HPC Workshop Series: *Compilation*

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Research Computing

Objects

Outline

- Makefile basics
- Creating Shared & Static Libraries
- Linking Shared & Static Libraries
- Environment considerations
- Linking order

Before we begin

- ssh username@tutorial-login.rc.colorado.edu
- ssh scompile
- ml intel

Nano survival guide

- Ctrl+o save (need to confirm filename)
- Ctrl+x exit
- Ctrl+k cut
- Ctrl+u paste

GNU Make

- Helps manage compilation of source code.
- Examine the files in the makefiles subdirectory
- Compile:
  - icc hello.c hellofunc.c -I. -o hello.exe
- Drawbacks?
  - Have to remember compilation syntax
  - Possibly machine-specific (no Intel on my laptop?)

Simple Makefile (1)

- Create a file named Makefile in the makefiles directory
- Add these lines (use tab, not 4 spaces):

```
hello.exe: hello.c hellofunc.c
	icc -I . hello.c hellofunc.c -o hello.exe
```

TAB

- This is a **rule** for making the **target file** hello.exe
- Type ***make***
- Checks target and dependencies for:
  - existence
  - modifications (based on timestamp)

Simple Makefile (1)

- Make executes every command indented below the target/dependency line.
- Can use any Linux commands

```
hello.exe: hello.c hellofunc.c
TAB  echo "Compiling hello.exe"
TAB  icc -I . hello.c hellofunc.c -o hello.exe
```

- Make displays the command executed on the screen
- Suppress by prepending @ symbol: echo → @echo

Simple Makefile (1)

- Standard to include a target named clean:

```
hello.exe: hello.c hellofunc.c
TAB	@echo "Compiling hello.exe"
TAB	icc -I . hello.c hellofunc.c -o hello.exe
clean:
TAB	rm –f  *.o
TAB	rm –f  hello.exe
```

Simple Makefile (1)

- Complication. Run these commands:
  - touch clean
  - make clean
- A file named clean will conflict with our target named clean.
- Solution – add .PHONY target:

```
.PHONY: clean
```

- Understood that targets in .PHONY list are not files

Makefile (1): A Good Start

```
.PHONY: clean

hello.exe: hello.c hellofunc.c
 TAB  @echo "Compiling hello.exe"
 TAB  icc -I . hello.c hellofunc.c -o hello.exe

clean:
 TAB  rm –f  *.o
 TAB  rm –f  hello.exe
```

Variables in Make

- Compilers and optimization flags may differ between machines
- Use variables to avoid rewriting compilation commands for each new machine
- Best to do at top of Makefile

Define variables via **=**

```
CC = icc
```

Evaluate variables via **$( )**

```
echo $(CC)
```

Simple Makefile (2)

- Modify your makefile to include these changes
- (keep clean and .PHONY as they were)

```
CC = icc
INCLUDE_FLAGS = -I .
OPT_FLAGS = -O2
CFLAGS  = $(INCLUDE_FLAGS) $(OPT_FLAGS)

hello.exe: hello.c hellofunc.c
	@echo "Compiling hello.exe"
	$(CC) $(CFLAGS) . hello.c hellofunc.c -o hello.exe
```

Special Variables

- These variables are useful within rules/recipes
- The variable **$@**
  - Refers to the rule target (e.g., hello.exe)
- The variable **$<**
  - Refers to the 1st dependency (e.g., hello.c)
- The variables **$^**
  - Refers to all dependencies (e.g., hello.c hellofunc.c)
- Exercise:
  - Rewrite the rule for hello.exe using **$@** and **$^**

My Solution

I defined a new variable…

```
…
CFLAGS = $(OPT_FLAGS) $(INCLUDE_FLAGS)
PROG = hello.exe
```

Now hello.exe appears in only 1 place.

```
$(PROG): hello.c hellofunc.c
	@echo "Compiling " $(PROG) "."
	$(CC) $(CFLAGS) $^ -o $@

clean:
	rm -f *.o
	rm -f $(PROG)
```

Simple Makefile (3)

- We often have a number of object files that needed to build the program.
- Make this small modification:

```
$(PROG): hello.c hellofunc.c
```

```
$(PROG): hello.o hellofunc.o
```

- By default, Make uses CFLAGS and CC to build the .o files
- We can control this behavior ourselves

Wildcards

- The % symbol acts a wildcard.
- Add the following target/rule:

```
%.o: %.c
	@echo "Compling "$@ " using " $<
	$(CC) $(CFLAGS) -c $< -o $@
```

- This tells Make:
  - Use this rule if a file ending in .o is needed
  - Before file.o can be created, file.c must exist
  - Build file.o via: $(CC) $(CFLAGS) -c file.c -o file.o

Portability

- If we move to a new machine, we may need to modify:
  - CC, OPT_FLAGS, INCLUDE_FLAGS
- To do so, we must edit the Makefile
- OK enough for small projects; really bad otherwise
- Good practice:
  - Create machine-specific definitions file
  - Include in Makefile

Portability

- Create a file named machine.def with these three lines

```
CC = icc
OPT_FLAGS = -O2
INCLUDE_FLAGS = -I .
```

- In your Makefile, make this replacement:

```
CC = icc
OPT_FLAGS = -O2
INCLUDE_FLAGS = -I .
```

→

```
include machine.def
```

- Makefile works on any machine now
- only machine.def is modified

II. Library Creation & Linking

Outline

- Compilation vs. Linking
- Shared vs. Static Libraries
- Creating static and shared libraries
- LD_LIBRARY_PATH
- ldd and nm
- RPATH
- Link order

Compiling vs. Linking

- Compilation generates object files (machine code) from source code
- Linking bundles object files together to generate a complete executable
- Often carried out via single command for small projects.
- Multiple stages for complex projects

Compilation/Linking Examples

Single-Step

```
icc -I . hello.c hellofunc.c -o hello.exe
```

Separate Steps

```
icc –I . –c hellofunc.c         -o hellofunc.o
Icc –I . –c hello.c             -o hello.o

icc  hello.o hellofunc.o -o hello.exe
```

compilation

linking

Peering Behind the Curtain

- Quite a bit going on in the background
- Quick exercise:
  - In makefiles directory, edit machine.def
  - Change –O2 to –O2 –v
  - run make clean / make
- “-v” denotes “verbose”

Libraries

- Common practice to bundle related functionality into single library
- Can be used in multiple programs
- Two flavors
  - Shared (dynamically linked at runtime)
  - Static (bundled into executable at compile time)

Shared Libraries

- .so extension (e.g., libc.so)
- Advantages
  - Easy to manipulate via environment
  - HPC centers often provide optimized versions of commonly-used libraries.
  - Smaller executable size
  - RAM efficient (multiple processes can access same shared library)
- Disadvantages:
  - occasional version conflicts
  - User must be “environment-aware”
- Advice:
  - Use shared libraries when incorporating 3rd party software into your project.

Static Libraries

- .a extension (e.g., liblapack.a)
- Advantages
  - More difficult to introduce version conflicts
  - Conflicts discovered at compiled time
- Disadvantages:
  - Larger executable size
  - Potential for redundant code in memory
  - More difficult to incorporate updates
- Advice:
  - Where it seems natural, us static libraries to bundle portions of your own project.
  - Use static libraries for 3rd party packages that tend to change significantly between versions (e.g., Boost)

Hands-On Exercise

- We are going to work with a small project that uses statically- and dynamically-linked libraries that we create.
- We will examine how to switch between shared libraries in pkg1 and pkg2 at run-time

main.c
func1();
func2();
func3();

pkg1

func1.c
print "func1 (version 1)”

func2.c
print "func2 (version 1)"

func3.c
print "func3 (version 1)"

pkg2

func1.c
print "func1 (version 2)”

func2.c
print "func2 (version 2)"

func3.c
print "func3 (version 2)"

Our pkg1 Makefile

- Change to the directory “libraries” this is our project directory.
- Open pkg1/src/Makefile
- Let’s have a look.
- Presently, instructions for creating the shared and static library are missing…

Creating a Static Library

- Step1: Compile object files needed by library

```
icc –I . –O1 –c func1.c       -o func1.o
icc –I . –O1 –c func2.c       -o func2.o
icc –I . –O1 –c func3.c       -o func3.o
```

type this at command line

- Step2: Bundle your .o files using the archiver

```
ar rc libstatic.a func1.o func2.o func3.o
```

- GNU archiver options:
  - r – replace functions if already found to exist in library
  - c – create static library if it does not already exist

On Your Own

- Modify the (now empty) rule for $(LIBSTATIC) in your Makefile so that it:
  - Compiles the func.o files
  - Creates an archive from the func.o files
  - Use the variables defined in the Makefile and in machine.def
- Test it:
  - make libstatic.a

Creating a Static Library

- Step1: Compile object files with -fPIC

```
icc –I . –O1 –fPIC –c func1.c     -o func1.o
icc –I . –O1 –fPIC –c func2.c     -o func2.o
icc –I . –O1 –fPIC –c func3.c     -o func3.o
```

type this at command line

- Step2: Use icc with –shared flag to create .so file

```
icc -shared func1.o func2.o func3.o -o libshared.so
```

- Shared library options:
  - -fPIC – generate Position Independent Code
  - -shared – create a shared library

On Your Own

- Modify the (now empty) rule for $(LIBSHARED) in your Makefile so that it:
  - Compiles the func.o files
  - Creates a shared library from the func.o files
  - Use the variables defined in the Makefile and in machine.def
- Test it:
  - make libshared.so
  - make clean
  - make all (will build both libs and “install”)

Creating package 2

- Change back to the “libraries” directory
- cp –r pkg1 pkg2 (create pkg2 directory)
- Change to pkg2/src
- Modify each funcX.c to say “version 2”
- make all
- Change back to the “libraries” directory

Linking our Libraries

- Static and shared libraries are linked with different syntax at compile time
- Static libraries – provide full path to library:

```
icc -O2 -I . -I pkg1/include main.c pkg1/lib/libstatic.a -o test.static
```

- Shared libraries:
  - Indicate directory with –L flag
  - Indicate library using “l” shorthand (libshared.so = -lshared)

```
icc -O2 -I . -I pkg1/include main.c -Lpkg1/lib -lshared -o test.dynamic
```

- Try this at the command line

On Your Own

- Let's examine the Makefile in "libraries"
- Edit the LIBSTATIC and LIBSHARED variables so that test.dynamic and test.static build correctly.
- Run make clean & make to build
- Try it out:
  - ./test.static
  - ./test.dynamic
- What happens?

LD_LIBRARY_PATH

- Test.dynamic failed because the system did not know where to look for libshared

- Using dynamic libraries is a two-step process
  - Compile time: compiler pointed to library via –L
  - Run time: system checks system defaults and LD_LIBRARY_PATH directories for shared libraries

- LD_LIBRARY_PATH
  - Colon-separated list of directories
  - System checks first directory, then second, and so on when loading shared libraries at runtime.

LD_LIBRARY_PATH

- Example:
  - LD_LIBRARY_PATH = /lib:/home/mylib
  - System checks
    1. /lib first
    2. /home/mylib second
- Example:
  - LD_LIBRARY_PATH = /home/mylib:/usr/lib64
  - System checks
    1. /home/mylib first
    2. /lib second

Running Test.dynamic

- Save original LD_LIBRARY_PATH:

```
export LD_SAVE=$LD_LIBRARY_PATH
```

- Try this:

```
export LD_LIBRARY_PATH=pkg1/lib:$LD_SAVE
./test.dynamic
```

- And this:

```
export LD_LIBRARY_PATH=pkg2/lib:$LD_SAVE
./test.dynamic
```

Readelf: What is Needed?

- ELF = Executable Linkable Format
- Standard format for Linux executables and libraries
- Readelf: utility for parsing ELF files
- Tells us which dynamic libraries are needed
- readelf –h filename ***view header***
- readelf –d filename ***view dynamic section***
- Try it with test.dynamic and test.static

Readelf Output

readelf –d test.static

```
Dynamic section at offset 0x35c0 contains 27 entries:
  Tag        Type                         Name/Value
 0x0000000000000001 (NEEDED)             Shared library: [libm.so.6]
 0x0000000000000001 (NEEDED)             Shared library: [libgcc_s.so.1]
 0x0000000000000001 (NEEDED)             Shared library: [libc.so.6]
 0x0000000000000001 (NEEDED)             Shared library: [libdl.so.2]
```

readelf –d test.dynamic

```
Dynamic section at offset 0x35c0 contains 28 entries:
  Tag        Type                         Name/Value
 0x0000000000000001 (NEEDED)             Shared library: [libshared.so]
 0x0000000000000001 (NEEDED)             Shared library: [libm.so.6]
 0x0000000000000001 (NEEDED)             Shared library: [libgcc_s.so.1]
 0x0000000000000001 (NEEDED)             Shared library: [libc.so.6]
 0x0000000000000001 (NEEDED)             Shared library: [libdl.so.2]
```

LDD: Where am I Pointed?

- The ldd utility indicates which shared library will be used
- Depends on system defaults and current LD_LIBRARY_PATH
- Try it out:
  - ldd test.static
  - ldd test.dynamic

ldd Output

ldd test.static

```
linux-vdso.so.1 =>  (0x00007fff584c1000)
libm.so.6 => /lib/x86_64-linux-gnu/libm.so.6 (0x00007fe0d3e40000)
libgcc_s.so.1 => /lib/x86_64-linux-gnu/libgcc_s.so.1 (0x00007fe0d3c2a000)
libc.so.6 => /lib/x86_64-linux-gnu/libc.so.6 (0x00007fe0d3860000)
libdl.so.2 => /lib/x86_64-linux-gnu/libdl.so.2 (0x00007fe0d365c000)
/lib64/ld-linux-x86-64.so.2 (0x00007fe0d4149000)
```

ldd test.dynamic

```
linux-vdso.so.1 =>  (0x00007ffd11ddd000)
libshared.so => pkg1/lib/libshared.so (0x00007f379221b000)
libm.so.6 => /lib/x86_64-linux-gnu/libm.so.6 (0x00007f3791f12000)
libgcc_s.so.1 => /lib/x86_64-linux-gnu/libgcc_s.so.1 (0x00007f3791cfc000)
libc.so.6 => /lib/x86_64-linux-gnu/libc.so.6 (0x00007f3791932000)
libdl.so.2 => /lib/x86_64-linux-gnu/libdl.so.2 (0x00007f379172e000)
… (various Intel libraries here)
/lib64/ld-linux-x86-64.so.2 (0x00007f379241c000)
```

Exercise

- Sometimes dynamic linking creates unexpected problems.
- Copy pkg1 to a new directory pkg3
- Modify the FUNCS variable to omit func3.o
- Rebuild the library via: make clean / make
- Point LD_LIBRARY_PATH at pkg3/lib and re-run test.dynamic

Checking Symbols with nm

- Can use the nm utility to check symbols contained within a file
- e.g., nm pkg1/lib/libshared.so
- Examine the pkg1 and pkg3 libraries
- pkg1 shows the func3 symbol
- pkg3 does not

RPATH: Hard-coded Links

- If desired, we can both:
  - link dynamically
  - ignore LD_LIBRARY_PATH
- To do so, specify the RPATH when compiling, e.g.

```
-Wl,-rpath,$(PWD)/pkg1/lib
```

- RPATH supercedes LD_LIBRARY_PATH
- Examine libraries/Makefile

Running test.rpath

- Save original LD_LIBRARY_PATH:

```
export LD_SAVE=$LD_LIBRARY_PATH
```

- Try this:

```
export LD_LIBRARY_PATH=pkg1/lib:$LD_SAVE
./test.rpath
```

- And this:

```
export LD_LIBRARY_PATH=pkg2/lib:$LD_SAVE
./test.rpath
```

The ORIGIN Variable

- The ORIGIN variable allows us to specify a relative RPATH
- This makes it easier to copy code and shared libraries around.
- Compiler flags (double $ is correct):

```
-Wl,-rpath,"\$$ORIGIN"/lib
```

- Run: readelf –d test.origin

ORIGIN: Try it Out

- We can now move our executable and library wherever we like
- Test.origin will look for .so file in lib subdirectory

```
mkdir $USER/origin

mkdir $USER/origin/lib

cp test.origin $USER/origin/.

cp {pkg1 OR pkg2}/lib/libshared $USER/origin/lib

/$USER/origin/test.origin
```

Link Order

- Can link multiple libraries when compiling a program. E.g.,

  ifort main.f90 –o prog1 –lv1 –lv2 –lv3

- If libraries contain unique subroutines, order does not matter.

- If two or more libraries contain same subroutine names, it matters.

- Why would you have the same routine name?
  - Example: LAPACK & IBM ESSL
    - ESSL & LAPACK both have DGEMM
    - Only LAPACK has dgetrf (band solve routine)
    - May want to use ESSL DGEMM along with LAPACK dgetrf

Link Order

- Let’s examine the Makefile in the link_order directory
- Build the code: make clean / make
- Export LD_LIBRARY_PATH=lib:$LD_LIBRARY_PATH
- Run prog1: ./prog1

Link Order

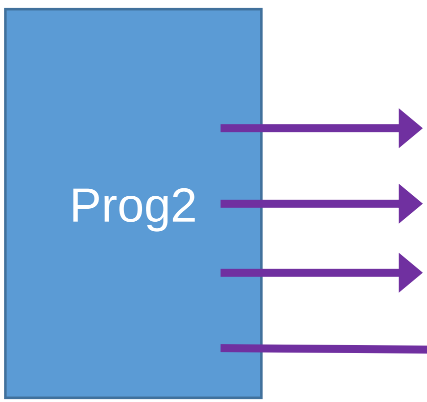
- How does order of linking matter?
- Most linkers check from left to right
- Stops once symbol is found
- Good practice: put “root” dependency last
- Ex: ifort main.f90 –o prog1 –lv1 –lv2 –lv3

Prog1

Libv1.so	Libv2.so	Libv3.so
Asub		
Bsub		Bsub
Csub		
	Dsub	Dsub

Link Order

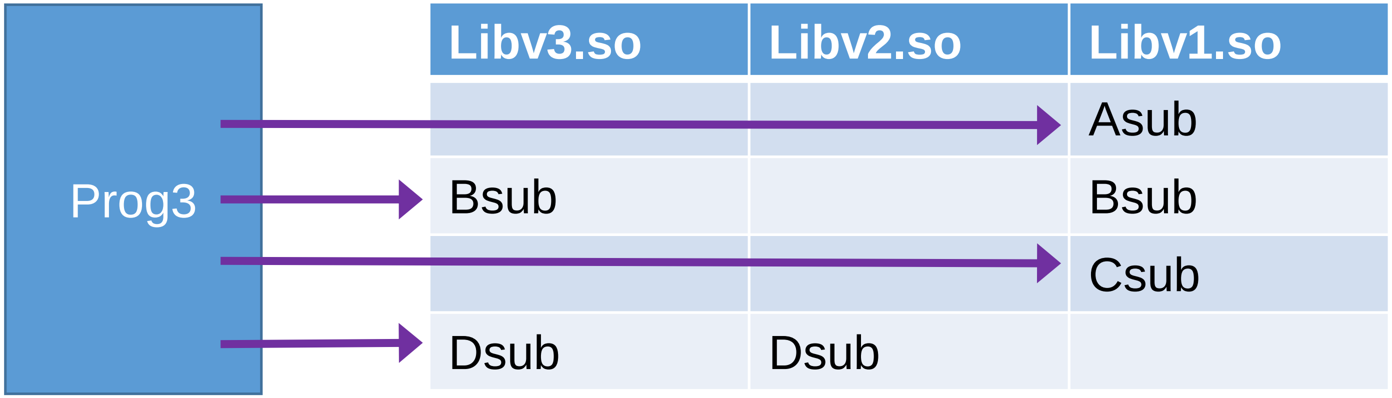
- Run prog2…
  - ifort main.f90 –o prog2 –lv1 –lv3 –lv2



Libv1.so	Libv3.so	Libv2.so
Asub		
Bsub	Bsub	
Csub		
	Dsub	Dsub

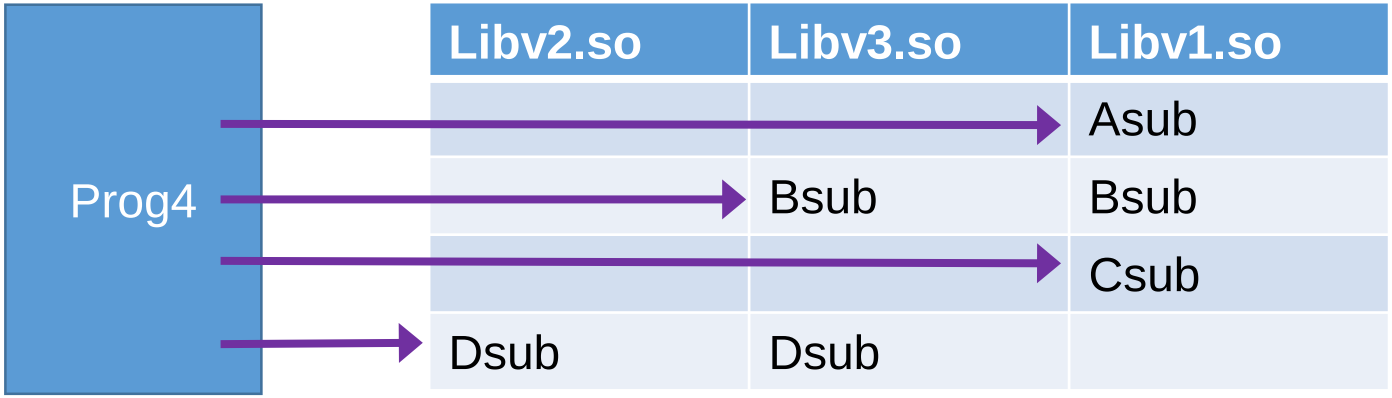
Link Order

- Run prog3…
  - ifort main.f90 –o prog2 –lv1 –lv3 –lv2



Link Order

- Run prog4…
  - ifort main.f90 –o prog2 –lv2 –lv3 –lv1



Test Yourself

- What will be the output of
  - ifort main.f90 –o prog1 –lv2 –lv1 –lv3
  - Ifort main.f90 –o prog1 –lv3 –lv1 –lv2

Libv1.so	Libv2.so	Libv3.so
Asub		
Bsub		Bsub
Csub		
	Dsub	Dsub