Compilation and Linking

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Sources of Information

- Books
  - Running Linux: O'Reilly
  - Linux in a Nutshell: O'Reilly
  - Unix Power Tools
- WEB
  - www.google.com (search engine)
  - www.nlsearch.com
  - www.hotbot.com

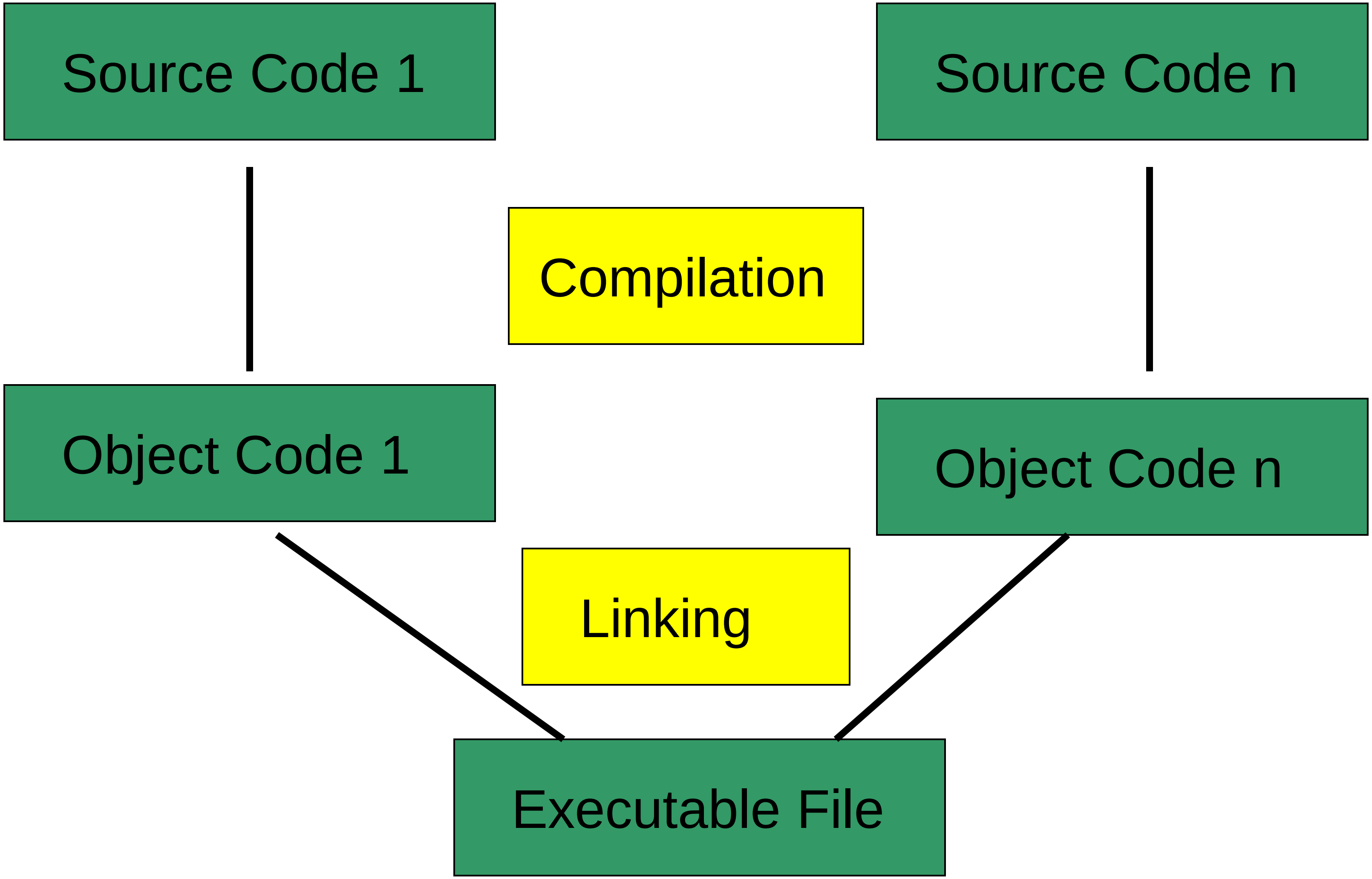
Linux/Unix man pages

- Search for list of items related to compiling
  - man –k compile
- Get information about a particular command
  - man fort77 (Fortran compiler)
  - man ar (library archiver)
  - man gcc (GNU C++ compiler)

Commonalities across machines and Operating Systems

- Files are contained in directories
- Directories form a tree, files are the leaves of that tree
- Compiled Languages (C/C++, Fortran, Java)
- Scripting languages (Perl, Python)
- File extensions (.cc, .f77, .as, .o)

Compile/Link/Execute



Compilers

- Fortran (fort77, f90, g77)
- C/C++
  - cc, gcc, g++ (Linux)
  - CC (IRIX)

Source Code

- Users write source code
- Ascii file, created with text editor
- Source code files have extensions .cpp, .cxx, .cc, .CC, .f77, .f90, etc.

From source code to binary code

- Source code (readable asci text) --->
- Assembler code (human readable machine code) --->
- Object code (machine code, symbols) --->
- Machine code (binary executable)
  - contains ascii symbols if debug option on
  - pure machine code if debug option off

Directory paths

- **Include file paths: -Idirs**

- Example: g++ -c -I. -I/home/source/include main.c
- Example: f77 -c -I. -I/home/source/include main.c

- **Library file paths: -ldirs**

- Example: g++ -c -L/home/lib main.c timer.o
- Example: f77 -c   -L/home/lib main.c timer.o

Include paths

- g++ -Ipath1 –Ipath2 source.cpp
  - Search for inlude files in succession of paths
  - System searches standard paths first
    - /usr/include
    - /usr/local/include
    - etc. (see manual for more information)

Include files

- #include <systemfile.h>
- #include “localfile.h”

- <…> : system include files
- “…” : user include files

Preprocessor

- #include <file1.h>
- #include “file2.h”

- #ifdef VAR
  #   define A 5
  #else
  #   define A 10
  #endif

Include contents of files1.h into source

Based on value of VAR, define A to be 5 or 10

Preprocessor

- Explicit call
  - /lib/cpp source.cpp [options] > new_source.cpp
- Automatically called by *most* compilers
- Options to preprocessor
  - -P   (remove comment lines)
  - -DdefineVar=value (set variable)

Preprocessing

```
#ifdef TEST
#  define A  3*3
#else
#  define A = 4*4
#endif

main()
{
        float c = A;
        print("c = %d\n“, c);
}
```

g++ testdef.cpp

TEST not defined

c=16

G++ -DTEST testdef.cpp

TEST is defined

c=9

Include File Directories

- /usr/include
- /usr/include/GL (OpenGL libraries)
- /usr/local/include
- user-specified include directories

Include file locations are based on convention.

There are no strong conventions.

Compilation

- g++ [Options] -c file1.c file2.c ...
- Common options:
  - -c : keep object files
  - array bound checking
  - print out all warnings
  - -O2, -O3 (control optimization level)
  - -Dvar=value (define variable name)
  - -IincludePath (path to include files)
  - -g   (enable debugging)
  - see man pages for many other options

Compilation Errors

- Easy to fix
- Pretty much described in English
- Search the web for the wording if you cannot find the source of the error
- Most common errors
  - Divide by zero
  - Type mismatch
  - Undefined variables

Object Files

- Source code is compiled into assembler code.
- Object files may or might not include variable names and other symbols (-g options for compilers) useful for debugging
- Multiple object code files are then combined to form an executable (linker)
- The executable is run by the user

What is in a library

- Convenient place to store object code
  - Obj1.o
  - Obj2.o
  - …

Libraries

- Shared libraries
  - libm.so,   libm.so.143,   libGL.so.1523
- Static libraries
  - libm.a,   libGL.a   ,   libX11.a,   etc …

Static Libraries

- The assembler code for all library files is included with the executable
  - Size of executable is very large
  - Space usage is duplicated if multiple copies of executable are used
  - Large programs can take longer to load

Shared Libraries

- Objects in libraries are shared across applications
- Routines are only loaded when needed
- Changes can be made to the libraries without recompiling code

Library directories (Unix/Linux)

- /usr/lib
- /usr/local/lib
- /usr/X11R6/lib (specific to Linux version)
- /usr/lib32 (IRIX)
- user-defined library directories

Creating a static library

- Collect object files file1.o file2.o into library libstuff.a
  - ar r libstuff.a file1.o file2.o …
- Create an index for the library (to help linker find files within the library)
  - ranlib libstuff.a
  - (not necessary on SGI’s)
- Combine both steps
  - ar rs

Creating a shared library

- Generate position-independent code (might be different for different compilers)
  - g++ –c –fPIC file1.c file2.c
- Create the shared library
  - g++ –shared –o libstuff.so file1.o file2.o

Linking

- Use same name as the compiler (most of the time): compiler is usually a front end script:
  - g++ [options] -o executable obj1.o obj2.o [libraries]
  - Common options
    - -Ldir1 –Ldir2 (directory path to library files)
    - -o executable (name of final executable)
    - -g (debugging option)
    - see man pages for other options

Linking

- Place object code *before* libraries
  - This order is not always required, but is more portable across operating systems (OS) and compilers.
  - Usually, the libraries are searched in the order they are listed
  - Always strive to compile and link in a portable fashion

Undefined Externals

- Your code is using a user routine or system routine that *cannot be found* in the list of libraries
- Must find the library that references that routine and add it to the link command.
- How to find this library?

Multiple definitions

- If a routine is listed multiple times in linker output,
  - the routine was found in multiple libraries
  - usually, the last routine found is used
  - this is a warning from the linker, usually not fatal
  - BUT: you must be aware. Sometimes the linker chooses the wrong routine

Using Libraries

- gcc –LPath1 –Lpath2 –o main.x main.o –lstuff –lm
  - shared libraries are used if possible
  - static libraries are used if shared library does not exist
  - -lstuff links in libstuff.a searching in directories path1 and path2
  - link in the math library libmath.a

Searching through libraries

- sh shell script to search a list of libraries for a specified module (could use perl, python):

  - ```
    for $i in lib*.a
    do
        echo $i
        ar t $i | grep –i $1
    done
    ```
    ```

How to debug linking problems

- Read error messages carefully
- Undefined function
  - ….
- Undefined external
  - ….

Tools to Search Libraries

- On Linux
  - ar (library archiver)
    - ar t libname.a
  - strings libname.a
    - Lists all ascii strings in the library
  - nm –a libname.a

Use of nm

nm /usr/libc.a > output_file

Section of output file:

```
printf.o:
00000000 T _IO_printf
         w __pthread_initialize
         w __pthread_initialize_minimal
00000000 T printf
         U stdout
         U vfprintf
```

Conclusion: printf is defined.

stdout and vfprintf are undefined.

Use of nm (cont.)

- In the same file:

```
vfprintf.o:
        U _IO_default_doallocate
        U _IO_default_finish
        U _IO_default_pbackfail
        U _IO_default_read
                    ....
```

Use of nm (cont.)

Searching for "stdout" at the beginning of the line produces no results. However, searching for "D stdout" produces

```
stdio.o:
         U _IO_2_1_stderr_
         U _IO_2_1_stdin_
         U _IO_2_1_stdout_
00000008 D _IO_stderr
00000000 D _IO_stdin
00000004 D _IO_stdout
         w __pthread_atfork
         w __pthread_getspecific
```

Stdout is *defined* in the routine stdio.o

Searching for string in libraries

```
#!/bin/bash
for i in /usr/lib/lib*a
 do
   echo $i
   nm $i | grep -i routine_to_find
done
```

Environment variables

- PATH
  - List of directory searched by the OS to find a command
  - Defined in .cshrc or .bashrc file
- LD_LIBRARY_PATH
  - List of directories searched when shared libraries are used
  - Placed in .cshrc or .bashrc file.

Makefiles

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GNU Make

Home page

http://www.gnu.org/software/make/make.html

Documentation

http://www.gnu.org/software/make/manual/

Compilation and Linking

- Many source files
- Many object files
- Many libraries

- Various types of preprocessing
  - /lib/cpp
  - Lex/yacc (not often used)
  - Python/perl/ranlib/etc.

Three Source files

- gcc –c file1.c
  gcc –c file2.c
  gcc –c file3.c

- gcc –o executable file1.o file2.o file3.o
  -lGLU –lGL –lext –lX11

Change file1.c

- What to do?
- Obvious solution: create a script in file compile.x:

```
gcc –c file1.c
gcc –c file2.c
gcc –c file3.c
gcc –o executable file1.o file2.o file3.o
   -lGLU –lGL –lext –lX11
```

First alternative

- Manually recompile file1.c and link:

```
gcc –c file1.c
gcc –o executable file1.o file2.o file3.o
    -lGLU –lGL –lext –lX11
```

- This approach is faster, but more prone to error

What if …

- 150 source files
- 7 source files are changed
- Compiling 150 source files: 20 min.
- Compiling 7 source files: 1 min
- Linking 150 object files: 3 min

What to do?

Problems …

- Hard to keep track of which files are changed
- Recompiling all files is inefficient: 143 files are compiled needlessly

Solution: Makefiles

- Each file keeps track of creation time and last modification time
  - To see this:
    - ls –l
- The executable file has a last modification time
- If any source file has been modified after the creation of the executable files, it must obviously be compiled

Why Makefiles?

- Manage complex projects
- Store project information in single place
- Reduce turnaround time for compile—link cycle
- Keeps track of file dependencies based on last modification time
  - Manual or automatic tracking

Project layouts

- Single operating system
  - Source and object files in single directory
- Multiple operating systems (Unix,Linux,Windows)
  - Source files in one directory
  - Object files in directory associated with particular OS

GNUmake

- Open source
- Very general
- Very flexible
- Easy to use (in simplest modes)
- Can generate extremely complex makefiles

Makefile names

- Default names   (make)
  - Makefile
  - makefile
  - GNUmakefile
- User-specified name
  - make –f makeFileName
  - e.g.,   make –f make01

Targets

- Targets appear on left side of colon (:)
- Targets are created (e.g., all, pgm, tar)
  - make all
  - make pgm
  - make tar

Prerequisites

- Targets depend on prerequisites
- Targets are compared to prerequisites based on the last modification file date
- If a prerequisite file is *newer* than the target, make will try to recreate it. For example,
  - pgm.x *depends* on pgm.o
  - pgm.o *depends* on pgm.c
  - pgm.c *depends* on pgm.h

Variables

- OBJS = main.c class1.c class2.c
  - Recursively expanded variable.
- OBJS := main.c class1.c class2.c
  - Simply expanded variable
  - Substitution occurs immediately
  - This method is safer

Variables (example)

CFLAGS = $(include_dirs) -O
include_dirs = -Ifoo -Ibar

CFLAGS = $(CFLAGS) -O
It will cause an infinite loop

x := foo
y := $(x) bar
x := later
is equivalent to
y := foo bar
x := later

Variables (example)

OBJS= *.o

The value of the variable OBJS is the string "*.o". However, if OBJS is used in a target or prerequisite, wildcard expansion will take place there.

```
pgm.x: $(OBJS)
    gcc –o pgm.x $(CFLAGS) $(OBJS)
```

Variables (example)

```
SRC := $(wildcard *.c)
  OBJ := $(patsubst %.c,%.o,$(wildcard *.c))
#  OBJ := $(SRC :.c=.o)
```

- Use of := is often safer
- Source files are rarely deleted
- Object list can be constructed automatically, regardless of whether object files actually exist

Example

- Source files
  - main.c
  - class1.c, class1.h
  - class2.c, class2.h

main.c

```
#include “class1.h”
#include “class2.h”
 main()
{
    ….
}
```

class1.c

```
class Class1
  {
        private:
          …
          public:
           ….
  }
```

Simple Makefile

- Variable definitions
- Target definitions
- Rules

Basic Structure

```
pgm.x:  main.o class1.o class2.o
        gcc –o pgm.x main.o class1.o class2.o
main.o: main.c class1.h
        gcc –c main.c
class1.o: class1.c class1.h
        gcc –c class1.c
class2.o: class2.c class2.h
        gcc –c class2.c
```

Problems with basic structure

- What if I add one or more additional source file
- What if I add another include statement into main.c (e.g., #include “main.h”)
- What if I change compilers?
- What if I work on multiple operating systems on a regular basis
- What if I have source files in multiple directories?
- What if I want to do more complicated functions
  - Installation, tar files, help messages, etc.

Use of Variables

```
CC=gcc
LD=gcc
OBJS= main.o class1.o class2.o

pgm.x:  $(OBJS)
$(LD) –o pgm.x $(OBJS)
main.o: main.c class1.h
$(CC) –c main.c
class1.o: class1.c class1.h
$(CC) –c class1.c
class2.o: class2.c class2.h
$(CC) –c class2.h
```

Use of patterns

```
CC=gcc
LD=gcc
CFLAGS=-c
EXEC=pgm.x
OBJS= main.o class1.o class2.o

$(EXEC):  $(OBJS)
$(LD) –o $(EXEC) $(OBJS)
%.o : %.c
$(CC) $(CFLAGS)   –o $@   $<
```

‘$@’ is the target, ‘$<‘ is the first prerequisite

Additional functions

```
 EXEC=pgm.x
$(EXEC):
        $(CC) –o $(EXEC) main.c
.PHONY clean
clean:
        rm *.o $(EXEC)
tar:
        tar $(EXEC).tar *.c *.h Makefile
```

Additional features

- Recursive makes
- Conditionals
- Manipulation of environment variables
- Many shortcut variables
- Pattern manipulation via text functions
- Include files
- Many many more …

Debuging

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Where do we stand

- You have written a code (C++/Fortran)
- The code compiles and links correctly
  - Warning messages have mostly been eliminated
  - If not eliminated, warning messages should be understood
- You execute the code and the unexpected happens:

What happened!

- The code crashes with a segmentation fault
- The computer produces the incorrect results
- You overran array bounds
- You divided by zero?
- You accessed an address outside the codes’s address space (zero pointer syndrome)

What do you do?

- You must debug the code
  - Print statements
  - Assert statements
  - Debugging objects
  - Command line debuggers (more common)
    - (dbx on unix, gdb on linux)
  - Visual debuggers (more specialized)
    - Visual C++, SGI/IBM/Compaq visual debuggers

Print statements

- Create a specialize routines (C/Fortran)

```
void print1(char* msg, float var)
{
        printf("%s: %f\n", msg, var);
}
void print2(char* msg, float var1, float var2)
{
        printf("%s: %f, %f\n", msg, var1, var2)
}
//-----------------------------
….
        print1(“variable 1”, area)
…
```

Print and Objects

```
class Shape {
private:
  float a,b;
  int c;
public:
  Shape(float a, float b, int c) {….}
  print(char* msg) {
     printf(“%s, a,b,c= %f, %f, %d\n”, a,b,c);
               printf("%s: %f\n", msg, var);
}
//---------------------------------
main() {
Shape sh(2.,3.,5);
sh.print(“Object sh:”);
…
```

Assert Statements

```
#include <assert.h>

 fct(float* a, int i)
{ ….
     ASSERT(i < 5);
    a[i] = 3.;
}
```

- If condition is violated, the ASSERT macro prints out some statement and exits.
- ASSERT is only active when –g option is used to compile (debug mode).
- Users can write macros to do anything they want. Effective debugging tool.

Assert Statements

- Assert statements exist in some for or other in all compilers.
- They are usually defined as macros:
  - #define ASSERT(a)

```
if (!(a)) {\
    printf("error at line %d\n", __LINE__) ;

    exit(1);

 } else {
}
```

- You can define your own. Use existing definitions as templates

Assert Statements

- Often used to check on consistency conditions upon entry to a subroutine/function
- Example, given a bank account object.
    - When entering the object, the bank account must be positive.
    - Upon exit, it must still be positive or zero.
    - Check this with ASSERT statement since these conditions should not be violated if program were working correctly.

Debuggers

- Compile and link program with –g option:
  - g++ -g –c prog.c
    g++ -g –c sub1.c
    g++ -g –o prog.x prog.o sub.o
- The executable (prog.x) now contains symbols, routine names, etc. It is much larger in size with –g than without.

Debugger on Linux: gdb

- gdb prog.x
- Commands:
  - print (p) (print variables)
  - break (b) (set breakpoints)
  - step (s) (step one line, go into routines)
  - next (n) (step on line, step over routines)
  - display (disp) (display a variable)

gdb (Opensource)

- Conditional breakpoints
- print expressions
- Many many options that I do not use

Useful tools

- ddd
  - debugger with visual interface, works with gdb
  - (I have never used it)
- Vim
  - Advanced version of vi editor
  - Can interface with gdb to simplify debugging process
- Emacs (of course)