1x.C     # => file q1x.C
```

- Shell provides concept of **working directory** (**current directory**), which is the active location in the file hierarchy.

- E.g., after sign on, the working directory starts at user's home directory.
- File name not starting with "/" is prefixed with working directory to create necessary absolute pathname.
- **Relative pathname** is file name/path prefixed with working directory.
  - E.g., when user jfdoe signs on, home/working directories set to /u/jfdoe.

```
.bashrc                 # => /u/jfdoe/.bashrc
cs246/a1/q1x.C          # => /u/jfdoe/cs246/a1/q1x.C
```

1.2 Quoting

- **Quoting** controls how shell interprets strings of characters.
- **Backslash** (\) : **escape** any character, including special characters.

```
$ echo .[!.]*           # globbing pattern
.bashrc  .emacs  .login  .vimrc
$ echo \.\[\!\.\]\*     # print globbing pattern
.[!.]*
```

- **Backquote** (`) or $() : execute text as a command, and substitute with command output.

```
$ echo `whoami`     # $ whoami => jfdoe
jfdoe
$ echo $(date)
Tue Dec 15 22:44:23 EST 2015
```

- Globbing does NOT occur within a single/double quoted string.
- **Single quote** (') : protect everything (even newline) except single quote.
  - E.g., file name containing special characters (blank/wildcard/comment).

```
$ echo Book Report #2
Book Report
$ echo 'Book Report #2'
Book Report #2
$ echo '.[!.]*'         # no globbing
.[!.]*
$ echo '\.\[\!\.\]\*' # no escaping
\.\[\!\.\]\*
$ echo '`whoami`'       # no backquote
`whoami`
$ echo 'abc    # yes newlineEnter
> cdf'          # prompt ">" means current line is incomplete
abc             # yes newline
cdf
$ echo '\''             # no escape single quote
>
```

A single quote cannot appear inside a single quoted string.

- **Double quote** (") : protect everything except double quote, backquote, and dollar sign (variables, see Section 1.11), which can be escaped.

```
$ echo ".[!.]*"        # protect special characters
.[!.]*
$ echo "\.\[\!\.\]\*" # no escaping
\.\[\!\.\]\*
$ echo "`whoami`"      # yes backquote
cs246
$ echo "abc            # yes newlineEnter
> cdf"
abc             # yes newline
cdf
$ echo "\""           # yes escape double quote
"
```

- String concatenation happens if text is adjacent to a string.

```
$ echo xxx"yyy"  "a"b"c"d  a"b"c"d"
xxxyyy abcd abcd
```

- ***To stop prompting or output from any shell command***, type <ctrl>-c (C-c), i.e., press <ctrl> then c key, causing shell to interrupt current command.

```
$ echo "abc
> C-c
$
```

1.3 Shell Commands

- A command typed after the prompt is executed by the shell (shell command) or the shell calls a command program (system command, see Section 1.4, p. 9).

- Shell commands read/write shell information/state.

- **help** : display information about bash commands (not sh or csh).

  help *[command-name]*

  ```
  $ help cd
  cd: cd [-L|-P] [dir]
      Change the shell working directory.  ...
  ```

  - without argument, lists all bash commands.

- **cd** : change the working directory (navigate file hierarchy).

cd *[directory]*

```
$ cd .          # change to current directory
$ cd ..         # change to parent directory
$ cd cs246      # change to subdirectory
$ cd cs246/a1   # change to subsubdirectory
$ cd ..         # where am I ?
```

- argument must be a directory and not a file
- **cd** : move to home directory, same as **cd** ~
- **cd** - : move to previous working directory (toggle between directories)
- **cd** ~/cs246 : move to cs246 directory contained in jfdoe home directory
- **cd** /usr/include : move to /usr/include directory
- **cd** .. : move up one directory level
- If path does not exist, **cd** fails and working directory is unchanged.

- **pwd** : print absolute path for working directory (when you're lost).

```
$ pwd
/u/jfdoe/cs246
```

- **history** and "!" (bang!) : print a numbered history of most recent commands entered and access them.

```
$ history
    1  date
    2  whoami
    3  echo Hi There
    4  help
    5  cd ..
    6  pwd
    7  history
```

```
$ !2  # rerun 2nd history command
whoami
jfdoe
$ !!  # rerun last history command
whoami
jfdoe
$ !ec # rerun last history command starting with "ec"
echo Hi There
Hi There
```

- !N rerun command N
- !! rerun last command
- !xyz rerun last command starting with the string "xyz"

- **alias** : substitution string for command name.

alias *[command-name=string]*

- No spaces before/after "=" (csh does not have "=").
- Provide *nickname* for frequently used or variations of a command.

```
$ alias d=date
$ d
Mon Oct 27 12:56:36 EDT 2008
$ alias off="clear; exit"  # why quotes?
$ off                      # clear screen before terminating shell
```

- ***Always use quotes to prevent problems.***
- Aliases are composable, i.e., one alias references another.

```
$ alias now="d"
$ now
Mon Oct 27 12:56:37 EDT 2008
```

- Without argument, print all currently defined alias names and strings.

```
$ alias
alias d='date'
alias now='d'
alias off='clear; exit'
```

- ***Alias CANNOT be command argument*** (see page 25).

```
$ alias a1=/u/jfdoe/cs246/a1
$ cd a1      # alias only expands for command
bash: cd: a1: No such file or directory
```

- Alias entered on command line disappears when shell terminates.
- Two options for making aliases persist across sessions:
  1. insert the **alias** commands in the appropriate (hidden) .*shell*rc file,
  2. place a list of **alias** commands in a file (often .aliases) and **source** (see page 28) that file from the .*shell*rc file.

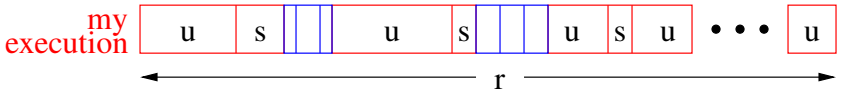
- **type** (csh **which**) : indicate how name is interpreted as command.

```
$ type now
now is aliased to ‘d’
$ type d
d is aliased to ‘date’
$ type date
date is hashed (/bin/date)    # hashed for faster lookup
$ type -p date                # -p => only print command file-name
/bin/date
$ type fred                   # no “fred” command
bash: type: fred: not found
$ type -p fred                # no output
```

- **echo** : write arguments, separated by spaces and terminated with newline.

```
$ echo We like ice cream    # 4 arguments, notice single spaces in output
We like ice cream
$ echo " We like ice cream " # 1 argument, notice extra spaces in output
 We like ice cream
```

- **time** : execute a command and print a time summary.
  - program execution is composed of user and system time.
    - **user time** is the CPU time used during execution of a program.
    - **system time** is the CPU time used by the operating system to support execution of a program (e.g., file or network access).
  - program execution is also interleaved with other programs:



    - **real time** is from start to end including interleavings: user + system ≈ real-time
  - different shells print these values differently.

$ **time** myprog		% **time** myprog
real	1.2	0.94u 0.22s 0:01.2
user	0.9	
sys	0.2	

  - test if program modification produces change in execution performance
    - used to compare user (and possibly system) times before and after modification

1.4 System Commands

- Command programs called by shell (versus executed by shell).
- sh / bash / csh / tcsh : start **subshell** to switch among shells.

```
$ ...           # bash commands
$ tcsh          # start tcsh in bash
% ...           # tcsh commands
% sh            # start sh in tcsh
$ ...           # sh commands
$ exit          # exit sh
% exit          # exit tcsh
$ exit          # exit original bash and terminal
```

- chsh : set login shell (bash, tcsh, etc.).

```
$ echo ${0}     # what shell am I using ?
tcsh
$ chsh          # change to different shell
Password: XXXXXX
Changing the login shell for jfdoe
Enter the new value, or press ENTER for the default
        Login Shell [/bin/tcsh]: /bin/bash
```

- man : print information about command, option names (see page 3) and function.

```
$ man bash
...                 # information about "bash" command
$ man man
...                 # information about "man" command
```

- cat/more/less : print files.

  cat *file-list*

  - cat shows the contents in one continuous stream.
  - more/less paginate the contents one screen at a time.

```
$ cat q1.h
...             # print file q1.h completely
$ more q1.h
...             # print file q1.h one screen at a time
                # type "space" for next screen, "q" to stop
```

- mkdir : create a new directory at specified location in file hierarchy.

  mkdir *directory-name-list*

```
$ mkdir d d1 d2 d3  # create 4 directories in working directory
```

- ls : list the directories and files in the specified directory.

  ls *[-al] [file or directory name-list]*

  - -a lists *all* files, including hidden files (see page 4)
  - -l generates a *long* listing (details) for each file
  - no file/directory name implies working directory

```
$ ls .              # list working directory (non-hidden files)
q1x.C   q2y.h   q2y.cc   q3z.cpp
$ ls -a             # list working directory plus hidden files
.   ..   .bashrc   .emacs   .login   q1x.C   q2y.h   q2y.cc   q3z.cpp
```

- cp : copy files; with the -r option, copy directories.

  cp *[-i] source-file target-file*
  cp *[-i] source-file-list target-directory*
  cp *[-i] -r source-directory-list target-directory*

  - -i prompt for verification if a target file is being replaced.
  - -r recursively copy contents of a source directory to a target directory.

```
$ cp f1 f2          # copy file f1 to f2
$ cp f1 f2 f3 d     # copy files f1, f2, f3 into directory d
$ cp -r d1 d2 d3 # copy directories d1, d2 recursively into directory d3
```

- mv : move files and/or directories to another location in the file hierarchy.

```
mv [ -i ] source-file   target-file
mv [ -i ] source-file-list/source-directory-list   target-directory
```

  - rename source-file if target-file does not exist; otherwise replace target-file.
  - -i prompt for verification if a target file is being replaced.

```
$ mv f1 foo       # rename file f1 to foo
$ mv f2 f3        # delete file f3 and rename file f2 to f3
$ mv f3 d1 d2 d3 # move file f3 and directories d1, d2 into directory d3
```

- rm : remove (delete) files; with the -r option, remove directories.

```
rm [ -ifr ] file-list/directory-list
```

```
$ rm f1 f2 f2     # file list
$ rm -r d1 d2     # directory list, and all subfiles/directories
$ rm -r f1 d1 f2  # file and directory list
```

  - -i prompt for verification for each file/directory being removed.
  - -f (default) do not prompt for removal verification for each file/directory.
  - -r recursively delete the contents of a directory.
  - ***UNIX does not give a second chance to recover deleted files; be careful when using* rm, *especially with globbing, e.g.,* rm * *or* rm .***
  - UW has hidden directory .snapshot in every directory containing backups of all files in that directory
    - per hour for 23 hours, per night for 9 days, per week for 30 weeks

```
$ ls .snapshot                 # directories containing backup files
hourly.2016-01-20_2205/    hourly.2016-01-20_2105/    ...
daily.2016-01-20_0010/     daily.2016-01-19_0010/     ...
weekly.2016-01-17_0015/    weekly.2016-01-10_0015/    ...
$ cp .snapshot/hourly.2016-01-20_2205/q1.h q1.h # restore previous hour
```

- **alias** : setting command options for particular commands.

```
$ alias cp="cp -i"
$ alias mv="mv -i"
$ alias rm="rm -i"
```

  which always uses the -i option (see page 10) on commands cp, mv and rm.

- Alias can be overridden by quoting or escaping the command name.

```
$ rm -f f1        # override -i and force removal
$ "rm" -r d1      # override alias completely
$ \rm -r d1
```

  which does not add the -i option.

- lp/lpstat/lprm/lpstat : add, query and remove files from the printer queues.

  lp *[-d printer-name] file-list*
  lpstat *[-d] [-p [printer-name]]*
  lprm *[-P printer-name] job-number*

  - if no printer is specified, use default printer (ljp_3016 in MC3016).
  - lpstat : -d prints default printer, -p without printer-name lists all printers
  - each job on a printer's queue has a unique number.
  - use this number to remove a job from a print queue.

```
$ lp -d ljp_3016 uml.ps  # print file to printer ljp_3016
$ lpstat                 # check status, default printer ljp_3016
Spool queue: lp (ljp_3016)
Rank    Owner       Job Files           Total Size
1st     rggowner    308 tt22            10999276 bytes
2nd     jfdoe       403 uml.ps          41262 bytes
$ lprm 403               # cancel printing
services203.math: cfA403services16.student.cs dequeued
$ lpstat                 # check if cancelled
Spool queue: lp (ljp_3016)
Rank    Owner       Job Files           Total Size
1st     rggowner    308 tt22            10999276 bytes
```

- cmp/diff : compare 2 files and print differences.

  cmp *file1 file2*
  diff *file1 file2*

  - return 0 if files equal (no output) and non-zero otherwise (output difference)
  - cmp generates the first difference between the files.

	file x	file y
1	a\n	a\n
2	b\n	b\n
3	c\n	c\n
4	**d**\n	**e**\n
5	g\n	h\n
6	h\n	i\n
7		g\n

```
$ cmp x y
x y differ: char 7, line 4
```

    newline is counted ⇒ 2 characters per line in files

  - diff generates output describing how to change first file into second file.

```
$ diff x y
4,5c4    # replace lines 4 and 5 of 1st file
< d      #    with line 4 of 2nd file
< g
---
> e
6a6,7    # after line 6 of 1st file
> i      #    add lines 6 and 7 of 2nd file
> g
```

- Useful for checking output from previous program with current program.
- ssh : (secure shell) encrypted, remote-login between hosts (computers).

  ssh *[-Y] [-l user] [user@]* hostname

  * -Y allows remote computer (University) to create windows on local computer (home).
  * -l login user on the server machine.
  * To login from home to UW environment:

```
$ ssh -Y -l jfdoe linux.student.cs.uwaterloo.ca
... # enter password, run commands (editor, programs)
$ ssh -Y jfdoe@linux.student.cs.uwaterloo.ca
```

- To allow a remote computer to create windows on local computer, the local computer must install an X Window Server.
  * Mac OS X, install XQuartz
  * Windows, install Xming
- scp : (secure copy) encrypted, remote-copy between hosts (computers).

  scp *[user1@host1:] source-file [user2@host2:] target-file*
  scp *[user1@host1:] source-file-list [user2@host2:] target-directory*
  scp -r *[user1@host1:] source-directory-list [user2@host2:] target-directory*

  * similar to cp, except hosts can be specified for each file
  * paths after ':' are relative to user's home directory
  * if no host is specified, localhost used

```
$ # copy remote file /u/jfdoe/f1 to local file f1
$ scp jfdoe@linux.student.cs.uwaterloo.ca:f1 f1
$ # copy local files f1, f2, f3 into remote directory /u/jfdoe/dir
$ scp f1 f2 f3 jfdoe@linux.student.cs.uwaterloo.ca:dir
$ # recursively copy local directory dir into remote directory /u/jfdoe/dir
$ scp -r dir jfdoe@linux.student.cs.uwaterloo.ca:dir
```

- sshfs : (secure shell filesystem) encrypted, remote-filesystem between hosts.
  fusermount : unmount remote-filesystem host.

  sshfs *[user@]*host: *[dir]* mountpoint
  fusermount -u mountpoint

  * mounts a remote filesystem to a local directory

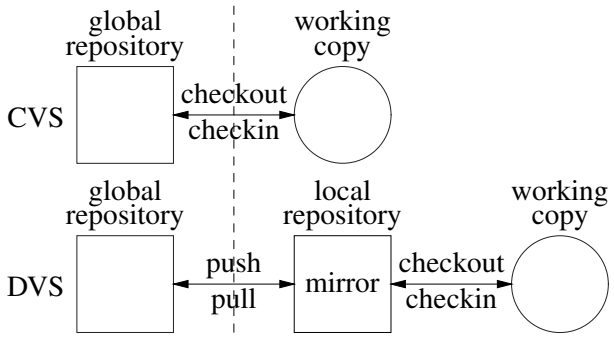
- remote files appear to exist on local machine
- can open remote file with local editor and changes saved to remote file
  - -o auto_cache ensures that mounted files are synchronized with remote files
  - -o reconnect automatically reconnects if session disconnects
  - -o fsname=NAME names the mounted filesystem "NAME"

```
$ # mount remote directory /u/jfdoe/cs246 to local directory ~/cs246
$ mkdir -p cs246          # create directory if does not exist
$ sshfs jfdoe@linux.student.cs.uwaterloo.ca:cs246 ~/cs246 \
        -oauto_cache,reconnect,fsname="cs246"
... # access files in directory cs246
$ fusermount -u cs246   # unmount directory
```

- Make an alias to simplify the sshfs command.

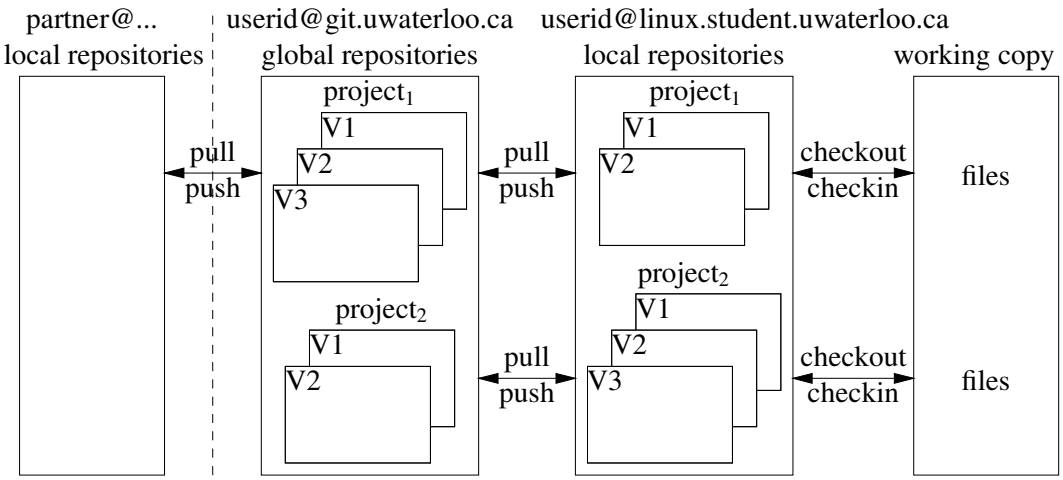
1.5 Source-Code Management

- As a program develops/matures, it changes in many ways.
  - UNIX files do not support the temporal development of a program (**version control**), i.e., history of program over time.
  - Access to older versions of a program is useful.
    - backing out of changes because of design problems
    - multiple development versions for different companies/countries/research
- Program development is often performed by multiple developers each making independent changes.
  - Sharing using files can damage file content for simultaneous writes.
  - Merging changes from different developers is tricky and time consuming.
- To solve these problems, a **source-code management-system** (SCMS) is used to provide versioning and control cooperative work.
- SCMS can provide centralized or distributed versioning (CVS)/(DVS)
  - CVS – global repository, checkout working copy
  - DVS – global repository, pull local mirror, checkout working copy



1.5.1 Global Repository

- **gitlab** is a University global (cloud) repository for:
  - storing git repositories,
  - sharing repositories among students doing group project.



- Perform the following steps to setup your userid in the global repository.
- Log into https://git.uwaterloo.ca/cs246/1161 (note https) with your WatIAm userid/password via LDAP login (top right).
- Click logout "⇒" (top right) in Dashboard to logout.
- These steps activate your account at the University repository.

1.5.2 Local Repository

- **git** is a distributed source-code management-system using the **copy-modify-merge** model.
  - master copy of all **project** files kept in a **global repository**,
  - multiple versions of the project files managed in the repository,
  - developers **pull** a local copy (mirror) of the global repository for modification,
  - developers change working copy and commit changes to local repository,
  - developers **push** committed changes from local repository with integration using **text merging**.

  Git works on file content not file time-stamps.

- config : registering.

```
$ git config --global user.name "Jane F Doe"
$ git config --global user.email jfdoe@uwaterloo.ca
$ git config --list
Jane F Doe
jfdoe@uwaterloo.ca
...
```

- creates hidden file .gitconfig in home directory

```
$ cat ~/.gitconfig
[user]
    name = Jane F Doe
    email = jfdoe@uwaterloo.ca
```

- clone : checkout branch or paths to working tree

```
$ git clone https://git.uwaterloo.ca/cs246/1161.git
```

When prompted, enter your WatIAM username and password.

- pull : update changes from global repository

```
$ git pull
```

Developers must periodically ***pull*** the latest global version to local repository.

1.6 Pattern Matching

- Shells provide pattern matching of file names, **globbing** (regular expressions), to reduce typing lists of file names.
- Different shells and commands support slightly different forms and syntax for patterns.
- Pattern matching is provided by characters, *, ?, {}, [], denoting different **wildcard**s (from card games, e.g., Joker is wild, i.e., can be any card).
- Patterns are composable: multiple wildcards joined into complex pattern (Aces, 2s and Jacks are wild).
- E.g., if the working directory is /u/jfdoe/cs246/a1 containing files:
  q1x.C, q2y.h, q2y.cc, q3z.cpp
  - * matches 0 or more characters

```
$ echo q*  # shell globs "q*" to match file names, which echo prints
q1x.C q2y.h q2y.cc q3z.cpp
```

  - ? matches 1 character

```
$ echo q*.??
q2y.cc
```

  - {. . . , . . .} matches any alternative in the set (at least one comma)

```
$ echo *.{C,cc,cpp}
q1x.C q2y.cc q3z.cpp
$ echo *.{C}                    # no comma => print pattern
*.{C}
```

  - [. . .] matches 1 character in the set

```
$ echo q[12]*
q1x.C q2y.h q2y.cc
```

  - [!. . .] (^ csh) matches 1 character ***not*** in the set

```
$ echo q[!1]*
q2y.h q2y.cc q3z.cpp
```

- Create ranges using hyphen (dash)

```
[0-3]       # => 0 1 2 3
[a-zA-Z]    # => lower or upper case letter
[!a-zA-Z]   # => any character not a letter
```

- Hyphen is escaped by putting it at start or end of set

```
[-?*]*      # => matches file names starting with -, ?, or *
```

- If globbing pattern does not match any files, the pattern becomes the argument (including wildcards).

```
$ echo q*.ww q[a-z].cc  # files do not exist so no expansion
q*.ww q[a-z].cc
```

csh prints: **echo**: No match.

- **Hidden file**s, starting with "." (dot), are ignored by globbing patterns
  - ⇒ * does not match all file names in a directory.
- Pattern .* matches all hidden files:
  - match ".", then zero or more characters, e.g., .bashrc, .login, etc., ***and*** ".", ".."
  - ***matching "." , ".." can be dangerous***

```
$ rm -r .*   # remove hidden files, and current/parent directory!!!
```

- Pattern .[!.]* matches all single "." hidden files but ***not*** "." and ".." directories.
  - match ".", then any character NOT a ".", and zero or more characters
  - ⇒ there must be at least 2 characters, the 2nd character cannot be a dot
  - "." starts with dot but fails the 2nd pattern requiring another character
  - ".." starts with dot but the second dot fails the 2nd pattern requiring non-dot character

- find : search for names in the file hierarchy.

find *[file/directory-list] [expr]*

- if *[file/directory-list]* omitted, search working directory, "."
- if *[expr]* omitted, match all file names, "-name "*""
- **recursively** find file/directory names starting in working directory matching pattern "t*"

```
$ find -name "t*"       # why quotes ?
./test.cc
./testdata
```

- -name *pattern* restrict file names to globbing pattern
- -type f | d select files of type file or directory
- -maxdepth *N* recursively descend at most *N* directory levels (0 ⇒ working directory)

- logical *not*, *and* and *or* (precedence order)

  -not *expr*
  expr -a *expr*
  expr -o *expr*

  -a assumed if no operator, *expr expr* ⇒ *expr* -a *expr*

- \(*expr* \) evaluation order

- recursively find only file names starting in working directory matching pattern "t*"

  ```
  $ find . -type f -name "t*"  # same as -type f -a -name "t*"
  test.cc
  ```

- recursively find only file names in file list (excluding hidden files) to a maximum depth of 3 matching patterns t* or *.C.

  ```
  $ find * -maxdepth 3 -a -type f -a \( -name "t*" -o -name "*.C" \)
  test.cc
  q1.C
  testdata/data.C
  ```

- egrep : (extended global regular expression print) search & print lines matching pattern in files (Google). (same as grep -E)

  egrep -irnv *pattern-string file-list*

  - list lines containing "main" in files with suffix ".cc"

    ```
    $ egrep main *.cc        # why no quotes ?
    q1.cc:int main() {
    q2.cc:int main() {
    ```

  - -i ignore case in both pattern and input files
  - -r recursively examine files in directories.
  - -n prefix each matching line with line number
  - -v select non-matching lines (invert matching)
  - returns 0 if one or more lines match and non-zero otherwise (counter intuitive)
  - list lines with line numbers containing "main" in files with suffix ".cc"

    ```
    $ egrep -n main *.cc
    q1.cc:33:int main() {
    q2.cc:45:int main() {
    ```

  - list lines containing "fred" in any case in file "names.txt"

    ```
    $ egrep -i fred names.txt
    names.txt:Fred Derf
    names.txt:FRED HOLMES
    names.txt:freddy mercury
    ```

- list lines that match start of line "^", "*#include*", 1 or more space or tab "[ ]+", either "" or "<", 1 or more characters ".+", either "" or ">", end of line "$" in files with suffix ".h" or ".cc"

```
$ egrep '^#include[ ]+["<].+[">]$' *.{h,cc}  # why quotes ?
egrep: *.h: No such file or directory
q1.cc:#include <iostream>
q1.cc:#include <iomanip>
q1.cc:#include "q1.h"
```

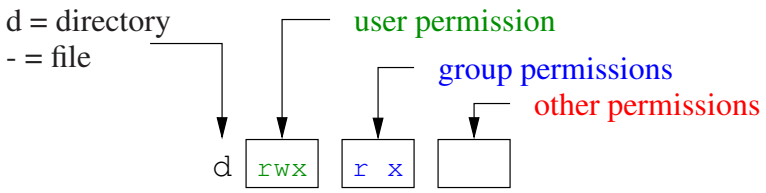
- **egrep pattern is different from globbing pattern** (see man egrep).
  Most important difference is "*" is a repetition modifier not a wildcard.

1.7 File Permission

- UNIX supports security for each file or directory based on 3 kinds of users:
  - user : owner of the file,
  - group : arbitrary name associated with a set of userids,
  - other : any other user.
- File or directory has permissions, read, write, and execute/search for the 3 sets of users.
  - Read/write allow specified set of users to read/write a file/directory.
  - Executable/searchable:
    - file : execute as a command, e.g., file contains a program or shell script,
    - directory : traverse through directory node but not read (cannot read file names)
- Use ls -l command to print file-permission information.

```
drwxr-x--- 2 jfdoe jfdoe  4096 Oct 19 18:19 cs246
drwxr-x--- 2 jfdoe jfdoe  4096 Oct 21 08:51 cs245
-rw------- 1 jfdoe jfdoe 22714 Oct 21 08:50 test.cc
-rw------- 1 jfdoe jfdoe 63332 Oct 21 08:50 notes.tex
```

- Columns are: permissions, #-of-directories (including "." and ".."), owner, group, file size, change date, file name.
- Permission information is:



- E.g., d **rwx r-x ---**, indicates

  - directory in which the user has read, write and execute permissions,
  - group has only read and execute permissions,
  - others have no permissions at all.

- ***In general, never allow "other" users to read or write your files.***

- Default permissions (usually) on:

  - file: **rw-** **r--** **---**, owner read/write, group only read, other none.
  - directory: **rwx** **---** **---**, owner read/write/execute, group/other none.

- chgrp : change group-name associated with file.

  chgrp *[-R] group-name file/directory-list*

  - -R recursively modify the group of a directory.

```
$ chgrp cs246_05 cs246   # course directory
$ chgrp -R cs246_05 cs246/a5   # assignment directory/files
```

  Must associate group along entire pathname and files.

- ***Creating/deleting group-names is done by system administrator.***

- chmod : add or remove from any of the 3 security levels.

  chmod *[-R] mode-list file/directory-list*

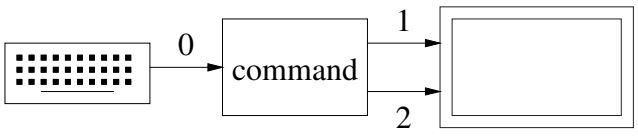
  - -R recursively modify the security of a directory.
  - *mode-list* has the form *security-level operator permission*.
  - Security levels are **u** for user, **g** for group, **o** for other, **a** for all (ugo).
  - Operator **+** adds, **-** removes, **=** sets specific permission.
  - Permissions are **r** for readable, **w** for writable and **x** for executable.
  - Elements of the *mode-list* are separated by commas.

```
chmod g-r,o-r,g-w,o-w foo    # long form, remove read/write for group/others users
chmod go-rw foo              # short form
chmod g=rx cs246             # allow group users read/search
chmod -R g+rw cs246/a5       # allow group users read/write, recursively
```

- To achieve desired access, must associate permission along entire pathname and files.

1.8 Input/Output Redirection

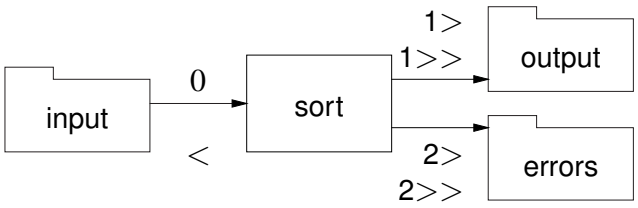
- Every command has three standard files: input (0), output (1) and error (2).
- By default, these are connected to the keyboard (input) and screen (output/error).




```
$ sort -n      # -n means numeric sort
7              sort reads unsorted values from keyboard
30
5
C-d            close input file
5              sort prints sorted values to screen
7
30
```

- ***To close an input file from the keyboard***, type <ctrl>-d (C-d), i.e., press <ctrl> then d key, causing the shell to close the keyboard input file.
- Redirection allows:
  - input from a file (faster than typing at keyboard),
  - saving output to a file for subsequent examination or processing.
- Redirection performed using operators < for input and > / >> for output to/from other sources.

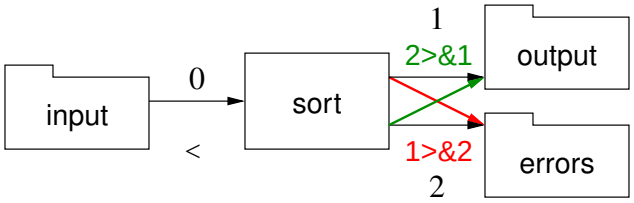
```
$ sort -n  < input  1> output  2> errors
```



  - < means read input from file rather than keyboard.
  - > (same as 1>), 1>, 2> means (create if needed) file and write output/errors to file rather than screen (destructive).
  - >> (same as 1>>), 1>>, 2>> means (create if needed) file and append output/errors to file rather than screen.
- Command is (usually) unaware of redirection.

- Can tie standard error to output (and vice versa) using ">&" ⇒ both write to same place.

```
$ sort -n  < input  >& both          # stderr (2) goes to stdout (1)
$ sort -n  < input  1> output  2>&1  # stderr (2) goes to stdout (1)
$ sort -n  < input  2> errors  1>&2  # stdout (1) goes to stderr (2)
```



- Order of tying redirection files is important.

```
$ sort 2>&1 > output # tie stderr to screen, redirect stdout to "output"
$ sort > output 2>&1 # redirect stdout to "output", tie stderr to "output"
```

- To ignore output, redirect to pseudo-file /dev/null.

```
$ sort data 2> /dev/null   # ignore error messages
```

- Source and target cannot be the same for redirection.

```
$ sort < data > data
```

data file is corrupted before it can be read.

- Redirection requires explicit creation of intermediate (temporary) files.

```
$ sort data > sortdata     # sort data and store in "sortdata"
$ egrep -v "abc" sortdata > temp  # print lines without "abc", store in "temp"
$ tr a b < temp > result   # translate a's to b's and store in "result"
$ rm sortdata temp         # remove intermediate files
```

- Shell pipe operator | makes standard output for a command the standard input for the next command, without creating intermediate file.

```
$ sort data | grep -v "abc" | tr a b > result
```

- Standard error is not piped unless redirected to standard output.

```
$ sort data 2>&1 | grep -v "abc" 2>&1 | tr a b > result 2>&1
```

now both standard output and error go through pipe.

- Print file hierarchy using indentation (see page 4).

```
$ find cs246
cs246
cs246/a1
cs246/a1/q1x.C
cs246/a1/q2y.h
cs246/a1/q2y.cc
cs246/a1/q3z.cpp
```

```
$ find cs246 | sed 's@[^/]*/@   @g'
cs246
   a1
      q1x.C
      q2y.h
      q2y.cc
      q3z.cpp
```

- sed : inline editor
  - pattern changes all occurrences (g) of string [^/]*/ (zero or more characters not "/" and then "/", where "*" is a repetition modifier not a wildcard) to 3 spaces.

1.9 Script

- A **shell program** or **script** is a file (scriptfile) containing shell commands to be executed.

```
#!/bin/bash  [ -x ]
date                # shell and OS commands
whoami
echo Hi There
```

- First line begins with magic comment: "*#!*" (sha-bang) with shell pathname for executing the script.
- Forces specific shell to be used, which is run as a subshell.
- If "*#!*" is missing, the subshell is the same as the invoking shell for sh shells (bash) and sh is used for csh shells (tcsh).
- ***Optional -x is for debugging and prints trace of the script during execution.***
- Script can be invoked directly using a specific shell:

```
$ bash scriptfile          # direct invocation
Sat Dec 19 07:36:17 EST 2009
jfdoe
Hi There!
```

or as a command if it has executable permissions.

```
$ chmod u+x scriptfile # Magic, make script file executable
$ ./scriptfile         # command execution
Sat Dec 19 07:36:17 EST 2009
jfdoe
Hi There!
```

- Script can have parameters.

```
#!/bin/bash  [ -x ]
date
whoami
echo ${1}              # parameter for 1st argument
```

- Arguments are passed on the command line:

```
$ ./scriptfile "Hello World"
Sat Dec 19 07:36:17 EST 2009
jfdoe
Hello World
$ ./scriptfile Hello World
Sat Dec 19 07:36:17 EST 2009
jfdoe
Hello
```

  Why no World?

- Special parameter variables to access arguments/result.
  - ${#} number of arguments, excluding script name
  - ${0} always name of shell script

    ```
    echo ${0}                    # in scriptfile
    ```

    prints scriptfile.
  - ${1}, ${2}, ${3}, ... refers to arguments by position (not name), i.e., 1st, 2nd, 3rd, ... argument
  - ${*} and ${@} list all arguments, e.g., ${1} ${2} ..., excluding script name

    Difference occurs inside double quotes:
    - "${*}" arguments as a single string string, e.g., "${1} ${2} . . ."
    - "${@}" arguments as separate strings, e.g., "${1}" "${2}" ...
  - ${$} process id of executing script.
  - ${?} exit status of the last command executed; 0 often ⇒ exited normally.

```
$ cat scriptfile
#!/bin/bash
echo ${#}                    # number of command-line arguments
echo ${0} ${1} ${2} ${3} ${4} # some arguments
echo "${*}"                  # all arguments as a single string
echo "${@}"                  # all arguments as separate strings
echo ${$}                    # process id of executing subshell
exit 21                      # script exit status

$ ./scriptfile a1 a2 a3 a4 a5
5                            # number of arguments
scriptfile a1 a2 a3 a4       # script-name / args 1-4
a1 a2 a3 a4 a5               # args 1-5, 1 string
a1 a2 a3 a4 a5               # args 1-5, 5 strings
27028                        # process id of subshell
$ echo ${?}                  # print script exit status
21
```

- Interactive shell session is a script reading commands from standard input.

```
$ echo ${0}                    # shell you are using (not csh)
bash
```

1.10 Shift

- **shift** *[* N *]* : destructively shift parameters to the left N positions, i.e., ${1}=${N+1}, ${2}=${N+2}, etc., and ${#} is reduced by N.
  - If no N, 1 is assumed.
  - ***If* N *is 0 or greater than ${#}, there is no shift.***

```
$ cat scriptfile          $ ./scriptfile 1 2 3 4 5 6 7
#!/bin/bash               1
echo ${1};  shift 1       2
echo ${1};  shift 2       4
echo ${1};  shift 3       7
echo ${1}
```

1.11 Shell Variables

- Each shell has a set of environment (global) and script (local/parameters) variables.
- variable-name syntax : [_a-zA-Z][_a-zA-Z0-9]*, "*" is repetition modifier
- **case-sensitive**:

  VeryLongVariableName Page1 Income_Tax _75

- **Keyword**s are reserved identifiers (e.g., **if**, **while**).
- Variable is declared ***dynamically*** by assigning a value with operator "=".

```
$ a1=/u/jfdoe/cs246/a1   # declare and assign
```

No spaces before or after "=".

- Variable can be removed.

```
$ unset var              # remove variable
$ echo var is ${var}
var is                   # no value for undefined variable "var"
```

- ***Variable ONLY holds string value (arbitrary length).***

```
$ i=3          # i has string value "3" not integer 3
```

- Variable's value is dereferenced using operators "$" or "${}".

```
$ echo $a1 ${a1}
/u/jfdoe/cs246/a1 /u/jfdoe/cs246/a1
$ cd $a1          # or ${a1}
```

- Dereferencing an undefined variable returns an empty string.

```
$ echo var is ${var}    # no value for undefined variable "var"
var is
$ var=Hello
$ echo var is ${var}
var is Hello
```

- ***Beware concatenation.***

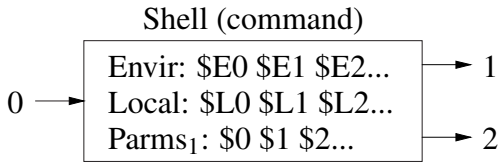
```
$ cd $a1data          # change to /u/jfdoe/cs246/a1data
```

  Where does this move to?

- Always use braces to allow concatenation with other text.

```
$ cd ${a1}data        # cd /u/jfdoe/cs246/a1data
```

- Shell has 3 sets of variables: environment, local, routine parameters.



- New variable declare on the local list.

```
$ var=3               # new local variable
```

- A variable is moved to environment list if exported.

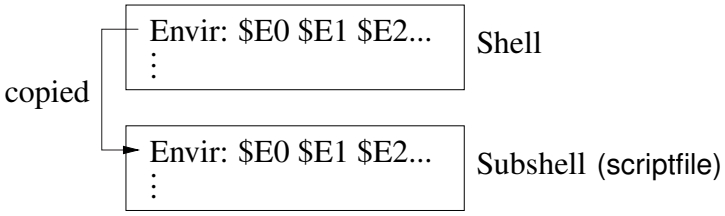
```
$ export var          # move from local to environment list
```

- Login shell starts with a number of useful environment variables, e.g.:

```
$ set                 # print variables/routines (and values)
HOME=/u/jfdoe         # home directory
HOSTNAME=linux006.student.cs    # host computer
PATH=...              # lookup directories for OS commands
SHELL=/bin/bash       # login shell
...
```

- A script executes in its own subshell with a ***copy*** of calling shell's environment variables (works across different shells), but not calling shell's locals or arguments.

```
$ ./scriptfile        # execute script in subshell
```



- When a (sub)shell ends, changes to its environment variables do not affect the containing shell (***environment variables only affect subshells***).
- ***Only put a variable in the environment list to make it accessible by subshells.***

1.12 Arithmetic

- Arithmetic requires integers, 3 + 7, not strings, "3" + "17".

```
$ i=3+1
$ j=${i}+2
$ echo ${i} ${j}
3+1 3+1+2
```

- Arithmetic is performed by:
  - converting a string to an integer (if possible),
  - performing an integer operation,
  - and converting the integer result back to a string.
- bash performs these steps with shell-command operator $((*expression*)).

```
$ echo $((3 + 4 - 1))
6
$ echo $((3 + ${i} * 2))
8
$ echo $((3 + ${k}))      # k is unset
bash: 3 + : syntax error: operand expected (error token is " ")
```

- Basic integer operations, +, -, *, /, % (modulus), with usual precedence, and ().
- For shells without arithmetic shell-command (e.g., sh, csh), use system command expr.

```
$ expr 3 + 4 - 1          # for sh, csh
6
$ expr 3 + ${i} \* 2      # escape *
8
$ expr 3 + ${k}           # k is unset
expr: non-numeric argument
```

1.13 Routine

- Routine is a script in a script.

```
routine_name() {      # number of parameters depends on call
    # commands
}
```

- Invoke like a script.

```
routine_name [ args ... ]
```

- Variables/routines should be created before used.
- E.g., create a routine to print incorrect usage-message.

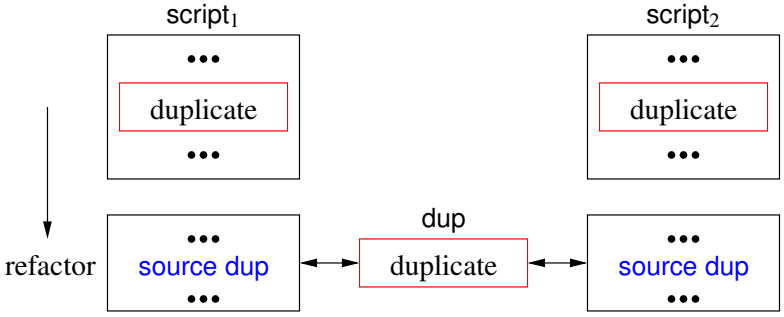
```
usage() {
    echo "Usage: ${0} -t -g -e input-file [ output-file ]"
    exit 1              # terminate script with non-zero exit code
}
usage                   # call, no arguments
```

- Routine arguments are accessed the same as in a script.

```
$ cat scriptfile
#!/bin/bash
rtn() {
    echo ${#}           # number of command-line arguments
    echo ${0} ${1} ${2} ${3} ${4} # arguments passed to routine
    echo "${*}"         # all arguments as a single string
    echo "${@}"         # all arguments as separate strings
    echo ${$}           # process id of executing subshell
    return 17           # routine exit status
}
rtn a1 a2 a3 a4 a5  # invoke routine
echo ${?}           # print routine exit status
exit 21             # script exit status

$ ./scriptfile      # run script
5                   # number of arguments
scriptfile a1 a2 a3 a4 # script-name / args 1-5
a1 a2 a3 a4 a5      # args 1-5, 1 string
a1 a2 a3 a4 a5      # args 1-5, 5 strings
27028               # process id of subshell
17                  # routine exit status
$ echo ${?}         # print script exit status
21
```

- **source** filename : execute commands from a file in the current shell.
  - For convenience or code sharing, subdivided script into multiple files.



  - No "*#!...*" at top, because not invoked directly like a script.
  - Sourcing file ***includes*** it into current shell script and ***evaluates*** lines.

```
source ./aliases       # include/evaluate aliases into .shellrc file
source ./usage.bash    # include/evaluate usage routine into scriptfile
```

- Created or modified variables/routines from sourced file immediately affect current shell.

1.14 Control Structures

- Shell provides control structures for conditional and iterative execution; syntax for bash is presented (csh is different).

1.14.1 Test

- **test** ([ ]) command compares strings, integers and queries files.

- **test** expression is constructed using the following:

test	operation	priority
! expr	not	**high**
\(expr \)	evaluation order (***must be escaped***)	
expr1 -a expr2	logical and (***not short-circuit***)	
expr1 -o expr2	logical or (***not short-circuit***)	**low**

- **test** comparison is performed using the following:

test	operation
string1 = string2	equal (***not ==***)
string1 != string2	not equal
integer1 -eq integer2	equal
integer1 -ne integer2	not equal
integer1 -ge integer2	greater or equal
integer1 -gt integer2	greater
integer1 -le integer2	less or equal
integer1 -lt integer2	less
-d file	exists and directory
-e file	exists
-f file	exists and regular file
-r file	exists with read permission
-w file	exists with write permission
-x file	exists with executable or searchable

- Logical operators -a (and) and -o (or) evaluate both operands.

- **test** returns 0 if expression is true and 1 otherwise (counter intuitive).

```
$ i=3
$ test 3 -lt 4              # integer test
$ echo ${?}                 # true
0
$ [ `whoami` = "jfdoe" ]    # string test, need spaces
$ echo ${?}                 # false
1
$ [ 2 -lt ${i} -o `whoami` = "jfdoe" ] # compound test
$ echo ${?}                 # true
0
$ [ -e q1.cc ]              # file test
$ echo ${?}                 # true
0
```

1.14.2 Selection

- An **if** statement provides conditional control-flow.

```
if test-command             if test-command ; then
  then
    commands                    commands
elif test-command           elif test-command ; then
  then
    commands                    commands
...                         ...
else                        else
    commands                    commands
fi                          fi
```

  Semi-colon is necessary to separate test-command from keyword.

- test-command is evaluated; exit status of zero implies true, otherwise false.

- Check for different conditions:

```
if [ "`whoami`" = "jfdoe" ] ; then
    echo "valid userid"
else
    echo "invalid userid"
fi

if diff file1 file2 > /dev/null ; then  # ignore diff output, check exit status
    echo "same files"
else
    echo "different files"
fi

if [ -x /usr/bin/cat ] ; then
    echo "cat command available"
else
    echo "no cat command"
fi
```

- ***Beware unset variables or values with special characters (e.g., blanks).***

```
if [ ${var} = 'yes' ] ; then ...  # var unset => if [ = 'yes' ]
bash: [: =: unary operator expected
if [ ${var} = 'yes' ] ; then ...  # var="a b c" => if [ a b c = 'yes' ]
bash: [: too many arguments
if [ "${var}" = 'yes' ] ; then ...  # var unset => if [ "" = 'yes' ]
if [ "${var}" = 'yes' ] ; then ...  # var="a b c" => if [ "a b c" = 'yes' ]
```

- ***When dereferencing, always quote variables***, except for safe variables ${#}, ${$}, ${?}, which generate numbers.

- A **case** statement selectively executes one of *N* alternatives based on matching a string expression with a series of patterns (globbing), e.g.:

```
case expression in
    pattern | pattern | ... )  commands  ;;
    ...
    * )  commands ;;    # optional match anything (default)
esac
```

- When a pattern is matched, the commands are executed up to ";;", and control exits the **case** statement.

- If no pattern is matched, the **case** statement does nothing.

- E.g., command with only one of these options:

  -h, --help, -v, --verbose, -f file, --file file

  use **case** statement to process option:

```
usage() { ... }                 # print message and terminate script
verbose=no                      # default value
case "${1}" in                  # process single option
  '-h' | '--help' ) usage ;;
  '-v' | '--verbose' ) verbose=yes ;;
  '-f' | '--file' )             # has additional argument
    shift 1                     # access argument
    file="${1}"
    ;;
  * ) usage ;;                  # default, has to be one argument
esac
if [ ${#} -ne 1 ] ; then usage ; fi # check only one argument remains
...                             # execute remainder of command
```

1.14.3 Looping

- **while** statement executes its commands zero or more times.

```
while test-command      while test-command ; do
  do
    commands                commands
done                    done
```

- test-command is evaluated; exit status of zero implies true, otherwise false.
- Check for different conditions:

```
# print command-line parameters, destructive
while [ "${1}" != "" ] ; do # string compare
    echo "${1}"
    shift                   # destructive
done

# print command-line parameters, non-destructive
i=1
while [ ${i} -le ${#} ] ; do
    eval echo "\${${i}}" # second substitution of "${1}" to its value
    i=$((${i} + 1))
done

# process files data1, data2, ...
i=1
file=data${i}
while [ -f "${file}" ] ; do # file regular and exists?
    ...                     # process file
    i=$((${i} + 1))         # advance to next file
    file=data${i}
done
```

- **for** statement is a specialized **while** statement for iterating with an index over list of whitespace-delimited strings.

```
for index [ in list ] ; do
    commands
done
for name in ric peter jo mike ; do
    echo ${name}
done
for arg in "${@}" ; do # process parameters, why quotes?
    echo ${arg}
done
```

  Assumes **in** "${@}", if no **in** clause.

- Or over a set of values:

```
for (( init-expr; test-expr; incr-expr )) ; do  # double parenthesis
    commands
done
for (( i = 1; i <= ${#}; i += 1 )) ; do
    eval echo "\${${i}}" # second substitution of "${1}" to its value
done
```

- Use directly on command line (rename .cpp files to .cc):

```
$ for file in *.cpp ; do mv "${file}" "${file%cpp}"cc ; done
```

  % removes matching suffix; # removes matching prefix

- A **while/for** loop may contain **break** and **continue** to terminate loop or advance to the next loop iteration.

```
i=1                              # process files data1, data2, ...
while [ 0 ] ; do                 # while true, infinite loop
    file=data${i}                # create file name
  if [ ! -f "${file}" ] ; then break ; fi # file not exist, stop ?
    ...                          # process file
  if [ ${?} -ne 0 ] ; then continue ; fi   # bad return, next file
    ...                          # process file
    i=$((${i} + 1))              # advance to next file
done
```

1.15 Examples

- How many times does word $1 appear in file $2?

```
#!/bin/bash
cnt=0
for word in `cat "${2}"` ; do  # process file one blank-separated word at a time
    if [ "${word}" = "${1}" ] ; then
        cnt=$((${cnt} + 1))
    fi
done
echo ${cnt}

$ ./word "fred" story.txt
42
```

  - Could fail if file is large. Why?

- Last Friday in any month is payday. What day is payday?
  (“.” indicates a space).

```
$ cal October 2013
....October.2013
Su.Mo.Tu.We.Th.Fr.Sa
.......1..2..3..4..5
.6..7..8..9.10.11.12
13.14.15.16.17.18.19
20.21.22.23.24.25.26
27.28.29.30.31
```

- Columns separated by blanks, where blanks separate empty columns
  (“^” indicates empty column).

```
^.^.^.^.October.2013
Su.Mo.Tu.We.Th.Fr.Sa
^.^.^.^.^.^.^.1.^.2.^.3.^.4.^.5
^.6.^.7.^.8.^.9.10.11.12
13.14.15.16.17.18.19
20.21.22.23.24.25.26
27.28.29.30.31
```

  What column is “9” in? What column is “25” in?

  - cut selects column -f 6 of each line, with columns separated by blanks -d ' '

```
$ cal October 2013 | cut -f 6 -d ' '
2013
Fr

8
18
25
```

- grep selects only the lines with numbers

```
$ cal October 2013 | cut -d ' ' -f 6 | grep "[0-9]"
2013
8
18
25
```

- tail -1 selects the last line

```
$ cal October 2013 | cut -d ' ' -f 6 | grep "[0-9]" | tail -1
25
```

- Generalize to any month/year.

1.15.1 Hierarchical Print Script (see Section 1.8, p. 22)

```
#!/bin/bash
#
# List directories using indentation to show directory nesting
#
# Usage: hi [ -l | -d ] [ directory-name ]*
# Examples:
#   $ hi -d dir1 dir2
# Limitations
#   * does not handle file names with special characters

opt= ; files= ;
while [ ${#} -ne 0 ] ; do      # option and files in any order
    case "${1}" in
     -l) opt=l  ;;
     -d) opt=d  ;;
     -h | -help | --help | -*)
         echo 'Usage: hi [ -l | -d | -s ] directory-list . . .' 1>&2
         exit 1  ;;
     *)  files="${files} ${1}"  ;;
    esac
    shift
done
case $opt in
    l) find ${files} -exec ls -ldh {} \; | sort -k9,9f | \
         sed 's|\./| |' | sed 's|[^ /]*/|  |g' ;; # add tab then spaces
    d) du -ah ${files} | sort -k2,2f | sed 's|[^      /]*/|  |g'  ;; # replace tab
    *) find ${files} -print | sort -f | sed 's|[^/]*/|  |g'  ;;  # sort ignore case
esac
exit 0
```

```
$ hi
.
   jfdoe
      cs246
         a1
            q1x.C
            q2y.h
            q2y.cc
            q3z.cpp
         a2
            q1p.C
            q2q.cc
            q2r.h
```

```
$ hi -d jfdoe
64K jfdoe
60K     cs246
28K         a1
4.0K            q1x.C
8.0K            q2y.cc
8.0K            q2y.h
4.0K            q3z.cpp
28K         a2
16K             q1p.C
4.0K            q2q.cc
4.0K            q2r.h
```

```
$ hi -l
drwx------ 3 jfdoe jfdoe 4.0K May  1 07:05 .
drwx------ 3 jfdoe jfdoe 4.0K May  1 07:05    jfdoe
drwx------ 4 jfdoe jfdoe 4.0K May  1 07:06       cs246
drwx------ 2 jfdoe jfdoe 4.0K May  1 07:32          a1
-rw------- 1 jfdoe jfdoe 3.2K May  1 07:32             q1x.C
-rw------- 1 jfdoe jfdoe 8.0K May  1 07:32             q2y.h
-rw------- 1 jfdoe jfdoe 4.1K May  1 07:32             q2y.cc
-rw------- 1 jfdoe jfdoe  160 May  1 07:32             q3z.cpp
drwx------ 2 jfdoe jfdoe 4.0K May  1 07:34          a2
-rw------- 1 jfdoe jfdoe  14K May  1 07:33             q1p.C
-rw------- 1 jfdoe jfdoe  800 May  1 07:33             q2q.cc
-rw------- 1 jfdoe jfdoe  160 May  1 07:33             q2r.h
```

1.15.2 Cleanup Script

```
#!/bin/bash
#
# List and remove unnecessary files in directories
#
# Usage: cleanup [ [ -r | -R ] [ -i | f ] directory-name ]+
#   -r | -R clean specified directory and all subdirectories
#   -i | -f prompt or not prompt for each file removal
# Examples:
#   $ cleanup jfdoe
#   $ cleanup -R .
#   $ cleanup -r dir1 -i dir2 -r -f dir3
# Limitations:
#   * only removes files named: core, a.out, *.o, *.d
#   * does not handle file names with special characters

usage() {                               # print usage message & terminate
    echo "Usage: ${0} [ [ -r | -R ] [ -i | -f ] directory-name ]+" 1>&2
    exit 1
}
defaults() {                            # defaults for each directory
    prompt="-i"                         # prompt for removal
    depth="-maxdepth 1"                 # not recursive
}
remove() {
    for file in `find "${1}" ${depth} -type f -a \( -name 'core' -o \
        -name 'a.out' -o -name '*.o' -o -name '*.d' \)`
    do
        echo "${file}"                  # print removed file
        rm "${prompt}" "${file}"
    done
}
if [ ${#} -eq 0 ] ; then usage ; fi     # no arguments ?
defaults                                # set defaults for directory
while [ ${#} -gt 0 ] ; do               # process command-line arguments
    case "${1}" in
      "-r" | "-R" ) depth="" ;;         # recursive ?
      "-i" | "-f") prompt="${1}" ;; # prompt for deletion ?
      "-h" | --help | -* ) usage ;;     # help ?
      * )                               # directory name ?
        if [ ! -x "${1}" ] ; then       # directory exist and searchable ?
            echo "${1} does not exist or is not searchable" 1>&2
        else
            remove "${1}"               # remove files in directory
            defaults                    # reset defaults for next directory
        fi
        ;;
    esac
    shift                               # remove argument
done
exit 0
```

2 C++

2.1 Design

- **Design** is a plan for solving a problem, but leads to multiple solutions.
- Need the ability to compare designs.
- 2 measures: coupling and cohesion
- **Coupling** is degree of interdependence ***among*** programming modules.
- Aim is to achieve lowest coupling or highest independence (i.e., each module can stand alone or close to it).
- Module is read and understood as a unit ⇒ changes do not effect other modules and can be isolated for testing purposes (like stereo components).
- **Cohesion** is degree of element association ***within*** a module (focus).
- Elements can be a statement, group of statements, or calls to other modules.
- Alternate names for cohesion: binding, functionality, modular strength.
- Highly cohesive module has strongly and genuinely related elements.
- **Low cohesion** (module elements NOT related) ⇒ **loose coupling**.
- **High cohesion** (module elements related) ⇒ tight coupling.

2.2 C/C++ Composition

- C++ is composed of 3 languages:
  1. ***Before*** compilation, preprocessor language (cpp) modifies (text-edits) the program (see Section 2.21, p. 97).
  2. ***During*** compilation, template (generic) language adds new types and routines (see Section 2.33, p. 149).
  3. ***During*** compilation,
     - C programming language specifying *basic* declarations and control flow.
     - C++ programming language specifying *advanced* declarations and control flow.
- A programmer uses the three programming languages as follows:

user edits → **preprocessor edits** → **templates expand** → **compilation**
(→ linking/loading → execution)

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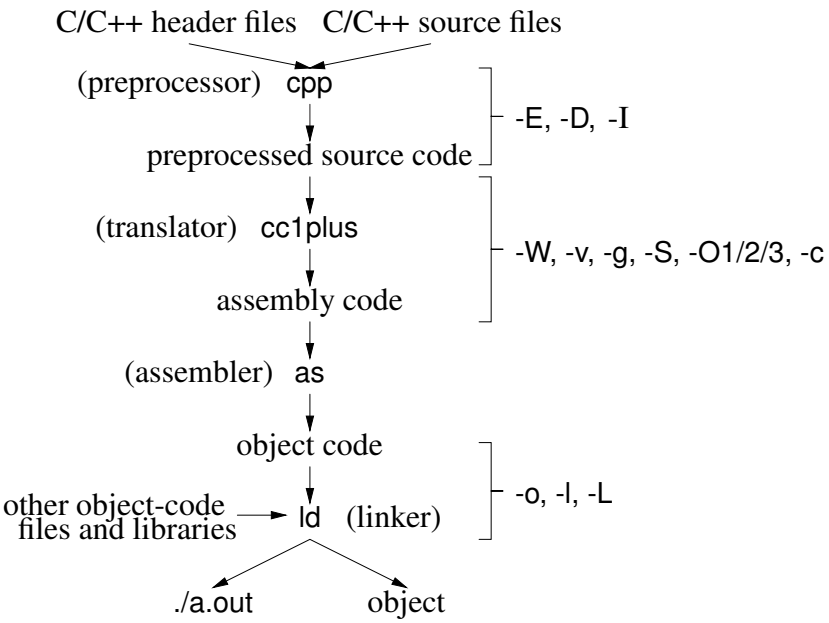
- C is composed of languages 1 & 3.
- The compiler interface controls all of these steps.



2.3 First Program

Java	C	C++

import java.lang.*; *// implicit*
class Hello {
  public static
  void main(String[] args) {
  System.out.println("Hello!");
  System.exit(0);
  }
}
	#include <stdio.h>
	
	int main() {
	  printf("Hello!\n");
	  return 0;
	}
		#include <iostream> *// access to output*
		using namespace std; *// direct naming*
		
		int main() { *// program starts here*
		  cout << "Hello!" << endl;
		  return 0; *// return 0 to shell, optional*
		}

- **#include** <iostream> copies (imports) basic I/O descriptions (no equivalent in Java).
- **using namespace** std allows imported I/O names to be accessed directly (otherwise qualification is necessary, see Section 2.16, p. 87).
- cout << "Hello!" << endl prints "Hello!" to standard output, called cout (System.out in Java, stdout in C).
- endl starts a newline after "Hello!" (println in Java, '\n' in C).
- Routine exit (Java System.exit) terminates a program at any location and returns a code to the shell, e.g., exit(0) (**#include** <cstdlib>).

  - Literals EXIT_SUCCESS and EXIT_FAILURE indicate successful or unsuccessful termination status.
  - e.g., **return** EXIT_SUCCESS or exit(EXIT_FAILURE).

- C program-files use suffix .c; C++ program-files use suffixes .C / .cpp / **.cc**.
- Compile with g++ command:

```
$ g++ -Wall -g -std=c++11 -o firstprog firstprog.cc # compile, create "a.out"
$ ./firstprog                                      # execute program
```

- -W***kind*** generate warning message for this "***kind***" of situation.
  - -W**all** print ALL warning messages.
  - -W**error** make warnings into errors so program does not compile.
- -g add symbol-table information to object file for debugging
- -std=**c++11** allow new C++11 extensions (requires gcc-4.8.0 or greater)
- -o file containing the executable (a.out default)
- create shell alias for g++ to use options **g++ -Wall -g -std=c++11**

2.4 Comment

- Comment may appear where whitespace (space, tab, newline) is allowed.

	Java / C / C++
1	/* ... */
2	// remainder of line

- **/*...*/ comment cannot be nested**:

```
/* ... /* ... */ ... */
          ↑   ↑
   end comment   treated as statements
```

- Be extremely careful in using this comment to elide/comment-out code. (page 99 presents another way to comment-out code.)

2.5 Declaration

- A declaration introduces names or redeclares names from previous declarations.

2.5.1 Basic Types

Java	C / C++	
boolean	**bool** (C <stdbool.h>)	
char	**char** / **wchar_t**	ASCII / unicode character
byte	**char** / **wchar_t**	integral types
int	**int**	
float	**float**	real-floating types
double	**double**	
		label type, implicit

- C/C++ treat **char** / **wchar_t** as character and integral type.
- Java types **short** and **long** are created using type qualifiers (see Section 2.5.3).

2.5.2 Variable Declaration

- C/C++ declaration: type followed by list of identifiers, except label with an implicit type (same in Java).

Java / C / C++
char a, b, c, d; **int** i, j, k; **double** x, y, z; *id* :

- Declarations may have an initializing assignment:

```
int i = 3;          int i = 3, j = i, k = f( j );
int j = 4 + i;
int k = f( j );
```

- C restricts initializer elements to be constant for global declarations.

2.5.3 Type Qualifier

- Other integral types are composed with type qualifiers modifying integral types **char** and **int**.
- C/C++ provide size (**short**, **long**) and signed-ness (**signed** $\Rightarrow$ positive/negative, **unsigned** $\Rightarrow$ positive only) qualifiers.
- **int** provides ***relative*** machine-specific types: usually **int** $\geq$ 4 bytes for 32/64-bit computer, **long** $\geq$ **int**, **long long** $\geq$ **long**.
- **#include** <climits> specifies names for lower/upper bounds of a type's range of values for a machine, e.g., a 32/64-bit computer:

integral types	range (lower/upper bound name)
char (**signed char**)	SCHAR_MIN to SCHAR_MAX, e.g., -128 to 127
unsigned char	0 to UCHAR_MAX, e.g. 0 to 255
short (**signed short int**)	SHRT_MIN to SHRT_MAX, e.g., -32768 to 32767
unsigned short (**unsigned short int**)	0 to USHRT_MAX, e.g., 0 to 65535
int (**signed int**)	INT_MIN to INT_MAX, e.g.,-2147483648 to 2147483647
unsigned int	0 to UINT_MAX, e.g., 0 to 4294967295
long (**signed long int**)	LONG_MIN to LONG_MAX, e.g., -2147483648 to 2147483647
unsigned long (**unsigned long int**)	0 to ULONG_MAX, e.g. 0 to 4294967295
long long (**signed long long int**)	LLONG_MIN to LLONG_MAX, e.g.,-9223372036854775808 to 9223372036854775807
unsigned long long (**unsigned long long int**)	0 to ULLONG_MAX, e.g., 0 to 18446744073709551615

- C/C++ provide two basic real-floating types **float** and **double**, and one real-floating type generated with type qualifier.
- **#include** <cfloat> specifies names for precision and magnitude of real-floating values.

real-float types	range (precision, magnitude)
float	FLT_DIG precision, FLT_MIN_10_EXP to FLT_MAX_10_EXP, e.g,. 6+ digits over range 10^{-38} to 10^{38}, IEEE (4 bytes)
double	DBL_DIG precision, DBL_MIN_10_EXP to DBL_MAX_10_EXP, e.g., 15+ digits over range 10^{-308} to 10^{308}, IEEE (8 bytes)
long double	LDBL_DIG precision, LDBL_MIN_10_EXP to LDBL_MAX_10_EXP, e.g., 18-33+ digits over range 10^{-4932} to 10^{4932}, IEEE (12-16 bytes)

float : ±1.17549435e-38 to ±3.40282347e+38
double : ±2.2250738585072014e-308 to ±1.7976931348623157e+308
long double : ±3.36210314311209350626e-4932 to ±1.18973149535723176502e+4932

2.5.4 Literals

- Variables contain values; values have **constant** (C) or **literal** (C++) meaning.

```
3 = 7;   // disallowed
```

- C/C++ and Java share almost all the same literals for the basic types.

type	literals
boolean	**false**, **true**
character	`'a'`, `'b'`, `'c'`
string	`"abc"`, `"a b c"`
integral	decimal : 123, -456, 123456789 octal, prefix 0 : 0144, -045, 04576132 hexadecimal, prefix 0X / 0x : 0xfe, -0X1f, 0xe89abc3d
real-floating	.1, 1., -1., 0.52, -7.3E3, -6.6e-2, E/e exponent

- Use the right literal for a variable's type:

```
bool b = true;              // not 1
int i = 1;                  // not 1.0
double d = 1.0              // not 1
char c = 'a';               // not 97
const char *cs = "a";       // not 'a'
```

- Literal are **undesignated**, compiler chooses smallest type, or **designated**, programmer chooses type with suffixes: L/l ⇒ **long**, LL/ll ⇒ **long long**, U/u ⇒ **unsigned**, and F/f ⇒ **float**.

```
-3                          // undesignated, int
-3L                         // designated, long int
10000000000000000           // undesignated, long long int (why?)
10000000000000000LL         // designated, long long int
4U                          // designated, unsigned int
10000000000000000ULL        // designated, unsigned long long int
3.5E3                       // undesignated, double
3.5E3F                      // designated, float
```

- Juxtaposed string literals are concatenated.

```
"John"      // divide literal for readability
"Doe";      //   even over multiple lines
"JohnDoe";
```

- Every string literal is implicitly terminated with a character `'\0'` (**sentinel**).
  - `"abc"` is 4 characters: `'a'`, `'b'`, `'c'`, and `'\0'`, which occupies 4 bytes.
  - String cannot contain a character with the value `'\0'`.
  - Computing string length requires $O(N)$ search for `'\0'`.

- Escape sequence provides quoting of special characters in a character/string literal using a backslash, \.

`'\\'`	backslash
`'\''`	single quote
`'\"'`	double quote
`'\t'`, `'\n'`	(special names) tab, newline, ...
`'\0'`	zero, string termination character

- C/C++ provide user literals (write-once/read-only) with type qualifier **const** (Java **final**).

Java	C/C++
final char Initial = 'D'; **final short int** Size = 3, SupSize; SupSize = Size + 7; **final double** PI = 3.14159;	**const char** Initial = 'D'; **const short int** Size = 3, SupSize = Size + 7; **disallowed** **const double** PI = 3.14159;

- C/C++ **const** variable ***must*** be assigned a value at declaration (see also Section 2.22.6, p. 113); the value can be the result of an expression.

- A constant variable can (only) appear in contexts where a literal can appear.

```
Size = 7;    // disallowed
```

- **Good practise is to name literals so all usages can be changed via its initialization value.** (see Section 2.12.1, p. 75)

```
const short int Mon=0, Tue=1, Wed=2, Thu=3, Fri=4, Sat=5, Sun=6;
```

2.5.5 C++ String

- **string** (**#include** <string>) is a sequence of characters with powerful operations performing actions on groups of characters.

- C provided strings by an array of **char**, string literals, and library facilities.

```
char s[10];          // string of at most 10 characters
```

- Because C-string variable is fixed-sized array:

  - management of variable-sized strings is the programmer's responsibility,
  - requiring complex storage management.

- C++ solves these problems by providing a "string" type:

  - maintaining string length versus sentinel character `'\0'`,
  - managing storage for variable-sized string.

Java String	**C char** []	**C++** string
	strcpy, strncpy	=
+, concat	strcat, strncat	+
equal, compareTo	strcmp, strncmp	==, !=, <, <=, >, >=
length	strlen	length
charAt	[]	[]
substring		substr
replace		replace
indexOf, lastIndexOf	strstr	find, rfind
	strcspn	find_first_of, find_last_of
	strspn	find_first_not_of, find_last_not_of
		c_str

- find routines return value string::npos of type string::size_type, if unsuccessful search.

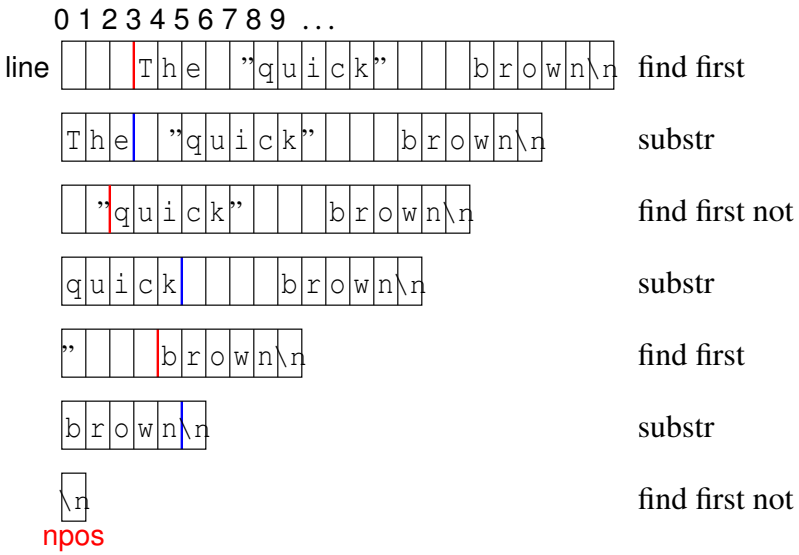
- c_str converts a string to a **char** * pointer ('\0' terminated).

```
string a, b, c;          // declare string variables
cin >> c;                // read white-space delimited sequence of characters
cout << c << endl;       // print string
a = "abc";               // set value, a is "abc"
b = a;                   // copy value, b is "abc"
c = a + b;               // concatenate strings, c is "abcabc"
if ( a <= b )            // compare strings, lexigraphical ordering
string::size_type l = c.length(); // string length, l is 6
char ch = c[4];          // subscript, ch is 'b', zero origin
c[4] = 'x';              // subscript, c is "abcaxc", must be character
string d = c.substr(2,3); // extract starting at position 2 (zero origin) for length 3, d is "cax"
c.replace(2,1,d); // replace starting at position 2 for length 1 and insert d, c is "abcaxaxc"
string::size_type p = c.find( "ax" ); // search for 1st occurrence of string "ax", p is 3
p = c.rfind( "ax" );  // search for last occurrence of string "ax", p is 5
p = c.find_first_of( "aeiou" ); // search for first vowel, p is 0
p = c.find_first_not_of( "aeiou" ); // search for first consonant (not vowel), p is 1
p = c.find_last_of( "aeiou" ); // search for last vowel, p is 5
p = c.find_last_not_of( "aeiou" ); // search for last consonant (not vowel), p is 7
```

- **Note different call syntax c.substr(2, 3) versus substr(c, 2, 3)** (see Section 2.22, p. 99).

- Count and print words in string line containing words composed of lower/upper case letters.

```
unsigned int count = 0;
string line, alpha = "abcdefghijklmnopqrstuvwxyz"
                     "ABCDEFGHIJKLMNOPQRSTUVWXYZ";
... // line is initialized with text
line += "\n";                    // add newline as sentinel
for ( ;; ) {                     // scan words off line
    // find position of 1st alphabetic character
    string::size_type posn = line.find_first_of( alpha );
  if ( posn == string::npos ) break; // any characters left ?
    line = line.substr( posn );  // remove leading whitespace
    // find position of 1st non-alphabetic character
    posn = line.find_first_not_of( alpha );
    // extract word from start of line
    cout << line.substr( 0, posn ) << endl; // print word
    count += 1;                  // count words
    line = line.substr( posn );  // delete word from line
} // for
```



- Contrast C and C++ style strings (note, management of string storage):

```
#include <string.h>       // C string routines
#include <string>         // C++ string routines
using namespace std;
int main() {
    // C++ string
    const string X = "abc", Y = "def", Z = "ghi";
    string S = X + Y + Z;
    // C string
    const char *x = "abc", *y = "def", *z = "ghi";
    char s[strlen(x)+strlen(y)+strlen(z)+1]; // pre-compute size
    strcpy( s, "" );      // initialize to null string
    strcat( strcat( strcat( s, x ), y ), z );
}
```

Why "+1" for dimension of s?

- **Good practice is NOT to iterate through the characters of a string variable!**

2.6 Input/Output

- Input/Output (I/O) is divided into two kinds:

1. **Formatted I/O** transfers data with implicit conversion of internal values to/from human-readable form.
2. **Unformatted I/O** transfers data without conversion, e.g., internal integer and real-floating values.

2.6.1 Formatted I/O

Java	C	C++
import java.io.*; import java.util.Scanner;	**#include** <stdio.h>	**#include** <iostream>
File, Scanner, PrintStream	FILE	ifstream, ofstream
Scanner in = **new** Scanner(**new** File("f"))	in = fopen("f", "r");	ifstream in("f");
PrintStream out = **new** PrintStream("g")	out = fopen("g", "w")	ofstream out("g")
in.close()	close(in)	scope ends, in.close()
out.close()	close(out)	scope ends, out.close()
nextInt()	fscanf(in, "%d", &i)	in >> T
nextFloat()	fscanf(in, "%f", &f)	
nextByte()	fscanf(in, "%c", &c)	
next()	fscanf(in, "%s", &s)	
hasNext()	feof(in)	in.fail()
hasNextT()	fscanf return value	in.fail()
		in.clear()
skip("regexp")	fscanf(in, "%*[regexp]")	in.ignore(n, c)
out.print(String)	fprintf(out, "%d", i)	out << T
	fprintf(out, "%f", f)	
	fprintf(out, "%c", c)	
	fprintf(out, "%s", s)	

- Formatted I/O occurs to/from a **stream file**, and values are conversed based on the type of variables and format codes.
- C++ has three implicit stream files: cin, cout and cerr, which are implicitly declared and opened (Java has in, out and err).
- C has stdin, stdout and stderr, which are implicitly declared and opened.
- **#include** <iostream> imports all necessary declarations to access cin, cout and cerr.
- cin reads input from the keyboard (unless redirected by shell).
- cout/cerr write to the terminal screen (unless redirected by shell).
- ***Error and debugging messages should always be written to* cerr**:
  - normally not redirected by the shell,
  - unbuffered so output appears immediately.
- Stream files other than 3 implicit ones require declaring each file object.

```
#include <fstream>  // required for stream-file declarations
ifstream infile( "myinfile" );      // input file
ofstream outfile( "myoutfile" );    // output file
```

- File types, ifstream/ofstream, indicate whether the file can be read or written.
- File-name type, "myinfile"/"myoutfile", is **char** * (**not string**, see page 53).
- Declaration **open**s an operating-system file making it accessible through the variable name:
  - infile reads from file myinfile
  - outfile writes to file myoutfile

  where both files are located in the directory where the program is run.
- Check for successful opening of a file using the stream member fail, e.g., infile.fail(), which returns **true** if the open failed and **false** otherwise.

```
if ( infile.fail() ) ... // open failed, print message and exit
if ( outfile.fail() ) ... // open failed, print message and exit
```

- C++ I/O library overloads (see Section 2.19, p. 93) the bit-shift operators << and >> to perform I/O.
- C I/O library uses fscanf(outfile,...) and fprintf(infile,...), which have short forms scanf(...) and printf(...) for stdin and stdout.
- Both I/O libraries can cascade multiple I/O operations, i.e., input or output multiple values in a single expression.

2.6.1.1 Formats

- Format of input/output values is controlled via **manipulators** defined in **#include** <iomanip>.

oct (%o)	integral values in octal
dec (%d)	integral values in decimal
hex (%x)	integral values in hexadecimal
left / right (default)	values with padding after / before values
boolalpha / noboolalpha (default)	bool values as false/true instead of 0/1
showbase / noshowbase (default)	values with / without prefix 0 for octal & 0x for hex
showpoint / noshowpoint (default)	print decimal point if no fraction
fixed (default) / scientific	float-point values without / with exponent
setfill('ch')	padding character before/after value (default blank)
setw(W) (%Wd)	NEXT VALUE ONLY in minimum of W columns
setprecision(P) (%.Pf)	fraction of float-point values in maximum of P columns
endl (\n)	flush output buffer and start new line (**output only**)
skipws (default) / noskipws	skip whitespace characters (**input only**)

- **Manipulators are not variables for input/output**, but control I/O formatting for all literals/variables after it, continuing to the next I/O expression for a specific stream file.

- **Except manipulator setw, which only applies to the next value in the I/O expression.**

- endl is not the same as `'\n'`, as `'\n'` does not flush buffered data.

- For input, skipws/noskipws toggle between ignoring whitespace between input tokens and reading whitespace (i.e., tokenize versus raw input).

2.6.1.2 Output

- Java output style converts values to strings, concatenates strings, and prints final long string:

```
System.out.println( i + " " + j );        // build a string and print it
```

- C/C++ output style has a list of formats and values, and output operation generates strings:

```
cout << i << " " << j << endl;        // print each string as formed
```

- No implicit conversion from the basic types to string in C++ (but one can be constructed).

- **While it is possible to use the Java string-concatenation style in C++, it is incorrect style.**

- Use manipulators to generate specific output formats:

```
#include <iostream>      // cin, cout, cerr
#include <iomanip>       // manipulators
using namespace std;
int i = 7; double r = 2.5; char c = 'z'; const char *s = "abc";
cout << "i:" << setw(2) << i
     << " r:" << fixed << setw(7) << setprecision(2) << r
     << " c:" << c << " s:" << s << endl;

#include <stdio.h>
fprintf( stdout, "i:%2d r:%7.2f c:%c s:%s\n", i, r, c, s );

i: 7 r:    2.50 c:z s:abc
```

2.6.1.3 Input

- C++ formatted input has ***implicit*** character conversion for all basic types and is extensible to user-defined types (Java/C use an ***explicit*** Scanner/fscanf).

Java	C	C++

import java.io.*;
import java.util.Scanner;
Scanner in =
  new Scanner(**new** File("f"));
PrintStream out =
  new PrintStream("g");
int i, j;
while (in.hasNext()) {
  i = in.nextInt(); j = in.nextInt();
  out.println("i:"+i+" j:"+j);
}
in.close();
out.close();
	#include <stdio.h>
	FILE *in = fopen("f", "r");
	
	FILE *out = fopen("g", "w");
	
	int i, j;
	for (;;) {
	  fscanf(in, "%d%d", &i, &j);
	  if (feof(in)) **break**;
	  fprintf(out,"i:%d j:%d\n",i,j);
	}
	close(in);
	close(out);
		#include <fstream>
		ifstream in("f");
		
		ofstream out("g");
		
		int i, j;
		for (;;) {
		  in >> i >> j;
		  if (**in.fail()**) **break**;
		  out << "i:" << i
		  <<" j:"<<j<<endl;
		}
		// in/out closed implicitly

- Numeric input values are C/C++ undesignated literals : 3, 3.5e-1, etc., separated by whitespace.
- Character/string input values are characters separated by whitespace.
- Type of operand indicates the kind of value expected in the stream.
  - e.g., an integer operand means an integer value is expected.
- Input starts reading where the last input left off, and scans lines to obtain necessary number of values.
  - Hence, placement of input values on lines of a file is often arbitrary.
- C/C++ must attempt to read ***before*** end-of-file is set and can be tested.
- **End of file** is the detection of the physical end of a file; **there is no end-of-file character**.
- In shell, typing <ctrl>-d (C-d), i.e., press <ctrl> and d keys simultaneously, causes shell to close current input file marking its physical end.
- In C++, end of file can be explicitly detected in two ways:
  - stream member eof returns **true** if the end of file is reached and **false** otherwise.
  - stream member fail returns **true** for invalid values OR no value if end of file is reached, and **false** otherwise.
- Safer to check fail and then check eof.

```
for ( ;; ) {
    cin >> i;
  if ( cin.eof() ) break;     // should use "fail()"
    cout << i << endl;
}
```

- If "abc" is entered (invalid integer value), fail becomes **true** but eof is **false**.
- Generates infinite loop as invalid data is not skipped for subsequent reads.
- Stream is implicitly converted to **bool** in an integer context: if ! fail(), true; otherwise false.

```
while ( cin >> i ) ...      // read and check cin to != 0
```

  - results in side-effects in the expression (changing variable i)
  - does not allows analysis of the input stream (cin) without code duplication

```
while ( cin >> i ) {
    cout << cin.good() << endl;

    ...
}
cout << cin.good() << endl;
```

```
for ( ;; ) {
    cin >> i;
    cout << cin.good() << endl;
  if ( cin.fail() ) break;
    ...
}
```

- After unsuccessful read, call clear() to reset fail() before next read.

```
#include <iostream>
#include <limits>                   // numeric_limits
using namespace std;
int main() {
    int n;
    cout << showbase;               // prefix hex with 0x
    cin >> hex;                     // input hex value
    for ( ;; ) {
        cout << "Enter hexadecimal number: ";
        cin >> n;
        if ( cin.fail() ) {         // problem ?
      if ( cin.eof() ) break;       // eof ?
            cerr << "Invalid hexadecimal number" << endl;
            cin.clear();            // reset stream failure
            cin.ignore( numeric_limits<int>::max(),'\n'); // skip until newline
        } else {
            cout << hex << "hex:" << n << dec << " dec:" << n << endl;
        }
    }
    cout << endl;
}
```

- ignore skips *n* characters, e.g., cin.ignore(5) or until a specified character.
- getline(stream, string, **char**) reads strings with white spaces allowing different delimiting characters (no buffer overflow):

```
getline( cin, c, ' ' ); // read characters until ' ' => cin >> c
getline( cin, c, '@' ); // read characters until '@'
getline( cin, c, '\n' ); // read characters until newline (default)
```

- Read in file-names, which may contain spaces, and process each file:

```
#include <fstream>
using namespace std;
int main() {
    ifstream fileNames( "fileNames" );  // open list of file names
    string fileName;
    for ( ;; ) {                        // process each file
        getline( fileNames, fileName ); // name may contain spaces
      if ( fileNames.fail() ) break;    // handle no terminating newline
        ifstream file( fileName );      // open each file
        // read and process file
    }
}
```

- In C, routine feof returns **true** when eof is reached and fscanf returns EOF.

- Parameters in C are always passed by value (see Section 2.18.1, p. 91), so arguments to fscanf must be preceded with & (except arrays) so they can be changed.

- stringstream allows I/O from a string.

- Tokenize whitespace separated word.

```
#include <sstream>
string tok, line = "  The \"quick\"  brown\n";
stringstream ss;
ss.str( line );                 // initialize input stream
while ( ss >> tok ) {           // read each word
    cout << tok << endl;        // print word
}
ss.clear();                     // reset
ss.str( "17" );                 // initialize input stream
int i;
ss >> i;                        // convert characters to number
cout << i << endl;              // print number
```

- Is this as powerful as tokenizing words composed of lower/upper case letters?

2.7 Expression

	Java	C/C++	priority
postfix	., [], call	::, ., -> [], call, cast	high
prefix (unary)	+, -, !, ~, cast, **new**	+, -, !, ~, &, *, cast, **new**, **delete**, **sizeof**	
binary	*, /, %	*, /, %	
	+, -	+, -	
bit shift	<<, >>, >>>	<<, >>	
relational	<, <=, >, >=, instanceof	<, <=, >, >=	
equality	==, !=	==, !=	
bitwise	& and	&	
	^ exclusive-or	^	
	| or	|	
logical	&& short-circuit	&&	
	||	||	
conditional	?:	?:	
assignment	=, +=, -=, *=, /=, %=	=, +=, -=, *=, /=, %=	
	<<=, >>=, >>>=, &=, ^=, |=	<<=, >>=, &=, ^=, |=	
comma		,	low

- Subexpressions and argument evaluation is unspecified (Java left to right)

```
( i + j ) * ( k + j );      // either + done first
( i = j ) + ( j = i );      // either = done first
g( i ) + f( k ) + h( j );   // g, f, or h called in any order
f( p++, p++, p++ );         // arguments evaluated in any order
```

- **Beware of overflow.**

```
unsigned int a = 4294967295, b = 4294967295, c = 4294967295;
(a + b) / c;      // => 0 as a+b overflows leaving zero
a / c + b / c;    // => 2
```

Perform divides *before* multiplies (if possible) to keep numbers small.

- C++ relational/equality return **false/true**; C return 0/1.

- Referencing (address-of), &, and dereference, *, operators (see Section 2.12.2, p. 76) do not exist in Java because access to storage is restricted.

- General assignment operators only evaluate left-hand side (lhs) once:

```
v[ f(3) ] += 1;              // only calls f once
v[ f(3) ] = v[ f(3) ] + 1;   // calls f twice
```

- Bit-shift operators, << (left), and >> (right) shift bits in integral variables left and right.
  - left shift is multiplying by 2, modulus variable's size;
  - right shift is dividing by 2 if unsigned or positive (like Java >>>);

- undefined if right operand is negative or $\geq$ to length of left operand.

```
int x, y, z;
x = y = z = 1;
cout << (x << 1) << ' ' << (y << 2) << ' ' << (z << 3) << endl;
x = y = z = 16;
cout << (x >> 1) << ' ' << (y >> 2) << ' ' << (z >> 3) << endl;
2 4 8
8 4 2
```

Why are parenthesis necessary?

2.7.1 Conversion

- **Conversion** transforms a value to another type by changing the value to the new type's representation (see Section 2.22.3.2, p. 104).
- Conversions occur implicitly by compiler or explicitly by programmer using **cast** operator or C++ **static_cast** operator.

```
int i;   double d;
d = i;                  // implicit (compiler)
d = (double) i;         // explicit with cast (programmer)
d = static_cast<double>( i ); // C++
```

- Two kinds of conversions:
  - **widening/promotion** conversion, no information is lost:

bool	$\rightarrow$	char	$\rightarrow$	short int	$\rightarrow$	long int	$\rightarrow$	double
true		1		1		1		1.000000000000000

  where **false** $\rightarrow$ 0; **true** $\rightarrow$ 1

  - **narrowing** conversion, information can be lost:

double	$\rightarrow$	long int	$\rightarrow$	short int	$\rightarrow$	char	$\rightarrow$	bool
77777.77777777777		77777		12241		209		true

  where 0 $\rightarrow$ **false**; non-zero $\rightarrow$ **true**

- C/C++ have implicit widening and narrowing conversions (Java only implicit widening).
- **Beware of implicit narrowing conversions:**

```
int i;   double d;
i = d = 3.5;  // d -> 3.5
d = i = 3.5;  // d -> 3.0 truncation
```

- Good practice is to perform narrowing conversions explicitly with cast as documentation.

```
int i;   double d1 = 7.2, d2 = 3.5;
i = (int) d1;           // explicit narrowing conversion
i = (int) d1 / (int) d2; // explicit narrowing conversions for integer division
i = static_cast<int>(d1 / d2); // alternative technique after integer division
```

- C++ supports casting among user defined types (see Section 2.22, p. 99).

2.7.2 Coercion

- **Coercion** reinterprets a value to another type but the result is may not be meaningful in the new type's representation.

- Some narrowing conversions are considered coercions.

  - E.g., when a value is truncated or converting non-zero to **true**, the result is nonsense in the new type's representation.

- Also, having type **char** represent ASCII characters ***and*** integral (byte) values allows:

```
char ch = 'z' - 'a';    // character arithmetic!
```

  which is often unreasonable as it can generate an invalid character.

- But the most common coercion is through pointers (see Section 2.12.2, p. 76):

```
int i, *ip = &i;          // ip is a pointer to an integer
double d, *dp = &d; // dp is a pointer to a double
dp = (double *) ip;  // lie, say dp points at double but really an integer
dp = reinterpret_cast<double *>( ip );
```

  Using explicit cast, programmer has lied to compiler about type of ip.

- Signed/unsigned coercion.

```
unsigned int size;
cin >> size;  // negatives become positives
if ( size < 0 ) cout << "invalid range" << endl;
int arr[size];
```

- size is unsigned because an array cannot have negative size.

- cin does not check for negative values for **unsigned** ⇒ -2 read as 4294967294.

- Use *safe* coercion for checking range of size.

```
if ( (int)size < 0 ) cout << "invalid range" << endl;
```

- Must be consistent with types.

```
for ( int i = 0; i < size; i += 1 ) { }
...
test.cc:12:22: warning: comparison between signed and unsigned integer expressions
```

- **Good practice is to limit narrowing conversions and NEVER lie about a variable's type.**

2.8 Unformatted I/O

- Expensive to convert from internal (computer) to external (human) forms (bits ⇔ characters).
- When data does not have to be seen by a human, use efficient unformatted I/O so no conversions.
- Uses same mechanisms as formatted I/O to connect variable to file (open/close).
- read and write routines directly transfer bytes from/to a file, where each takes a pointer to the data and number of bytes of data.

```
read( char *data, streamsize num );
write( char *data, streamsize num );
```

- Read/write of types other than characters requires a coercion cast (see Section 2.7.2) or C++ **reinterpret_cast**.

```
#include <iostream>
#include <fstream>
using namespace std;
int main() {
    const unsigned int size = 10;
    int arr[size];
    { // read array
        ifstream infile( "myfile" );        // open input file "myfile"
        infile.read( reinterpret_cast<char *>(&arr), size * sizeof( arr[0] ) );  // coercion
    } // close file
    ... // modify array
    { // print array
        ofstream outfile( "myfile" );       // open output file "myfile"
        outfile.write( (char *)&arr, size * sizeof( arr[0] ) );  // coercion
    } // close file
}
```

- Need special command to view unformatted file as printable characters (not shell cat).
- E.g., view internal values as byte sequence for 32-bit **int** values (little endian, no newlines).

```
$ od -t u1 myfile
0000000   0   0   0   0   1   0   0   0   2   0   0   0   3   0   0   0
0000020   4   0   0   0   5   0   0   0   6   0   0   0   7   0   0   0
0000040   8   0   0   0   9   0   0   0
```

- Coercion is unnecessary if buffer type was **void** *.

2.9 Math Operations

- **#include** <cmath> provides overloaded real-float mathematical-routines for types **float**, **double** and **long double**:

operation	routine	operation	routine
$\lvert x \rvert$	abs(x)	$x \bmod y$	fmod(x, y)
$\arccos x$	acos(x)	$\ln x$	log(x)
$\arcsin x$	asin(x)	$\log x$	log10(x)
$\arctan x$	atan(x)	x^y	pow(x, y)
$\lceil x \rceil$	ceil(x)	$\sin x$	sin(x)
$\cos x$	cos(x)	$\sinh x$	sinh(x)
$\cosh x$	cosh(x)	$\sqrt{x}$	sqrt(x)
e^x	exp(x)	$\tan x$	tan(x)
$\lfloor x \rfloor$	floor(x)	$\tanh x$	tanh(x)

and math constants:

```
M_E         2.7182818284590452354   // e
M_LOG2E     1.4426950408889634074   // log_2 e
M_LOG10E    0.43429448190325182765  // log_10 e
M_LN2       0.69314718055994530942  // log_e 2
M_LN10      2.30258509299404568402  // log_e 10
M_PI        3.14159265358979323846  // pi
M_PI_2      1.57079632679489661923  // pi/2
M_PI_4      0.78539816339744830962  // pi/4
M_1_PI      0.31830988618379067154  // 1/pi
M_2_PI      0.63661977236758134308  // 2/pi
M_2_SQRTPI  1.12837916709551257390  // 2/sqrt(pi)
M_SQRT2     1.41421356237309504880  // sqrt(2)
M_SQRT1_2   0.70710678118654752440  // 1/sqrt(2)
```

- Some systems also provide **long double** math constants.

- pow(x,y) (x^y) is computed using logarithms, $10^{y \log x}$ (versus repeated multiplication), when y is non-integral value $\Rightarrow y \geq 0$

  pow(-2.0, 3.0); $-2^3 = -2 \times -2 \times -2 = -8$
  pow(-2.0, 3.1); $-2^{3.1} = 10^{3.1 \times log -2.0} =$ nan (not a number)

  nan is generated because $\log -2$ is undefined.

- Quadratic roots of $ax^2 + bx + c$ are $r = (-b \pm \sqrt{b^2 - 4ac}\,)/2a$

```
#include <iostream>
#include <cmath>
using namespace std;

int main() {
    double a = 3.5, b = 2.1, c = -1.2;
    double dis = sqrt( b * b - 4.0 * a * c ), dem = 2.0 * a;
    cout << "root1: " << ( -b + dis ) / dem << endl;
    cout << "root2: " << ( -b - dis ) / dem << endl;
}
```

2.10 Control Structures

	Java	C/C++
block	{ *intermixed decls/stmts* }	{ *intermixed decls/stmts* }
selection	**if** (*bool-expr1*) *stmt1* **else if** (*bool-expr2*) *stmt2* ... **else** *stmtN*	**if** (*bool-expr1*) *stmt1* **else if** (*bool-expr2*) *stmt2* ... **else** *stmtN*

	switch (*integral-expr*) {
	case c1: *stmts1*; **break**;
	...
	case cN: *stmtsN*; **break**;
	default: *stmts0*;
	}
		switch (*integral-expr*) {
		case c1: *stmts1*; **break**;
		...
		case cN: *stmtsN*; **break**;
		default: *stmts0*;
		}

looping	**while** (*bool-expr*) *stmt*	**while** (*bool-expr*) *stmt*
	do *stmt* **while** (*bool-expr*) ;	**do** *stmt* **while** (*bool-expr*) ;
	for (*init-expr*;*bool-expr*;*incr-expr*) *stmt*	**for** (*init-expr*;*bool-expr*;*incr-expr*) *stmt*
transfer	**break** *[label]*	**break**
	continue *[label]*	**continue**
		goto *label*
	return *[expr]*	**return** *[expr]*
	throw *[expr]*	**throw** *[expr]*
label	*label* : *stmt*	*label* : *stmt*

2.10.1 Block

- Compound statement serves two purposes:
  - bracket several statements into a single statement
  - introduce local declarations.
- **Good practice is use a block versus single statement to allow adding statements.**

no block

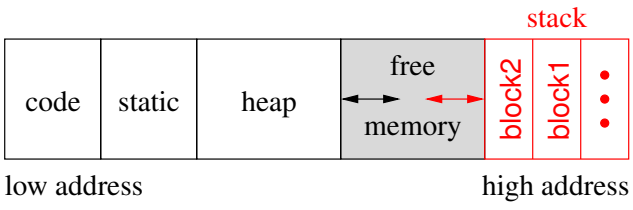
```
if ( x > y )
    x = 0;
```

block

```
if ( x > y ) {
    x = 0;
}
```

- Does the shell have this problem?
- Nested block variables are allocated last-in first-out (LIFO) from the **stack** memory area.

```
{ // block1
    // variables
    { // block2
        // variables
    }
}
```



- Nested block declarations reduces declaration clutter at start of block.

```
int i, j, k; // global          int i;
... // use i, j, k             ... // use i
                                {    int j; // local
                                     ... // use i, j
                                     {    int k; // local
                                          ... // use i, j, k
```

  However, can also make locating declarations more difficult.

- Variable names can be reused in different blocks, i.e., possibly **shadow** (hiding) prior variables.

```
int i = 1; ...          // first i
{    int k = i, i = 2, j = i; ... // k = first i, second i overrides first
     {    int i = 3;... // third i (overrides second)
```

2.10.2 Selection

- C/C++ selection statements are **if** and **switch** (same as Java).
- For nested **if** statements, **else** matches closest **if**, which results in the **dangling else** problem.
- E.g., reward WIDGET salesperson who sold $10,000 or more worth of WIDGETS and dock pay of those who sold less than $5,000.

Dangling Else	Fix Using Null Else	Fix Using Block

`if ( sales < 10000 )`
`  if ( sales < 5000 )`
`  income -= penalty;`
 	
`else // incorrect match!!!`
`  income += bonus;`
	`if ( sales < 10000 )`
	`  if ( sales < 5000 )`
	`  income -= penalty;`
	`  else ; // null statement`
	`else`
	`  income += bonus;`
		`if ( sales < 10000 ) {`
		`  if ( sales < 5000 )`
		`  income -= penalty;`
		
		`} else`
		`  income += bonus;`

- Unnecessary equality for boolean as value is already **true** or **false**.

```
bool b;
if ( b == true )          if ( b )
```

- Redundant **if** statement.

```
if ( a < b ) return true;          return a < b;
else return false;
```

- Conversion causes problems (use -Wall).

```
if ( -0.5 <= x <= 0.5 )...      // looks right and compiles
if ( ( ( -0.5 <= x ) <= 0.5 ) )... // what does this do?
```

- Assign in expressions causes problems because conditional expression is tested for $\neq 0$, i.e., *expr* $\equiv$ *expr* != 0 (use -Wall).

  ```
  if ( x = y )... // what does this do?
  ```

  Possible in Java for one type?

- A **switch** statement selectively executes one of N alternatives based on matching an ***integral*** value with a series of case clauses (see Section 2.11, p. 71).

  ```
  switch ( day ) {                  // integral expression
      // STATEMENTS HERE NOT EXECUTED!!!
    case Mon: case Tue: case Wed: case Thu:  // case value list
      cout << "PROGRAM" << endl;
      break;                        // exit switch
    case Fri:
      wallet += pay;
      /* FALL THROUGH */
    case Sat:
      cout << "PARTY" << endl;
      wallet -= party;
      break;                        // exit switch
    case Sun:
      cout << "REST" << endl;
      break;                        // exit switch
    default:                        // optional
      cerr << "ERROR: bad day" << endl;
      exit( EXIT_FAILURE );         // TERMINATE PROGRAM
  }
  ```

- Only one label for each **case** clause but a list of **case** clauses is allowed.

- Once case label matches, the clauses statements are executed, and control continues to the ***next*** statement. **(comment each fall through)**

- If no case clause is matched and there is a **default** clause, its statements are executed, and control continues to the ***next*** statement.

- Unless there is a **break** statement to prematurely exit the **switch** statement.

- **It is a common error to forget the break in a case clause.**

- Otherwise, the **switch** statement does nothing.

- **case** label does not define a block:

  ```
  switch ( i ) {
    case 3: {           // start new block
      int j = i;        // can now declare new variable
      ...
    }
  }
  ```

2.10.3 Multi-Exit Loop (Review)

- **Multi-exit loop** (or mid-test loop) has one or more exit locations *within* the loop body.
- While-loop has 1 exit located at the top (Ada):

```
while i < 10 {        loop                    -- infinite loop
                        exit when i >= 10; -- loop exit
    ...                   ...          ↑ reverse condition
}                     end loop
```

- Repeat-loop has 1 exit located at the bottom:

```
do {                  loop                    -- infinite loop
    ...                   ...
                        exit when i >= 10; -- loop exit
} while ( i < 10 )    end loop       ↑ reverse condition
```

- Exit should not be restricted to only top and bottom, i.e., can appear in the loop body:

```
loop
    ...
  exit when i >= 10;
    ...
end loop
```

- Loop exit has ability to change kind of loop solely by moving the exit line.
- In general, your coding style should allow changes and insertion of new code with minimal changes to existing code.
- Advantage: eliminate priming (duplicated) code necessary with **while**:

```
read( input, d );              loop
while ! eof( input ) do            read( input, d );
    ...                          exit when eof( input );
    read( input, d );              ...
end while                      end loop
```

- **Good practice is to reduce or eliminate duplicate code.** Why?
- Loop exit is outdented or commented or both (**Eye Candy**) ⇒ easy to find without searching entire loop body.
- Same indentation rule as for the **else** of if-then-else (outdent **else**):

```
if ... then       if ... then
    XXX               XXX
    else          else    // outdent to see else clause
    XXX               XXX
end if            end if
```

- A multi-exit loop can be written in C/C++ in the following ways:

```
for ( ;; ) {                    while ( true ) {                do {
    ...                             ...                         ...
  if ( i >= 10 ) break;           if ( i >= 10 ) break;       if ( i >= 10 ) break;
    ...                             ...                         ...
}                               }                           } while( true );
```

- The **for** version is more general as easily modified to have a loop index.

```
for ( int i = 0; i < 10; i += 1 ) { // add/remove loop index
```

- Eliminate **else** on loop exits:

BAD	GOOD

for (;;) {
  S1
  if (C1) {
  S2
  } else {
  break;
  }
  S3
}
	for (;;) {
	  S1
	  if (! C1) break;
	  S2
	
	  S3
	}

BAD	GOOD

for (;;) {
  S1
  if (C1) {
  break;
  } else {
  S2
  }
  S3
}
	for (;;) {
	  S1
	  if (C1) break;
	
	  S2
	
	  S3
	}

S2 is logically part of loop body ***not*** part of an **if**.

- Easily allow multiple exit conditions:

```
for ( ;; ) {
    S1
  if ( i >= 10 ) break;

    S2
  if ( j >= 10 ) break;

    S3
}
```

```
bool flag1 = false, flag2 = false;
while ( ! flag1 & ! flag2 ) {
    S1
    if ( C1 ) flag1 = true;
    } else {
        S2
        if ( C2 ) flag2 = true;
        } else {
            S3
        }
    }
}
```

- No flag variables necessary with loop exits.
  - **flag variable** is used solely to affect control flow, i.e., does not contain data associated with a computation.
- Case study: examine linear search such that:
  - no invalid subscript for unsuccessful search
  - index points at the location of the key for successful search.
- First approach: use only control-flow constructs **if** and **while**:

```
int i = -1;  bool found = false;
while ( i < size - 1 & ! found ) { // both arguments are evaluated
    i += 1;
    found = key == list[i];
}
if ( found ) { ...      // found
} else { ...            // not found
}
```

Why must the program be written this way?

- Second approach: allow short-circuit control structures.

```
for ( i = 0; i < size && key != list[i]; i += 1 );
    // rewrite: if ( i < size ) if ( key != list[i] )
if ( i < size ) { ...       // found
} else { ...                // not found
}
```

- How does && prevent subscript error?
- Short-circuit && does not exist in all programming languages (Shell test), and requires knowledge of Boolean algebra (false and anything is?).
- Third approach: use multi-exit loop (especially if no && exits).

```
for ( i = 0; ; i += 1 ) { // or  for ( i = 0; i < size; i += 1 )
  if ( i >= size ) break;
  if ( key == list[i] ) break;
}
if ( i < size ) { ...       // found
} else { ...                // not found
}
```

- When loop ends, it is known if the key is found or not found.
- Why is it necessary to re-determine this fact after the loop?
- Can it always be re-determined?
- Extra test after loop can be eliminated by moving it into loop body.

```
for ( i = 0; ; i += 1 ) {
  if ( i >= size ) { ▪ ▪ ▪      // not found
        break;
    } // exit
  if ( key == list[i] ) { ▪ ▪ ▪  // found
        break;
    } // exit
} // for
```

- E.g., an element is looked up in a list of items:

- if it is not in the list, it is added to the end of the list,
- if it exists in the list, increment its associated list counter.

```
for ( int i = 0; ; i += 1 ) {
  if ( i >= size ) {
        list[size].count = 1;  // add element to list
        list[size].data = key;
        size += 1;  // needs check for array overflow
        break;
    } // exit
  if ( key == list[i].data ) {
        list[i].count += 1;   // increment counter
        break;
    } // exit
} // for
```

- None of these approaches is best in all cases; select the approach that best fits the problem.

2.10.4 Static Multi-Level Exit

- **Static multi-level exit** transfers out of multiple control structures where exit points are *known* at compile time.
- Transfer point marked with **label variable** declared by prefixing "identifier**:**" to a statement.

```
L1: i += 1;           // associated with expression
L2: if ( ... ) ...;   // associated with if statement
L3: ;                 // associated with empty statement
```

- Labels have ***routine scope*** (see Section 2.5.2, p. 42), i.e., cannot be overridden in local blocks.

```
int L1;               // identifier L1
L2: ;                 // identifier L2
{
    double L1;        // can override variable identifier
    double L2;        // cannot override label identifier
}
```

- One approach for multi-level exit is labelled exit (**break/continue**) (Java):

```
L1: {
    ... declarations ...
    L2: switch ( ... ) {
        L3: for ( ... ) {
            ... break L1; ... // exit block
            ... break L2; ... // exit switch
            ... break L3; ... // exit loop
        }
        ...
    }
    ...
}
```

- Labelled **break/continue** transfer control out of the control structure with the corresponding label, terminating any block that it passes through.

- C/C++ do not have labelled **break/continue** $\Rightarrow$ simulate with **goto**.

- **goto** *label* allows arbitrary transfer of control ***within*** a routine.

- **goto** transfers control backwards/forwards to labelled statement.

```
L1: ;
...
goto L1;            // transfer backwards, up
goto L2;            // transfer forward, down
...
L2: ;
```

- Transforming labelled **break** to **goto**:

```
{
    ... declarations ...
    switch ( ... ) {
        for ( ... ) {
            ... goto L1; ... // exit block
            ... goto L2; ... // exit switch
            ... goto L3; ... // exit loop
        }
        L3: ; // empty statement
        ...
    }
    L2: ;
    ...
}
L1: ;
```

- Why are labels at the end of control structures not as good as at start?

- Why is it good practice to associate a label with an empty statement?

- Multi-level exits are commonly used with nested loops:

```
int i, j;

for ( i = 0; i < 10; i += 1 ) {

    for ( j = 0; j < 10; j += 1 ) {

        ...
      if ( ... ) goto B2;  // outdent

        ... // rest of loop
  if ( ... ) goto B1;  // outdent

        ... // rest of loop


    } B2: ;

    ... // rest of loop

} B1: ;
```

```
int i, j;
bool flag1 = false;
for ( i = 0; i < 10 && ! flag1; i += 1 ) {
    bool flag2 = false;
    for ( j = 0; j < 10 &&
          ! flag1 && ! flag2; j += 1 ) {
        ...
        if ( ... ) flag2 = true;
        else {
            ... // rest of loop
            if ( ... ) flag1 = true;
            else {
                ... // rest of loop
            } // if
        } // if
    } // for
    if ( ! flag1 ) {
        ... // rest of loop
    } // if
} // for
```

- Indentation matches with control-structure terminated.
- Eliminate all flag variables with multi-level exit!
    - ***Flag variables are the variable equivalent to a goto*** because they can be set/reset/tested at arbitrary locations in a program.
- Simple case (exit 1 level) of multi-level exit is a multi-exit loop.
- Why is it good practice to label all exits?
- Normal and labelled **break** are a **goto** with restrictions:
    - Cannot be used to create a loop (i.e., cause a backward branch); hence, all repeated execution is clearly delineated by loop constructs.
    - Cannot be used to branch ***into*** a control structure.
- **Only use goto to perform static multi-level exit, e.g., simulate labelled break and continue.**
- **return** statements can simulate multi-exit loop and multi-level exit.
- Multi-level exits appear infrequently, but are extremely concise and execution-time efficient.

2.10.5 Non-local Transfer

- Basic and advanced control structures allow virtually any control flow ***within*** a routine.
- **Modularization**: any contiguous code block can be factored into a (helper) routine and called from anywhere in the program (modulo scoping rules).

- Modularization fails when factoring exits, e.g., multi-level exits:

```
B1: for ( i = 0; i < 10; i += 1 ) {
    ...
    B2: for ( j = 0; j < 10; j += 1 ) {
        ...
        if ( ... ) break B1;
        ...
    }
    ...
}
```

```
void rtn( ... ) {
    B2: for ( j = 0; j < 10; j += 1 ) {
        ...
        if ( ... ) break B1;
        ...
    }
}
B1: for ( i = 0; i < 10; i += 1 ) {
    ...
    rtn( ... )
    ...
}
```

- **Modularized version fails to compile because labels only have routine scope** (local vs non-local scope).

- $\Rightarrow$ ***among*** routines, control flow is controlled by call/return mechanism.

    - given A calls B calls C, it is impossible to transfer directly from C back to A, terminating B in the transfer.

- Fundamentally, a routine can have multiple kinds of return.

    - routine call returns normally, i.e., statement after the call
    - exceptional returns, i.e., control transfers to statements **not** after the call

- Generalization of multi-exit loop and multi-level exit.

    - control structures end with or without an exceptional transfer.

- Pattern addresses fact that:

    - algorithms have multiple outcomes
    - separating outcomes makes it easy to read and maintain a program

- Non-local transfer allows multiple forms of returns to any level.

    - Normal return transfers to statement after the call, often implying completion of routine's algorithm.
    - Non-local return transfers to statement **not** after the call, indicating an ancillary completion (but not necessarily an error).

- Multiple returns often simulated with **return code**, i.e., value indicating kind of return.

```
int retcode = f(...);       // routine with multiple returns
if ( retcode > 0 ) {        // analyze return code
    // normal return
} else if ( recode == 0 ) {
    // alternate return 1
} else {        // recode < 0
    // alternate return 2
}
```

- Most library routines use a return code.
  - e.g., printf() returns number of bytes transmitted or negative value for I/O error.
- **Problems**
  - checking return code is optional ⇒ can be delayed or omitted, i.e., passive versus active.
  - does not handle returning multiple levels
  - tight coupling

non-local transfer

```
void f( int i, int j ) {

    for ( ... ) {
        int k;
        ...
    if ( i < j && k > i )
            goto L;
        ...
    }
    ...
}
void g( int i ) {

    for ( ... ) {
        int j;
        ... f( i, j );
        ...
    }


}
void h() {

    for ( ... ) {
        int i;
        ... g( i ); ...

    }
    ... return;
    L: ...
}
```

local transfer/multi-level exit

```
int f( int i, int j ) {

    for ( ... ) {
        int k;
        ...
    if (i < j && k > i) return −1;
        ...
    }
    ...
    return 0;
}
int g( int i ) {

    for ( ... ) {
        int j;
        ... if (f(i,j)== −1 ) return −1
        ...
    }
    ...
    return 0;
}
void h() {

    for ( ... ) {
        int i;
      if ( g( i ) == −1 ) goto L;
        ...
    }
    ... return;
    L: ...
}
```

local transfer/no multi-level exit

```
int f( int i, int j ) {
    bool flag = false;
    for ( ! flag && ... ) {
        int k;
        ...
    if ( i < j && k > i ) flag = true;
        else { ... }
    }
    if ( ! flag ) { ... }
    return flag ? −1 : 0;
}
int g( int i ) {
    bool flag = false;
    for ( ! flag && ... ) {
        int j;
        ... if (f(i,j)== −1 ) flag = true
        else { ... }
    }
    if ( ! flag ) { ... }
    return flag ? −1 : 0;
}
void h() {
    bool flag = false;
    for ( ! flag && ... ) {
        int i;
        ... if ( g( i ) == −1 ) flag = true;
        else { ... }
    }
    if ( ! flag ) { ... return; }
    ...
}
```

2.10.6 Dynamic Multi-Level Exit

- Dynamic multi-level exit allows complex forms of transfers among routines (***reverse*** direction to normal routine calls), called **exception handling**.
- Exception handling is more than error handling.
- An **exceptional event** is an event that is (usually) known to exist but which is *ancillary* to an algorithm.
  - an exceptional event usually occurs with low frequency
  - e.g., division by zero, I/O failure, end of file, pop empty stack
- Do not know statically where **throw** is caught.

```
struct L {};                            // declare exception label
void f(...) { ... throw L(); ... }      // dynamic transfer point
void g(...) { ... f(...) ... }
void h(...) {
    try { ... g(...) ...;               // primary outcome
    } catch( L ) { ... }                // H1, secondary outcome
    try { ... g(...) ...;               // primary outcome
    } catch( L ) { ... }                // H2, secondary outcome
}
```

  throw can transfer to H1 or H2 depending on when or if **throw** is executed.

- A routine *implicitly* can raise exceptions or have exceptions propagate through it.
- A routine can *explicitly* specify if it does or does not have alternate outcomes, i.e., may or may not propagate exceptions.

```
void f(...) noexcept(true) { /* can NOT propagate exceptions */ }
void g(...) noexcept(false) { /* can propagate exceptions */ }
```

  where **noexcept** $\Rightarrow$ **noexcept**(**true**)

- **handler** is inline (nested) routine responsible for handling raised exception.
  - handler **catch**es exception by **match**ing with one or more exception types
  - after catching, a handler executes like a normal subroutine
  - handler can end, reraise the current exception, or raise a new exception
- **reraise** terminates current handling and continues propagation of the caught exception.
  - useful if a handler cannot deal with an exception but needs to propagate same exception to handler further down the stack.
  - provided by a throw statement without an exception type:

```
... throw;    // no exception type
```

    where a raise must be in progress.

- **catch-any** is a mechanism to match any exception.

```
try {
    // may raise any exception
} catch( ... ) { // handle all exceptions
    // recover action (often clean up)
}
```

- Used as a general cleanup when a non-specific exception occurs and reraise to continue exception.

- Contract between thrower and handler environments:

  - thrower does change environment during computation; if computation fails, thrower does not reset environment, and handler recovers from modified state (**basic safety**).
  - thrower does not change environment during computation (copy values); if computation fails, thrower discards copies (rollback), and handler recovers from original state (**strong safety**).

- **Exception parameters** allow passing information from the throw to handler.

- Inform a handler about details of the exception.

- Parameters are defined inside the exception:

```
struct E { int i, j; };
void f(...) { ... E a; a.i = 3; a.j = 5; throw( a ); ... } // argument
void g(...) { ... f(...) ... }
int main() {
    try {
        g(...);
    } catch( E p ) { // parameter
        // use p.i and p.j
    }
}
```

- Exceptions make robust programming easier.

- **Robustness** results because exceptions are active versus passive (return codes), forcing programs to react immediately when an exceptional event occurs.

2.11 Command-line Arguments

- Starting routine main has two overloaded prototypes.

```
int main(); // C: int main( void );
int main( int argc, char * argv[] ); // parameter names may be different
```

- Second form is used to receive command-line arguments from the shell, where the command-line string-tokens are transformed into C/C++ parameters.

- argc is the number of string-tokens on the command line, including the command name.
- Java does not include command name, so number of tokens is one less.
- argv is an array of pointers to C character strings that make up token arguments.

```
% ./a.out -option infile.cc outfile.cc
        0       1        2          3
argc     = 4                // number of command-line tokens
argv[0]  = ./a.out\0        // not included in Java
argv[1]  = -option\0
argv[2]  = infile.cc\0
argv[3]  = outfile.cc\0
argv[4]  = 0                // mark end of variable length list
```

- Because shell only has string variables, a shell argument of "32" does not mean integer 32, and may have to converted.
- Routine main usually begins by checking argc for command-line arguments.

Java	C/C++

class Prog {
  public static void main(String[] **args**) {
  switch (**args.length**) {
  case 0: . . . // *no args*
  break;
  case 1: . . . **args[0]** . . . // *1 arg*
  break;
  case . . . // *others args*
  break;
  default: . . . // *usage message*
  System.exit(1);
  }
  . . .
	int main(**int argc**, **char** *__argv__[]) {
	  switch(**argc**) {
	  case 1: . . . // *no args*
	  break;
	  case 2: . . . **args[1]** . . . // *1 arg*
	  break;
	  case . . . // *others args*
	  break;
	  default: . . . // *usage message*
	  exit(EXIT_FAILURE);
	  }
	  . . .

- Arguments are processed in the range argv[1] through argv[argc - 1].
- Process following arguments from shell command line for command:

```
cmd [ size (> 0) [ code (> 0) [ input-file [ output-file ] ] ] ]
```

  - **new**/**delete** versus malloc/free,
  - stringstream versus atoi, which does not indicate errors,
  - no duplicate code.

```
#include <iostream>
#include <fstream>
#include <sstream>
#include <cstdlib>                              // exit
using namespace std;                            // direct access to std

bool convert( int &val, char *buffer ) {        // convert C string to integer
    stringstream ss( buffer );                  // connect stream and buffer
    string temp;
    ss >> dec >> val;                           // convert integer from buffer
    return ! ss.fail() &&                       // conversion successful ?
        ! ( ss >> temp );                       // characters after conversion all blank ?
} // convert

enum { sizeDefIt = 20, codeDefIt = 5 };         // global defaults

void usage( char *argv[] ) {
    cerr << "Usage: " << argv[0] << " [ size (>= 0 : " << sizeDefIt <<
     ") [ code (>= 0 : " << codeDefIt << ") [ input-file [ output-file ] ] ] ]"
     << endl;
    exit( EXIT_FAILURE );                       // TERMINATE PROGRAM
} // usage

int main( int argc, char *argv[] ) {
    unsigned int size = sizeDefIt, code = codeDefIt; // default value
    istream *infile = &cin;                     // default value
    ostream *outfile = &cout;                   // default value
    switch ( argc ) {
      case 5:
        outfile = new ofstream( argv[4] );
        if ( outfile->fail() ) usage( argv ); // open failed ?
        // FALL THROUGH
      case 4:
        infile = new ifstream( argv[3] );
        if ( infile->fail() ) usage( argv );  // open failed ?
        // FALL THROUGH
      case 3:
        if ( ! convert( (int &)code, argv[2] ) || (int)code < 0 ) usage( argv ) ; // invalid ?
        // FALL THROUGH
      case 2:
        if ( ! convert( (int &)size, argv[1] ) || (int)size < 0 ) usage( argv ); // invalid ?
        // FALL THROUGH
      case 1:                                   // all defaults
        break;
      default:                                  // wrong number of options
        usage( argv );
    }
    // program body
    if ( infile != &cin ) delete infile;        // close file, do not delete cin!
    if ( outfile != &cout ) delete outfile;     // close file, do not delete cout!
} // main
```

- C++ I/O can be toggled to raise exceptions versus return codes.

```
infile->exceptions( ios_base::failbit ); // set cin/cout to use exceptions
outfile->exceptions( ios_base::failbit );
try {
    switch ( argc ) {
      case 5:
        try {
            outfile = new ofstream( argv[4] ); // open outfile file
            outfile->exceptions( ios_base::failbit ); // set exceptions
        } catch( ios_base::failure ) {
            throw ios_base::failure( "could not open output file" );
        } // try
        // FALL THROUGH
      case 4:
        try {
            infile = new ifstream( argv[3] ); // open input file
            infile->exceptions( ios_base::failbit ); // set exceptions
        } catch( ios_base::failure ) {
            throw ios_base::failure( "could not open input file" );
        } // try
        // FALL THROUGH
      case 3:
        if ( ! convert( (int &)code, argv[2] ) || (int)code < 0 ) { // invalid integer ?
            throw ios_base::failure( "invalid code" );
        } // if
      ...
      default:                          // wrong number of options
        throw ios_base::failure( "wrong number of arguments" );
    } // switch
} catch( ios_base::failure err ) {
    cerr << err.what() << endl; // print message in exception
    cerr << "Usage: " << argv[0] << ... // usage message
    exit( EXIT_FAILURE );               // TERMINATE
} // try
...
try {
    for ( ;; ) {                        // loop until end-of-file
        *infile >> ch;                  // raise ios_base::failure at EOF
    } // for
} catch ( ios_base::failure ) {} // end of file
```

2.12 Type Constructor

- **Type constructor** declaration builds more complex type from basic types.

constructor	Java	C/C++
enumeration	**enum** Colour { R, G, B }	**enum** Colour { R, G, B }
pointer		*any-type* *p;
reference	(final) *class-type* r;	*any-type* &r; (C++ only)
array	*any-type* v[ ] = **new** *any-type*[10]; *any-type* m[ ][ ] = **new** *any-type*[10][10];	*any-type* v[10]; *any-type* m[10][10];
structure	**class**	**struct** or **class**

2.12.1 Enumeration

- Can create literals with **const** declaration (see page 44).

```
const short int Mon=0,Tue=1,Wed=2,Thu=3,Fri=4,Sat=5,Sun=6;
short int day = Sat;
days = 42;              // assignment allowed
```

- An **enumeration** is a type defining a set of named literals with only assignment, comparison, and conversion to integer:

```
enum Days {Mon,Tue,Wed,Thu,Fri,Sat,Sun}; // type declaration, implicit numbering
Days day = Sat;                  // variable declaration, initialization
enum {Yes, No} vote = Yes;       // anonymous type and variable declaration
enum Colour {R=0x1,G=0x2,B=0x4} colour; // type/variable declaration, explicit numbering
colour = B;                      // assignment
```

- Identifiers in an enumeration are called **enumerator**s.

- First enumerator is implicitly numbered 0; thereafter, each enumerator is implicitly numbered +1 the previous enumerator.

- Enumerators can be explicitly numbered.

```
enum { A = 3, B, C = A - 5, D = 3, E }; // 3 4 -2 3 4
enum { Red = 'R', Green = 'G', Blue = 'B' }; // 82, 71, 66
```

- Enumeration in C++ denotes a new type; enumeration in C is alias for **int**.

```
day = Sat;          // enumerator must match enumeration
day = 42;           // disallowed C++, allowed C
day = R;            // disallowed C++, allowed C
day = colour;       // disallowed C++, allowed C
```

- C/C++ enumerators must be unique in block.

```
enum CarColour { Red, Green, Blue, Black };
enum PhoneColour { Red, Orange, Yellow, Black };
```

Enumerators Red and Black conflict. (Java enumerators are always qualified).

- In C, "**enum**" must also be specified for a declaration:

```
enum Days day = Sat;    // repeat "enum" on variable declaration
```

- Trick to count enumerators (if no explicit numbering):

```
enum Colour { Red, Green, Yellow, Blue, Black, No_Of_Colours };
```

No_Of_Colours is 5, which is the number of enumerators.

- Iterating over enumerators:

```
for ( Colour c = Red; c < No_Of_Colours; c = (Colour)(c + 1) ) {
    cout << c << endl;
}
```

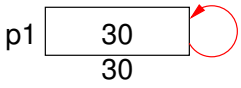
  Why is the cast, (Colour), necessary? Is it a conversion or coercion?

2.12.2 Pointer/Reference

- **pointer/reference** is a memory address.

```
int x, y;
int *p1 = &x, *p2 = &y, *p3 = 0; // or p3 is uninitialized
```

- Used to access the value stored in the memory location at pointer address.
- Can a pointer variable point to itself?



- Pointer to a string literal must be **const**. Why?

```
const char *cs = "abc";
```

- Pointer variable has two forms of assignment:
  - pointer assignment

```
p1 = &x;        // pointer assignment
p2 = p1;        // pointer assignment
```

    no dereferencing to access values.
  - value assignment

```
*p2 = *p1;      // value assignment, y = x
```

    dereferencing to access values.

- Value used more often than pointer.

```
*p2 = ((*p1 + *p2) * (*p2 - *p1)) / (*p1 - *p2);
```

- Less tedious and error prone to write:

```
p2 = ((p1 + p2) * (p2 - p1)) / (p1 - p2);
```

- C++ reference pointer provides extra implicit dereference to access target value:

```
int &r1 = x, &r2 = y;
r2 = ((r1 + r2) * (r2 - r1)) / (r1 - r2);
```

- **Hence, difference between plain and reference pointer is an extra implicit dereference.**
  - I.e., do you want to write the "*", or let the compiler write the "*"?

- However, implicit dereference generates problem for pointer assignment.

```
r2 = r1;    // not pointer assignment
```

- C++ solves the missing pointer assignment by making reference pointer a constant (**const**), like a plain variable.
  - Hence, a reference pointer cannot be assigned after its declaration, **so pointer assignment is impossible**.
  - As a constant, initialization must occur at declaration, but initializing expression has implicit referencing because address is ***always*** required.

```
int &r1 = &x; // error, should not have & before x
```

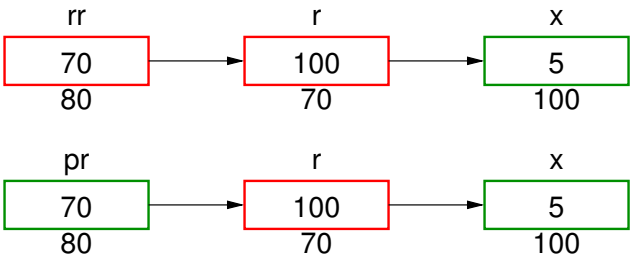
- Java solves this problem by only using reference pointers, only having pointer assignment, and using a different mechanism for value assignment (clone).
- Is there one more solution?
- Since reference means its target's value, address of a reference means its target's address.

```
int &r = x;
&r;              ⇒ &x not &r
```

- Hence, cannot initialize reference to reference or pointer to reference.

```
int & &rr = r;     // reference to reference, rewritten &r
int &*pr = &r;     // pointer to reference
```

Cannot get address of r.

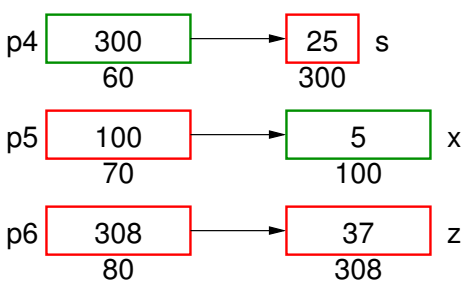


- As well, an array of reference is disallowed (reason unknown).

```
int &ra[3] = { i, i, i };    // array of reference
```

- Type qualifiers (see Section 2.5.3, p. 42) can be used to modify pointer types.

```
const short int s = 25;
const short int *p4 = &s;

int * const p5 = &x;
int &p5 = x;

const long int z = 37;
const long int * const p6 = &z;
const long int &p6 = z;
```



- p4 may point at ***any*** **short int** variable (**const** or non-**const**) and may not change its value.

  Why can p4 point to a non-**const** variable?

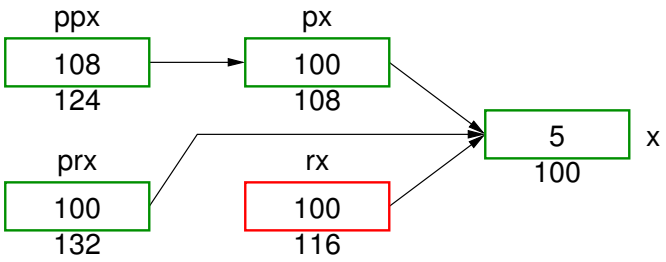
- p5 may only point at the **int** variable x and may change the value of x through the pointer.

  - * **const** and & are constant pointers but * **const** has no implicit dereferencing like &.

- p6 may only point at the **long int** variable z and may not change its value.

- Pointer variable has memory address, so it is possible for a pointer to address another pointer or object containing a pointer.

```
int *px = &x, **ppx = &px,
    &rx = x, *prx = &rx;
```



- **Pointer/reference type-constructor is not distributed across the identifier list.**

```
int* p1, p2;          p1 is a pointer, p2 is an integer     int *p1, *p2;
int& rx = i, ry = i;  rx is a reference, ry is an integer   int &rx =i, &ry = i;
```

2.12.3 Aggregates

- Aggregates are a set of homogeneous/heterogeneous values and a mechanism to access the values in the set.

2.12.3.1 Array

- **Array** is a set of **homogeneous values**.

```
int array[10];          // 10 int values
```

- Array type, **int**, is the type of each set value; array **dimension**, 10, is the maximum number of values in the set.

- An array can be structured to have multiple dimensions.

```
int matrix[10][20];    // 10 rows, 20 columns => 200 int values
char cube[5][6][7];    // 5 rows, 6 columns, 7 deep => 210 char values
```

  Common dimension mistake: matrix[**10, 20**]; means matrix[20] because 10, 20 is a comma expression not a dimension list.

- Number of dimensions is fixed at compile time, but dimension size may be:

- static (compile time),
- block dynamic (static in block),
- or dynamic (change at any time, see vector Section 2.33.1.1, p. 152).

- C++ only supports a compile-time dimension value; C/g++ allows a runtime expression.

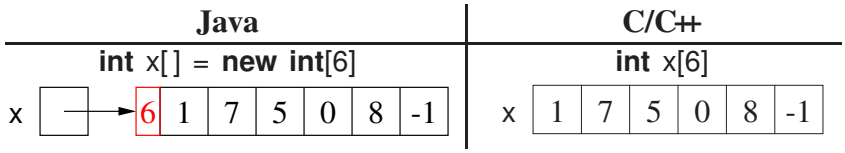
```
int r, c;
cin >> r >> c;          // input dimensions
int array[r];           // dynamic dimension, C/g++ only
int matrix[r][c];       // dynamic dimension, C/g++ only
```

- A dimension is subscripted from 0 to dimension-1.

```
array[5] = 3;           // location at column 5
i = matrix[0][2] + 1;   // value at row 0, column 2
c = cube[2][0][3];      // value at row 2, column 0, depth 3
```

Common subscript mistake: matrix[**3, 4**] means matrix[4], 4th row of matrix.

- **Do not use pointer arithmetic to subscript arrays: error prone and no more efficient.**
- C/C++ array is a contiguous set of elements not a reference to the element set as in Java.



- **C/C++ do not store dimension information in the array!**
- Hence, cannot query dimension sizes, ***no subscript checking***, and no array assignment.
- Declaration of a pointer to an array is complex in C/C++ (see also page 83).
- Because no array-size information, the dimension value for an array pointer is unspecified.

```
int i, arr[10];
int *parr = arr;        // think parr[], pointer to array of N ints
```

- However, no dimension information results in the following ambiguity:

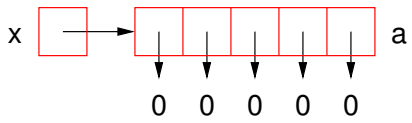
```
int *pvar = &i;         // think pvar[] and i[1]
int *parr = arr;        // think parr[]
```

- ***Variables* pvar *and* parr *have same type but one points at a variable and other an array!***
- Programmer decides if variable or array by not using or using subscripting.

```
*pvar                   // variable
*parr                   // variable, arr[0]
parr[0], parr[3]        // array, many
pvar[3]                 // array, but wrong
```

- ASIDE: Practise reading a complex declaration:
  - parenthesize type qualifiers based on operator priority (see Section 2.7, p. 54),
  - read inside parenthesis outwards,
  - start with variable name,
  - end with type name on the left.

```
const long int * const a[5] = {0,0,0,0,0};
const long int * const (&x)[5] = a;
const long int ( * const ( (&x)[5] ) ) = a;
```



x : reference to an array of 5 constant pointers to constant long integers

2.12.3.2 Structure

- **Structure** is a set of **heterogeneous values**, including (nested) structures.

Java	C/C++

class Foo {
  int i = 3;
  ... // *more fields*
}
	struct Foo {
	  int i = 3; // *C++11*
	  ... // *more members*
	}; // *semi-colon terminated*

- Structure fields are called **member**s subdivided into data and routines[1].
- All members of a structure are accessible (public) by default.
- Structure can be defined and instances declared in a single statement.

```
struct Complex { double re, im; } s; // definition and declaration
```

- In C, "**struct**" must also be specified for a declaration:

```
struct Complex a, b;    // repeat "struct" on variable declaration
```

- Pointers to structures have a problem:
  - C/C++ are unique in having the priority of selection operator "." higher than dereference operator "*".
  - Hence, *p.f executes as *(p.f), which is incorrect most of the time. Why?
  - To get the correct effect, use parenthesis: (*p).f.

```
(*sp1).name.first[0] = 'a';
(*sp1).age = 34;
(*sp1).marks[5] = 95;
```

- Alternatively, use (special) operator -> for pointers to structures:

[1] Java subdivides members into fields (data) and methods (routines).

- performs dereference and selection in correct order, i.e., p->f rewritten as (*p).f.

```
sp1->name.first[0] = 'a';
sp1->age = 34;
sp1->marks[5] = 95;
```

- for reference pointers, -> is unnecessary because r.f means (*r).f, so r.f makes more sense than (&r)->f.

- **Makes switching from a pointer to reference difficult** (. $\leftrightarrow$ ->).
- Structures ***must*** be compared member by member.
  - comparing bits (e.g., memcmp) fails as alignment padding leaves undefined values between members.
- **Recursive types** (lists, trees) are defined using a self-referential pointer in a structure:

```
struct Student {
    ...                 // data members
    Student *link;      // pointer to another Student
}
```

- A **bit field** allows direct access to individual bits of memory:

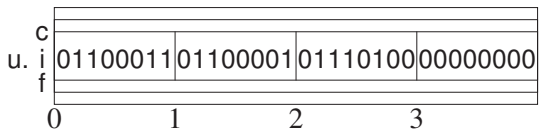
```
struct S {
    int i : 3;      // 3 bits
    int j : 7;      // 7 bits
    int k : 6;      // 6 bits
} s;
s.i = 2;        // 010
s.j = 5;        // 0000101
s.k = 9;        // 001001
```

- A bit field must be an integral type.
- Unfortunately allocation of bit-fields is implementation defined $\Rightarrow$ not portable (maybe left to right or right to left!).
- Hence, the bit-fields in variable s above may need to be reversed.
- While it is unfortunate C/C++ bit-fields lack portability, they are the highest-level mechanism to manipulate bit-specific information.

2.12.3.3 Union

- **Union** is a set of **heterogeneous values**, including (nested) structures, **where all members overlay the same storage**.

```
union U {
    char c[4];
    int i;
    float f;
} u;
```



- Used to access internal representation or save storage by reusing it for different purposes at different times.

```
u.c[0] = 'c'; u.c[1] = 'a'; u.c[2] = 't'; u.c[3] = '\0';
cout << u.c << " " << u.i << " " << u.f << " " << bitset<32>(u.i) << endl;
```

produces:

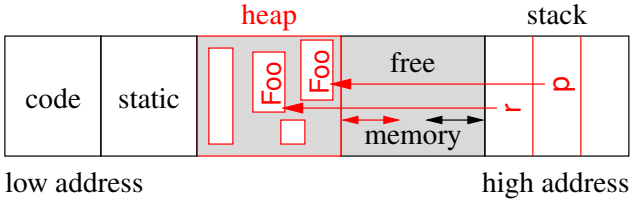
```
cat 7627107 1.06879e-38 00000000011101000110000101100011
```

- **Reusing storage is dangerous and can usually be accomplished via other techniques.**

2.13 Dynamic Storage Management

- Java/Scheme are **managed language**s because the language controls all memory management, e.g., **garbage collection** to free dynamically allocated storage.
- C/C++ are **unmanaged language**s because the programmer is involved in memory management, e.g., no garbage collection so dynamic storage must be explicitly freed.
- C++ provides dynamic storage-management operations **new**/**delete** and C provides malloc/free.
- ***Do not mix the two forms in a C++ program.***

Java	C	C++
class Foo { **char** c1, c2; } Foo r = **new** Foo(); r.c1 = 'X'; *// r garbage collected*	**struct** Foo { **char** c1, c2; }; **struct** Foo *p = (**struct** Foo *) *// coerce* malloc(*// allocate* **sizeof**(**struct** Foo) *// size*); p->c1 = 'X'; free(p); *// explicit free*	**struct** Foo { **char** c1, c2; }; Foo *p = **new** Foo(); p->c1 = 'X'; **delete** p; *// explicit free* Foo &r = *new Foo(); r.c1 = 'X'; **delete** &r; *// explicit free*



Unallocated memory in heap is also free.

- Allocation has 3 steps:
  1. determine size of allocation,
  2. allocate heap storage of correct size/alignment,
  3. coerce undefined storage to correct type.
- C++ operator **new** performs all 3 steps implicitly; each step is explicit in C.

- Coercion cast is required in C++ for malloc but optional in C.
  - C has implicit cast from **void** * (pointer to anything) to specific pointer (***dangerous!***).
  - Good practise in C is to use a cast so compiler can verify type compatibility on assignment.
- Parenthesis after the type name in the **new** operation are optional.
- For reference r, why is there a "*" before **new** and an "&" in the **delete**?
- Storage for dynamic allocation comes from a memory area called the **heap**.
- If heap is full (i.e., no more storage available), malloc returns 0, and **new** raises an exception.
- Before storage can be used, it ***must*** be allocated.

```
Foo *p;              // forget to initialize pointer with "new"
p->c1 = 'R';         // places 'R' at some random location in memory
```

  Called an uninitialized variable.
- After storage is no longer needed it ***must*** be explicitly deleted.

```
Foo *p = new Foo;
p = new Foo;         // forgot to free previous storage
```

  Called a **memory leak**.
- After storage is deleted, it ***must*** not be used:

```
delete p;
p->c1 = 'R';         // result of dereference is undefined
```

  Called a **dangling pointer**.
- Unlike Java, C/C++ allow ***all*** types to be dynamically allocated not just object types, e.g., **new int**.
- As well, C/C++ allow ***all*** types to be allocated on the stack, i.e., local variables of a block.
- Declaration of a pointer to an array is complex in C/C++ (see also page 79).
- Because no array-size information, no dimension for an array pointer.

```
int *parr = new int[10];      // think parr[], pointer to array of 10 ints
```

- No dimension information results in the following ambiguity:

```
int *pvar = new int;          // basic "new"
int *parr = new int[10];      // parr[], array "new"
```

- Variables pvar and parr have the same type but one is allocated with the basic **new** and the other with the array **new**.

- Special syntax ***must*** be used to call the corresponding deletion operation for a variable or an array (any dimensions):

```
delete pvar;      // basic delete : single element
delete [] parr;   // array delete : multiple elements (any dimension)
```

- If basic **delete** is used on an array, only the first element is freed (memory leak).
- If array **delete** is used on a variable, storage after the variable is also freed (often failure).
- **Never do this:**

```
delete [] parr, pvar; // => (delete [] parr), pvar;
```

  which is an incorrect use of a comma expression; pvar is not deleted.

- **Dynamic allocation should be used only when a variable's storage must outlive the block in which it is allocated** (see also page 103).

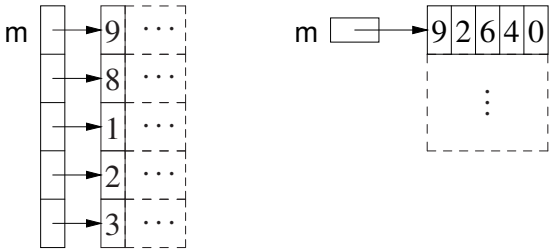
```
Type *rtn(...) {
    Type *tp = new Type;     // MUST USE HEAP
    ...                      // initialize/compute using tp
    return tp;               // storage outlives block
}                            // tp deleted later
```

- Stack allocation eliminates explicit storage-management (simpler) and is more efficient than heap allocation — **use it whenever possible.**

```
{ // good, use stack
    int size;
    cin >> size;
    int arr[size]
    ...

} // size, arr implicitly deallocated
```

```
{ // bad, unnecessary dynamic allocation
    int *sizep = new int;
    cin >> *sizep;
    int *arr = new int[*sizep];
    ...
    delete [] arr;
    delete sizep;
}
```

- Declaration of a pointer to a matrix is complex in C/C++, e.g., **int** *m[5] could mean:



- Left: array of 5 pointers to an array of unknown number of integers.
- Right: pointer to matrix of unknown number of rows with 5 columns of integers.

- Dimension is higher priority so declaration is interpreted as **int** (*(m[5])) (left).
- Right example cannot be generalized to a dynamically-sized matrix.

```
int R = 5, C = 4;                // 5 rows, 4 columns
int (*m)[C] = new int[R][C];     // disallowed, C must be literal, e.g, 4
```

  Compiler must know the stride (number of columns) to compute row.

- Left example can be generalized to a dynamically-sized matrix.

```
int main() {
    int R = 5, C = 4;            // or cin >> R >> C;
    int *m[R];                   // R rows
    for ( int r = 0; r < R; r += 1 ) {
        m[r] = new int[C];       // C columns per row
        for ( int c = 0; c < C; c += 1 ) {
            m[r][c] = r + c;     // initialize matrix
        }
    }

    for ( int r = 0; r < R; r += 1 ) { // print matrix
        for ( int c = 0; c < C; c += 1 ) {
            cout << m[r][c] << ", ";
        }
        cout << endl;
    }
    for ( int r = 0; r < R; r += 1 ) {
        delete [] m[r];          // delete each row
    }
}                                // implicitly deallocate array "m"
```

2.14 Type Nesting

- Type nesting is used to organize and control visibility of type names (see Section 2.30, p. 130):

```
enum Colour { R, G, B, Y, C, M };
struct Person {
    enum Colour { R, G, B };     // nested type
    struct Face {                // nested type
        Colour Eyes, Hair;       // type defined outside (1 level)
    };
    ::Colour shirt;              // type defined outside (top level)
    Colour pants;                // type defined same level
    Face looks[10];              // type defined same level
};
Colour c = R;                    // type/enum defined same level
Person::Colour pc = Person::R;   // type/enum defined inside
Person::Face pretty;             // type defined inside
```

- Variables/types at top nesting-level are accessible with unqualified "::".
- References to types inside the nested type do not require qualification (like declarations in nested blocks, see Section 2.5.2, p. 42).

- References to types nested inside another type are qualified with "::".

- Without nested types need:

```
enum Colour { R, G, B, Y, C, M };
enum Colour2 { R2, G2, B2 };    // prevent name clashes
struct Face {
    Colour2 Eyes, Hair;
};
struct Person {
    Colour shirt;
    Colour2 pants;
    Face looks[10];
};
Colour c = R;
Colour2 pc = R2;
Face pretty;
```

- ***Do not pollute lexical scopes with unnecessary names (name clashes).***

- C nested types moved to scope of top-level type.

```
struct Foo {
    struct Bar {      // moved outside
        int i;
    };
    struct Bar bars[10];
};
struct Foo foo;
struct Bar bar;       // no qualification
```

2.15 Type Equivalence

- In Java/C/C++, types are equivalent if they have the same name, called **name equivalence**.

```
struct T1 {                    struct T2 {    // identical structure
    int i, j, k;                   int i, j, k;
    double x, y, z;                double x, y, z;
};                             };
T1 t1, t11 = t1;   // allowed, t1, t11 have compatible types
T2 t2 = t1;        // disallowed, t2, t1 have incompatible types
T2 t2 = (T2)t1;    // disallowed, no conversion from type T1 to T2
```

- Types T1 and T2 are **structurally equivalent**, but have different names so they are incompatible, i.e., initialization of variable t2 is disallowed.

- An **alias** is a different name for same type, so alias types are equivalent.

- C/C++ provides **typedef** to create an alias for an existing type:

```
typedef short int shrint1;    // shrint1 => short int
typedef shrint1 shrint2;      // shrint2 => short int
typedef short int shrint3;    // shrint3 => short int
shrint1 s1;       // implicitly rewritten as: short int s1
shrint2 s2;       // implicitly rewritten as: short int s2
shrint3 s3;       // implicitly rewritten as: short int s3
```

- All combinations of assignments are allowed among s1, s2 and s3, because they have the same type name "**short int**".
- Use to prevent repetition of large type names:

```
void f( map<string, pair<vector<string>, map<string,string> > > p1,
        map<string, pair<vector<string>, map<string,string> > > p2 );

typedef map<string, pair<vector<string>, map<string,string> > > StudentInfo;
void f( StudentInfo p1, StudentInfo p2 );
```

- Java provides no mechanism to alias types.

2.16 Namespace

- C++ **namespace** is used to organize programs and libraries composed of multiple types and declarations ***to deal with naming conflicts***.
- E.g., namespace std contains all the I/O declarations and container types.
- Names in a namespace form a declaration region, like the scope of block.
- C++ allows multiple namespaces to be defined in a file, as well as among files (unlike Java packages).
- Types and declarations do not have to be added consecutively.

Java source files	C++ source file

package Foo; // *file*
public class X ... // *export one type*
// *local types / declarations*
	namespace Foo {
	  // *types / declarations*
	}
	namespace Foo {
	  // *more types / declarations*
	}
	namespace Bar {
	  // *types / declarations*
	}

package Foo; // *file* **public** enum Y ... // *export one type* // *local types / declarations*	
package Bar; // *file* **public class** Z ... // *export one type* // *local types / declarations*	

- Contents of a namespace are accessed using full-qualified names:

Java	C++
Foo.T t = **new** Foo.T();	Foo::T *t = **new** Foo::T();

- Or by importing individual items or importing all of the namespace content.

Java	C++
import Foo.T; **import** Foo.*;	**using** Foo::T; *// declaration* **using namespace** Foo; *// directive*

- **using** declaration ***unconditionally*** introduces an alias (like **typedef**, see Section 2.15, p. 86) into the current scope for specified entity in namespace.
  - May appear in any scope.
  - If name already exists in current scope, **using** fails.

```
namespace Foo { int i = 0; }
int i = 1;
using Foo::i; // i exists in scope, conflict failure
```

- **using** directive ***conditionally*** introduces aliases to current scope for all entities in namespace.
  - If name already exists in current scope, alias is ignored; if name already exists from **using** directive in current scope, **using** fails.

```
namespace Foo { int i = 0; }
namespace Bar { int i = 1; }
{
    int i = 2;
    using namespace Foo; // i exists in scope, alias ignored
}
{
    using namespace Foo;
    using namespace Bar; // i exists from using directive
    i = 0;   // conflict failure, ambiguous reference to 'i'
}
```

  - May appear in namespace and block scope, but not structure scope.

```
namespace Foo {             // start namespace
    enum Colour { R, G, B };
    int i = 3;
}
namespace Foo {             // add more
    struct C { int i; };
    int j = 4;
    namespace Bar {         // start nested namespace
        typedef short int shrint;
        char j = 'a';
        int C();
    }
}
```

```
int j = 0;                      // global
int main() {
    int j = 3;                  // local
    using namespace Foo;        // conditional import: Colour, i, C, Bar (not j)
    Colour c;                   // Foo::Colour
    cout << i << endl;          // Foo::i
    C x;                        // Foo::C
    cout << ::j << endl;        // global
    cout << j << endl;          // local
    cout << Foo::j << " " << Bar::j << endl;  // qualification
    using namespace Bar;        // conditional import: shrint, C() (not j)
    shrint s = 4;               // Bar::shrint
    using Foo::j;               // disallowed : unconditional import
    C();                        // disallowed : ambiguous "struct C" or "int C()"
}
```

- Never put a **using** declaration/directive in a header file (.h) (pollute local namespace) or before **#include** (can affect names in header file).

2.17 Type-Constructor Literal

enumeration	enumerators
pointer	**nullptr** indicates a null pointer
array	**int** v[3] = { 1, 2, 3 };
structure	**struct** { **double** r, i; } c = { 3.0, 2.1 };

- C uses 0/NULL and C++ uses **nullptr** to initialize pointers (Java null).
- Array and structure initialization can occur as part of a declaration.

```
int m[2][3] = { {93, 67, 72}, {77, 81, 86} };  // multidimensional array
struct { int i; struct { double r, i; } s; } d = { 1, { 3.0, 2.1 } };  // nested structure
```

- A multidimensional array or nested structure is created using nested braces.
- Initialization values are placed into a variable starting at beginning of the array or structure.
- Not all the members/elements must be initialized.
    - If not explicitly initialized, a variable is **default initialized** (see also Section 2.22.3, p. 102), which means zero-filled for basic types.

```
int b[10];          // uninitialized
int b[10] = {};     // zero initialized
```

- Cast allows construction of structure and array literals in statements:

```
void rtn( const int m[2][3] );
struct Complex { double r, i; } c;
rtn( (const int [2][3]){ {93, 67, 72}, {77, 81, 86} } );  // C99/g++ only
c = (Complex){ 2.1, 3.4 };  // C99/g++ only
c = { 2.1, 3.4 };  // C++11 only, infer type from left-hand side
```

- A cast indicates the type and structure of the literal.
- String literals can be used as a shorthand array initializer value:

```
char s[6] = "abcde";  rewritten as  char s[6] = { 'a', 'b', 'c', 'd', 'e', '\0' };
```

- It is possible to leave out the first dimension, and its value is inferred from the number of values in that dimension:

```
char s[] = "abcde";   // 1st dimension inferred as 6 (Why 6?)
int  v[] = { 0, 1, 2, 3, 4 } // 1st dimension inferred as 5
int  m[][3] = { {93, 67, 72}, {77, 81, 86} }; // 1st dimension inferred as 2
```

2.18 Routine

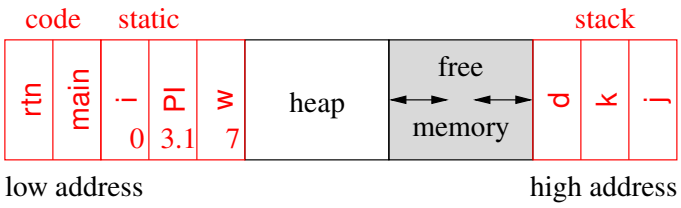
- Routine with no parameters has parameter **void** in C and empty parameter list in C++:

```
... rtn( void ) { ... }      // C: no parameters
... rtn() { ... }            // C++: no parameters
```

  - In C, empty parameters mean no information about the number or types of the parameters is supplied.

- If a routine is qualified with **inline**, the routine is expanded (maybe) at the call site, i.e., unmodularize, to increase speed at the cost of storage (no call).
- Routine cannot be nested in another routine (possible in gcc).
- Java requires all routines to be defined in a **class** (see Section 2.22.1, p. 101).
- Each routine call creates a new block on the stack containing its parameters and local variables, and returning removes the block.
- Variables declared outside of routines are defined in implicit **static block**.

```
int i;                    // static block, global
const double PI = 3.14159;
void rtn( double d )      // code block
{   static const int w = 7; // create static block
}                         // remove stack block
int main()                // code block
{   int j;                // create stack block
    {   int k;            // create stack block
        rtn( 3.0 );
    }                     // remove stack block
}                         // remove stack block
```



Where is the program executing?

- Static block is a separate memory area from stack and heap areas and ***is default zero filled***.
- Otherwise variables are **uninitialized**.
- **Good practise is to ONLY use static block for**
  - constants (anywhere)

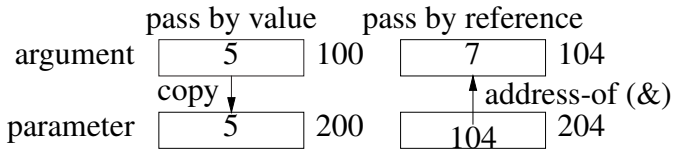
```
bool check( int key ) {
    static const int vals[] = { 12, 15, 34, 67, 88 }; // allocated ONCE
    ...
```

  - global variables accessed throughout program

```
int callCounter = 0;
int rtn1( int key ) { callCounter += 1; ... }
int rtn2( int key ) { callCounter += 1; ... }
...
```

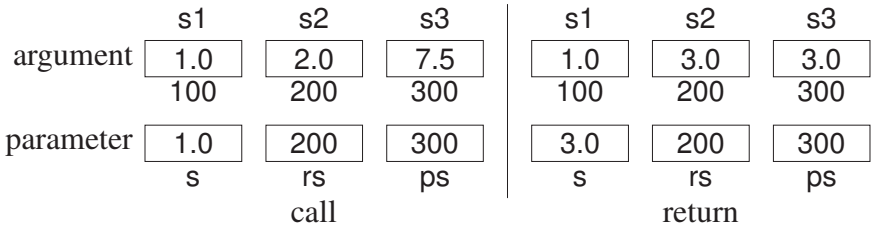
2.18.1 Argument/Parameter Passing

- Modularization without communication is useless; information needs to flow from call to routine and back to call.
- Communication is achieved by passing arguments from a call to parameters in a routine and back to arguments or return values.
  - **value parameter**: parameter is initialized by copying argument (input only).
  - **reference parameter**: parameter is a reference to the argument and is initialized to the argument's address (input/output).



- Java/C, parameter passing is by value, i.e., basic types and object references are copied.
- C++, parameter passing is by value or reference depending on the type of the parameter.
- For value parameters, each argument-expression result is copied into the corresponding parameter in the routine's block on the stack, ***which may involve an implicit conversion***.
- For reference parameters, each argument-expression result is referenced (address of) and this address is pushed on the stack as the corresponding reference parameter.

```
struct S { double d; };
void r1( S s, S &rs, S * const ps ) {
      s.d = rs.d = ps->d = 3.0;
}
int main() {
      S s1 = {1.0}, s2 = {2.0}, s3 = {7.5};
      r1( s1, s2, &s3 );
      // s1.d = 1.0, s2.d = 3.0, s3.d = 3.0
}
```



- C-style pointer-parameter simulates the reference parameter, but requires & on argument and use of –> with parameter.

- Value passing is most efficient for small values or for large values accessed frequently because the values are accessed directly (not through pointer).

- Reference passing is most efficient for large values accessed less frequently because the values are not duplicated in the routine but accessed via pointers.

- Problem: cannot pass a literal or temporary variable to reference parameter! Why?

```
void r2( int &i, Complex &c, int v[] );
r2( i + j, (Complex){ 1.0, 7.0 }, (int [3]){ 3, 2, 7 } );  // disallowed!
```

- Use type qualifiers to create read-only reference parameters so the corresponding argument is guaranteed not to change:

```
void r2( const int &i, const Complex &c, const int v[] ) {
      i = 3;    // disallowed, read only!
      c.re = 3.0;
      v[0] = 3;
}
r2( i + j, (Complex){ 1.0, 7.0 }, (int [3]){ 3, 2, 7 } );  // allowed!
```

- Provides efficiency of pass by reference for large variables, security of pass by value as argument cannot change, and allows literals and temporary variables as arguments.

- **Good practise uses reference parameters rather than pointer.**

- C++ parameter can have a **default value**, which is passed as the argument value if no argument is specified at the call site.

```
void r3( int i, double g, char c = '*', double h = 3.5 ) { ... }
r3( 1, 2.0, 'b', 9.3 );     // maximum arguments
r3( 1, 2.0, 'b' );          // h defaults to 3.5
r3( 1, 2.0 );               // c defaults to '*', h defaults to 3.5
```

- In a parameter list, once a parameter has a default value, all parameters to the right must have default values.
- In a call, once an argument is omitted for a parameter with a default value, no more arguments can be specified to the right of it.

2.18.2 Array Parameter

- Array copy is unsupported (see Section 2.12, p. 74) so arrays cannot be passed by value.
- Instead, array argument is a pointer to the array that is copied into the corresponding array parameter (pass by value).
- A formal parameter array declaration can specify the first dimension with a dimension value, [10] (which is ignored), an empty dimension list, [ ], or a pointer, *:

```
double sum( double v[5] );    double sum( double v[ ] );    double sum( double *v );
double sum( double *m[5] );   double sum( double *m[ ] );   double sum( double **m );
```

- **Good practice uses middle form as it clearly indicates variable can be subscripted.**
- An actual declaration cannot use [ ]; it must use *:

```
double sum( double v[ ] ) {  // formal declaration
    double *cv;              // actual declaration, think cv[]
    cv = v;                  // address assignment
```

- Routine to add up the elements of an arbitrary-sized array or matrix:

```
double sum( int cols, double v[ ] ) {
    double total = 0.0;
    for ( int c = 0; c < cols; c += 1 )
        total += v[c];
    return total;
}
```

```
double sum( int rows, int cols, double *m[ ] ) {
    double total = 0.0;
    for ( int r = 0; r < rows; r += 1 )
        for ( int c = 0; c < cols; c += 1 )
            total += m[r][c];
    return total;
}
```

2.19 Overloading

- **Overloading** is when a name has multiple meanings in the same context.
- Most languages have overloading, e.g., most built-in operators are overloaded on both integral and real-floating operands, i.e., + operator is different for 1 + 2 than for 1.0 + 2.0.
- Overloading requires disambiguating among identical names based on some criteria.

- Normal criterion is type information.
- In general, overloading is done on operations not variables:

```
int i;      // disallowed : variable overloading
double i;
void r( int ) { ... }  // allowed : routine overloading
void r( double ) { ... }
```

- ***Power of overloading occurs when programmer changes a variable's type: operations on the variable are implicitly reselected for new type.***
- E.g., after changing a variable's type from **int** to **double**, all operations implicitly change from integral to real-floating.
- Number and ***unique*** parameter types ***but not the return type*** are used to select among a name's different meanings:

```
int r( int i, int j ) { ... }  // overload name r three different ways
int r( double x, double y ) { ... }
int r( int k ) { ... }
r( 1, 2 );          // invoke 1st r based on integer arguments
r( 1.0, 2.0 );      // invoke 2nd r based on double arguments
r( 3 );             // invoke 3rd r based on number of arguments
```

- Implicit conversions between arguments and parameters can cause ambiguities:

```
r( 1, 2.0 ); // ambiguous, convert either argument to integer or double
```

  - Use explicit cast to disambiguate:

```
r( 1, (int)2.0 )        // 1st r
r( (double)1, 2.0 )     // 2nd r
```

- Subtle cases:

```
int i;  unsigned int ui;  long int li;
void r( int i ) { ... }  // overload name r three different ways
void r( unsigned int i ) { ... }
void r( long int i ) { ... }
r( i );         // int
r( ui );        // unsigned int
r( li );        // long int
```

- Parameter types with qualifiers other than **short/long/signed/unsigned** are ambiguous at definition:

```
int r( int i ) {...}          // rewritten: int r( signed int )
int r( signed int i ) {...} // disallowed : redefinition of first r
int r( const int i ) {...} // disallowed : redefinition of first r
int r( volatile int i ) {...} // disallowed : redefinition of first r
```

- Reference parameter types with same base type are ambiguous at call:

```
int r( int i ) {...}          // cannot be called
int r( int &i ) {...}         // cannot be called
int r( const int &i ) {...} // cannot be called
int i = 3;
const int j = 3;
r( i );     // disallowed : ambiguous
r( j );     // disallowed : ambiguous
```

  Cannot cast argument to select r(**int** i), r(**int** &i) or r(**const int** &i).

- Overload/conversion confusion: I/O operator << is overloaded with **char** * to print a C string and **void** * to print pointers.

```
char c;  int i;
cout << &c << " " << &i << endl;  // print address of variables
```

  type of* &c *is* char *, so printed as C string, which is undefined; type of &i is **int** *, which is converted to **void** *, so printed as an address.

- Fix using coercion.

```
cout << (void *)&c << " " << &i << endl;  // print address of variables
```

- Overlap between overloading and default arguments for parameters with same type:

Overloading	Default Argument
int r(**int** i, **int** j) { ... } **int** r(**int** i) { **int** j = 2; ... } r(3); // 2nd r	**int** r(**int** i, **int** j = 2) { ... } r(3); // default argument of 2

  If the overloaded routine bodies are essentially the same, use a default argument, otherwise use overloaded routines.

2.20 Declaration Before Use, Routines

- **Declaration Before Use** (DBU) means a variable declaration must appear before its usage in a block.

- In theory, a compiler could handle some DBU situations:

```
{
    cout << i << endl;    // prints 4 ?
    int i = 4;            // declaration after usage
}
```

  but ambiguous cases make this impractical:

```
int i = 3;
{
    cout << i << endl;    // which i?
    int i = 4;
    cout << i << endl;
}
```

- C always requires DBU.
- C++ requires DBU in a block and among types but not within a type.
- Java only requires DBU in a block, but not for declarations in or among classes.
- DBU has a fundamental problem specifying **mutually recursive** references:

```
void f() {    // f calls g
    g();      // g is not defined and being used
}
void g() {    // g calls f
    f();      // f is defined and can be used
}
```

Caution: these calls cause infinite recursion as there is no base case.

- Cannot type-check the call to g in f to ensure matching number and type of arguments and the return value is used correctly.
- Interchanging the two routines does not solve the problem.
- A **forward declaration** introduces a routine's type (called a **prototype/signature**) before its actual declaration:

```
int f( int i, double ); // routine prototype: parameter names optional
...                     // and no routine body
int f( int i, double d ) { // type repeated and checked with prototype
    ...
}
```

- Prototype parameter names are optional (good documentation).
- Actual routine declaration repeats routine type, which must match prototype.
- Routine prototypes also useful for organizing routines in a source file.

```
int main();             // forward declarations, any order
void g( int i );
void f( int i );
int main() {            // actual declarations, any order
    f( 5 );
    g( 4 );
}
void g( int i ) { ... }
void f( int i ) { ... }
```

- E.g., allowing main routine to appear first, and for separate compilation (see Section 2.23, p. 115).

2.21 Preprocessor

- Preprocessor is a text editor that modifies the program text ***before*** compilation.
- **Program you see is not what the compiler sees!**
- -E run only the preprocessor step and write preprocessor output to standard out.

```
$ g++ -E *.cc ...
... much output from the preprocessor
```

2.21.1 File Inclusion

- File inclusion copies text from a file into a C/C++ program.
- **#include** statement specifies the file to be included.
- C convention uses suffix ".h" for include files containing C declarations.
- C++ convention drops suffix ".h" for its standard libraries and has special file names for equivalent C files, e.g., cstdio versus stdio.h.

```
#include <stdio.h>      // C style
#include <cstdio>       // C++ style
#include "user.h"
```

- -v show each compilation step and its details:

```
$ g++ -v *.cc *.o ...
... much output from each compilation step
```

E.g., include directories where cpp looks for system includes.

```
#include <...> search starts here:
 /usr/include/c++/4.6
 /usr/include/c++/4.6/x86_64-linux-gnu/.
 /usr/include/c++/4.6/backward
 /usr/lib/gcc/x86_64-linux-gnu/4.6/include
 /usr/local/include
 /usr/lib/gcc/x86_64-linux-gnu/4.6/include-fixed
 /usr/include/x86_64-linux-gnu
 /usr/include
```

- -I***directory*** search directory for include files;
  - files within the directory can now be referenced by relative name using **#include** <file-name>.

2.21.2 Variables/Substitution

- **#define** statement declares a preprocessor string variable or macro, and its value/body is the text after the name up to the end of line.

- Preprocessor can transform the syntax of C/C++ program (**discouraged**).

```
#define Malloc( T ) (T *)malloc( sizeof( T ) )
int *ip = Malloc( int );

#define For( v, N ) for ( unsigned int v = 0; i < N; i += 1 )
For( i, 10 ) { ... }

#define Exit( c ) if ( c ) break
for ( ;; ) {
    ...
  Exit( a > b );
    ...
}
```

- Replace **#define** constants with **enum** (see Section 2.12.1, p. 75) for integral types; otherwise use **const** declarations (see Section 2.5.3, p. 42) (Java **final**).

```
enum { arraySize = 100 };          #define arraySize 100
enum { PageSize = 4 * 1024 };      #define PageSize (4 * 1024)
const double PI = 3.14159;         #define PI 3.14159
int array[arraySize], pageSize = PageSize;
double x = PI;
```

- Use **inline** routines in C/C++ rather that **#define** macros (see page 149).

```
inline int MAX( int a, int b ) { return a > b ? a : b; }
```

- -D define and optionally initialize preprocessor variables from the compilation command:

```
% g++ -DDEBUG="2" -DASSN ... source-files
```

  Initialization value is text after =.

- Same as following **#define**s in a program without changing the program:

```
#define DEBUG 2
#define ASSN 1
```

- **Redefinition warning if both -D and #define for the same variable.**

- Predefined preprocessor-variables exist identifying hardware and software environment, e.g., mcpu is kind of CPU.

2.21.3 Conditional Inclusion

- Preprocessor has an **if** statement, which may be nested, to conditionally add/remove code from a program.

- Conditional **if** uses the same relational and logical operators as C/C++, but operands can only be integer or character values.

```
#define DEBUG 0   // declare and initialize preprocessor variable
...
#if DEBUG == 1    // level 1 debugging
#   include "debug1.h"
...
#elif DEBUG == 2  // level 2 debugging
#   include "debug2.h"
...
#else             // non-debugging code
...
#endif
```

- By changing value of preprocessor variable DEBUG, different parts of the program are included for compilation.

- To exclude code (comment-out), use 0 conditional as 0 implies false.

```
#if 0
...                          // code commented out
#endif
```

- Like Shell, possible to check if a preprocessor variable is defined or not defined using **#ifdef** or **#ifndef**:

```
#ifndef __MYDEFS_H__     // if not defined
#define __MYDEFS_H__ 1 //   make it so
...
#endif
```

- Used in an **#include** file to ensure its contents are only expanded once (see Section 2.23, p. 115).

- Note difference between checking if a preprocessor variable is defined and checking the value of the variable.

- The former capability does not exist in most programming languages, i.e., checking if a variable is declared before trying to use it.

2.22 Object

- ***Object***-oriented programming was developed in the mid-1960s by Dahl and Nygaard and first implemented in SIMULA67.

- Object programming is based on structures, used for organizing logically related data (see Section 2.12.3, p. 78):

unorganized	organized

int people_age[30];
bool people_sex[30];
char people_name[30][50];
	struct Person {
	  int age;
	  bool sex;
	  char name[50];
	} people[30];

- Both approaches create an identical amount of information.
- Difference is solely in the information organization (and memory layout).
- Computer does not care as the information and its manipulation is largely the same.
- Structuring is an administrative tool for programmer understanding and convenience.
- Objects extend organizational capabilities of a structure by allowing routine members.
- Java has either a basic type or an object, i.e., all routines are embedded in a **struct/class** (see Section 2.18, p. 90).

structure form	object form

struct Complex {
  double re, im;
};
double abs(**const** Complex &This) {
  return sqrt(This.re * This.re +
  This.im * This.im);
}
Complex x; *// structure*
d = abs(x); *// call abs*
	struct Complex {
	  double re, im;
	  double abs() **const** {
	  return sqrt(re * re +
	  im * im);
	  }
	};
	Complex x; *// object*
	d = x.abs(); *// call abs*

- ***An object provides both data and the operations necessary to manipulate that data in one self-contained package.***
- Both approaches use routines as an abstraction mechanism to create an interface to the information in the structure.
- Interface separates usage from implementation at the interface boundary, allowing an object's implementation to change without affecting usage.
- E.g., if programmers do not access Complex's implementation, it can change from Cartesian to polar coordinates and maintain same interface.
- ***Developing good interfaces for objects is important.***
  - e.g., mathematical types (like complex) should use value semantics (functional style) versus reference to prevent changing temporary values.

2.22.1 Object Member

- A routine member in a structure is constant, and cannot be assigned (e.g., **const** member).
- What is the scope of a routine member?
- Structure creates a scope, and therefore, a routine member can access the structure members, e.g., abs member can refer to members re and im.
- Structure scope is implemented via a T * **const** this parameter, implicitly passed to each routine member (like left example).

```
double abs() const {
    return sqrt( this->re * this->re + this->im * this->im );
}
```

Since implicit parameter "this" is a const pointer, it should be a reference.

- Except for the syntactic differences, the two forms are identical.
- ***The use of implicit parameter this, e.g., this->f, is seldom necessary.***
- Member routine declared **const** is read-only, i.e., cannot change member variables.
- Member routines are accessed like other members, using member selection, x.abs, and called with the same form, x.abs().
- No parameter needed because of implicit structure scoping via **this** parameter.
- ***Nesting of object types only allows static not dynamic scoping*** (see Section 2.14, p. 85) (Java allows dynamic scoping).

```
struct Foo {
    int g;
    int r() { ... }
    struct Bar {                    // nested object type
        int s() { g = 3; r(); }     // disallowed, dynamic reference
    };                              //   to specific object
} x, y, z;
```

References in s to members g and r in Foo disallowed because must know the **this** for specific Foo object, i.e., which x, y or z.

- Extend type Complex by inserting an arithmetic addition operation:

```
struct Complex {
    ...
    Complex add( Complex c ) {
        return { re + c.re, im + c.im };
    }
};
```

- To sum x and y, write x.add(y), which looks different from normal addition, x + y.

- Because addition is a binary operation, add needs a parameter as well as the implicit context in which it executes.
- Like outside a type, C++ allows overloading members in a type.

2.22.2 Operator Member

- It is possible to use operator symbols for routine names:

```
struct Complex {
    ...
    Complex operator+( Complex c ) { // rename add member
        return { re + c.re, im + c.im };
    }
};
```

- Addition routine is called +, and x and y can be added by x.**operator**+(y) or y.**operator**+(x), which looks slightly better.
- Fortunately, C++ implicitly rewrites x + y as x.**operator**+(y).

```
Complex x = { 3.0, 5.2 }, y = { -9.1, 7.4 };
cout << "x:" << x.re << "+" << x.im << "i" << endl;
cout << "y:" << y.re << "+" << y.im << "i" << endl;
Complex sum = x + y;   // rewritten as  x.operator+( y )
cout << "sum:" << sum.re << "+" << sum.im << "i" << endl;
```

2.22.3 Constructor

- A **constructor** member ***implicitly*** performs initialization after object allocation to ensure the object is valid before use.
  - implicit constructor

```
struct Complex {
    double re = 0.0, im = 0.0; // C++11
    ... // other members
};
```

  - explicit constructor

```
struct Complex {
    double re, im;
    Complex() { re = im = 0.0; } // default constructor
    ... // other members
};
```

- Explicit constructor can perform arbitrary execution (e.g., ifs, loops, calls).

```
Complex x;
Complex *y = new Complex;
```

implicitly rewritten as

```
Complex x;  x.Complex();
Complex *y = new Complex;
             y->Complex();
```

- Constructor name ***must*** match the structure name.
- Constructor without parameters is the **default constructor**, for initializing a new object.
- Both implicit and explicit constructors allowed ⇒ double initialization.
- Unlike Java, C++ does not initialize all object members to default values.
- Constructor normally initializes members ***not initialized via other constructors***, i.e., some members are objects with their own constructors.
- A constructor may have parameters but no return type (not even **void**).
- Never put parentheses to invoke default constructor for declaration.

```
Complex x(); // routine prototype, no parameters returning a complex
```

- Overloading and default parameters allowed.

```
struct Complex {
    double re, im;
    Complex( double r = 0.0, double i = 0.0 ) { re = r; im = i; }
    ...
};
```

- Call constructor using parameters or field initialization.

```
Complex x, y( 3.2 ), z( 3.2, 4.5 );
Complex x, y = { 3.2 }, z = { 3.2, 4.5 }; // C++11, rewrites to first
Complex x, y{ 3.2 }, z{ 3.2, 4.5 }; // C++11, rewrites to first
```

- Declarations implicitly rewritten as:

```
Complex x;  x.Complex( 0.0, 0.0 );
Complex y;  y.Complex( 3.2, 0.0 );
Complex z;  z.Complex( 3.2, 4.5 );
```

(see declaring stream files page 48)

- For dynamic allocation, constructor arguments after type:

```
Complex *x = new Complex; // x->Complex();
Complex *y = new Complex( 3.2, 4.5 ); // y->Complex( 3.2, 4.5 );
Complex *z = new Complex{ 3.2 }; // z->Complex( 3.2 );
```

- Constructor may force dynamic allocation when initializating an array of objects.

```
Complex ac[10];          // complex array default initialized to 0.0+0.0i
for ( int i = 0; i < 10; i += 1 ) {
    ac[i] = { i, i + 2.0 }; // assignment, constructor already called
}

Complex *ap[10];         // array of complex pointers
for ( int i = 0; i < 10; i += 1 ) {
    ap[i] = new Complex( i, i + 2.0 );  // initialization, constructor called
}
...
for ( int i = 0; i < 10; i += 1 ) {
    delete ap[i];
}
```

See Section 2.22.5, p. 108 for difference between initialization and assignment.

- ***If only non-default constructors are specified, i.e., ones with parameters, an object cannot be declared without an initialization value:***

```
struct Foo {
    // no default constructor
    Foo( int i ) { ... }
};
Foo x;  // disallowed!!!
Foo x( 1 );  // allowed
```

- Constructor can be called explicitly in another constructor (see Section 2.22.6, p. 113 for constructor initialization syntax):

Java	C++

`class Foo {`
`  int i, j;`
`  Foo( int p ) { i = p; j = 1; }`
`  Foo() { this( 2 ); }`
`}`
	`struct Foo {`
	`  int i, j;`
	`  Foo( int p ) { i = p; j = 1; }`
	`  Foo() : Foo( 2 ) {} // C++11`
	`};`

2.22.3.1 Literal

- Constructors can be used to create object literals (see Section 2.17, p. 89):

```
Complex x, y, z;
x = { 3.2 };                  // Complex( 3.2 )
y = x + { 3.2, 4.5 };         // disallowed
y = x + (Complex){ 3.2, 4.5 }; // g++
z = x + Complex( 2 ) + y;     // 2 widened to 2.0, Complex( 2.0 )
```

2.22.3.2 Conversion

- Constructors are implicitly used for conversions (see Section 2.7.1, p. 55):

```
int i;
double d;
Complex x, y;
x = 3.2;                    x = Complex( 3.2 );
y = x + 1.3;    implicitly  y = x.operator+( Complex(1.3) );
y = x + i;      rewritten as y = x.operator+( Complex( (double)i );
y = x + d;                  y = x.operator+( Complex( d ) );
```

- Allows built-in literals and types to interact with user-defined types.
- Note, two implicit conversions are performed on variable i in x + i: **int** to **double** and then **double** to Complex.
- Can require only explicit conversions with qualifier **explicit** on constructor:

```
struct Complex {
    // turn off implicit conversion
    explicit Complex( double r = 0.0, double i = 0.0 ) { re = r; im = i; }
    ...
};
```

- Problem: implicit conversion disallowed for commutative binary operators.
- 1.3 + x, disallowed because it is rewritten as (1.3).**operator**+(x), but member **double operator**+(Complex) does not exist in built-in type **double**.
- Solution, move operator + out of the object type and made into a routine, which can also be called in infix form (see Section 2.19, p. 93):

```
struct Complex { ... }; // same as before, except operator + removed
Complex operator+( Complex a, Complex b ) {  // 2 parameters
    return Complex( a.re + b.re, a.im + b.im );
}
x + y;                  operator+(x, y)
1.3 + x;    implicitly  operator+(Complex(1.3), x)
x + 1.3;    rewritten as operator+(x, Complex(1.3))
```

- Compiler checks for an appropriate operator in object type or an appropriate routine (it is ambiguous to have both).
  - For operator in object type, applies conversions to only the second operand.
  - For operator routine, applies conversions to ***both*** operands.
- In general, commutative binary operators should be written as routines to allow implicit conversion on both operands.
- I/O operators << and >> often overloaded for user types:

```
ostream &operator<<( ostream &os, Complex c ) {
    return os << c.re << "+" << c.im << "i";
}
cout << "x:" << x;  // rewritten as: operator<<( cout.operator<<("x:"), x )
```

- Standard C++ convention for I/O operators to take and return a stream reference to allow cascading stream operations.
- << operator in object cout is used to first print string value, then overloaded routine << to print the complex variable x.
- Why write as a routine versus a member?

2.22.4 Destructor

- A **destructor** (finalize in Java) member ***implicitly*** performs uninitialization at object deallocation:

Java	C++

class Foo {
  ...
  finalize() { ... }
}
	struct Foo {
	  ...
	  ~Foo() { ... } // *destructor*
	};

- Object type has one destructor; its name is the character "~" followed by the type name (like a constructor).
- Destructor has no parameters nor return type (not even **void**):
- ***Destructor is only necessary if an object is non-contiguous, i.e., composed of multiple pieces within its environment***, e.g., files, dynamically allocated storage, etc.
- A **contiguous object**, like a Complex object, requires no destructor as it is self-contained (see Section 2.24, p. 119 for a version of Complex requiring a destructor).
- Destructor is invoked *before* an object is deallocated, either implicitly at the end of a block or explicitly by a **delete**:

```
{                                          { // allocate local storage
    Foo x, y( x );                             Foo x, y;  x.Foo(); y.Foo( x );
    Foo *z = new Foo;                          Foo *z = new Foo; z->Foo();
    ...                       implicitly       ...
    delete z;                 rewritten as     z->~Foo();  delete z;
    ...                                        ...
                                               y.~Foo();  x.~Foo();
}                                          } // deallocate local storage
```

- For local variables in a block, destructors ***must be*** called in reverse order to constructors because of dependencies, e.g., y depends on x.

- Destructor is more common in C++ than finalize in Java as no garbage collection in C++.
- ***If an object type performs dynamic storage allocation, it is non-contiguous and needs a destructor to free the storage:***

```
struct Foo {
    int *i;    // think int i[]
    Foo( int size ) { i = new int[size]; } // dynamic allocation
    ~Foo() { delete [] i; }     // must deallocate storage
    ...
};
```

- Except if the dynamic object is transfered to another object for deallocation.
- C++ destructor is invoked at a deterministic time (block termination or **delete**), ensuring prompt cleanup of the execution environment.
- Java finalize is invoked at a non-deterministic time during garbage collection or *not at all*, so cleanup of the execution environment is unknown.
- Destructor is implicitly **noexcept**, unless inheriting from class with **noexcept**(**false**) destructor.
- Hence, a destructor ***can*** raise an exception.

```
struct E {};
struct C {
    ~C() noexcept(false) { throw E(); }
};
try {           // outer try
    C x;        // raise on deallocation
    try {       // inner try
        C y; // raise on deallocation
    } catch( E ) {...}  // inner handler
} catch( E ) {...}  // outer handler
```

```
y's destructor
    | throw E
inner try
    | y
outer try
    | x
```

```
x's destructor
    | throw E
outer try
    | x
```

  - y's destructor called at end of inner **try** block, it raises an exception E, which unwinds destructor and **try**, and handled at inner **catch**
  - x's destructor called at end of outer **try** block, it raises an exception E, which unwinds destructor and **try**, and handled at outer **catch**
- A destructor ***cannot*** raise an exception during propagation.

```
struct F {};
try {
    C x;                // raise on deallocation
    ... throw F(); ...
} catch( E ) {...}
  catch( F ) {...}
```

1. raise of F causes unwind of inner **try** block

2. x's destructor called during unwind, it raises an exception E, which terminates program

- Reason:

1. Cannot start second exception without handler to deal with first exception, i.e., cannot drop exception and start another.
2. Cannot postpone first exception because second exception may remove its handlers during its stack unwinding.

- Allocation/deallocation (RAII – Resource Acquisition Is Initialization)

```
struct Alloc {
    Complex *ptr;
    int size;
  public:
    Alloc( Complex *ptr, int size ) : ptr( ptr ), size( size ) {
        for ( int i = 0; i < size; i += 1 ) {
            ptr[i] = new Complex( i, i + 2.0 );
        }
    }
    ~Alloc() {
        for ( int i = 0; i < size; i += 1 ) {
            delete ptr[i];
        }
    }
};
void f(...) {
    Complex *ap[10], *bp[20]; // array of complex pointers
    Alloc alloca( ap, 10 ), allocb( bp, 20 ); // allocate complex elements
    ... // normal, local and non-local return
} // automatically delete objs by destructor
```

- Storage released for normal, local transfer (**break/return**), and exception.

- Special pointer type with RAII deallocation for each array element.

```
#include <memory>
{
    unique_ptr<Complex> uac[10], ubc[20]; // C++11
    for ( int i = 0; i < 10; i += 1 ) {
        uac[i].reset( new Complex( i, i + 2.0 ) ); // C++11
        uab[i].reset( new Complex( i, i + 2.0 ) ); // C++11
        // uac[i] = make_unique<Complex>( i, i + 2.0 ); // initialization, C++14
    }
} // automatically delete objs for each uac by destructor
```

2.22.5 Copy Constructor / Assignment

- There are multiple contexts where an object is copied.

1. declaration initialization (ObjType obj2 = obj1)
2. pass by value (argument to parameter)

3. return by value (routine to temporary at call site)
4. assignment (obj2 = obj1)

- Cases 1 to 3 involve a newly allocated object with undefined values.
- Case 4 involves an existing object that may contain previously computed values.
- C++ differentiates between these situations: initialization and assignment.
- Constructor with a **const** reference parameter of class type is used for initialization (declarations/parameters/return), called **copy constructor**:

```
Complex( const Complex &c ) { ... }
```

- Declaration initialization:

```
Complex y = x;   implicitly rewritten as   Complex y; y.Complex( x );
```

  - "=" is misleading as copy constructor is called not assignment operator.
  - value on the right-hand side of "=" is argument to copy constructor.

- Parameter/return initialization:

```
Complex rtn( Complex a, Complex b ) { ... return a; }
Complex x, y;
x = rtn( x, y );          // creates temporary before assignment
```

  - parameter is initialized by corresponding argument using its copy constructor:

```
Complex rtn( Complex a, Complex b ) {
    a.Complex( arg1 ); b.Complex( arg2 ); // initialize parameters
    ...                                   //    with arguments
```

  - temporaries *may* be created for arguments and return value, initialized using copy constructor:

```
x = rtn(...);    implicitly rewritten as    Complex t1( x ), t2( y );
                                            Complex tr( rtn( t1, t2 ) );
                                            x.operator=( tr );
                                                    or
                                            x.operator=( rtn( x, y ) );
```

- Assignment routine is used for assignment:

```
Complex &operator=( const Complex &rhs ) { ... }
```

  - usually most efficient to use reference for parameter and return type.
  - value on the right-hand side of "=" is argument to assignment operator.

```
x = y;   implicitly rewritten as   x.operator=( y );
```

- If a copy constructor or assignment operator is not defined, an implicit one is generated that does a **memberwise copy** of each subobject.

- basic type, **bitwise copy**
- class type, use class's copy constructor or assignment operator
- array, each element is copied appropriate to the element type

```
struct B {
    B() { cout << "B() "; }
    B( const B &c ) { cout << "B(&) "; }
    B &operator=( const B &rhs ) { cout << "B= "; }
};
struct D {                          // implicit copy and assignment
    int i;                          // basic type, bitwise
    B b;                            // object type, memberwise
    B a[5];                         // array, element/memberwise
};
int main() {
    cout << "b  a" << endl;
    D i;       cout << endl;        // B' s default constructor
    D d = i; cout << endl;          // D' s default copy-constructor
    d = i;     cout << endl;        // D' s default assignment
}
```

outputs the following:

```
b    a                              // member variables
B()  B() B() B() B() B()            // D i
B(&) B(&) B(&) B(&) B(&) B(&)       // D d = i
B=   B= B= B= B= B=                 // d = i
```

- Often only a bitwise copy as subobjects have no copy constructor or assignment operator.
- If D defines a copy-constructor/assignment, it overrides one in subobject.

```
struct D {
    ... // same declarations
    D() { cout << "D() "; }
    D( const D &c ) : i( c.i ), b( c.b ), a( c.a ) { cout << "D(&) "; }
    D &operator=( const D &rhs ) {
        i = rhs.i;  b = rhs.b;
        for ( int i = 0; i < 5; i += 1 ) a[i] = rhs.a[i]; // array copy
        cout << "D= ";
        return *this;
    }
};
```

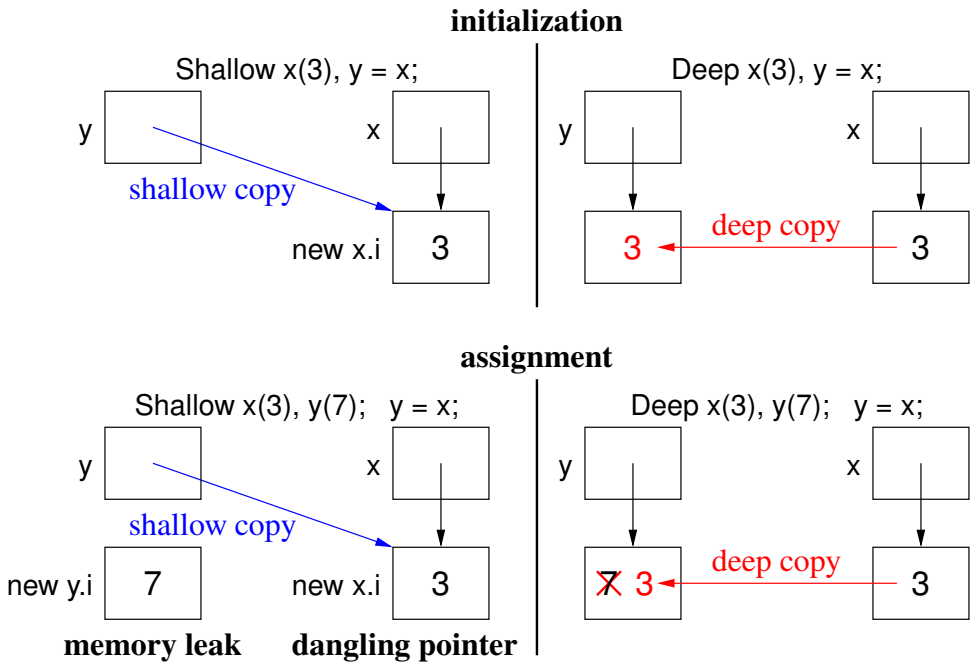
outputs the following:

```
b   a                               // member variables
B() B() B() B() B() B() D()         // D i
B(&) B(&) B(&) B(&) B(&) B(&) D(&)  // D d = i
B= B= B= B= B= B= D=                // d = i
```

Must copy each subobject to get same output.

- When an object type has pointers, it is often necessary to do a deep copy, i.e, copy the contents of the pointed-to storage rather than the pointers (see also Section 2.24, p. 119).

```
struct Shallow {
    int *i;
    Shallow( int v ) { i = new int; *i = v; }
    ~Shallow() { delete i; }
};
struct Deep {
    int *i;
    Deep( int v ) { i = new int;  *i = v; }
    ~Deep() { delete i; }
    Deep( Deep &d ) { i = new int; *i = *d.i; }     // copy value
    Deep &operator=( const Deep &rhs ) {
        *i = *rhs.i;  return *this;                 // copy value
    }
};
```



- For shallow copy:
  - memory leak occurs on the assignment
  - dangling pointer occurs after x or y is deallocated; when the other object is deallocated, it reuses this pointer to delete the same storage.
- Deep copy does not change the pointers only the values associated within the pointers.
- Duplicate code, correctness, and performance.

```
struct Varray {                          // variable-sized array
    unsigned int size;
    int *a;
    Varray( unsigned int s ) { size = s; a = new int[size]; }
    ~Varray() { delete [] a; }
    Varray( const Varray &rhs ) {        // copy constructor
        a = new int[rhs.size];           // create storage
        size = rhs.size;                 // set new size
        for ( unsigned int i = 0; i < size; i += 1 )
            a[i] = rhs.a[i];             // copy values
    }
    Varray &operator=( const Varray &rhs ) { // deep copy
        delete [] a;                     // delete old storage
        a = new int[rhs.size];           // create new storage
        size = rhs.size;                 // set new size
        for ( unsigned int i = 0; i < size; i += 1 )
            a[i] = rhs.a[i];             // copy values
        return *this;
    }
};
Varray x( 5 ), y( x );
x = y;   // works
y = y;   // could fail
```

- Remove duplicate code with **copy and swap** idiom.

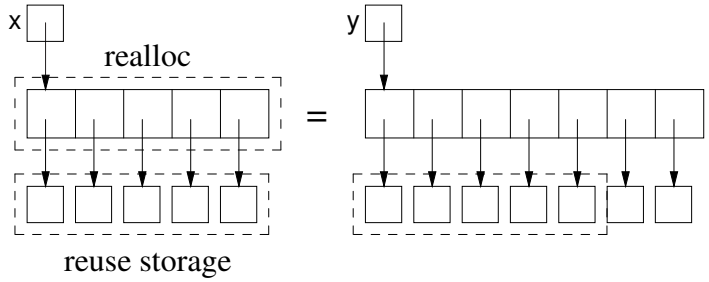
```
Varray &operator=( const Varray &rhs ) {
    Varray temp( rhs );          // calls copy constructor
    swap( size, temp.size );     // polymorphic swap members
    swap( a, temp.a );
    // temp's destructor frees a's storage because of swap
    return *this;
} // temp deallocated
```

- Beware **self-assignment** for pointer variables, y = y.
  - Which pointer problem is this, and why can it go undetected?
  - How can this problem be fixed for both approaches?
- Performance is a problem because of excessive dynamic allocation.
  - realloc is often twice as fast as delete/new/copy.

```
void copy( const Varray &rhs ) {     // remove duplicate code
    size = rhs.size;                 // set new size
    for ( unsigned int i = 0; i < size; i += 1 )
        a[i] = rhs.a[i];             // copy values
}
Varray( const Varray &rhs ) {        // copy constructor
    a = new int[rhs.size];           // create storage
    copy( rhs );
}
```

```
Varray &operator=( const Varray &rhs ) {
    a = (int *)realloc( a, rhs.size * sizeof(a[0]) ); // resize storage
    copy( rhs );
}
```

- realloc uses any free space at end of allocation; otherwise does delete/new/copy.
- Handles self-assignment. Why?
- Copy/swap performance is 4+ times slower for pointers to data as no storage reused.



- Resize array, add/remove nodes to equal right-hand side, and reuse remaining nodes.

- May also need an equality operator (**operator**==) performing a deep compare, i.e., compare values not pointers.

2.22.6 Initialize const / Object Member

- C/C++ **const** members and local objects of a structure must be initialized at declaration:

```
struct Bar {
    Bar( int i ) {}
    // no default constructor
} bar( 3 ), baz( 4 );
struct Foo {
    const int i = 3;  // C++11
    Bar * const p = &bar;
    Bar &rp = bar;
    Bar b = { 7 };  // b( 7 )
};
Foo w1,
    w2 = { 2, &baz, baz, 9 }, // disallowed, no constructor
    w3( 2, &baz );    // disallowed, no constructor
```

- Add constructor:

```
Foo( const int i = 3, Bar * const p = &bar, Bar &rp = bar, Bar b = { 7 } ) {
    Foo::i = i;         // disallowed
    Foo::p = p;         // disallowed
    Foo::rp = rp;
    Foo::b = b;
}
```

- Assignment disallowed as constants could be used before initialization:

```
cout << i << endl;    // no value in constant
Foo::i = i;
```

- Special syntax to initialize at point of declaration.

```
Foo( const int i = 3, Bar * const p = &bar, Bar &rp = bar, Bar b = { 7 } )
        : i( i ), p( p ), rp( rp ), b( b ) { // special initialization syntax
    cout << i << endl;  // now value in constant
}
```

- Ensures **const**/object members are initialized before used in constructor.

- ***Must be initialized in declaration order to prevent use before initialization.***

- Syntax may also be used to initialize any local members:

```
struct Foo {
    Complex c;
    int k;
    Foo() : c( 1, 2 ), k( 14 ) {    // initialize c, k
        c = Complex( 1, 2 );    // or assign c, k
        k = 14;
    }
};
```

- Initialization may be more efficient versus default constructor and assignment.

2.22.7 Static Member

- Static data-member creates a single instance for object type versus for object instances.

```
struct Foo {
    static int cnt;    // one for all objects
    int i;             // one per object
    ...
};
```

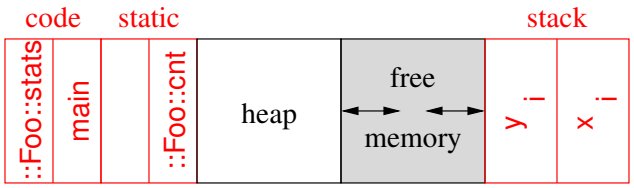
  - exist even if no instances of object exist
  - ***must still be defined (versus declared in the type) in a .cc file.***
  - allocated in static block not in object.

- Static routine-member, used to access static data-members, has no **this** parameter (i.e., like a regular routine)

- E.g., count the number of Foo objects created.

```
int cnt = 0;

void stats() {
    cout << cnt;
}
struct Foo {
    int i;
    void mem() {...}
    Foo() {
        ::cnt += 1;
    }
};

int main() {
    Foo x, y;
    ...
    stats();
}
```

```
struct Foo {
    static int cnt;
    int i;
    static void stats() {
        cout << cnt;      // allowed
        i = 3;            // disallowed
        mem();            // disallowed
    }
    void mem() {...}
    Foo() {
        cnt += 1;         // allowed
    }
};
int Foo::cnt = 0; // declaration (optional initialization)
int main() {
    Foo x, y;
    ...
    Foo::stats();
}
```



- Object member mem can reference i, cnt and stats.
- Static member stats can only reference cnt.

2.23 Separate Compilation, Routines

- As program size increases, so does cost of compilation.
- **Separate compilation** divides a program into units, where each unit can be independently compiled.
- Advantage: saves time by recompiling only program unit(s) that change.
    - In theory, if an expression is changed, only that expression needs to be recompiled.
    - In practice, compilation unit is coarser: **translation unit** (TU), which is a file in C/C++.
    - In theory, each line of code (expression) could be put in a separate file, but impractical.
    - ***So a TU should not be too big and not be too small.***
- Disadvantage: TUs depend on each other because a program shares many forms of information, especially types (done automatically in Java).

- Hence, need mechanism to **import** information from referenced TUs and **export** information needed by referencing TUs.

- E.g., program in file prog.cc using multiple routines:

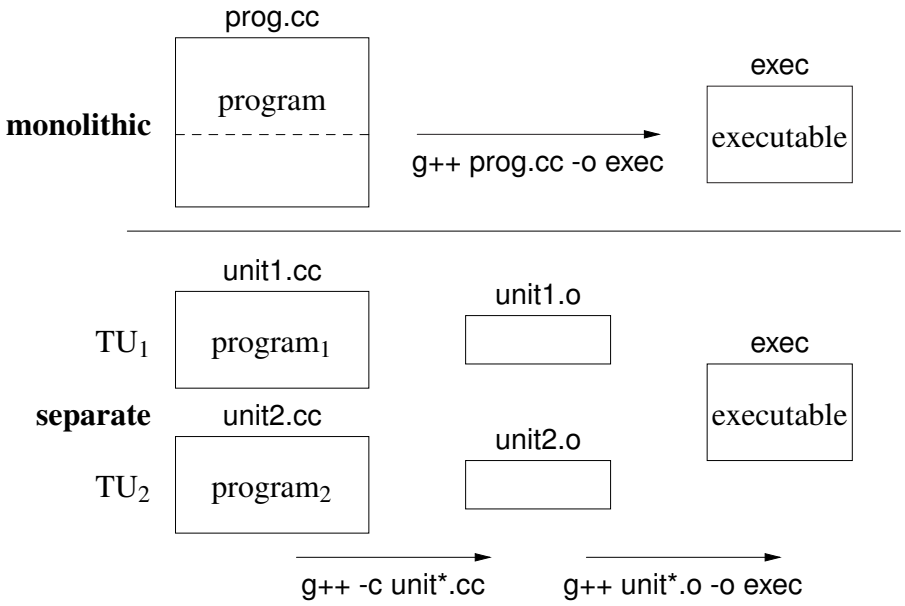
prog.cc

```
#include <iostream>          // import
#include <cmath>             // sqrt
double f( double );
double g( double );
int cntf = 0;
double f( double d ) {
    cntf += 1;               // count f calls
    cout << d << endl;
    return g( d );
}
double g( double d ) {
    cout << d << endl;
    return f( sqrt( d ) );
}
int main() {
    cout << cntf << " " << f( 3.5 ) << " " << g( 7.1 ) << endl;
}
```

- TU prog.cc has references to items in iostream and cmath.

- As well, there are references within TU, e.g., main references f and g.

- Subdividing program into TUs in C/C++ is complicated because of import/export mechanism.



- TU_i is NOT a program; program formed by combining TUs.

- Compile each TU_i with **−c** compiler flag to generate executable code in **.o** file (Java has .class file).

```
$ g++ -c unit*.cc ...  // compile only modified TUs
```

generates files unit1.o containing a compiled version of source code (machine code).

- Combine TU_i with **−o** compiler flag to generate executable program.

```
$ g++ unit*.o -o exec    // create new excutable program "exec"
```

- Separate program into 3 TUs in files f.cc, g.cc and prog.cc (arbitrary names):

f.cc

```
#include <iostream> // import
using namespace std;
extern double g( double );
int cntf = 0;           // export
double f( double d ) {
    cntf += 1;    // count f calls
    cout << d << endl;
    return g( d );
}
```

g.cc

```
#include <iostream> // import
#include <cmath>
using namespace std;
extern double f( double );
double g( double d ) { // export
    cout << d << endl;
    return f( sqrt( d ) );
}
```

prog.cc

```
#include <iostream> // import
using namespace std;
extern double f( double );
extern double g( double );
extern int cntf;
int main() {           // export
    cout << cntf << " " << f( 3.5 ) << " " << g( 7.1 ) << endl;
}
```

- TU explicitly imports using **extern** declarations, and implicitly exports variable and routine definitions.

- Compilation takes 4 steps:

```
$ g++ -Wall -c f.cc              # creates compiled file f.o
$ g++ -Wall -c g.cc              # creates compiled file g.o
$ g++ -Wall -c prog.cc           # creates compiled file prog.o
$ g++ prog.o f.o g.o -o prog     # creates executable file a.out
$ ./prog                         # run program
...
```

Why no -Wall flag when creating executable?

- ***All .o files MUST be compiled for same hardware architecture, e.g., x86.***

- Change to f.cc only needs 2 step compilation:

```
$ g++ -Wall -c f.cc              # creates new compiled file f.o
$ g++ prog.o f.o g.o -o prog     # creates new executable file a.out
$ ./prog                         # run program
...
```

- Problem: many duplicate import declarations. What if type of f changes?
- Subdivide TUs: interface for import (.h) and implementation for code (.cc).

f.h

```
extern double f( double );
extern int cntf;
```

f.cc

```
#include <iostream> // import
using namespace std;
#include "f.h"      // optional
#include "g.h"
int cntf = 0;           // export
double f( double d ) {
    cntf += 1;    // count f calls
    cout << d << endl;
    return g( d );
}
```

g.h

```
extern double g( double );
```

g.cc

```
#include <iostream> // import
#include <cmath>
using namespace std;
#include "g.h"      // optional
#include "f.h"
double g( double d ) { // export
    cout << d << endl;
    return f( sqrt( d ) );
}
```

prog.cc

```
#include <iostream> // import
using namespace std;
#include "g.h"
#include "f.h"
int main() {            // export
    cout << cntf << " " << f( 3.5 ) << " " << g( 7.1 ) << endl;
}
```

  - Why not include f.cc and g.cc into prog.cc?
  - Is there still duplicated information that has to be maintained?
  - Why is it a good practise to include f.h in f.cc?
  - If f.cc includes f.h, is it correct to export and import in the same TU?
  - Why use quotes " rather than chevrons <> for the .h files?
  - Why not put includes for iostream and cmath into .h files?

- (Usually) no code, just descriptions : preprecessor variables, C/C++ types and forward declarations (see Section 2.20, p. 95).
- Implementation is composed of definitions and code.
- **extern** qualifier means variable or routine definition is located elsewhere (not for types).
- Preprocessor **#include**s indirectly import by copying in **extern** declarations, e.g., iostream copies in **extern** ostream cout;.

- Problem: infinite inclusion of included file f.h and g.h!

- Use preprocessor trick (see Section 2.21.3, p. 99) to only expand file once:

f.h
```
#ifndef __F_H__          // if not defined
#define __F_H__ 1        //    make it so
extern double f( double );
#endif
```

2.24 Separate Compilation, Objects

- Separately compiling classes has its own complexities.

- For example, program in file prog.cc using complex numbers:

prog.cc
```
#include <iostream>              // import
#include <cmath>                 // sqrt
using namespace std;
struct Complex {
    static int objects;          // shared counter
    double re, im;
    Complex( double r = 0.0, double i = 0.0 ) { objects += 1; ...}
    double abs() const { return sqrt( re * re + im * im ); };
    static void stats() { cout << objects << endl; }
};
int Complex::objects;            // declare
Complex operator+( Complex a, Complex b ) {...}
... // other arithmetic and logical operators
ostream &operator<<( ostream &os, Complex c ) {...}
const Complex C_1( 1.0, 0.0 );
int main() {
    Complex a( 1.3 ), b( 2., 4.5 ), c( -3, -4 );
    cout << a + b + c + C_1 << c.abs() << endl;
    Complex::stats();
}
```

- TU prog.cc has references to items in iostream and cmath.

- As well, there are many references within the TU, e.g., main references Complex.

- Separate original program into two TUs in files complex.cc and prog.cc:

complex.cc

```
#include <iostream>          // import
#include <cmath>
using namespace std;
struct Complex {
    static int objects;      // shared counter
    double re, im;           // implementation
    Complex( double r = 0.0, double i = 0.0 ) { objects += 1; ...}
    double abs() const { return sqrt( re * re + im * im ); }
    static void stats() { cout << objects << endl; }
};
int Complex::objects;        // declare
Complex operator+( Complex a, Complex b ) {...}
... // other arithmetic and logical operators
ostream &operator<<( ostream &os, Complex c ) {...}
const Complex C_1( 1.0, 0.0 );
```

TU complex.cc has references to items in iostream and cmath.

prog.cc

```
int main() {
    Complex a( 1.3 ), b( 2., 4.5 ), c( -3, -4 );
    cout << a + b + c + C_1 << c.abs() << endl;
    Complex::stats();
}
```

TU prog.cc has references to items in iostream and complex.cc.

- Complex interface placed into file complex.h, for inclusion (import) into TUs.

complex.h

```
#ifndef __COMPLEX_H__
#define __COMPLEX_H__  // protect against multiple inclusion
#include <iostream>          // import
// NO "using namespace std", use qualification to prevent polluting scope
struct Complex {
    static int objects;      // shared counter
    double re, im;           // implementation
    Complex( double r = 0.0, double i = 0.0 );
    double abs() const;
    static void stats();
};
extern Complex operator+( Complex a, Complex b );
... // other arithmetic and logical operator descriptions
extern std::ostream &operator<<( std::ostream &os, Complex c );
extern const Complex C_1;
#endif // __COMPLEX_H__
```

- Complex implementation placed in file complex.cc.

complex.cc

```
#include "complex.h"        // do not copy interface
#include <cmath>            // import
using namespace std;        // ok to pollute implementation scope
int Complex::objects;       // defaults to 0
void Complex::stats() { cout << Complex::objects << endl; }
Complex::Complex( double r, double i ) { objects += 1; ...}
double Complex::abs() const { return sqrt( re * re + im * im ); }
Complex operator+( Complex a, Complex b ) {
    return Complex( a.re + b.re, a.im + b.im );
}
ostream &operator<<( ostream &os, Complex c ) {
    return os << c.re << "+" << c.im << "i";
}
const Complex C_1( 1.0, 0.0 );
```

- Compile TU complex.cc to generate complex.o.

```
$ g++ -c complex.cc
```

- What variables/routines are exported from complex.o?

```
$ nm -C complex.o | egrep ' T | B '
C_1
Complex::stats()
Complex::objects
Complex::Complex(double, double)
Complex::Complex(double, double)
Complex::abs() const
operator<<(std::ostream&, Complex)
operator+(Complex, Complex)
```

- In general, why are type names not in the .o file?

- To compile prog.cc, it must import complex.h

prog.cc

```
#include "complex.h"
#include <iostream>         // included twice!
using namespace std;

int main() {
    Complex a( 1.3 ), b( 2., 4.5 ), c( -3, -4 );
    cout << a + b + c + C_1 << c.abs() << endl;
    Complex::stats();
}
```

- Why is **#include** <iostream> in prog.cc when it is already imported by complex.h?

- Compile TU prog.cc to generate prog.o.

```
$ g++ -c prog.cc
```

- Link together TUs complex.o and prog.o to generate exec.

```
$ g++ prog.o complex.o -o exec
```

2.25 Testing

- A major phase in program development is testing ($> 50\%$).
- This phase often requires more time and effort than design and coding phases combined.
- Testing is not debugging.
- **Testing** is the process of "executing" a program with the intent of determining differences between the specification and actual results.
  - Good test is one with a high probability of finding a difference.
  - Successful test is one that finds a difference.
- Debugging is the process of determining why a program does not have an intended testing behaviour and correcting it.
- **Human Testing** : systematic examination of program to discover problems.
  - Studies show 30–70% of logic design and coding errors can be detected in this manner.
- **Machine Testing** : systematic running of program using test data designed to discover problems.
  - Speed up testing, occur more frequently, improve testing coverage, greater consistency and reliability, use less people-time testing
- Three major approaches:
  - **Black-Box Testing** : program's design / implementation is unknown when test cases are drawn up.
  - **White-Box Testing** : program's design / implementation is used to develop the test cases.
  - **Gray-Box Testing** : only partial knowledge of program's design / implementation know when test cases are drawn up.
- Start with the black-box approach and supplement with white-box tests.
- **Black-Box Testing**
  - **equivalence partitioning** : completeness without redundancy
    - partition all possible input cases into equivalence classes
    - select only one representative from each class for testing

    * E.g., payroll program with input HOURS

```
      HOURS <= 40
40 < HOURS <= 45 (time and a half)
45 < HOURS       (double time)
```

    * 3 equivalence classes, plus invalid hours
    * many types of invalid data ⇒ partition into equivalence classes
  - **boundary value** : test cases below, on, and above boundary cases

    *

```
39, 40, 41   (hours)      valid cases
 0,  1,  2      "
−2, −1,  0      "         invalid cases
59, 60, 61      "
```

  - **error guessing**
    * surmise, through intuition and experience, what the likely errors are and then test for them

- **White-Box Testing** (logic coverage)
  - develop test cases to cover (exercise) important program logic paths
  - try to test every decision alternative at least once
  - test all combinations of decisions (often impossible due to size)
  - test every routine and member for each type
  - ***cannot test all permutations and combinations of execution***

- **Test Harness** : a collection of software and test data configured to run a program (unit) under varying conditions and monitor its outputs.

2.26 Assertions

- **Assertion**s document program assumptions:
  - pre-conditions – true before a computation (e.g., all values are positive),

```
assert( x > 0 && y > 0 );     // before
```

  - invariants – true across the computation (e.g., all values during the computation are positive, because only +,*, / operations),

```
x = ...
assert( x > 0 );              // during
```

  - post-conditions – true after the computation (e.g., all results are positive).

```
assert( x > 0 && y > 0 );     // after
```

- Common to check for null pointer:

```
assert( p != nullptr );
```

- Use comma expression to add documentation to assertion message.

```
#include <cassert>
unsigned int stopping_distance( Car car ) {
    ... assert( ("Internal error", distance > 0) ); ...
}
$ a.out
a.out: test.cc:19: unsigned int stopping_distance(Car):
      Assertion ('"Internal error", distance > 0)' failed.
```

- Assertions in **hot spot**, i.e., point of high execution, can significantly increase program cost.

- Compiling a program with preprocessor variable NDEBUG defined removes all asserts.

```
% g++ -DNDEBUG ...  # all asserts removed
```

- Therefore, never put computations needed by a program into an assertion.

```
assert( needed_computation(...) > 0 );  // may not be executed
```

2.27 Debugging

- **Debugging** is the process of determining why a program does not have an intended behaviour.

- Often debugging is associated with fixing a program after a failure.

- However, debugging can be applied to fixing other kinds of problems, like poor performance.

- Before using debugger tools it is important to understand what you are looking for and if you need them.

2.27.1 Debug Print Statements

- An excellent way to debug a program is to *start* by inserting debug print statements (i.e., as the program is written).

- It takes more time, but the alternative is wasting hours trying to figure out what the program is doing.

- The two aspects of a program that you need to know are: where the program is executing and what values it is calculating.

- Debug print statements show the flow of control through a program and print out intermediate values.

- E.g., every routine should have a debug print statement at the beginning and end, as in:

```
int p( ... ) {
    // declarations
    cerr << "Enter p " << parameter variables << endl;
    ...
    cerr << "Exit p " << return value(s) << endl;
    return r;
}
```

- Result is a high-level audit trail of where the program is executing and what values are being passed around.

- Finer resolution requires more debug print statements in important control structures:

```
if ( a > b ) {
    cerr << "a > b" << endl;
    for ( ... ) {
        cerr << "x=" << x << ", y=" << y << endl;
        ...
    }
} else {
    cerr << "a <= b" << endl;
    ...
}
```

- By examining the control paths taken and intermediate values generated, it is possible to determine if the program is executing correctly.

- Unfortunately, debug print statements generate lots of output.

> ***It is of the highest importance in the art of detection to be able to recognize out of a number of facts which are incidental and which vital. (Sherlock Holmes, The Reigate Squires)***

- Gradually comment out debug statements as parts of the program begin to work to remove clutter from the output, but do not delete them until the program works.

- When you go for help, your program should contain debug print-statements to indicate some attempt at understanding the problem.

- Use a preprocessor macro to simplify debug prints for printing entry, intermediate, and exit locations and data:

```
#define DPRT( title, expr ) \
 { std::cerr << #title "\t\"" << __PRETTY_FUNCTION__ << "\" " << \
 expr << " in " << __FILE__ << " at line " << __LINE__ << std::endl; }
```

```
#include <iostream>
#include "DPRT.h"
int test( int a, int b ) {
    DPRT( ENTER, "a:" << a << " b:" << b );
    if ( a < b ) DPRT( a < b, "a:" << a << " b:" << b );
    DPRT( , a + b );                    // empty title
    DPRT( HERE, "" );                   // empty expression
    DPRT( EXIT, a );
    return a;
}

ENTER "int test(int, int)" a:3 b:4 in test.cc at line 14
a < b   "int test(int, int)" a:3 b:4 in test.cc at line 16
    "int test(int, int)" 7 in test.cc at line 18
HERE   "int test(int, int)"  in test.cc at line 19
EXIT   "int test(int, int)" 3 in test.cc at line 20
```

2.28 Valgrind

- Incorrect memory usage is difficult to detect, e.g., memory leak or dangling pointer (see Section 2.13, p. 82).
- **Valgrind** is a program that detects memory errors.
- Valgrind has false positives, i.e., claim memory errors that are not errors.
- Note, valgrind significantly slows program execution.
- Control output from valgrind for an empty program:

```
int main() {
}

$ g++ -g test.cc
$ valgrind ./a.out
==61795== Memcheck, a memory error detector
==61795== Copyright (C) 2002-2011, and GNU GPL'd, by Julian Seward et al.
==61795== Using Valgrind-3.7.0 and LibVEX; rerun with -h for copyright info
==61795== Command: ./a.out
==61795==
==61795== HEAP SUMMARY:
==61795==     in use at exit: 0 bytes in 0 blocks
==61795==   total heap usage: 0 allocs, 0 frees, 0 bytes allocated
==61795==
==61795== All heap blocks were freed -- no leaks are possible
==61795==
==61795== For counts of detected and suppressed errors, rerun with: -v
==61795== ERROR SUMMARY: 0 errors from 0 contexts (suppressed: 2 from 2)
```

- Output states:
    - HEAP SUMMARY:

    - how much heap memory was in use when the program exited
    - how much heap memory was allocated in total.
  - Note, allocs = frees does not ⇒ no memory leaks.
  - Must see "All heap blocks were freed – no leaks are possible".

- Control output from valgrind for an allocation:

```
int main() {
    int *p = new int;
    delete p;
}
```

```
$ valgrind ./a.out
...
==61570== HEAP SUMMARY:
==61570==     in use at exit: 72,704 bytes in 1 blocks
==61570==   total heap usage: 2 allocs, 1 frees, 72,708 bytes allocated
==61570==
==61570== LEAK SUMMARY:
==61570==    definitely lost: 0 bytes in 0 blocks
==61570==    indirectly lost: 0 bytes in 0 blocks
==61570==      possibly lost: 0 bytes in 0 blocks
==61570==    still reachable: 72,704 bytes in 1 blocks
==61570==         suppressed: 0 bytes in 0 blocks
...
```

- ***Only 1 dynamic allocation, but 2 reported as C++ runtime does not free all memory.***

- LEAK SUMMARY:
  - Non-zero values for definitely, indirectly, and possibly lost ⇒ memory leak.
  - Non-zero value for still reachable ⇒ memory leak from C++ runtime (ignore).

- Introduce memory leak:

```
1   int main() {
2       struct Foo { char c1, c2; };
3       Foo *p = new Foo;
4       p = new Foo;        // forgot to free previous storage
    }
```

```
==45326== HEAP SUMMARY:
==45326==     in use at exit: 72,708 bytes in 3 blocks
==45326==   total heap usage: 3 allocs, 0 frees, 72,708 bytes allocated
==45326==
==45326== LEAK SUMMARY:
==45326==    definitely lost: 4 bytes in 2 blocks
==45326==    indirectly lost: 0 bytes in 0 blocks
==45326==      possibly lost: 0 bytes in 0 blocks
==45326==    still reachable: 72,704 bytes in 1 blocks
==45326==         suppressed: 0 bytes in 0 blocks
==45326== Rerun with --leak-check=full to see details of leaked memory
```

- What happened?
  - Second allocation overwrites first without a free.
  - Second allocation is not freed.
  - 2 x 2 byte unfreed, each in a different allocation block.
- Add --leak-check=full flag:

```
$ valgrind --leak-check=full ./a.out    # flag must precede filename
...
==19639== 2 bytes in 1 blocks are definitely lost in loss record 1 of 2
==19639==    at 0x4C2B1C7: operator new(unsigned long) (in /usr/lib/valgrind/...)
==19639==    by 0x400659: main (test.cc:3)
...
```

- Introduce memory errors:

```
1   #include <iostream>
2   using namespace std;
3   int main() {
4       int * x;
5       cout << x << endl;   // uninitialized read
6       x = new int[10];
7       x[0] = x[10];        // subscript error, invalid read
8       x[10] = 10;          // subscript error, invalid write
9       delete[] x;
10      delete[] x;          // invalid free
11      x[0] = 3;            // dangling pointer, invalid write
    }
```

```
==870== Use of uninitialised value of size 8 ... by main (test2.cc:5)
==870== Conditional jump or move depends on uninitialised value(s) ... by main (test2.cc:5)
==870== Invalid read of size 4 ... at main (test2.cc:7) ... by main (test2.cc:6)
==870== Invalid write of size 4 ... at main (test2.cc:8) ... by main (test2.cc:6)
...
==870== Invalid free() / delete / delete[] / realloc()
==870==    at 0x4C2A09C: operator delete[](void*) (in /usr/lib/valgrind/...)
==870==    by 0x40091C: main (test2.cc:10)
==870==  Address 0x5a91c80 is 0 bytes inside a block of size 40 free'd
==870==    at 0x4C2A09C: operator delete[](void*) (in /usr/lib/valgrind/...)
==870==    by 0x400909: main (test2.cc:9)
...
==870== Invalid write of size 4 ... at main (test2.cc:11) ... by main (test2.cc:9)
==870== ERROR SUMMARY: 7 errors from 7 contexts (suppressed: 2 from 2)
```

- What happened? (output trimmed to focus on errors)
  - valgrind identifies all memory errors, giving the line number where each error occurred.
  - For Invalid free()
    - first 3 lines indicate the delete on line 10 is already freed.
    - next 3 lines indicate the memory previously freed on line 9.

2.29 Random Numbers

- **Random number**s are values generated independently, i.e., new values do not depend on previous values (independent trials).
- E.g., lottery numbers, suit/value of shuffled cards, value of rolled dice, coin flipping.
- While programmers spend much time ensuring computed values are not random, random values are useful:
  - gambling, simulation, cryptography, games, etc.
- **Random-number generator** is an algorithm computing independent values.
- If algorithm uses deterministic computation (predictable sequence), it generates **pseudo random-numbers** versus "true" random numbers.
- All **pseudo random-number generator**s (PRNG) involve some technique that scrambles the bits of a value, e.g., **multiplicative recurrence**:

```
seed_ = 36969 * (seed_ & 65535) + (seed_ >> 16); // scramble bits
```

- Multiplication of large values adds new least-significant bits and drops most-significant bits.

bits 63-32	bits 31-0
0	3e8e36
5f	718c25e1
ad3e	7b5f1dbe
bc3b	ac69ff19
1070f	2d258dc6

- By dropping bits 63-32, bits 31-0 become scrambled after each multiply.
- E.g., struct PRNG generates a ***fixed*** sequence of LARGE random values that repeats after 2^{32} values (but might repeat earlier).[2]

```
struct PRNG {
    uint32_t  seed_;     // same results on 32/64-bit architectures

    PRNG( uint32_t  s = 362436069 ) {  // default seed
        seed_ = s;                     // set seed
    }
    uint32_t seed() {                  // read seed
        return seed_;
    }
    void seed( uint32_t  s ) {         // reset seed
        seed_ = s;                     // set seed
    }
```

[2] http://www.bobwheeler.com/statistics/Password/MarsagliaPost.txt

```
        uint32_t operator()(){                  // [0,UINT_MAX]
            seed_ = 36969*(seed_ & 65535)+(seed_ >> 16); // scramble bits
            return seed_;
        }
        uint32_t operator()( uint32_t u ) {     // [0,u]
            return operator()() % (u + 1);      // call operator()()
        }
        uint32_t operator()( uint32_t l, uint32_t u ) { // [l,u]
            return operator()( u - l ) + l;     // call operator()( uint32_t )
        }
};
```

- Problem:
  - generate next random number via routine call prng(5) not member call prng.get(5)
  - but routine cannot retain state (seed_) between calls (), so must use an object.
- Use function-call operator member, with name (), (**functor**), allowing object to behave like a routine **but retain state between calls in object**.

```
PRNG prng;      // often create single generator for entire program
prng();         // [0,UINT_MAX],  prng.operator()()
prng( 5 );      // [0,5],  prng.operator()( 5 )
prng( 5, 10 );  // [5,10],  prng.operator()( 5, 10 )
```

- Scaled large values from prng using modulus, e.g., random number between 5-21:

```
for ( int i = 0; i < 10; i += 1 ) {
    cout << prng() % 17 + 5 << endl; // values 0-16 + 5 = 5-21
    cout << prng( 16 ) + 5 << endl;
    cout << prng( 5, 21 ) << endl;
}
```

- Initializing PRNG with external "seed" generates different sequence:

```
PRNG prng( getpid() );  // process id of program (better)
prng.seed( time() );    // current time
```

- **#include** <cstdlib> provides C random routines srand and rand.

```
srand( getpid() );      // seed random genrator
r = rand();             // obtain next random value
```

2.30 Encapsulation

- **Encapsulation** hides implementation to support abstraction (**access control**).
- Access control applies to types NOT objects, i.e., all objects of the same type have identical levels of encapsulation.
- ***Abstraction and encapsulation are neither essential nor required to develop software.***

- E.g., programmers could follow a convention of not directly accessing the implementation.
- However, relying on programmers to follow conventions is dangerous.
- **Abstract data-type** (ADT) is a user-defined type practicing abstraction and encapsulation.
- Encapsulation is provided by a combination of C and C++ features.
- C features work largely among source files, and are indirectly tied into separate compilation (see Section 2.23, p. 115).
- C++ features work both within and among source files.
- C++ provides 3 levels of access control for object types:

Java	C++

class Foo {
  private ...
  ...
  protected ...
  ...
  public ...
  ...
};
	struct Foo {
	  private: *// within and friends*
	  // private members
	  protected: *// within, friends, inherited*
	  // protected members
	  public: *// within, friends, inherited, users*
	  // public members
	};

- C++ groups members with the same encapsulation, i.e., all members after a label, **private**, **protected** or **public**, have that visibility.
- Visibility labels can occur in any order and multiple times in an object type.
- Encapsulation supports abstraction by making implementation members private and interface members public.
- ***Note, private/protected members are still visible to programmer but inaccessible*** (see page 133 for invisible implementation.

```
struct Complex {
  private:
    double re, im;  // cannot access but still visible
  public:
    // interface routines
};
```

- **struct** has an implicit **public** inserted at beginning, i.e., by default all members are public.
- **class** has an implicit **private** inserted at beginning, i.e., by default all members are private.

```
struct S {
  // public:
     int z;
  private:
     int x;
  protected:
     int y;
};
```

```
class C {
  // private:
     int x;
  protected:
     int y;
  public:
     int z;
};
```

- Use encapsulation to preclude object copying by hiding copy constructor and assignment operator:

```
class Lock {
     Lock( const Lock & );  // definitions not required
     Lock &operator=( Lock & );
  public:
     Lock() {...}
     ...
};
void rtn( Lock f ) {...}
Lock x, y;
rtn( x );  // disallowed, no copy constructor for pass by value
x = y;   // disallowed, no assignment operator for assignment
```

- Prevent object forgery (lock, boarding-pass, receipt) or copying that does not make sense (file, database).

- Encapsulation introduces problems when factoring for modularization, e.g., previously accessible data becomes inaccessible.

```
class Complex {
     double re, im;
  public:
     Complex operator+(Complex c);
     ...
};
ostream &operator<<(ostream &os,
                    Complex c);
```

```
class Cartesian { // implementation type
     double re, im;
};
class Complex {
     Cartesian impl;
  public:
     ...
};
Complex operator+(Complex a, Complex b);
ostream &operator<<(ostream &os,
                    Complex c);
```

- Implementation is factored into a new type Cartesian, "+" operator is factored into a routine outside and output "<<" operator must be outside (see Section 2.22.3.2, p. 104).

- Both Complex and "+" operator need to access Cartesian implementation, i.e., re and im.

- Creating get and set interface members for Cartesian provides no advantage over full access.

- C++ provides a mechanism to state that an outside type/routine is allowed access to its implementation, called **friendship**.

```
class Complex; // forward
class Cartesian { // implementation type
    friend Complex operator+( Complex a, Complex b );
    friend ostream &operator<<( ostream &os, Complex c );
    friend class Complex;
    double re, im;
};
class Complex {
    friend Complex operator+( Complex a, Complex b );
    friend ostream &operator<<( ostream &os, Complex c );
    Cartesian impl;
  public:
    ...
};
Complex operator+( Complex a, Complex b ) {
    return Complex( a.impl.re + b.impl.re, a.impl.im + b.impl.im );
}
ostream &operator<<( ostream &os, Complex c ) {
    return os << c.impl.re << "+" << c.impl.im << "i";
}
```

- Cartesian makes re/im accessible to friends, and Complex makes impl accessible to friends.

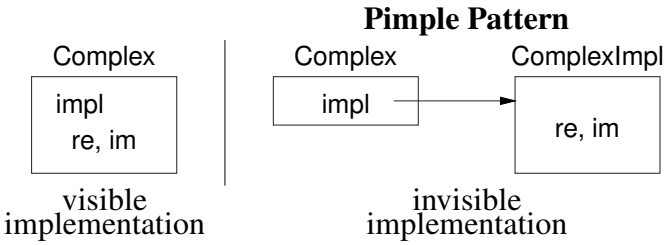
- Alternative design is to nest the implementation type in Complex and remove encapsulation (use **struct**).

```
class Complex {
    friend Complex operator+( Complex a, Complex b );
    friend ostream &operator<<( ostream &os, Complex c );
    class Cartesian { // implementation type
        double re, im;
    } impl;
  public:
    Complex( double r = 0.0, double i = 0.0 ) {
        impl.re = r; impl.im = i;
    }
};
...
```

- Complex makes Cartesian, re, im and impl accessible to friends.

- Note, .h file encapsulates implementation but implementation is still visible.

- To completely hide the implementation requires a (more expensive) reference, called **bridge** or **pimpl pattern**:



complex.h

```
#ifndef __COMPLEX_H__
#define __COMPLEX_H__  // protect against multiple inclusion
#include <iostream>    // import
// NO "using namespace std", use qualification to prevent polluting scope
class Complex {
    friend Complex operator+( Complex a, Complex b );
    friend std::ostream &operator<<( std::ostream &os, Complex c );
    static int objects;          // shared counter
    struct ComplexImpl;          // hidden implementation, nested class
    ComplexImpl &impl;           // indirection to implementation
  public:
    Complex( double r = 0.0, double i = 0.0 );
    Complex( const Complex &c );  // copy constructor
    ~Complex();                   // destructor
    Complex &operator=( const Complex &c ); // assignment operator
    double abs() const;
    static void stats();
};
extern Complex operator+( Complex a, Complex b );
extern std::ostream &operator<<( std::ostream &os, Complex c );
extern const Complex C_1;
#endif // __COMPLEX_H__
```

complex.cc

```
#include "complex.h"       // do not copy interface
#include <cmath>           // import
using namespace std;       // ok to pollute implementation scope
int Complex::objects;      // defaults to 0
struct Complex::ComplexImpl { double re, im; }; // implementation
Complex::Complex( double r, double i ) : impl(*new ComplexImpl) {
    objects += 1; impl.re = r; impl.im = i;
}
Complex::Complex( const Complex &c ) : impl(*new ComplexImpl) {
    objects += 1; impl.re = c.impl.re; impl.im = c.impl.im;
}
Complex::~Complex() { delete &impl; }
Complex &Complex::operator=( const Complex &c ) {
    impl.re = c.impl.re; impl.im = c.impl.im; return *this;
}
```

```
double Complex::abs() {return sqrt(impl.re * impl.re + impl.im * impl.im);}
void Complex::stats() { cout << Complex::objects << endl; }
Complex operator+( Complex a, Complex b ) {
    return Complex( a.impl.re + b.impl.re, a.impl.im + b.impl.im );
}
ostream &operator<<( ostream &os, Complex c ) {
    return os << c.impl.re << "+" << c.impl.im << "i";
}
```

- A copy constructor and assignment operator are used because complex objects now contain a reference pointer to the implementation (see page 111).

- To hide global variables/routines (but NOT class members) in TU, qualify with **static**.

```
complex.cc
    static int Complex::objects; // not exported
    Complex::Complex( double r, double i ) : impl(*new ComplexImpl) {
        objects += 1; impl.re = r; impl.im = i;
    }
    ...
```

  - here **static** means linkage NOT storage allocation (see Section 2.22.7, p. 114).

- Alternatively, place variables/routines in an unnamed namespace.

```
complex.cc
    namespace {
        int Complex::objects; // not exported
    }
    // equivalent to
    namespace UNIQUE {}  // compiler generates unique name
    using namespace UNIQUE; // make contents visible in TU
    namespace UNIQUE {   // add items local to TU
        ...
    }
```

- Encapsulation is provided by giving a user access to:

  - include file(s) (.h) and
  - compiled source file(s) (.o),
  - but not implementation in the source file(s) (.cc).

2.31 Declaration Before Use, Objects

- Like Java, C++ does not always require DBU within a type:

Java	C++

class T {
  void f() { c = Colour.R; g(); }
  void g() { c = Colour.G; f(); }
  Colour c;
  enum Colour { R, G, B };
};
	void g() {} *// not selected by call in T::f*
	struct T {
	  void f() { **c** = **R**; **g**(); } *// c, R, g not DBU*
	  void g() { **c** = **G**; **f**(); } *// c, G not DBU*
	  enum Colour { R, G, B }; *// type must be DBU*
	  Colour c;
	};

- Unlike Java, C++ requires a forward declaration for mutually-recursive declarations ***among types***:

Java	C++

class T1 {
  T2 t2;
  T1() { t2 = **new** T2(); }
};
class T2 {
  T1 t1;
  T2() { t1 = **new** T1(); }
};
T1 t1 = **new** T1();
	struct T1 {
	  T2 t2; *// DBU failure, T2 size?*
	};
	struct T2 {
	  T1 t1;
	};
	T1 t1;

Caution: these types cause infinite expansion as there is no base case.

- Java version compiles because t1/t2 are references not objects, and Java can look ahead at T2.
- C++ version disallowed because DBU on T2 means it does not know the size of T2.
- An object declaration and usage requires the object's size and members so storage can be allocated, initialized, and usages type-checked.
- Solve using Java approach: break definition cycle using a forward declaration and pointer.

Java	C++

class T1 {
  T2 t2;
  T1() { t2 = **new** T2(); }
};
class T2 {
  T1 t1;
  T2() { t1 = **new** T1(); }
};
	struct T2; *// forward*
	struct T1 {
	  T2 &t2; *// pointer, break cycle*
	  T1() : t2(***new T2**) {} *// DBU failure, size?*
	};
	struct T2 {
	  T1 t1;
	};

- Forward declaration of T2 allows the declaration of variable T1::t2.
- Note, a forward type declaration only introduces the name of a type.

- Given just a type name, only pointer/reference declarations to the type are possible, which allocate storage for an address versus an object.

- C++'s solution still does not work as the constructor cannot use type T2.

- Use forward declaration and syntactic trick to move member definition ***after both types are defined***:

```
struct T2;              // forward
struct T1 {
    T2 &t2;             // pointer, break cycle
    T1();               // forward declaration
};
struct T2 {
    T1 t1;
};
T1::T1() : t2( *new T2 ) {} // can now see type T2
```

- Use of qualified name T1::T1 allows a member to be logically declared in T1 but physically located later (see Section 2.24, p. 119).

2.32 Inheritance

- Object-***oriented*** languages provide **inheritance** for writing reusable program-components.

Java	C++
class Base { ... } **class** Derived **extends** Base { ... }	**struct** Base { ... } **struct** Derived : **public** Base { ... };

- Inheritance has two orthogonal sharing concepts: implementation and type.
  - Implementation inheritance provides reuse of code ***inside*** an object type.
  - Type inheritance provides reuse ***outside*** the object type by allowing existing code to access the base type.

2.32.1 Implementation Inheritance

- Implementation inheritance reuses program components by composing a new object's implementation from an existing object, taking advantage of previously written and tested code.

- Substantially reduces the time to generate and debug a new object type.

- One way to understand implementation inheritance is to model it via composition:

Composition	Inheritance

struct Engine { *// Base*
  int cyls;
  int r(...) { ... }
  Engine() { ... }
};
struct Car { *// Derived*
  Engine e; *// explicit composition*
  int s(...) { e.cyls = 4; e.r(...); ... }
  Car() { ... }
} vw;
vw.**e**.cyls = 6; *// composition reference*
vw.**e**.r(...); *// composition reference*
vw.s(...); *// direct reference*
	struct Engine { *// Base*
	  int cyls;
	  int r(...) { ... }
	  Engine() { ... }
	};
	struct Car : **public Engine** { *// implicit composition*
	  int s(...) { cyls = 4; r(...); ... }
	  Car() { ... }
	} vw;
	vw.cyls = 3; *// direct reference*
	vw.r(...); *// direct reference*
	vw.s(...); *// direct reference*

- Composition explicitly creates object member, e, to aid in implementation.
  - A Car "has-a" Engine.
  - A Car is not an Engine nor is an Engine a Car, i.e., they are not logically interchangable.
- Inheritance, "**public** Engine" clause, implicitly:
  - creates an anonymous base-class object-member,
  - ***opens*** the scope of anonymous member so its members are accessible without qualification, both inside and outside the inheriting object type.
- E.g., Car declaration creates:
  - invisible Engine object in Car object, like composition,
  - allows direct access to variables Engine::i and Engine::r in Car::s.
- Constructors and destructors must be invoked for all implicitly declared objects in inheritance hierarchy as for an explicit member in composition.

```
Car d;          implicitly      Engine b;  b.Engine(); // implicit, hidden declaration
...             rewritten as    Car d;  d.Car();
                                ...
                                d.~Car();  b.~Engine(); // reverse order of construction
```

- If base type has members with the same name as derived type, it works like nested blocks: inner-scope name overrides outer-scope name (see Section 2.5.2, p. 42).
- Still possible to access outer-scope names using "::" qualification (see Section 2.14, p. 85) to specify the particular nesting level.

Java	C++

class Base1 {
  int i;
}
class Base2 **extends** Base1 {
  int i;
}
class Derived **extends** Base2 {
  int i;
  void s() {
  int i = 3;
  this.i = 3;
  ((Base2)**this**).i = 3; *// super.i*
  ((Base1)**this**).i = 3;
  }
}
	struct Base1 {
	  int i;
	};
	struct Base2 : **public** Base1 {
	  int i; *// overrides Base1::i*
	};
	struct Derived : **public** Base2 {
	  int i; *// overrides Base2::i*
	  void r() {
	  int i = 3; *// overrides Derived::i*
	  Derived::i = 3; *// this.i*
	  Base2::i = 3;
	  Base2::Base1::i = 3; *// or Base1::i*
	  }
	};

- ***Friendship is not inherited.***

```
class C {
    friend class Base;
    ...
};
class Base {
    // access C's private members
    ...
};
class Derived : public Base {
    // not friend of C
};
```

- Unfortunately, having to inherit all of the members is not always desirable; some members may be inappropriate for the new type (e.g, large array).
- As a result, both the inherited and inheriting object must be very similar to have so much common code.

2.32.2 Type Inheritance

- Type inheritance establishes an "**is-a**" relationship among types.

```
class Employee {
    ... // personal info
};
class FullTime : public Employee {
    ... // wage & benefits
};
class PartTime : public Employee {
    ... // wage
};
```

  - A FullTime "is-a" Employee; a PartTime "is-a" Employee.

- A FullTime and PartTime are logically interchangable with an Employee.
- A FullTime and PartTime are not logically interchangable.

- Type inheritance extends name equivalence (see Section 2.12, p. 74) to allow routines to handle multiple types, called **polymorphism**, e.g.:

```
struct Foo {                    struct Bar {
    int i;                          int i;
    double d;                       double d;
                                    ...
} f;                            } b;
void r( Foo f ) { ... }
r( f );   // allowed
r( b );   // disallowed, name equivalence
```

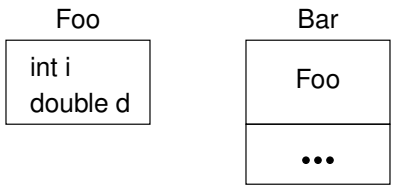
- Since types Foo and Bar are structurally equivalent, instances of either type should work as arguments to routine r (see Section 2.15, p. 86).

- Even if type Bar has more members at the end, routine r only accesses the common ones at the beginning as its parameter is type Foo.

- However, name equivalence precludes the call r(b).

- ***Type inheritance relaxes name equivalence by aliasing the derived name with its base-type names.***

```
struct Foo {                    struct Bar : public Foo { // inheritance
    int i;                          // remove Foo members
    double d;
                                    ...
} f;                            } b;
void r( Foo f ) { ... }
r( f );   // valid call, derived name matches
r( b );   // valid call because of inheritance, base name matches
```



- E.g., create a new type Mycomplex that counts the number of times abs is called for each Mycomplex object.

- Use both implementation and type inheritance to simplify building type Mycomplex:

```
struct Mycomplex : public Complex {
    int cntCalls;                          // add
    Mycomplex() : cntCalls(0) {}           // add
    double abs() {   // override, reuse complex' s abs routine
        cntCalls += 1;
        return Complex::abs();
    }
    int calls() { return cntCalls; }       // add
};
```

- Derived type Mycomplex uses the implementation of the base type Complex, adds new members, and overrides abs to count each call.
- Why is the qualification Complex:: necessary in Mycomplex::abs?
- Allows reuse of Complex's addition and output operation for Mycomplex values, because of the relaxed name equivalence provided by type inheritance between argument and parameter.
- Redeclare Complex variables to Mycomplex to get new abs, and member calls returns the current number of calls to abs for any Mycomplex object.
- Two significant problems with type inheritance.

1. ○ Complex routine **operator**+ is used to add the Mycomplex values because of the relaxed name equivalence provided by type inheritance:

```
int main() {
    Mycomplex x;
    x = x + x;    // disallowed
}
```

   ○ However, result type from **operator**+ is Complex, not Mycomplex.

   ○ Assignment of a complex (base type) to Mycomplex (derived type) disallowed because the Complex value is missing the cntCalls member!

   ○ Hence, a Mycomplex can mimic a Complex but not vice versa.

   ○ This fundamental problem of type inheritance is called **contra-variance**.

   ○ C++ provides various solutions, all of which have problems and are beyond this course.

2.
```
void r( Complex &c ) {
    c.abs();       // calls Complex::abs not Mycomplex::abs
}
int main() {
    Mycomplex x;
    x.abs();       // direct call of abs
    r( x );        // indirect call of abs
    cout << "x:" << x.calls() << endl;
}
```

   ○ While there are two calls to abs on object x, only one is counted! (see Section 2.32.6, p. 144)

- **public** inheritance means both implementation and type inheritance.
- **private** inheritance means only implementation inheritance.

  ```
  class bus : private car { ...
  ```

  Use implementation from car, but bus is not a car.
- No direct mechanism in C++ for type inheritance without implementation inheritance.

2.32.3 Constructor/Destructor

- Constructors are executed top-down, from base to most derived type.
- Mandated by scope rules, which allow a derived-type constructor to use a base type's variables so the base type must be initialized first.
- Destructors are executed bottom-up, from most derived to base type.
- Mandated by the scope rules, which allow a derived-type destructor to use a base type's variables so the base type must be uninitialized last.
- To pass arguments to other constructors, use same syntax as for initializing **const** members.

Java	C++

class Base {
  Base(**int** i) { ... }
};
class Derived **extends** Base {
  Derived() { **super**(3); ... }
  Derived(**int** i) { **super**(i); ... }
};
	struct Base {
	  Base(**int** i) { ... }
	};
	struct Derived : **public** Base {
	  Derived() : **Base(3)** { ... }
	  Derived(**int** i) : **Base(i)** {...}
	};

2.32.4 Copy Constructor / Assignment

- Each aggregate type has a default/copy constructor, assignment operator, and destructor (see page 109), so these members cannot be inherited as they exist in the derived type.
- Otherwise, copy-constructor/assignment work like composition (see Section 2.22.5, p. 108).

```
struct B {
    B() { cout << "B() "; }
    B( const B &c ) { cout << "B(&) "; }
    B &operator=( const B &rhs ) { cout << "B= "; }
};
struct D : public B {
    int i;                          // basic type, bitwise
};
int main() {
    D i;       cout << endl;    // B's default constructor
    D d = i; cout << endl;    // D's default copy-constructor
    d = i;     cout << endl;    // D's default assignment
}
```

outputs the following:

```
B()             // D i
B(&)            // D d = i
B=              // d = i
```

- D's default copy-constructor/assignment does memberwise copy of each subobject.
- If D defines a copy-constructor/assignment, it overrides that in any subobject.

```
struct D : public B {
    ... // same declarations
    D() { cout << "D() "; }
    D( const D &c ) : B( c ), i( c.i ) { cout << "D(&) "; }
    D &operator=( const D &rhs ) {
        i = rhs.i;  (B &)*this = rhs;
        cout << "D= ";
        return *this;
    }
};
```

outputs the following:

```
B() D()         // D i
B(&) D(&)       // D d = i
B= D=           // d = i
```

Must copy each subobject to get same output. **Note coercion!**

2.32.5 Overloading

- Overloading a member routine in a derived class overrides all overloaded routines in the base class with the same name.

```
class Base {
  public:
    void mem( int i ) {}
    void mem( char c ) {}
};
class Derived : public Base {
  public:
    void mem() {}  // overrides both versions of mem in base class
};
```

- Hidden base-class members can still be accessed:
  - Provide explicit wrapper members for each hidden one.

```
class Derived : public Base {
  public:
    void mem() {}
    void mem( int i ) { Base::mem( i ); }
    void mem( char c ) { Base::mem( c ); }
};
```

- Collectively provide implicit members for all of them.

```
class Derived : public Base {
  public:
    void mem() {}
    using Base::mem;  // all base mem routines visible
};
```

- Use explicit qualification to call members (violates abstraction).

```
Derived d;
d.Base::mem( 3 );
d.Base::mem( 'a' );
d.mem();
```

2.32.6 Virtual Routine

- When a member is called, it is usually obvious which one is invoked even with overriding:

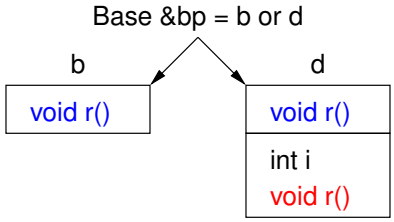
```
struct Base {
    void r() { ... }
};
struct Derived : public Base {
    void r() { ... }   // override Base::r
};
Base b;
b.r();                 // call Base::r
Derived d;
d.r();                 // call Derived::r
```

- However, not obvious for arguments/parameters and pointers/references:

```
void s( Base &b ) { b.r(); } // Base::r or Derived::r ?
s( d );              // inheritance allows call: Base::r or Derived::r ?
Base &bp = d;        // assignment allowed because of inheritance
bp.r();              // Base::r or Derived::r ?
```

- Inheritance masks actual object type, but expectation is both calls should invoke Derived::r as argument b and reference bp point at an object of type Derived.

- If variable d is replaced with b, expectation is the calls should invoke Base::r.



- To invoke a routine defined in a referenced object, qualify member routine with **virtual**.

- To invoke a routine defined by the type of a pointer/reference, do not qualify member routine with **virtual**.

- C++ uses non-virtual as the default because it is more efficient.
- Java ***always*** uses virtual for all calls to objects.
- Once a base type qualifies a member as virtual, ***it is virtual in all derived types regardless of the derived type's qualification for that member***.
- Programmer may want to access members in Base even if the actual object is of type Derived, which is possible because Derived *contains* a Base.
- C++ provides mechanism to override the default at the call site.

Java	C++

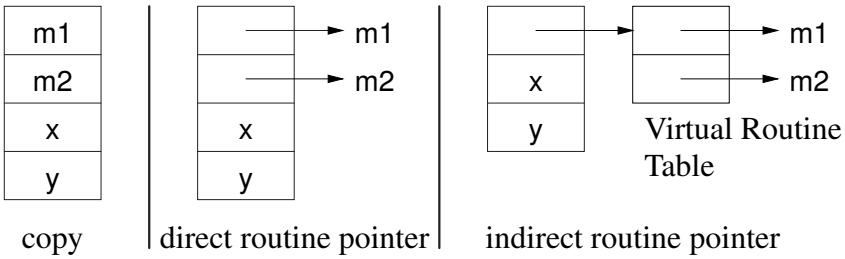
class Base {
  public void f() {} // *virtual*
  public void g() {} // *virtual*
  public void h() {} // *virtual*
}
class Derived **extends** Base {
  public void g() {} // *virtual*
  public void h() {} // *virtual*
  public void e() {} // *virtual*
}
final Base bp = **new** Derived();
bp.f(); // *Base.f*
((Base)bp).g(); // *Derived.g*
bp.g(); // *Derived.g*
((Base)bp).h(); // *Derived.h*
bp.h(); // *Derived.h*
	struct Base {
	  void f() {} // *non-virtual*
	  void g() {} // *non-virtual*
	  virtual void h() {} // *virtual*
	};
	struct Derived : **public** Base {
	  void g() {}; // *replace, non-virtual*
	  void h() {}; // *replace, virtual*
	  void e() {}; // *extension, non-virtual*
	};
	Base &bp = *__new__ Derived(); // *polymorphic assignment*
	bp.f(); // *Base::f, pointer type*
	bp.g(); // *Base::g, pointer type*
	((Derived &)bp).g(); // *Derived::g, pointer type*
	bp.Base::h(); // *Base::h, explicit selection*
	bp.h(); // *Derived::h, object type*
	// *cannot access "e" through bp*

- Java casting does not provide access to base-type's member routines.
- ***Virtual members are only necessary to access derived members through a base-type reference or pointer.***
- If a type is not involved in inheritance (final class in Java), virtual members are unnecessary so use more efficient call to its members.
- C++ virtual members are qualified in base type as opposed to derived type.
- Hence, C++ requires the base-type definer to presuppose how derived definers might want the call default to work.
- **Good practice for inheritable types is to make all routine members virtual.**
- Any type with virtual members needs to make the destructor virtual (even if empty) so the most derived destructor is called through a base-type pointer/reference.

- Virtual routines are normally implemented by routine pointers.

```
class Base {
    int x, y;                   // data members
    virtual void m1(...);       // routine members
    virtual void m2(...);
};
```

- Maybe implemented in a number of ways:



2.32.7 Downcast

- Type inheritance can mask the actual type of an object through a pointer/reference (see Section 2.32.2, p. 139).

- A **downcast** dynamically determines the actual type of an object pointed to by a polymorphic pointer/reference.

- The Java operator instanceof and the C++ **dynamic_cast** operator perform a dynamic check of the object addressed by a pointer/reference (not coercion):

Java	C++
Base bp = **new** Derived(); **if** (**bp instanceof Derived**) ((Derived)bp).rtn();	Base *bp = **new** Derived; Derived *dp; dp = **dynamic_cast<Derived *>(bp)**; **if** (dp != 0) { *// 0 => not Derived* dp->rtn(); *// only in Derived*

- ***To use* dynamic_cast *on a type, the type must have at least one virtual member.***

2.32.8 Slicing

- Polymorphic copy or assignment can result in object truncation, called **slicing**.

```
struct B {
    int i;
};
struct D : public B {
    int j;
};
void f( B b ) {...}
int main() {
    B b;
    D d;
    f( d );         // truncate D to B
    b = d;          // truncate D to B
}
```

- ***Avoid polymorphic value copy/assignment; use polymorphic pointers.***

2.32.9 Protected Members

- Inherited object types can access and modify public and protected members allowing access to some of an object's implementation.

```
class Base {
  private:
    int x;
  protected:
    int y;
  public:
    int z;
};
class Derived : public Base {
  public:
    Derived() { x; y; z; };  // x disallowed; y, z allowed
};
int main() {
    Derived d;
    d.x; d.y; d.z;          // x, y disallowed; z allowed
}
```

2.32.10 Abstract Class

- **Abstract class** combines type and implementation inheritance solely for structuring new types.

- Contains at least one pure virtual member that ***must*** be implemented by derived class.

```
class Shape {
    int colour;
  public:
    virtual void move( int x, int y ) = 0; // pure virtual member
};
```

- Strange initialization to 0 means pure virtual member.

- Define type hierarchy (taxonomy) of abstract classes moving common data and operations as high as possible in the hierarchy.

Java	C++

abstract class Shape {
  protected int colour = White;
  public
 	
  abstract void move(int x, int y);
}
abstract class Polygon **extends** Shape {
  protected int edges;
  public abstract int sides();
}
class Rectangle **extends** Polygon {
  protected int x1, y1, x2, y2;
 	
  public Rectangle(...) {...}
  public void move(**int** x, **int** y) {...}
  public int sides() { **return** 4; }
}
class Square **extends** Rectangle {
  // check square
  Square(...) { **super**(...); ...}
}
	class Shape {
	  protected: **int** colour;
	  public:
	  Shape() { colour = White; }
	  virtual void move(int x, int y) = 0;
	};
	class Polygon : **public** Shape {
	  protected: **int** edges;
	  public: **virtual int sides() = 0;**
	};
	class Rectangle : **public** Polygon {
	  protected: **int** x1, y1, x2, y2;
	  public:
	  Rectangle(...) {...} *// init corners*
	  void move(**int** x, **int** y) {...}
	  int sides() { **return** 4; }
	};
	struct Square : **public** Rectangle {
	  // check square
	  Square(...) : Rectangle(...) {...}
	};

- Use **public/protected** to define interface and implementation access for derived classes.
- Provide (pure) virtual member to allow overriding and force implementation by derived class.
- Provide default variable initialization and implementation for **virtual** routine (non-abstract) to simplify derived class.
- Provide non-virtual routine to ***force*** specific implementation; ***derived class should not override these routines***.
- **Concrete class** inherits from one or more abstract classes defining all pure virtual members, i.e., can be instantiated.
- ***Cannot instantiate abstract class, but can declare pointer/reference to it.***
- Pointer/reference used to write polymorphic data structures and routines:

```
void move3D( Shape &s ) { ... s.move(...); ... }
Polygon *polys[10] = { new Rectangle(), new Square(), ... };
for ( unsigned int i = 0; i < 10; i += 1 ) {
    cout << polys[i]->sides() << endl;  // polymorphism
    move3D( *polys[i] );  // polymorphism
}
```

- To maximize polymorphism, ***write code to the highest level of abstraction***[3], i.e. use Shape over Polygon, use Polygon over Rectangle, etc.

2.33 Template

- Inheritance provides reuse for types organized into a hierarchy that extends name equivalence.

- **Template** provides alternate kind of reuse with no type hierarchy and types are not equivalent.

- E.g., overloading (see Section 2.19, p. 93), where there is identical code but different types:

```
int max( int a, int b ) { return a > b ? a : b; }
double max( double a, double b ) { return a > b ? a : b; }
```

- **Template routine** eliminates duplicate code by using types as compile-time parameters:

```
template<typename T>  T max( T a, T b ) { return a > b ? a : b; }
```

- **template** introduces type parameter T used to declare return and parameter types.

- Template routine is called with value for T, and compiler constructs a routine with this type.

```
cout << max<int>( 1, 3 );     // T -> int
cout << max<double>( 1.1, 3.5 ); // T -> double
```

- In many cases, the compiler can infer type T from argument(s):

```
cout << max( 1, 3 );          // T -> int
cout << max( 1.1, 3.5 );      // T -> double
```

- Inferred type must supply all operations used within the template routine.

    - e.g., types used with template routine max must supply **operator>**.

- **Template type** prevents duplicating code that manipulates different types.

- E.g., collection data-structures (e.g., stack), have common code to manipulate data structure, but type stored in collection varies:

[3] Also called "program to an interface not an implementation", which does not indicate the highest level of abstraction.

```
template<typename T=int, unsigned int N=10> // default type/value
  struct Stack {                  // NO ERROR CHECKING
    T elems[N];                   // maximum N elements
    unsigned int size;            // position of free element after top
    Stack() { size = 0; }
    T top() { return elems[size - 1]; }
    void push( T e ) { elems[size] = e; size += 1; }
    T pop() { size -= 1; return elems[size]; }
};
template<typename T, unsigned int N>  // print stack
  ostream &operator<<( ostream &os, const Stack<T, N> &stk ) {
    for ( int i = 0; i < stk.size; i += 1 ) os << stk.elems[i] << " ";
    return os;
}
```

- Type parameter, T, specifies the element type of array elems, and return and parameter types of the member routines.

- Integer parameter, N, denotes the maximum stack size.

- Unlike template routines, type cannot be inferred by compiler because type is created at declaration before any member calls.

```
Stack<> si;                     // stack of int, 10
si.push( 3 );                   // si : 3
si.push( 4 );                   // si : 3 4
si.push( 5 );                   // si : 3 4 5
cout << si.top() << endl;       // 5
int i = si.pop();               // i : 5, si : 3 4
Stack<double> sd;               // stack of double, 10
sd.push( 5.1 );                 // sd : 5.1
sd.push( 6.2 );                 // sd : 5.1 6.2
cout << sd << endl;             // 5.1 6.2
double d = sd.pop();            // d : 6.2, sd : 5.1
Stack<Stack<int>,20> ssi;       // stack of (stack of int, 10), 20
ssi.push( si );                 // ssi : (3 4)
ssi.push( si );                 // ssi : (3 4) (3 4)
ssi.push( si );                 // ssi : (3 4) (3 4) (3 4)
cout << ssi << endl;            // 3 4  3 4  3 4
si = ssi.pop();                 // si : 3 4, ssi : (3 4) (3 4)
```

  Why does cout << ssi << endl have 2 spaces between the stacks?

- Specified type must supply all operations used within the template type.

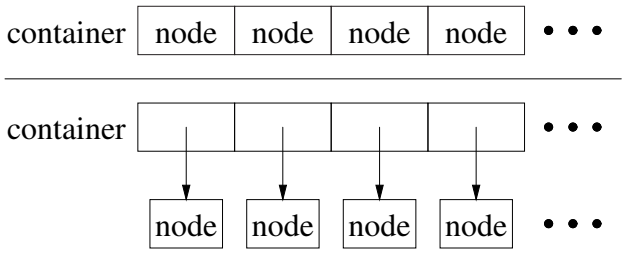
- ***Compiler requires a template definition for each usage so both the interface and implementation of a template must be in a .h file, precluding some forms of encapsulation and separate compilation.***

- ***C++03 requires space between the two ending chevrons or >> is parsed as operator>>.***

```
template<typename T> struct Foo { ... };
Foo<Stack<int>> foo;  // syntax error (fixed C++11)
Foo<Stack<int> > foo; // space between chevrons
```

2.33.1 Standard Library

- C++ Standard Library is a collection of (template) classes and routines providing: I/O, strings, data structures, and algorithms (sorting/searching).
- Data structures are called **container**s: vector, map, list (stack, queue, deque).
- In general, nodes of a data structure are either in a container or pointed-to from the container.

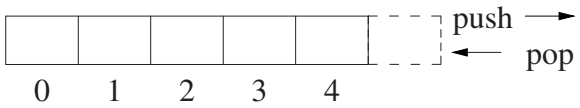


- To copy a node into a container requires its type have a default and/or copy constructor so instances can be created without constructor arguments.
- ***Standard library containers use copying ⇒ node type must have default constructor.***
- **All containers are dynamic sized so nodes are allocated in heap** (arrays can be on stack).
- To provide encapsulation (see Section 2.30, p. 130), containers use a nested **iterator** type (see Section 2.14, p. 85) to traverse nodes.
    - Knowledge about container implementation is completely hidden.
- Iterator capabilities often depend on kind of container:
    - singly-linked list has unidirectional traversal
    - doubly-linked list has bidirectional traversal
    - hashing list has random traversal
- Iterator operator "++" moves forward to the next node, until ***past*** the end of the container.
- For bidirectional iterators, operator "−−" moves in the reverse direction to "++".

2.33.1.1 Vector

- vector has random access, length, subscript checking (at), and assignment (like Java array).

std::vector<T>	
vector() vector(size, *[initialization]*) ~vector()	create empty vector create vector with N empty/initialized elements erase all elements
unsigned int size() **bool** empty() T &**operator**[](**int** i) T &at(**int** i)	vector size size() == 0 access ith element, NO subscript checking access ith element, subscript checking
vector &**operator**=(**const** vector &) **void** push_back(**const** T &x) **void** pop_back() **void** resize(**int** n) **void** clear() iterator begin() iterator end() iterator rbegin() iterator rend() iterator insert(iterator posn, **const** T &x) iterator erase(iterator posn)	vector assignment add x after last element remove last element add or erase elements at end so size() == n erase all elements iterator pointing to first element iterator pointing **AFTER** last element iterator pointing to last element iterator pointing **BEFORE** first element insert x before posn erase element at posn



- Vector declaration ***may*** specify an initial size, e.g., vector<**int**> v(size), like a dimension.

- When size is known, more efficient to dimension and initialize to reduce dynamic allocation.

```
int size;
cin >> size;                    // read dimension
vector<int> v1( size );         // think int v1[size]
vector<int> v2( size, 0 );      // think int v2[size] = { 0 }
int a[] = { 16, 2, 77, 29 };
vector<int> v3( a, &a[4] );     // think int v3[4]; v3 = a;
vector<int> v4( v3 );           // think int v4[size]; v4 = v3
```

- vector is alternative to C/C++ arrays (see Section 2.12.3.1, p. 78).

```
#include <vector>
int i, elem;
vector<int> v;                  // think: int v[0]
for ( ;; ) {                    // create/assign vector
    cin >> elem;
  if ( cin.fail() ) break;
    v.push_back( elem );        // add elem to vector
}
vector<int> c;                  // think: int c[0]
c = v;                          // array assignment
for ( i = c.size() - 1; 0 <= i; i -= 1 ) {
    cout << c.at(i) << " ";     // subscript checking
}
cout << endl;
v.clear();                      // remove ALL elements for reuse
```

- vector does not grow implicitly for subscripting.

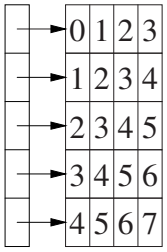
```
v[27] = 17;                     // segmentation fault!
v.at(27) = 17;                  // out_of_range exception (subscript error)
```

- Matrix declaration is a vector of vectors (see also page 85):

```
vector< vector<int> > m;
```

- Again, it is more efficient to dimension, when size is known.

```
#include <vector>
vector< vector<int> > m( 5, vector<int>(4) );
for ( int r = 0; r < m.size(); r += 1 ) {
    for ( int c = 0; c < m[r].size(); c += 1 ) {
        m[r][c] = r+c;      // or m.at(r).at(c)
    }
}
for ( int r = 0; r < m.size(); r += 1 ) {
    for ( int c = 0; c < m[r].size(); c += 1 ) {
        cout << m[r][c] << ", ";
    }
    cout << endl;
}
```

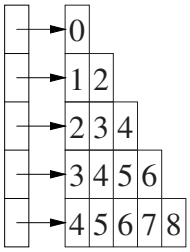


- Optional second argument is initialization value for each element, i.e., 5 rows of vectors each initialized to a vector of 4 integers initialized to zero.

- All loop bounds use dynamic size of row or column (columns may be different length).

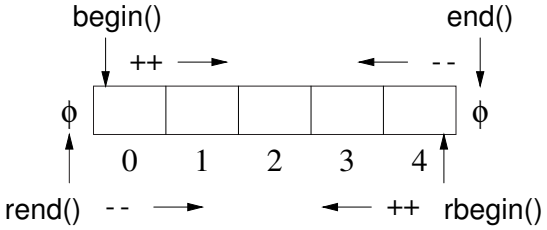
- Alternatively, each row is dynamically dimensioned to a specific size, e.g., triangular matrix.

```
vector< vector<int> > m( 5 ); // 5 empty rows
for ( int r = 0; r < m.size(); r += 1 ) {
    m[r].resize( r + 1 ); // different length
    for ( int c = 0; c < m[r].size(); c += 1 ) {
        m[r][c] = r+c;     // or m.at(r).at(c)
    }
}
```



- Iterator allows traversal in insertion order or random order.

std::vector<T>::iterator	
++, −− (insertion order)	forward/backward operations
+, +=, −, −= (random order)	movement operations



- Iterator's value is a pointer to its current vector element ⇒ dereference to access element.

```
vector<int> v(3);
vector<int>::iterator it;
v[0] = 2;                   // initialize first element
it = v.begin();             // intialize iterator to first element
cout << v[0] << " " << *v.begin() << " " << *it << endl;
```

- ***If* erase *and* insert *took subscript argument, no iterator necessary!***

- Use iterator like subscript for random access by adding/subtracting from begin/end.

```
v.erase( v.begin() );       // erase v[0], first
v.erase( v.end() - 1 );     // erase v[N - 1], last (why "- 1"?)
v.erase( v.begin() + 3 );   // erase v[3]
```

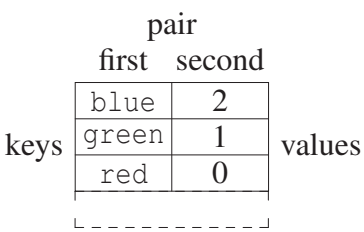
- ***Insert or erase during iteration using an iterator causes failure.***

```
vector<int> v;
for ( int i = 0 ; i < 5; i += 1 ) // create
    v.push_back( 2 * i );          // values: 0, 2, 4, 6, 8

v.erase( v.begin() + 3 );          // remove v[3] : 6

int i;    // find position of value 4 using subscript
for ( i = 0; i < 5 && v[i] != 4; i += 1 );
v.insert( v.begin() + i, 33 );     // insert 33 before value 4

// print reverse order using iterator (versus subscript)
vector<int>::reverse_iterator r;
for ( r = v.rbegin(); r != v.rend(); r ++ ) // ++ move towards rend
    cout << *r << endl;            // values: 8, 4, 33, 2, 0
```

2.33.1.2 Map

- map (dictionary) has random access, sorted, unique-key container of pairs (Key, Val).
- set (dictionary) is like map but the value is also the key (array maintained in sorted order).

std::map<Key,Val> / std::pair<**const** Key,Val>	
map(*[initialization]*) ~map()	create empty/initialized map erase all elements
unsigned int size() **bool** empty() Val &**operator**[](**const** Key &k) **int** count(Key key)	map size size() == 0 access pair with Key k 0 ⇒ no key, 1 ⇒ key (unique keys)
map &**operator**=(**const** map &) insert(pair<**const** Key,Val>(k, v)) erase(Key k) **void** clear() iterator begin() iterator end() iterator rbegin() iterator rend() iterator find(Key &k) iterator insert(iterator posn, **const** T &x) iterator erase(iterator posn)	map assignment insert pair erase key k erase all pairs iterator pointing to first pair iterator pointing **AFTER** last pair iterator pointing to last pair iterator pointing **BEFORE** first pair find position of key k insert x before posn erase pair at posn



```
#include <map>
map<string, int> m;             // Key => string, Val => int
m["green"] = 1;                 // create, set to 1
m["blue"] = 2;                  // create, set to 2
m["red"];                       // create, set to 0 for int
m["green"] = 5;                 // overwrite 1 with 5
cout << m["green"] << endl; // print 5
m.insert( pair<string,int>( "yellow", 3 ) ); // m["yellow"] = 3
map<string, int> c( m );        // Key => string, Val => int
c = m;                          // map assignment
if ( c.count( "black" ) != 0 ) // check for key "black"
c.erase( "blue" );              // erase pair( "blue", 2 )
```

- First key subscript creates entry; initialized to default or specified value.

- Iterator can search and return values in key order.

std::map<T>::iterator / std::map<T>::reverse_iterator	
++, -- (sorted order)	forward/backward operations

- Iterator returns a pointer to a pair, with fields first (key) and second (value).

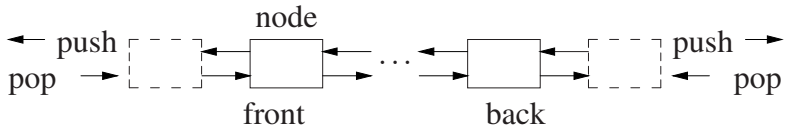
```
#include <map>
map<string,int>::iterator f = m.find( "green" ); // find key position
if ( f != m.end() )             // found ?
    cout << "found " << f->first << ' ' << f->second << endl;

for ( f = m.begin(); f != m.end(); f ++ )  // increasing order
    cout << f->first << ' ' << f->second << endl;

map<string,int>::reverse_iterator r;
for ( r = m.rbegin(); r != m.rend(); r ++ )  // decreasing order
    cout << r->first << ' ' << r->second << endl;
m.clear();                      // remove ALL pairs
```

2.33.1.3 List

- In certain cases, it is more efficient to use a single (stack/queue/deque) or double (list) linked-list container than random-access container.

- Examine list (arbitrary removal); stack, queue, deque are similar (restricted insertion/removal).

std::list<T>	
list()	create empty list
list(size, *[initialization]*)	create list with N empty/initialized elements
~list()	erase all elements
unsigned int size()	list size
bool empty()	size() == 0
list &**operator**=(**const** list &)	list assignment
T front()	first node
T back()	last node
void push_front(**const** T &x)	add x before first node
void push_back(**const** T &x)	add x after last node
void pop_front()	remove first node
void pop_back()	remove last node
void clear()	erase all nodes
iterator begin()	iterator pointing to first node
iterator end()	iterator pointing **AFTER** last node
iterator rbegin()	iterator pointing to last node
iterator rend()	iterator pointing **BEFORE** first node
iterator insert(iterator posn, **const** T &x)	insert x before posn
iterator erase(iterator posn)	erase node at posn



- Like vector, list declaration ***may*** specify an initial size, like a dimension.

- When size is known, more efficient to dimension and initialize to reduce dynamic allocation.

```
int size;
cin >> size;                    // read dimension
list<int> l1( size );
list<int> l2( size, 0 );
int a[] = { 16, 2, 77, 29 };
list<int> l3( a, &a[4] );
list<int> l4( l3 );
```

- Iterator returns a pointer to a node.

std::list<T>::iterator / std::list<T>::reverse_iterator	
++, −− (insertion order)	forward/backward operations

```
#include <list>
struct Node {
    char c;  int i;  double d;
    Node( char c, int i, double d ) : c(c), i(i), d(d) {}
};
list<Node> dl;                          // doubly linked list
for ( int i = 0; i < 10; i += 1 ) {     // create list nodes
    dl.push_back( Node( 'a'+i, i, i+0.5 ) ); // push node on end of list
}
list<Node>::iterator f;
for ( f = dl.begin(); f != dl.end(); f ++ ) { // forward order
    cout << "c:" << f->c << " i:" << f->i << " d:" << f->d << endl;
}
while ( 0 < dl.size() ) {               // destroy list nodes
    dl.erase( dl.begin() );             // remove first node
} // same as dl.clear()
```

2.33.1.4 for_each

- Template routine for_each provides an alternate mechanism to iterate through a container.
- An action routine is called for each node in the container passing the node to the routine for processing (Lisp apply).

```
#include <iostream>
#include <list>
#include <vector>
#include <algorithm>                    // for_each
using namespace std;
void print( int i ) { cout << i << " "; } // print node
int main() {
    list< int > int_list;
    vector< int > int_vec;
    for ( int i = 0; i < 10; i += 1 ) { // create lists
        int_list.push_back( i );
        int_vec.push_back( i );
    }
    for_each( int_list.begin(), int_list.end(), print ); // print each node
    for_each( int_vec.begin(), int_vec.end(), print );
}
```

- Type of the action routine is **void** rtn(T), where T is the type of the container node.
- E.g., print has an **int** parameter matching the container node-type.
- Use functor (see page 130) (retain state between calls) for more complex actions.
- E.g., an action to print on a specified stream must store the stream and have an **operator**() allowing the object to behave like a function:

```
struct Print {
    ostream &stream;                    // stream used for output
    Print( ostream &stream ) : stream( stream ) {}
    void operator()( int i ) { stream << i << " "; }
};
int main() {
    list< int > int_list;
    vector< int > int_vec;
    ...
    for_each( int_list.begin(), int_list.end(), Print(cout) );
    for_each( int_vec.begin(), int_vec.end(), Print(cerr) );
}
```

- Expression Print(cout) creates a constant Print object, and for_each calls **operator**()(Node) in the object.

2.34 Git, Advanced

Git Command	Action
add *file/dir-list*	schedules files for addition to repository
checkout *repository-name*	extract working copy from the repository
clone *file/dir-list*	checkout branch or paths to working tree
commit -m "string"	update the repository with changes in working copy
config	update the repository with changes in working copy
rm *file/dir-list*	remove files from working copy and schedule removal from repository
diff	show changes between commits, commit and working tree, etc.
init	create empty git repository or reinitialize an existing one
log	show commit logs
mv *file/dir-list*	rename file in working copy and schedule renaming in repository
rm	remove files from the working tree and from the index
remote	manage set of tracked repositories
status	displays changes between working copy and repository

2.34.1 Gitlab Global Setup

- Create a gitlab project and add partner to the project.

1. sign onto Gitlab https://git.uwaterloo.ca
2. click **New project** on top right
3. enter **Project path** "project name", e.g., WATCola, CC3K
4. enter **Description** of project
5. click **Visibility Level** Private (should be default)
6. click **Create Project** (project page appears)

7. click **HTTPS** and get URL: **https://git.uwaterloo.ca/jfdoe/project.git**
   - alternative: create SSH key, load SSH key into gitlab, and click **SSH**
8. click **Project Members** (seventh icon on left icon bar, looks like a student's head exploding)
9. click **Add members**
10. type your partner's userid (or name) into **People** and select your partner when their name appears
11. click **Project Access** and select Master (allows push/pull to your project)
12. click **Add users to project**

2.34.2 Git Local Setup

- create local repository directory and change to that directory.

```
$ mkdir project
$ cd project
```

- init : create and initialize a repository.

```
$ git init     # create empty git repository or reinitialize existing one
Initialized empty Git repository in /u/jfdoe/project/.git/
$ ls -aF
./  ../  .git/
```

  - creates hidden directory .git to store local repository information.

- remote : connect local with global repository

```
$ git remote add origin https://git.uwaterloo.ca/jfdoe/project.git
```

  If mistake typing **origin** URL, remove and add again.

```
$ git remote rm origin
```

- status : compare working copy structure with local repository

```
$ git status
# On branch master
#
# Initial commit
nothing to commit (create/copy files and use "git add" to track)
```

- add : add file contents to index

```
$ emacs README.md   # project description
$ git add README.md
$ git status
# On branch master
#
# Initial commit
#
# Changes to be committed:
#   (use "git rm --cached <file>..." to unstage)
#
#    new file:   README.md
```

- By convention, file README.md contains short description of project.
- If project directory exists, create README.md and add existing files.
- ***Addition only occurs on next commit.***
- Forgetting git add for new files is a common mistake.
- ***Add only source files into repository***, e.g., *.o, *.d, a.out, do not need to be versioned.
- Create hidden file .gitignore in projct directory and list working files not versioned.

```
# ignore self
.gitignore
# build files
*.[do]
a.out
```

- commit : record changes to local repository

```
$ git commit -a -m "initial commit"
[master (root-commit) e025356] initial commit
 1 file changed, 1 insertion(+)
 create mode 100644 README.md
$ git status
# On branch master
nothing to commit (working directory clean)
```

- -a (all) automatically stage modified and deleted files
- -m (message) flag documents repository change.
- if no -m (message) flag specified, prompts for documentation (using an editor if shell environment variable EDITOR set).

- push : record changes to global repository

```
$ git push -u origin master
Username for 'https://git.uwaterloo.ca': jfdoe
Password for 'https://jfdoe@git.uwaterloo.ca': xxxxxxxx
Counting objects: 3, done.
Writing objects: 100% (3/3), 234 bytes, done.
Total 3 (delta 0), reused 0 (delta 0)
To gitlab@git.uwaterloo.ca:jfdoe/project.git
 * [new branch]      master -> master
Branch master set up to track remote branch master from origin.
```

- Options **-u origin master** only required for first push of newly created repository.
- Subsequently, use **git push** with no options.
- ***Always make sure your code compiles and runs before pushing;*** it is unfair to pollute a shared global-repository with bugs.

- After project starts, joining developers ***clone*** the existing project.

```
$ git clone https://git.uwaterloo.ca/jfdoe/project.git
Username for 'https://git.uwaterloo.ca': kdsmith
Password for 'https://jfdoe@git.uwaterloo.ca': yyyyyyyy
```

- pull : record changes from global repository

```
$ git pull
Username for 'https://git.uwaterloo.ca': jfdoe
Password for 'https://jfdoe@git.uwaterloo.ca': xxxxxxxx
```

All developers must periodically ***pull*** the latest global version to local repository.

2.34.3 Modifying

- Editted files in working copy are implicitly ***scheduled*** for update on next commit.

```
$ emacs README.md # modify project description
```

- Add more files.

```
$ mkdir gizmo
$ cd gizmo
$ emacs Makefile x.h x.cc y.h y.cc    # add text into these files
$ ls -aF
./  ../  Makefile  x.cc  x.h  y.cc  y.h
$ git add Makefile  x.cc  x.h  y.cc  y.h
```

```
$ git status
# On branch master
# Changes to be committed:
#   (use "git reset HEAD <file>..." to unstage)
#
#   new file:   Makefile
#   new file:   x.cc
#   new file:   x.h
#   new file:   y.cc
#   new file:   y.h
#
# Changes not staged for commit:
#   (use "git add <file>..." to update what will be committed)
#   (use "git checkout -- <file>..." to discard changes in working directory)
#
#   modified:   ../README.md
```

- Commit change/adds to local repository.

```
$ git commit -a -m "update README.md, add gizmo files"
[master 0f4162d] update README.md, add gizmo files
 6 files changed, 6 insertions(+)
 create mode 100644 gizmo/Makefile
 create mode 100644 gizmo/x.cc
 create mode 100644 gizmo/x.h
 create mode 100644 gizmo/y.cc
 create mode 100644 gizmo/y.h
$ git status
# On branch master
# Your branch is ahead of 'origin/master' by 1 commit.
#
# nothing to commit (working directory clean)
```

- rm removes files from **BOTH local directory and repository**.

```
$ git rm x.*                    # globbing allowed
rm 'gizmo/x.cc'
rm 'gizmo/x.h'
$ ls -aF
./  ../  Makefile  y.cc  y.h
$ git status
# On branch master
# Your branch is ahead of 'origin/master' by 1 commit.
#
# Changes to be committed:
#   (use "git reset HEAD <file>..." to unstage)
#
#   deleted:    x.cc
#   deleted:    x.h
```

  Use --cached option to ***ONLY*** remove from repository.

- And update a file.

```
$ emacs y.cc          # modify y.cc
```

- Possible to revert state of working copy ***BEFORE*** commit.

```
$ git checkout HEAD x.cc x.h y.cc  # cannot use globbing
$ ls -aF
./  ../  Makefile  x.cc  x.h  y.cc  y.h
$ git status
# On branch master
# Your branch is ahead of 'origin/master' by 1 commit.
#
# nothing to commit (working directory clean)
```

  - **HEAD** is symbolic name for last commit,
    titled "update README.md, add gizmo files".

- Possible to revert state ***AFTER*** commit by accessing files in previous commits.

```
$ git commit -a -m "remove x files, update y.cc"
[master ecfbac4] remove x files, update y.cc
 3 files changed, 1 insertion(+), 2 deletions(-)
 delete mode 100644 gizmo/x.cc
 delete mode 100644 gizmo/x.h
```

- Revert state from previous commit.

```
$ git checkout HEAD~1 x.cc x.h y.cc
$ ls -aF
./  ../  Makefile  x.cc  x.h  y.cc  y.h
```

  - **HEAD~1** means one before current commit (subtract 1),
    titled "update README.md, add gizmo files".

- Check log for revision number.

```
$ git log
commit ecfbac4b80a2bf5e8141bddfdd2eef2f2dcda799
Author: Jane F Doe <jfdoe@uwaterloo.ca>
Date:   Sat May 2 07:30:17 2015 -0400

    remove x files, update y.cc

commit 0f4162d3a95a2e0334964f95495a079341d4eaa4
Author: Jane F Doe <jfdoe@uwaterloo.ca>
Date:   Sat May 2 07:24:40 2015 -0400

    update README.md, add gizmo files

commit e025356c6d5eb2004314d54d373917a89afea1ab
Author: Jane F Doe <jfdoe@uwaterloo.ca>
Date:   Sat May 2 07:04:10 2015 -0400

    initial commit
```

  - Count top to bottom for relative commit number, or use a commit name ecfbac4b80a2bf5e8141bddfdd2eef2f2dcda799.

- Commit restored files into local repository.

```
$ git commit -a -m "undo file changes"
[master 265d6f8] undo files changes
 3 files changed, 2 insertions(+), 1 deletion(-)
 create mode 100644 gizmo/x.cc
 create mode 100644 gizmo/x.h
```

- git mv renames file in BOTH local directory and repository.

```
$ git mv x.h w.h
$ git mv x.cc w.cc
$ ls -aF
./  ../  Makefile  w.cc  w.h  y.cc  y.h
```

- Copy files in the repository by copying working-copy files and add them.

```
$ cp y.h z.h
$ cp y.cc z.cc
$ git add z.*
$ git status
# On branch master
# Your branch is ahead of 'origin/master' by 3 commits.
#
# Changes to be committed:
#   (use "git reset HEAD <file>..." to unstage)
#
#   renamed:   x.cc -> w.cc
#   renamed:   x.h -> w.h
#   new file:   z.cc
#   new file:   z.h
```

- Commit changes in local repository.

```
$ git commit -a -m "renaming and copying"
[master 0c5f473] renaming and copying
 4 files changed, 2 insertions(+)
 rename gizmo/{x.cc => w.cc} (100%)
 rename gizmo/{x.h => w.h} (100%)
 create mode 100644 gizmo/z.cc
 create mode 100644 gizmo/z.h
```

- Push changes to global repository.

```
$ git push
Counting objects: 19, done.
Delta compression using up to 48 threads.
Compressing objects: 100% (10/10), done.
Writing objects: 100% (17/17), 1.34 KiB, done.
Total 17 (delta 1), reused 0 (delta 0)
To gitlab@git.uwaterloo.ca:jfdoe/project.git
   e025356..0c5f473  master -> master
Branch master set up to track remote branch master from origin.
```

- Only now can partner see changes.

2.34.4 Conflicts

- When multiple developers work on ***SAME*** files, source-code conflicts occur.

jfdoe	kdsmith
modify y.cc	modify y.cc
	remove y.h
	add t.cc

- Assume kdsmith commits and pushes changes.

- jfdoe commits change and attempts push.

```
$ git push
To gitlab@git.uwaterloo.ca:jfdoe/project.git
 ! [rejected]        master -> master (non-fast-forward)
error: failed to push some refs to 'gitlab@git.uwaterloo.ca:jfdoe/project.git'
To prevent you from losing history, non-fast-forward updates were rejected
Merge the remote changes (e.g. 'git pull') before pushing again.  See the
'Note about fast-forwards' section of 'git push --help' for details.
```

- Resolve differences between local and global repository by **pulling**.

```
$ git pull
remote: Counting objects: 5, done.
remote: Compressing objects: 100% (3/3), done.
remote: Total 5 (delta 1), reused 0 (delta 0)
Unpacking objects: 100% (5/5), done.
From git.uwaterloo.ca:jfdoe/project
   2a49710..991683a  master     -> origin/master
Removing gizmo/y.h
Auto-merging gizmo/y.cc
CONFLICT (content): Merge conflict in gizmo/y.cc
Automatic merge failed; fix conflicts and then commit the result.
```

- File y.h is deleted, t.cc added, but conflict reported in gizmo/y.cc

```
$ ls -aF
./  ../  Makefile  t.cc  w.cc  w.h  y.cc  z.cc  z.h
$ cat y.cc
<<<<<<< HEAD
I like file y.cc
=======
This is file y.cc
>>>>>>> 5d89df953499a8fdfd6bc92fa3a6be9c8358dbd1
```

- Chevrons "<" bracket conflicts throughout the file.
- jfdoe can resolve by reverting their change or getting kdsmith to revert their change.
- No further push allowed by jfdoe until conflict is resolved but can continue to work in local repository.
- jfdoe decides to revert to kdsmith version by removing lines from file.

  ```
  $ cat y.cc
  This is file y.cc
  ```

  and commits the reversion so pull now indicates up-to-date.

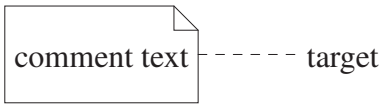
  ```
  $ git commit -a -m "revert y.cc"
  [master 5497d17] revert y.cc
  $ git pull
  Already up-to-date.
  ```

- Conflict resolution tools exist to help with complex conflicts (unnecessary for this course).

2.35 UML

- **Unified Modelling Language** (UML) is a graphical notation for describing and designing software systems, with emphasis on the object-oriented style.
- UML modelling has multiple viewpoints:
  - **class model** : describes static structure of the system for creating objects
  - **object model** : describes dynamic (temporal) structure of system objects
  - **interaction model** : describes the kinds of interactions among objects

  Focus on class modelling.
- Note / comment



- **Classes diagram** defines class-based modelling, where a class is a type for instantiating objects.

- Class has a name, attributes and operations, and may participate in inheritance hierarchies.

class name	Person	
attributes (data)	- name : String - age : Integer - sex : Boolean - owns : Car [0..5]	optional
operations (routines)	+ getName : String + getAge : Integer + getCars : Car [0..5] + buy(in car : Car, inout card : CreditCard) : Boolean	optional

- **Attribute** describes a property in a class.

  [visibility] name [":" [type] ["[" multiplicity "]"] ["=" default]]

  - visibility : access to property
    $+ \Rightarrow$ public, $- \Rightarrow$ private, $\# \Rightarrow$ protected, $\sim \Rightarrow$ package
  - name : identifier for property (like field name in structure)
  - type : kind of property (language independent)
    Boolean, Integer, Float, String, class-name
  - multiplicity : cardinality for instantiation of property:
    $0..(N|*)$, 0 to N or unlimited,
    N short for $N..N$,
    $*$ short for $0..*$,
    defaults to 1
  - default : expression that evaluates to default value(s) for property

- **operation** : action invoked in context of object from the class

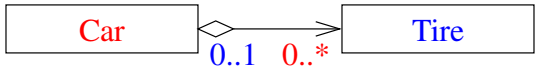
  [visibility] name ["(" [parameter-list] ")"] [":" return-type] ["[" multiplicity "]"]

  - parameter-list : comma separated list of input/output types for operation
    [direction] parameter-name ":" type ["[" multiplicity "]"]
    ["=" default] ["{" modifier-list "}"]]
  - direction : direction of parameter data flow
    "in" (default) | "out" | "inout"
  - return-type : output type from operation

- **Only specify attributes/operations useful in modelling: no flags, counters, temporaries, constructors, helper routines, etc.**

- Attribute with type other than basic type often has an **association**: aggregation or composition.

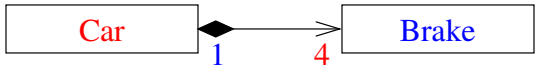
- **Aggregation** (◇) is an association between an aggregate attribute and its parts (**has-a**).



  - car can have 0 or more tires and a tire can only be on 0 or 1 car
  - aggregate may not create/destroy its parts, e.g., many different tires during car's lifetime and tires may exist after car's lifetime (snow tires).

```
class Car {
    Tires *tires[4];  // array of pointers to tires
    ...
```

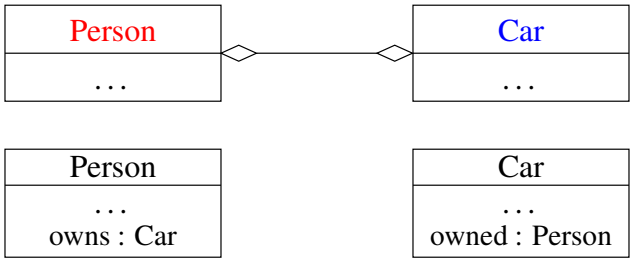
- **Composition** (◆) is a stronger aggregation where a part is included in at most one composite at a time (**owns-a**).



  - car has 4 brakes and each brake is on 1 car
  - composite aggregate often does create/destroy its parts, i.e., same brakes for lifetime of car and brakes deleted when car deleted (unless brakes removed at junkyard)

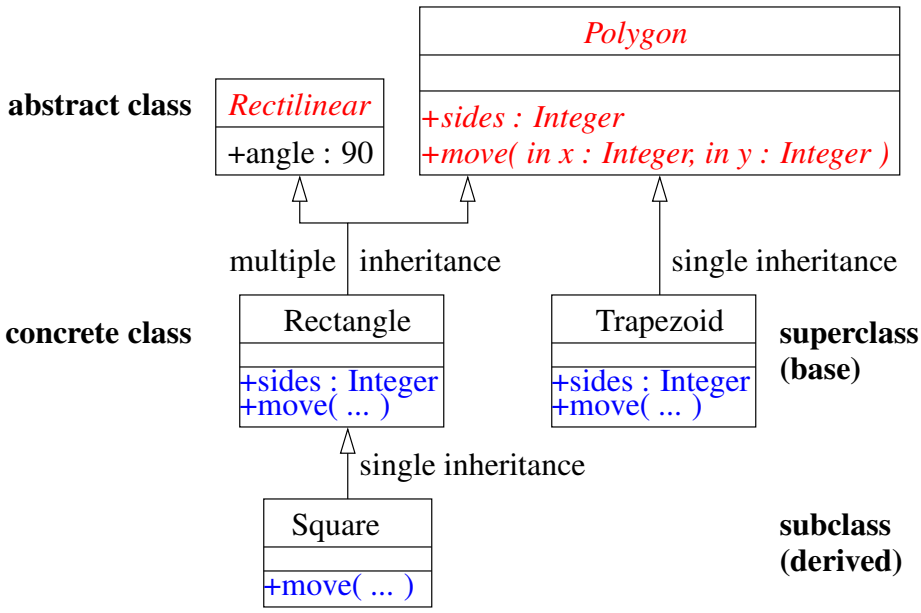
```
class Car {
    DiscBrake brakes[4];  // array of brakes
    ...
```

- Association can be written with an attribute or line, as well as bidirectional.



  - If UML graph is cluttered with lines, create association in class rather than using a line.
  - E.g., if 20 classes associated with Car, replace 20 lines with attributes in each class.

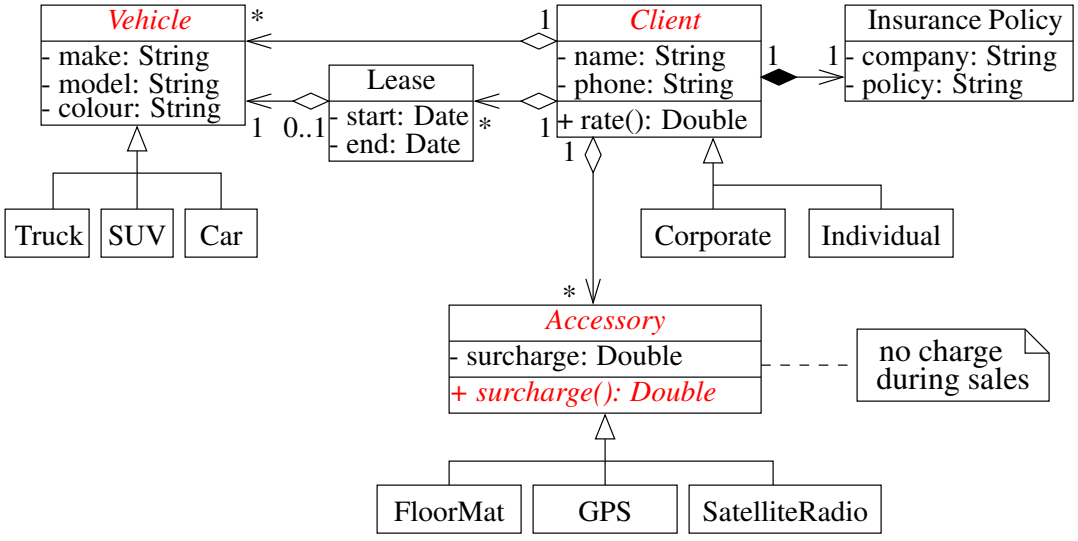
- **Generalization** : reuse through forms of inheritance.



- Represent inheritance by arrowhead △ to establish is-a relationship on type, and reuse of attributes and operations.
- Association class can be implemented with forms of multiple inheritance (mixin).

- For abstract class, the class name and abstract operations are *italicized*.

Classes Diagram



- **UML diagram is too complex if it contains more than about 25 boxes.**

- UML has many facilities, supporting complex descriptions of relationships among entities.

2.36 Composition / Inheritance Design

- Duality between "has-a" (composition) and "is-a" (inheritance) relationship (see page 137).
- Types created from multiple composite classes; types created from multiple superclasses.

Composition	Inheritance
class A {...}; **class** B { A a; ...}; **class** C {...}; **class** D { B b; C c; ...};	**class** A {...}; **class** B : A {...}; **class** C {...}; **class** D : B, C {...};

- Both approaches:
  - remove duplicated code (variable/code sharing)
  - have separation of concern into components/superclasses.
- Choose inheritance when evolving hierarchical types (taxonomy) needing polymorphism.

```
Vehicle
  Construction
    Heavy Machinery
      Crane, Grader, Back-hoe
    Haulage
      Semi-trailer, Flatbed
  Passenger
    Commercial
      Bus, Fire-truck, Limousine, Police-motorcycle
    Personal
      Car, SUV, Motorcycle
```

- For maximum reuse and to eliminate duplicate code, place variables/operations as high in the hierarchy as possible.
- ***Polymorphism requires derived class maintain base class's interface (substitutability).***
  - derived class should also have **behavioural** compatibility with base class.
- However, all taxonomies are an organizational compromise: when is a car a limousine and vice versa.
- Not all objects fit into taxonomy: flying-car, boat-car.
- Inheritance is rigid hierarchy.
- Choose composition when implementation can be **delegated**.

```
class Car {
    SteeringWheel s;      // fixed
    Donut spare;
    Wheel *wheels[4];     // dynamic
    Engine *eng;
    Transmission *trany;
  public:
    Car( Engine *e = fourcyl, Transmission *t = manual ) :
        eng( e ), trany( t ) { wheels[i] = ...}
    rotate() {...}            // rotate tires
    wheels( Wheels *w[4] ) {...} // change wheels
    engine( Engine *e ) {...}  // change engine
};
```

- Composition may be fixed or dynamic (pointer/reference).
- Composition still uses hierarchical types to generalize components.
    - Engine is abstract class that is specialized to different kinds of engines, e.g., 3,4,6,8 cylinder, gas/diesel/hybrid, etc.

2.37 Design Patterns

- **Design pattern**s have existed since people/trades developed formal approaches.
- E.g., chef's cooking meals, musician's writing/playing music, mason's building pyramid/cathedral.
- **Pattern** is a common/repeated issue; it can be a problem or a solution.
- Name and codify common patterns for educational and communication purposes.
- Patterns help:
    - extend developers' vocabulary
    - offer higher-level abstractions than routines or classes

2.37.1 Singleton Pattern

- **singleton** patterns single instance of class

```
#include <Database.h>
class Database {
    Database() { ... } // no create, copy, assignment
    Database( const Database &database ) { ... }
    Database &operator=( const Database &database ) { ... }
  public:
    static Database &getDB() {
        static Database database;  // actual database object
        return database;
    }
    ... // members to access database
};
```

- Allow each users to have they own declaration but still access same value.

```
Database &database = Database::getDB(); // user 1
Database &db = Database::getDB(); // user 2
Database &info = Database::getDB(); // user 3
```

- Alternative is global variable, which forces name and may violate abstraction.

2.37.2 Template Method

- **template method** : provide algorithm but defer some details to subclass

```
class PriceTag {                        // abstract template
    virtual string label() = 0;         // details for subclass
    virtual string price() = 0;
    virtual string currency() = 0;
  public:
    string tag() { return label() + price() + currency(); }
};
class FurnitureTag : public PriceTag {  // actual method
    string label() { return "furniture "; }
    string price() { return "$1000 "; }
    string currency() { return "Cdn"; }
};
class ClothingTag : public PriceTag {   // actual method
    ...
};
FurnitureTag ft;
ClothingTag ct;
cout << ft.tag() << " " << ct.tag() << endl;
```

- template-method routines are non-virtual, i.e., not overridden

2.37.3 Observer Pattern

- **observer** pattern : 1 to many dependency $\Rightarrow$ change updates dependencies

```
struct Fan {                            // abstract
    Band &band;
    Fan( Band &band ) : band( band ) {}
    virtual void notify( CD cd ) = 0;
};
struct Groupie : public Fan {           // concrete
    Groupie( Band &band ) : Fan( band ) { band.attach( *this ); }
    ~Groupie() { band.deattach( *this ); }
    void notify( CD cd ) { buy/listen new cd }
};
struct Band {
    list<Fan *> fans;                   // list of fans
    void attach( Fan &fan ) { fans.push_back( &fan ); }
    void deattach( Fan &fan ) { fans.remove( &fan ); }
    void notifyFans() { /* loop over fans performing action */ }
};
Band dust;                              // create band
Groupie g1( dust ), g2( dust );         // register
dust.notifyFans();                      // inform fans about new CD
```

- manage list of interested objects, and push new events to each
- alternative design has interested objects pull the events from the observer
    - ⇒ observer must store events until requested

2.37.4 Decorator Pattern

- **decorator** pattern : attach additional responsibilities to an object dynamically

```
struct Window {                         // abstract
    virtual void scroll( int amt ) = 0;
    virtual void setTitle( string t ) = 0;
    virtual void draw() = 0;
    ...
};
struct PlainWindow : public Window { // concrete
    void scroll( int amt ) { };
    void setTitle( string t ) { };
    void draw() { /* draw a plain window */ };
};
struct Decorator : public Window {  // specialize
    Window &component;              // composition
    Decorator( Window &component ) : component( component ) {}
    void scroll( int amt ) { component.scroll( amt ); };
    void setTitle( string t ) { component.setTitle( t ); };
    void draw() { component.draw(); };
};
```

```
struct Scrollbar : public Decorator {       // specialize
    ...
    enum Kind { Hor, Ver };
    Scrollbar( Window &window, Kind k ) : Decorator( window ), ... {}
    void scroll( int amt ) { /* add horizontal/vertical scroll bar */ }
};
struct Title : public Decorator {           // specialize
    ...
    Title( Window &window, ... ) : Decorator( window ), ... {}
    void setTitle( string t ) { /* add title at top of window */ }
};
struct Border : public Decorator {          // specialize
    ...
    enum Colour { RED, GREEN, BLUE };
    Border( Window &window, Colour c, int width ) : Decorator( window ), ... {}
    void draw() { /* add border around window */ }
};


PlainWindow w1;
Scrollbar vsb1( w1, Scrollbar::Ver );       // add vertical scroll bar
Border rb5( vsb1, Border::RED, 5 );         // add red border
Border borderedScrollable( rb5, Border::BLUE, 10 ); // add blue border

PlainWindow w2;
Scrollbar vsb2( w2, Scrollbar::Ver );       // add vertical scrollbar
Scrollbar hsb( vsb2, Scrollbar::Hor );      // add horizontal scrollbar
Title titledScrollable( hsb );              // add title
```

- decorator only mimics object's type through base class

- decorator has same interface but delegates to component to specialize operations

- decorator can be applied multiple times in different ways to produce new combinations at runtime

- allows decorator to be dynamically associated with different object's, or multiple decorators associated with same object

2.37.5 Factory Pattern

- **factory** pattern : generalize creation of family of products with multiple variants

```
struct Food {...};                          // abstract product
struct Pizza : public Food {...};           // concrete product
struct Burger : public Food {...};          // concrete product

struct Restaurant {                         // abstract factory product
    enum Kind { Pizza, Burger };
    virtual Food *order() = 0;
    virtual int staff() = 0;
};
struct Pizzeria : public Restaurant { // concrete factory product
    Food *order() {...}
    int staff() {...}
};
struct Burgers : public Restaurant { // concrete factory product
    Food *order() {...}
    int staff() {...}
};

enum Type { PizzaHut, BugerKing };
struct RestaurantFactory {                  // abstract factory
    virtual Restaurant *create() = 0;
};
struct PizzeriaFactory : RestaurantFactory { // concrete factory
    Restaurant *create() {...}
};
struct BurgerFactory : RestaurantFactory { // concrete factory
    Restaurant *create() {...}
};

PizzeriaFactory pizzeriaFactory;
BurgerFactory burgerFactory;
Restaurant *pizzaHut = pizzeriaFactory.create();
Restaurant *burgerKing = burgerFactory.create();
Food *dispatch( Restaurant::Kind food ) { // parameterized creator
    switch ( food ) {
        case Restaurant::Pizza: return pizzaHut->order();
        case Restaurant::Burger: return burgerKing->order();
        default: ; // error
    }
}
```

- use factory-method pattern to construct generated product (Food)
- use factory-method pattern to construct generated factory (Restaurant)
- clients obtain a concrete product (Pizza, Burger) from a concrete factory (PizzaHut, BugerKing), but product type is unknown
- client interacts with product object through its abstract interface (Food)

2.38 Debugger

- An interactive, symbolic **debugger** effectively allows debug print statements to be added and removed to/from a program dynamically.
- Do not rely solely on a debugger to debug a program.
- Some systems do not have a debugger or the debugger may not work for certain kinds of problems.
- A good programmer uses a combination of debug print statements and a debugger when debugging a complex program.
- A debugger does not debug a program, it merely helps in the debugging process.
- Therefore, you must have some idea (hypothesis) about what is wrong with a program before starting to look.

2.38.1 GDB

- The two most common UNIX debuggers are: dbx and gdb.
- File test.cc contains:

```
1  int r( int a[] ) {
2      int i = 100000000;
3      a[i] += 1;  // really bad subscript error
4      return a[i];
5  }
6  int main() {
7      int a[10] = { 0, 1 };
8      r( a );
9  }
```

- Compile program using the -g flag to include names of variables and routines for symbolic debugging:

```
$ g++ -g test.cc
```

- Start gdb:

```
$ gdb ./a.out
... gdb disclaimer
(gdb) ← gdb prompt
```

- Like a shell, gdb uses a command line to accept debugging commands.

GDB Command	Action
<Enter>	repeat last command
run *[shell-arguments]*	start program with shell arguments
backtrace	print current stack trace
print *variable-name*	print value in variable-name
frame *[n]*	go to stack frame n
break *routine / file-name:line-no*	set breakpoint at routine or line in file
info breakpoints	list all breakpoints
delete *[n]*	delete breakpoint n
step *[n]*	execute next n lines (into routines)
next *[n]*	execute next n lines of current routine
continue *[n]*	skip next n breakpoints
list	list source code
quit	terminate gdb

- Command abbreviations are in **red**.
- <Enter> without a command repeats the last command.
- **r**un command begins execution of the program:

```
(gdb) run
Starting program: /u/userid/cs246/a.out
Program received signal SIGSEGV, Segmentation fault.
0x000106f8 in r (a=0xffbefa20) at test.cc:3
3           a[i] += 1;     // really bad subscript error
```

  - If there are no errors in a program, running in GDB is the same as running in a shell.
  - If there is an error, control returns to gdb to allow examination.
  - If program is not compiled with -g flag, only routine names given.

- **ba**cktrace command prints a stack trace of called routines.

```
(gdb) backtrace
#0  0x000106f8 in r (a=0xffbefa08) at test.cc:3
#1  0x00010764 in main () at test.cc:8
```

  - stack has 2 frames main (#1) and r (#0) because error occurred in call to r.

- **p**rint command prints variables accessible in the current routine, object, or external area.

```
(gdb) print i
$1 = 100000000
```

- Can print any C++ expression:

```
(gdb) print a
$2 = (int *) 0xffbefa20
(gdb) p *a
$3 = 0
(gdb) p a[1]
$4 = 1
(gdb) p a[1]+1
$5 = 2
```

- **set var**iable command changes the value of a variable in the current routine, object or external area.

```
(gdb) set variable i = 7
(gdb) p i
$6 = 7
(gdb) set var a[0] = 3
(gdb) p a[0]
$7 = 3
```

  Change the values of variables while debugging to:

  - investigate how the program behaves with new values without recompile and restarting the program,
  - to make local corrections and then continue execution.

- **f**rame *[n]* command moves the **current stack frame** to the nth routine call on the stack.

```
(gdb) f 0
#0  0x000106f8 in r (a=0xffbefa08) at test.cc:3
3           a[i] += 1;     // really bad subscript error
(gdb) f 1
#1  0x00010764 in main () at test.cc:8
8           r( a );
```

  - If n is not present, prints the current frame
  - Once moved to a new frame, it becomes the current frame.
  - All subsequent commands apply to the current frame.

- To trace program execution, **breakpoint**s are used.

- **b**reak command establishes a point in the program where execution suspends and control returns to the debugger.

```
(gdb) break main
Breakpoint 1 at 0x10710: file test.cc, line 7.
(gdb) break test.cc:3
Breakpoint 2 at 0x106d8: file test.cc, line 3.
```

  - Set breakpoint using routine name or source-file:line-number.

- **i**nfo breakpoints command prints all breakpoints currently set.

```
(gdb) info break
Num Type           Disp Enb Address    What
1   breakpoint     keep y   0x00010710 in main at test.cc:7
2   breakpoint     keep y   0x000106d8 in r(int*) at test.cc:3
```

- Run program again to get to the breakpoint:

```
(gdb) run
The program being debugged has been started already.
Start it from the beginning? (y or n) y
Starting program: /u/userid/cs246/a.out
Breakpoint 1, main () at test.cc:7
7         int a[10] = { 0, 1 };
(gdb) p a[7]
$8 = 0
```

- Once a breakpoint is reached, execution of the program can be continued in several ways.

- **s**tep *[n]* command executes the next n lines of the program and stops, so control enters routine calls.

```
(gdb) step
8         r( a );
(gdb) s
r (a=0xffbefa20) at test.cc:2
2         int i = 100000000;
(gdb) s
Breakpoint 2, r (a=0xffbefa20) at test.cc:3
3         a[i] += 1;     // really bad subscript error
(gdb) <Enter>
Program received signal SIGSEGV, Segmentation fault.
0x000106f8 in r (a=0xffbefa20) at test.cc:3
3         a[i] += 1;     // really bad subscript error
(gdb) s
Program terminated with signal SIGSEGV, Segmentation fault.
The program no longer exists.
```

  - If n is not present, 1 is assumed.
  - If the next line is a routine call, control enters the routine and stops at the first line.

- **n**ext *[n]* command executes the next n lines of the current routine and stops, so routine calls are not entered (treated as a single statement).

```
(gdb) run
...
Breakpoint 1, main () at test.cc:7
7       int a[10] = { 0, 1 };
(gdb) next
8       r( a );
(gdb) n
Breakpoint 2, r (a=0xffbefa20) at test.cc:3
3       a[i] += 1;    // really bad subscript error
(gdb) n
Program received signal SIGSEGV, Segmentation fault.
0x000106f8 in r (a=0xffbefa20) at test.cc:3
3       a[i] += 1;    // really bad subscript error
```

- **c**ontinue *[n]* command continues execution until the next breakpoint is reached.

```
(gdb) run
...
Breakpoint 1, main () at test.cc:7
7       int a[10] = { 0, 1 };
(gdb) c
Breakpoint 2, r (a=0x7fffffffe7d0) at test.cc:3
3       a[i] += 1;    // really bad subscript error
(gdb) p i
$9 = 100000000
(gdb) set var i = 3
(gdb) c
Continuing.
Program exited normally.
```

- **l**ist command lists source code.

```
(gdb) list
1    int r( int a[] ) {
2        int i = 100000000;
3        a[i] += 1;    // really bad subscript error
4        return a[i];
5    }
6    int main() {
7        int a[10] = { 0, 1 };
8        r( a );
9    }
```

  - with no argument, list code around current execution location
  - with argument line number, list code around line number

- **q**uit command terminate gdb.

```
(gdb) run
...
Breakpoint 1, main () at test.cc:7
7           int a[10] = { 0, 1 };
1: a[0] = 67568
(gdb) quit
The program is running.  Exit anyway? (y or n) y
```

2.39 Compiling Complex Programs

- As number of TUs grow, so do the references to type/variables (dependencies) among TUs.
- When one TU is changed, other TUs that depend on it must change and be recompiled.
- ***For a large numbers of TUs, the dependencies turn into a nightmare with respect to re-compilation.***

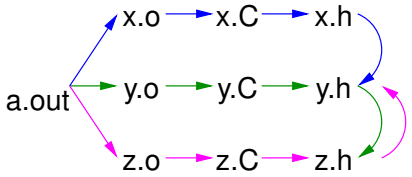
2.39.1 Dependencies

- A **dependency** occurs when a change in one location (entity) requires a change in another.
- Dependencies can be:
  - loosely coupled, e.g., changing source code may require a corresponding change in user documentation, or
  - tightly coupled, changing source code may require recompiling of some or all of the components that compose a program.
- Dependencies in C/C++ occur as follows:
  - executable depends on .o files (linking)
  - .o files depend on .C files (compiling)
  - .C files depend on .h files (including)

source code

```
x.h     #include "y.h"
x.C     #include "x.h"

y.h     #include "z.h"
y.C     #include "y.h"

z.h     #include "y.h"
z.C     #include "z.h"
```

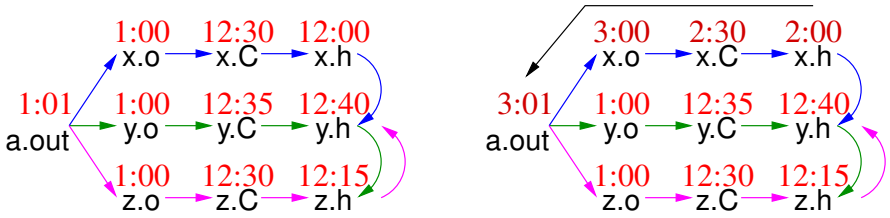
dependency graph



- Cycles in **#include** dependencies are broken by **#ifndef** checks (see page 99).
- The executable (a.out) is generated by compilation commands:

```
$ g++ -c z.C        # generates z.o
$ g++ -c y.C        # generates y.o
$ g++ -c x.C        # generates x.o
$ g++ x.o y.o z.o   # generates a.out
```

- However, it is inefficient and defeats the point of separate compilation to recompile all program components after a change.
- If a change is made to y.h, what is minimum recompilation necessary? (all!)
- Does ***any*** change to y.h require these recompilations?
- Often no mechanism to know the kind of change made within a file, e.g., changing a comment, type, variable.
- Hence, "change" may be coarse grain, i.e., based on ***any*** change to a file.
- One way to denote file change is with **time stamps**.
- UNIX directory stores the time a file is last changed, with second precision.
- Using time to denote change means dependency graph is temporal ordering where root has newest (or equal) time and leafs oldest (or equal) time.

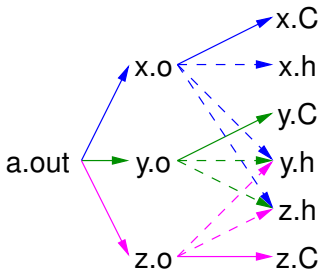


  - File x.h includes y.h and z.h, file y.h includes z.h, file z.h includes y.h,
  - Files x.o, y.o and z.o created at 1:00 from compilation of files created before 1:00.
  - File a.out created at 1:01 from link of x.o, y.o and z.o.
  - Changes are subsequently made to x.h and x.C at 2:00 and 2:30.
  - Only files x.o and a.out need to be recreated at 3:00 and 3:01. (Why?)

2.39.2 Make

- **make** is a system command taking a dependency graph and uses file change-times to trigger rules that bring the dependency graph up to date.
- make dependency-graph is relationship between product and set of sources.
- **make does not understand relationships among sources, one that exists at the source-code level and is crucial.**

- Hence, make dependency-graph loses some relationships (dashed lines):



- E.g., source x.C depends on source x.h but x.C is not a product of x.h like x.o is a product of x.C and x.h.

- Two most common UNIX makes are: make and gmake (on Linux, make is gmake).

- Like shells, there is minimal syntax and semantics for make, which is mostly portable across systems.

- Most common non-portable features are specifying dependencies and implicit rules.

- Basic make file has string variables with initialization, and a list of targets and rules.

- Make file can have any name, but make implicitly looks for a file named makefile or Makefile if no file name is specified.

- Each target has a list of dependencies, and possibly a set of commands specifying how to re-establish the target.

```
variable = value                          # variable
target : dependency1 dependency2 ...      # target / dependencies
    command1                              # rules
    command2
    ...
```

- ***Commands must be indented by one tab character.***

- make is invoked with a target, which is root or subnode of a dependency graph.

- make builds the dependency graph and decorates the edges with time stamps for the specified files.

- If any of the dependency files (leafs) is newer than the target file, or if the target file does not exist, the commands are executed by the shell to update the target (generating a new product).

- Makefile for previous dependencies:

```
a.out : x.o y.o z.o              # place final target first
    g++ x.o y.o z.o -o a.out
x.o : x.C x.h y.h z.h            # now order doesn't matter
    g++ -g -Wall -c x.C
y.o : y.C y.h z.h
    g++ -g -Wall -c y.C
z.o : z.C z.h y.h
    g++ -g -Wall -c z.C
```

- Check dependency relationship (assume source files just created):

```
$ make -n -f Makefile a.out
g++ -g -Wall -c x.C
g++ -g -Wall -c y.C
g++ -g -Wall -c z.C
g++ x.o y.o z.o -o a.out
```

  All necessary commands are triggered to bring target a.out up to date.

  - -n builds and checks the dependencies, showing rules to be triggered (leave off to execute rules)
  - -f Makefile is the dependency file (leave off if named [Mm]akefile)
  - a.out target name to be updated (leave off if first target)

- Generalize and eliminate duplication using variables:

```
CXX = g++                        # compiler
CXXFLAGS = -g -Wall -c           # compiler flags
OBJECTS = x.o y.o z.o            # object files forming executable
EXEC = a.out                     # executable name

${EXEC} : ${OBJECTS}             # link step
    ${CXX} ${OBJECTS} -o ${EXEC}
x.o : x.C x.h y.h z.h            # targets / dependencies / commands
    ${CXX} ${CXXFLAGS} x.C
y.o : y.C y.h z.h
    ${CXX} ${CXXFLAGS} y.C
z.o : z.C z.h y.h
    ${CXX} ${CXXFLAGS} z.C
```

- Eliminate common rules:

  - make can deduce simple rules when dependency files have specific suffixes.
  - E.g., given target with dependencies:

    ```
    x.o : x.C x.h y.h z.h
    ```

    make deduces the following rule:

    ```
    ${CXX} ${CXXFLAGS} -c -o x.o     # special variable names
    ```

    where -o x.o is redundant as it is implied by -c.

- This rule uses variables ${CXX} and ${CXXFLAGS} for generalization.

- Therefore, all rules for x.o, y.o and z.o can be removed.

```
CXX = g++                       # compiler
CXXFLAGS = -g -Wall             # compiler flags, remove -c
OBJECTS = x.o y.o z.o           # object files forming executable
EXEC = a.out                    # executable name

${EXEC} : ${OBJECTS}            # link step
    ${CXX} ${OBJECTS} -o ${EXEC}
x.o : x.C x.h y.h z.h           # targets / dependencies
y.o : y.C y.h z.h
z.o : z.C z.h y.h
```

- Because dependencies are extremely complex in large programs, programmers seldom construct them correctly or maintain them.

- **Without complete and up to date dependencies, make is useless.**

- Automate targets and dependencies:

```
CXX = g++                       # compiler
CXXFLAGS = -g -Wall -MMD        # compiler flags
OBJECTS = x.o y.o z.o           # object files forming executable
DEPENDS = ${OBJECTS:.o=.d}      # substitute ".o" with ".d"
EXEC = a.out                    # executable name

${EXEC} : ${OBJECTS}            # link step
    ${CXX} ${OBJECTS} -o ${EXEC}

-include ${DEPENDS}             # copies files x.d, y.d, z.d (if exists)

.PHONY : clean                  # not a file name
clean :                         # remove files that can be regenerated
    rm -rf ${DEPENDS} ${OBJECTS} ${EXEC}  # alternative *.d *.o
```

  - Preprocessor traverses all include files, so it knows all source-file dependencies.
  - g++ flag -MMD writes out a dependency graph for user source-files to file *source-file*.d

file	contents
x.d	x.o: x.C x.h y.h z.h
y.d	y.o: y.C y.h z.h
z.d	z.o: z.C z.h y.h

  - g++ flag -MD generates a dependency graph for user/system source-files.
  - -**include** reads the .d files containing dependencies.
  - .**PHONY** indicates a target that is not a file name and never created; it is a recipe to be executed every time the target is specified.
    - A phony target avoids a conflict with a file of the same name.

- Phony target clean removes product files that can be rebuilt (save space).

```
$ make clean          # remove all products (don't create "clean")
```

- Hence, possible to have universal Makefile for single or multiple programs.

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