HPC Workshop Series: *Compilation*

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Slides:
https://github.com/ResearchComputing/Makefiles_and_Linking

Objects

Outline

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

Before we begin

- ssh username@tutorial-login.rc.colorado.edu
- ssh scompile
- ml intel
- Clone the repository (all one line):
- git clone https://github.com/ResearchComputing/Makefiles_and_Linking.git
- cd Makefiles_and_Linking

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

(TAB before each command)

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

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

TAB TAB TAB TAB

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

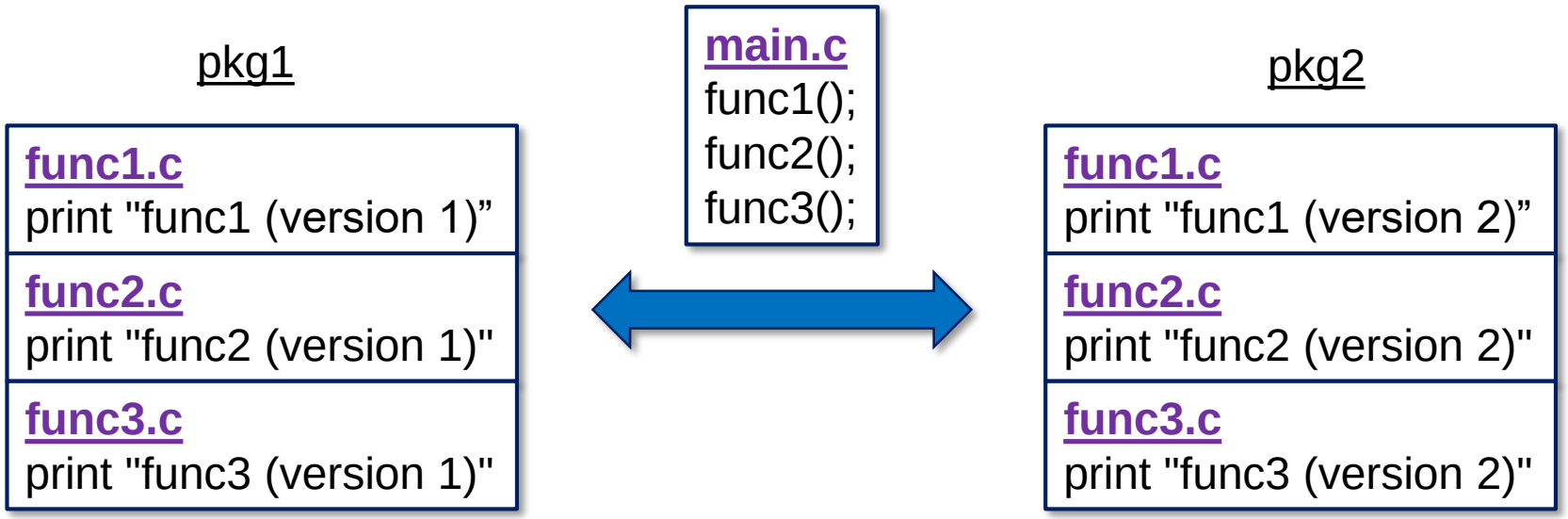
- .so extension (e.g., libc.so)
- Advantages
  - Easy to manipulate via environment
  - HPC centers often provide optimized versions of commonly-used libraries.
  - Smaller executable size
  - RAM efficient (multiple processes can access same shared library)
- Disadvantages:
  - occasional version conflicts
  - 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



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 Shared 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.

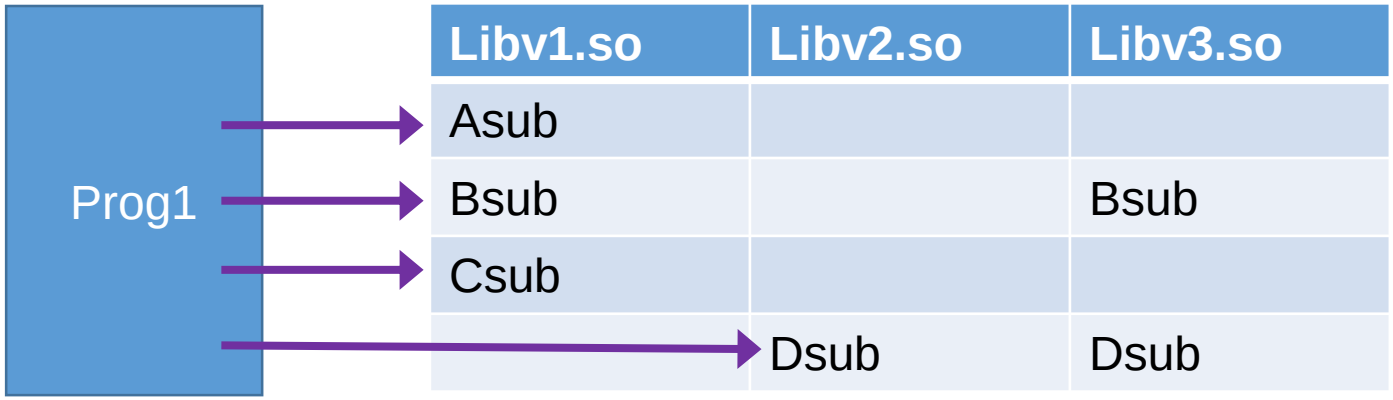
- Why would you have the same routine name?
  - Example: LAPACK & IBM ESSL
    - ESSL & LAPACK both have DGEMM
    - Only LAPACK has dgetrf (band solve routine)
    - May want to use ESSL DGEMM along with LAPACK dgetrf

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

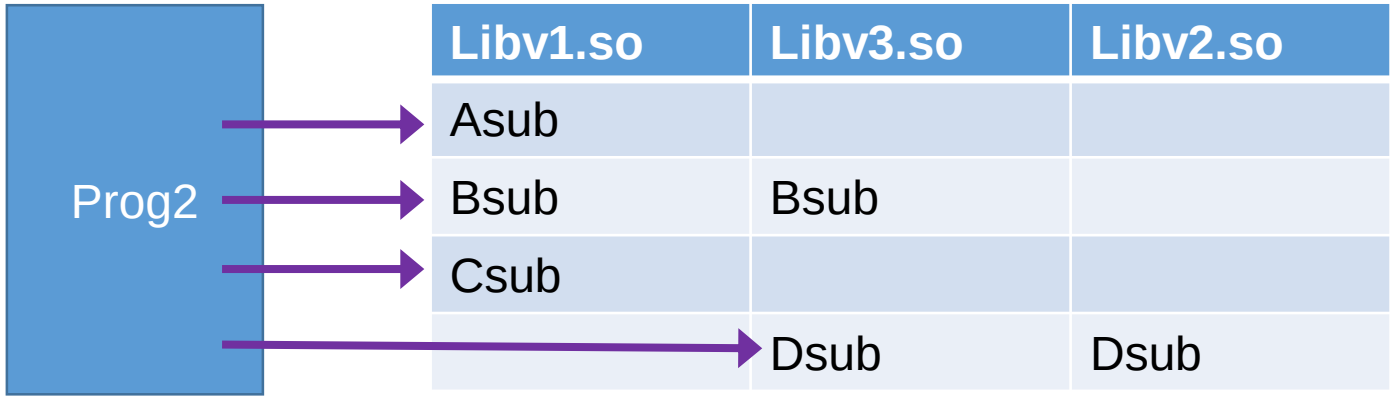
Link Order

- 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



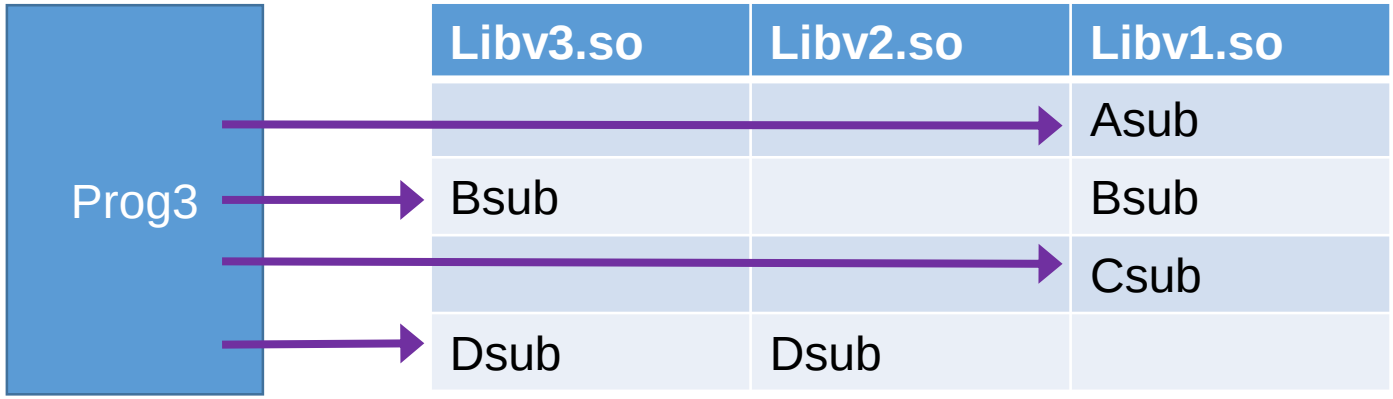
Link Order

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



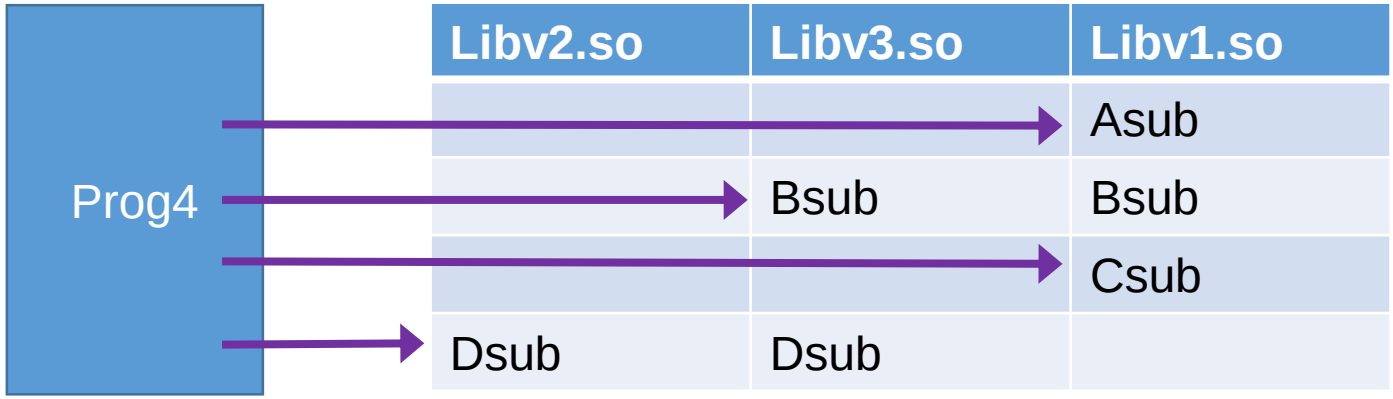
Link Order

- 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