Lecture 04 – Elements of Development: *Configuring, Compiling, Linking*

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NERS/ENGR 570 - Methods and Practice of Scientific Computing (F22)

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Outline

- Motivation and Introduction
- Configuring
- Compiling
- Linking

Learning Objectives: By the end of Today's Lecture you should be able to

- (*Knowledge*) explain what happens at each step of configuring, compiling, and linking
- (*Skill*) How to troubleshoot compilation
- (*Skill*) How to troubleshoot linking
- (*Knowledge*) explain dynamic vs static linking

Motivation

- How do we get other people to use our software?
- How do we use other people's software?
- We wish that it be as easy as:
  - apt-get install / yum install
  - conda install
  - python -m pip install --user

- Presently, this is not the case
  - HPCs are highly specialized machines
  - Some software is highly specialized

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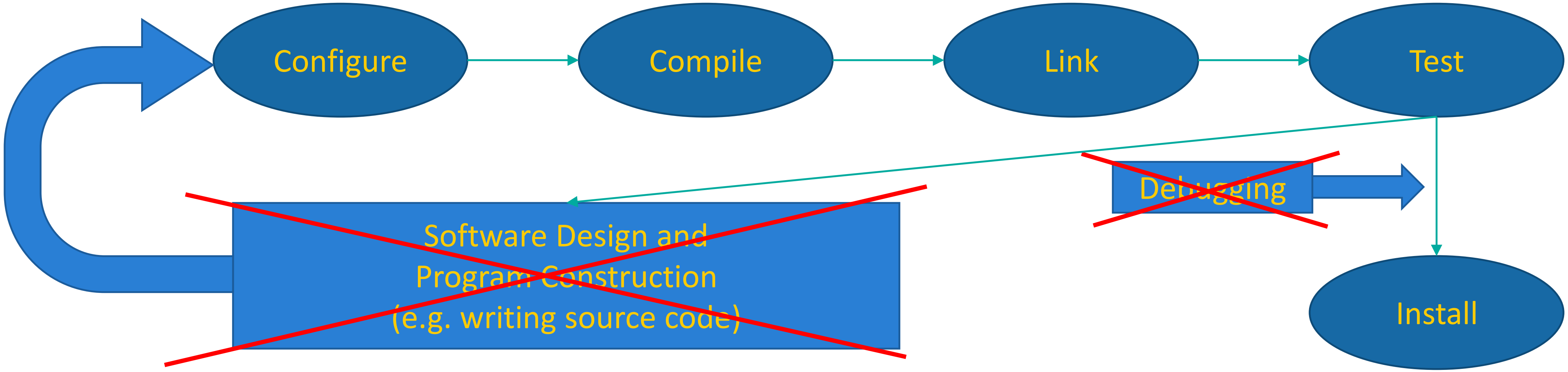
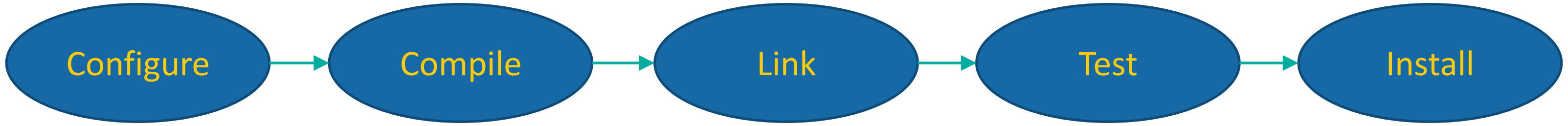
- This is a bigger problem that is being worked on

Elements to Development

- Program Design, Testing, and Debugging are all integral parts of development.
  - They each will get their own lecture later in the semester.
- This lecture is focused on the ***tools and steps*** needed to build software:

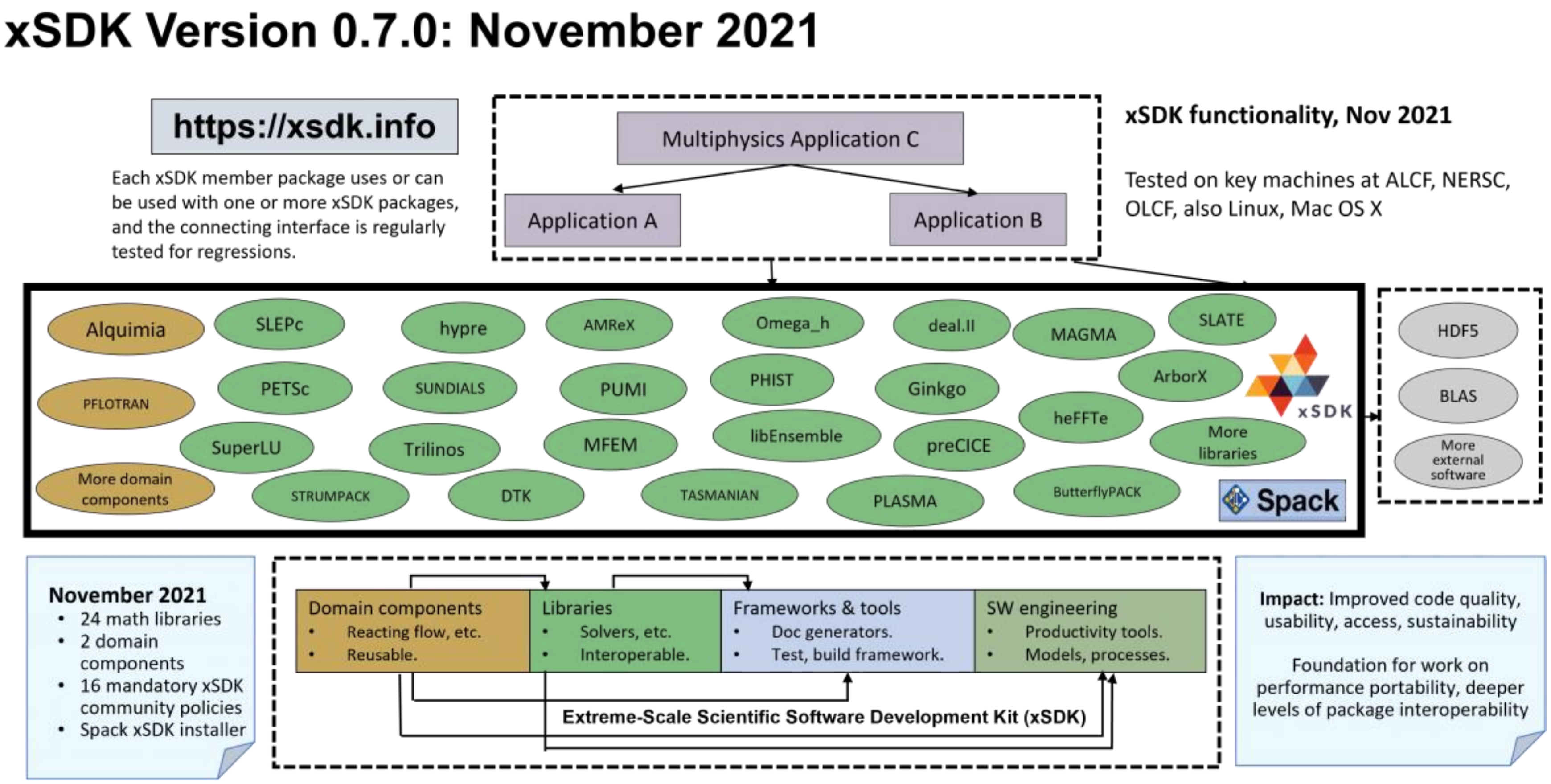

Configure
Compile
Link
Test
~~Debugging~~
Install
~~Software Design and Program Construction (e.g. writing source code)~~

The “Toolchain”



- The tools (e.g. programs and their libraries) typically used by the developer that are needed to take your source files (as input) and produce executables.
- Frequently the definition of a tool chain will also include:
  - a program for “configuring”
  - a “make” script and compiler (compiler version and vendor matters)
  - a distribution of MPI
- Third Party Libraries (TPLs) are typically not considered part of the “toolchain”
  - MPI is sort of the exception to this
- Toolchains represent part of the “Minimum Requirements” for a software package.
  - Software packages can also support multiple toolchains

xSDK – Extreme-scale Scientific Software Development Kit



xSDK Version 0.7.0: November 2021

https://xsdk.info

Each xSDK member package uses or can be used with one or more xSDK packages, and the connecting interface is regularly tested for regressions.

xSDK functionality, Nov 2021

Tested on key machines at ALCF, NERSC, OLCF, also Linux, Mac OS X

November 2021

- 24 math libraries
- 2 domain components
- 16 mandatory xSDK community policies
- Spack xSDK installer

Domain components
- Reacting flow, etc.
- Reusable.

Libraries
- Solvers, etc.
- Interoperable.

Frameworks & tools
- Doc generators.
- Test, build framework.

SW engineering
- Productivity tools.
- Models, processes.

Extreme-Scale Scientific Software Development Kit (xSDK)

Impact: Improved code quality, usability, access, sustainability

Foundation for work on performance portability, deeper levels of package interoperability

https://xsdk.info

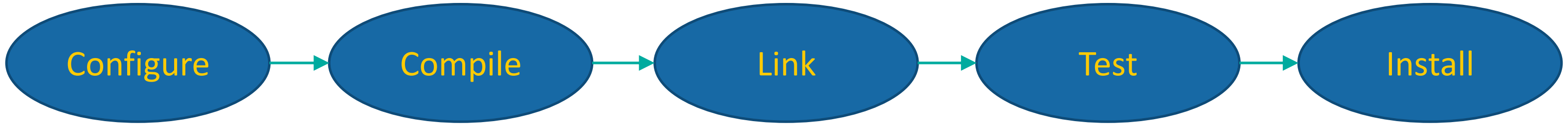
Some Terminology about “Time”

- *configure-time* – when you are configuring
- *compile-time/build-time* – when you are compiling
- *link-time* – when you are linking (very last step in “compiling”)
- *run-time* – when you are running the executable

- Important for communicating “when things went wrong”

An Imperfect Cooking Analogy

Any volunteers that do not mind sharing details of their kitchen?



Configure → Compile → Link → Test → Install

Configuring: Preparing to cook

Cooking

- Look around and find all the necessary ingredients and cookware (pots, pans, knives) to make dinner
  - Your stomach
  - Appliances
  - Spatula, spoon and knives
  - Salt, Pepper, Spices and Sauces
- Detailed instructions to cook in your kitchen
- Cookbooks
- Writing your own cookbook for others
- It's a part of life
- Use pre-packaged frozen meals

Software

- Purpose is to probe the system for to determine
  - the computer architecture (e.g. x86, AIX, ARM, etc.)
  - what compilers are installed, and where they are installed
  - what additional system software is installed
  - what third party libraries are available
- Basically creates "Makefiles" for a specific computer and environment for use in compiling (the next step)
- Specialized programs exist to perform the "configure" step.
  - autotools (autoconf/automake) → `configure`
  - CMake → `cmake`
- Most difficult part to establishing complex software systems.
- Considered part software infrastructure
- **AUTOMATE as much as possible**

Compiling: Cooking

Cooking

- Basically following the steps
  - Chop the onion
  - Season the ….
  - Fry the egg
  - Bake in the oven
- Lots of different kinds of steps/things we do in cooking
- Objective: prepare everything in the meal to go on the plate

Software

- Compilers do lots of different things.
  - Preprocessing
  - Optimizing
  - Check for errors
  - Give warnings
  - Generate assembly
  - Include this other file
- Objective: prepare all the machine code to go into the executable

Linking: Plating the Meal

Cooking

- Objective: put everything you’ve made together into a delicious meal.
- Considerations
  - Where did I put this cooked thing
  - Fresh parmesan?
  - Bowl or Plate
  - Spoon or Fork

Software

- Objective: put everything together into a functional executable
- Considerations
  - Where is this function/library coming from?
  - Library or executable
  - Shared or static

Configuring Software

Things that Configuring Can Control

- Where the libraries and executables produced from compilation are installed
- Compiler options:
  - e.g. whether the libraries and executables are “debug” (slow) or “release” (fast)
  - e.g. whether the compilation produces “dynamic” or “static” binaries
- What features of the library are enabled
  - e.g. with HDF5 you can specify whether you want the compiled library to include Fortran interfaces or just C interfaces.
  - e.g. what third party libraries to include (often provide additional capability in the software package)
    - In HDF5 the “Z” library can be included to provide data compression.
- Various other options that would be specific to the software package.

Configuration Options

The Cliff's Notes

- Depends on the tool!
- You will *always have to read documentation*
  - Usually files are named `INSTALL` or `README`
- Hopefully libraries and programs you work with are well documented
- Make sure you document your configuration steps well (or make them "robust") in software you produce
  - People won't use your software if it is difficult to install or build.

"Common" Usage and Options

- Autotools (autoconf/automake)
  - `./configure [options]`
    - `--prefix=<path_to_install>`
    - `CC=<c_compiler>`
    - `FC=<fortran_compiler>`
- CMake
  - `cmake [options] <path_source_dir>`
    - `-DCMAKE_BUILD_TYPE="Release"`
    - `-DCMAKE_C_COMPILER`
    - `-DCMAKE_CXX_COMPILER`
    - `-DCMAKE_Fortran_COMPILER`

Examples of Configuration Scripts

CMake (CMakeLists.txt) for METIS

```
cmake_minimum_required(VERSION 2.8)
project(METIS)

set(GKLIB_PATH "GKlib" CACHE PATH "path to GKlib")
set(SHARED FALSE CACHE BOOL "build a shared library")
if(MSVC)
  set(METIS_INSTALL FALSE)
else()
  set(METIS_INSTALL TRUE)
endif()
# Configure libmetis library.
if(SHARED)
  set(METIS_LIBRARY_TYPE SHARED)
else()
  set(METIS_LIBRARY_TYPE STATIC)
endif(SHARED)
include(${GKLIB_PATH}/GKlibSystem.cmake)
# Add include directories.
include_directories(${GKLIB_PATH})
# Recursively look for CMakeLists.txt in subdirs.
add_subdirectory("include")
add_subdirectory("libmetis")
add_subdirectory("programs")
```

Autoconf (configure.in) for PAPI

```
AC_PREREQ(2.59)
AC_INIT(PAPI, 5.5.0.0, ptools-perfapi@eecs.utk.edu)
AC_CONFIG_SRCDIR([papi.c])
AC_CONFIG_HEADER([config.h])

AC_MSG_CHECKING(for architecture)
AC_ARG_WITH(arch,
                  [  --with-arch=<arch>   Specify architecture (uname -m)],
                  [arch=$withval],
                  [arch=`uname -m`])
AC_MSG_RESULT($arch)

AC_ARG_WITH(bitmode,
            [  --with-bitmode=<32,64>  Specify bit mode of library],
            [bitmode=$withval])

AC_MSG_CHECKING(for OS)
```

Autotools Configure Example Cont.

```
#!/bin/sh
# Guess values for system-dependent variables and create Makefiles.
# Generated by GNU Autoconf 2.59 for PAPI 5.5.0.0.

# Identity of this package.
PACKAGE_NAME='PAPI'
PACKAGE_TARNAME='papi'
PACKAGE_VERSION='5.5.0.0'
PACKAGE_STRING='PAPI 5.5.0.0'
PACKAGE_BUGREPORT='ptools-perfapi@eecs.utk.edu'

ac_unique_file="papi.c"
# Factoring default headers for most tests.
ac_includes_default="\
#...
#if STDC_HEADERS
# include <stdlib.h>
# include <stddef.h>
#else
# if HAVE_STDLIB_H
#  include <stdlib.h>
# endif
#endif
```

- As a user you typically will not run `autoconf`
  - But as a developer you might
- As a user you will run configure shell script produced by autoconf.
- Conventional wisdom for developers
  - CMake >> ~~Autohell~~ Autotools
- **If starting new, start with CMake.**

Troubleshooting the Configure Step

For Scientific Software Development

- My configure failed! What do I do?
  - Uh oh… Usually difficult to resolve
- At best, problem is solved by modifying your environment.
- At worst, may require some other software be installed
  - And you may not have privileges to do so!
  - In this case you're likely
  - …unless you're willing to put in way more time than is appropriate

For Cooking

- I can't find everything I need to cook dinner!
  - I'm hungry now, but I need to grill this steak!
- Ask your neighbor for a cup of sugar and some eggs or a melon baller
- You mean I need a grill!?
  - But I live in an apartment!
  - Guess you'll go hungry
  - …unless I can make friends with someone who has a grill

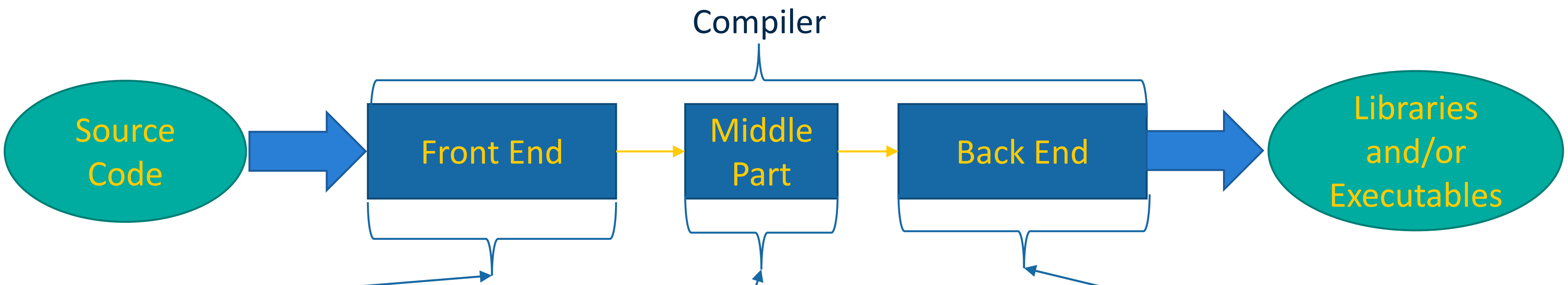
Configure Hands-on Example

Compilers/Compiling

What is a Compiler?

- Translates a high-level programming language (suitable for humans) into a low level machine language required by the computer.
- Typically have several common features
  - Checking for syntax and programming errors
  - Supply debugging information
  - Perform optimizations
- It’s a program written by people
  - so it has bugs
  - And different versions and the behavior between versions can vary significantly.

Modern Compiler Program Architectures



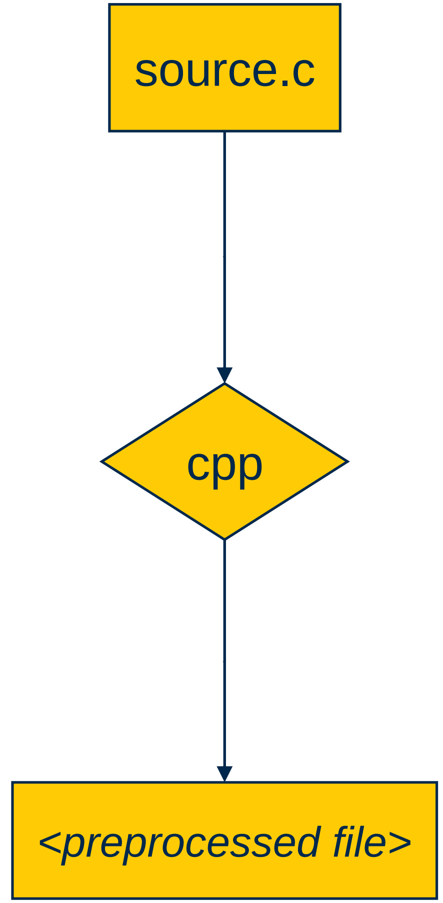
- Lexical Analysis
    - Read and parse text in source files into *tokens*
- Syntax Analysis
    - Arrange tokens in syntax tree to reflect program structure
- Type checking
    - Checks syntax tree for mistakes (e.g. undefined variables)

- Intermediate coded generation
    - Translation to simple machine independent language
    - Typically will vary between compilers
- Optimization
    - Apply algorithms for optimization to intermediate language

- Register allocation
    - Translate variables to machine registers (memory locations)
- Machine code generation
    - Translate intermediate language to machine code (assembly)
- Assembly and linking
    - Convert assembly to binary and resolve addresses for variables and functions

Other things a compiler does (sort of)

- Preprocess (separate program executed by compiler during compilation, “**cpp**”)
  - ***Modifies source files***
  - A part of C, but can be used in the compilation of C++ & Fortran
    - In Fortran file extensions control default behavior:
    - *.F, *.F90 are automatically preprocessed, and *.f, *.f90 are not
  - Based on “directives”, start with “#” in first column.
    - Include files, macro expansion, conditional compilation
  - Compilers will predefine some symbols for you
- Link (separate program executed by compiler during compilation, “**ld**”)
  - We’ll discuss linking in a few slides…



Some Preprocessor Examples

C

```
#include <stdio.h>

//Define macros
#define PI 3.14159
#define RADTODEG(x) ((x) * 57.29578)

int main()
{
    float x;
    x=RADTODEG(PI*0.5);
    printf("PI/2 radians in degrees is %.6f\n",x);
    return 0;
}
```

```
int main()
{
    float x;
    x=((3.14159*0.5) * 57.29578);
    printf("PI/2 radians in degrees is %.6f\n",x);
    return 0;
}
```

Fortran

```
PROGRAM main

#ifdef __GFORTRAN__
  WRITE(0,'(a,i2,a)') 'File: "'//__FILE__//'", line ',__LINE__, &
    " was compiled with gfortran!"
#else
  WRITE(0,'(a,i2,a)') 'File: "'//__FILE__//'", line ',__LINE__, &
    " was NOT compiled with gfortran!"
#endif

ENDPROGRAM
```

```
PROGRAM main


  WRITE(0,'(a,i2,a)') 'File: "'//"hello.F90"//'", line ',4, &
    " was compiled with gfortran!"


ENDPROGRAM
```

Compiler options for debugging

GCC compiler option	Meaning
`-g`	Produce debugging information in the operating system's native format (stabs, COFF, XCOFF, or DWARF). GDB can work with this debugging information.
`-fsanitize=<opt>`	Enable AddressSanitizer, a fast memory error detector.
`-fbounds-check`	Generate additional code to check that indices used to access arrays are within the declared range during run time.
`-fcheck-pointer-bounds`	Each memory reference is instrumented with checks of the pointer used for memory access against bounds associated with that pointer.
`-fstack-check`	Generate code to verify that you do not go beyond the boundary of the stack.

Pretty much only `-g` is important.
For the other run-time checks, significant overhead in run time may be observed.

Other compiler options

GCC compiler option	Meaning
-c	Compile without linking
-o	Name of output file.
-I	Search path for included header files (there are predefined system paths)
-L	Search path for libraries
-l	Library name to link in
-D ***<symbol>***	Define preprocessor symbol ***<symbol>*** during compilation
-E	Output preprocessed source file
-S	Output assembly from compilation
-fPIC	Compile **P**osition **I**ndependent **C**ode (necessary for shared objects)
-fopenmp	Process OpenMP directives
-p	Generate profiling information during run time for profiling analysis tools (e.g. gprof)
-ftest-coverage	Generate coverage information during run time for coverage analysis tools (e.g. gcov)

Object code & Binary output

- Compiling a source file `source.F90` (e.g. –c) produces an object file `source.o`
  - Object files are *relocatable* machine code.
  - Typical object file format for linux is ELF.
  - Cannot view object files in text editors
- ELF files contain
  - Program header table describing 0 or more segments
    - Contains run-time information
  - Section header table describing 0 or more sections
    - Contains link-time information
  - Data referred to by segments and sections
- How can you inspect ELF files/object code/object files?

Snippet of object file from program on slide 15 in vi

```
^?ELF^B^A^A^@^@^@^@^@^@^@^@^@^A^@>^@^A^@^@^@^@
^@^@^@^@^@^@^@^@^@^@^@^@^@^@^@^@¸^B^@^@^@^@^@^@^
@^@^@^@@^@^@^@^@^@@^@^M^@
^@UH<89>åH<81>ìà^A^@^@HÇ<85>(þÿÿ^@^@^@^@Ç<85>0
þÿÿ^E^@^@^@HÇ<85>hþÿÿ^@^@^@^@Ç<85>pþÿÿ^H^@^@^@
Ç<85> þÿÿ^@^P^@^@Ç<85>$þÿÿ^@^@^@^@H<8d><85>
þÿÿH<89>Çè^@^@^@^@H<8d><85>
þÿÿ°^X^@^@^@¾^@^@^@^@H<89>Çè^@^@^@^@H<8d><85>
þÿÿ°^D^@^@^@¾^@^@^@^@H<89>Çè^@^@^@^@H<8d><85>
þÿÿ°^\^@^@^@¾^@^@^@^@H<89>Çè^@^@^@^@H<8d><85>
þÿÿH<89>Çè^@^@^@^@ÉÃUH<89>åH<83>ì^P<89>}üH<89>
uðH<8b>Uð<8b>EüH<89>Ö<89>Çè^@^@^@^@¾^@^@^@^@¿^
H^@^@^@è^@^@^@^@è^Xÿÿÿ¸^@^@^@^@ÉÃ^@^@^@^@^@^@^
@^@^@^@^@^@^@^@^@^@^@hello.F90^@(a,i2,a)File:
"hello.F90", line ^@^@^D^@^@^@ was compiled
with
gfortran!^@^@^@^@^@^@^@^@^@^@^@^@^@^@^@^@^@^@^
@^@D^@^@^@ÿ^A^@^@^@^@^@^@^@^@^@^@^@^@^@^A^@^
@^@^@^@^@^@^A^@^@^@^@GCC: (Ubuntu/Linaro
4.6.4-1ubuntu1~12.04)
4.6.4^@^@^@^@^@^@^@^@^T^@^@^@^@^@^@^@^AzR^@^Ax
^P^A^[^L^G^H<90>^A^@^@^\^@^@^@^\^@^@^@^@^@^@^@
´^@^@^@^@A^N^P<86>^BC^M^F^B¯^L^G^H^@^@^\^@^@^@
<^@^@^@^@^@^@^@;^@^@^@^@A^N^P<86>^BC^M^Fv^L^G^
H^@^@^@^@.symtab^@.strtab^@.shstrtab^@.rela.te
xt^@.data^@.bss^@.rodata^@.comment^@.note.
```

Inspecting Object Files

readelf -a source.o

```
Symbol table '.symtab' contains 18 entries:
   Num:    Value          Size Type    Bind   Vis      Ndx Name
     0: 0000000000000000     0 NOTYPE  LOCAL  DEFAULT  UND
     1: 0000000000000000     0 FILE    LOCAL  DEFAULT  ABS hello.F90
     2: 0000000000000000     0 SECTION LOCAL  DEFAULT    1
     3: 0000000000000000     0 SECTION LOCAL  DEFAULT    3
     4: 0000000000000000     0 SECTION LOCAL  DEFAULT    4
     5: 0000000000000000     0 SECTION LOCAL  DEFAULT    5
     6: 0000000000000000   180 FUNC    LOCAL  DEFAULT    1 MAIN__
     7: 0000000000000060    32 OBJECT  LOCAL  DEFAULT    5 options.1.1538
     8: 0000000000000000     0 SECTION LOCAL  DEFAULT    7
     9: 0000000000000000     0 SECTION LOCAL  DEFAULT    8
    10: 0000000000000000     0 SECTION LOCAL  DEFAULT    6
    11: 0000000000000000     0 NOTYPE  GLOBAL DEFAULT  UND _gfortran_st_write
    12: 0000000000000000     0 NOTYPE  GLOBAL DEFAULT  UND _gfortran_transfer_charac
    13: 0000000000000000     0 NOTYPE  GLOBAL DEFAULT  UND _gfortran_transfer_intege
    14: 0000000000000000     0 NOTYPE  GLOBAL DEFAULT  UND _gfortran_st_write_done
    15: 00000000000000b4    59 FUNC    GLOBAL DEFAULT    1 main
    16: 0000000000000000     0 NOTYPE  GLOBAL DEFAULT  UND _gfortran_set_args
    17: 0000000000000000     0 NOTYPE  GLOBAL DEFAULT  UND _gfortran_set_options
```

nm source.o

```
0000000000000000 t MAIN__
                 U _gfortran_set_args
                 U _gfortran_set_options
                 U _gfortran_st_write
                 U _gfortran_st_write_done
                 U _gfortran_transfer_character_write
                 U _gfortran_transfer_integer_write
00000000000000b4 T main
0000000000000060 r options.1.1538
```

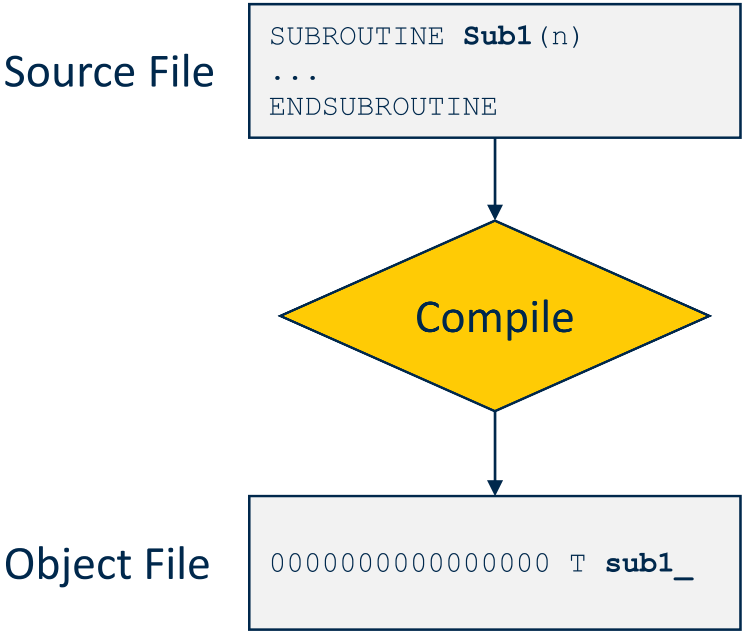
Wait… Why do I need to know what’s in my object files?

97% of the time you don’t need to know. However, this can be useful in resolving link errors and multi-language programs

Name Mangling (Fortran)

Fortran

- Binary symbol name is different from high level programming language name
- Variants:
  - Lower, Lower_, Lower__
  - Upper, Upper_, Upper__
- Used to be critical for calling Fortran from C.
  - Now the Fortran standard provides features that give programmer more control over name mangling.



```
SUBROUTINE Sub1(n)
...
ENDSUBROUTINE
```

```
0000000000000000 T sub1_
```

This example is “Lower_”

```
SUBROUTINE Sub1(n) BIND(C,NAME=“Sub1”)
...
ENDSUBROUTINE
```

```
0000000000000000 T Sub1
```

Name Mangling (C++)

```cpp
#include <iostream>
#include <string>

using namespace std;

template <typename T>
inline T const& Max (T const& a, T const& b)
{
    return a < b ? b:a;
}

int main ()
{
    int i = 39; int j = 20;
    cout << "Max(i, j): " << Max(i, j) << endl;

    double f1 = 13.5; double f2 = 20.7;
    cout << "Max(f1, f2): " << Max(f1, f2) << endl;

    string s1 = "Hello"; string s2 = "World";
    cout << "Max(s1, s2): " << Max(s1, s2) << endl;
    return 0;
}
```

- Shows up with templating
  - Have to produce different binary code for each templated type
  - Necessary for linking

```
00000000000001c6 t _Z41__static_initialization_and_destruction_0ii
                 U _ZNKSs7compareERKSs
                 U _ZNSaIcEC1Ev
                 U _ZNSaIcED1Ev
                 U _ZNSolsEPFRSoS_E
                 U _ZNSolsEd
                 U _ZNSolsEi
                 U _ZNSsC1EPKcRKSaIcE
                 U _ZNSt8ios_base4InitC1Ev
                 U _ZNSt8ios_base4InitD1Ev
                 U _ZSt4cout
                 U _ZSt4endlIcSt11char_traitsIcEERSt13basic_ostreamIT_T0_ES6_
0000000000000000 b _ZStL8__ioinit
                 U _ZStlsISt11char_traitsIcEERSt13basic_ostreamIcT_ES5_PKc
0000000000000000 W _ZStltIcSt11char_traitsIcESaIcEEbRKSbIT_T0_T1_ES8_
```

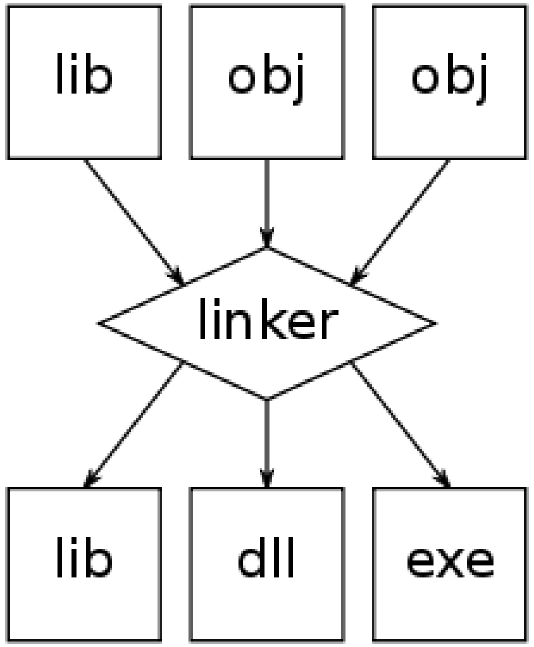
Example from: https://www.tutorialspoint.com/cplusplus/cpp_templates.htm

Compilation Hands-on Examples

Linking

What is Linking?

- Linking is the process of combining the various objects and libraries output from compilation into a single executable (or library or object).
  - May also include binaries (e.g. libraries) already installed on the system
- Sometimes performed by external program called by compiler (e.g. `ld`)
- Sometimes part of compiler (depends on the vendor)
- Key steps in linking are
  - *Resolving external symbols* that the linker uses to figure out how to piece together the executable
  - *Relocating load addresses* of various program parts (e.g. function addresses and variable addresses) to reflect the assigned addresses in the whole program.
- Linking can produce targets thatare ***statically*** linked or ***dynamically*** linked



Dynamic Linking vs. Static Linking

Static Linking

- Probably what you think of when you think "linking"
- Copy all binary code from all libraries and objects then package into a single executable image
  - Usually results in larger executable file sizes
- A little more portable since all the binary code is packaged together
- Requires all libraries that are linked to be static libraries (e.g. `lib`*`<name>`*`.a`)
- Sometimes a requirement on large clusters
  - Compute nodes and login nodes are different

Dynamic Linking

- Symbol resolution is delayed until executable is run
  - Executable code has undefined symbols
  - Requires all libraries that are linked to be dynamic libraries (e.g. `lib`*`<name>`*`.so`)
- Some advantages
  - For system libraries used by every program, no need to copy into every executable (e.g. `libc`)
  - If there is a bug in a library, and a new version of the library that fixes the bug is installed, all programs benefit.
    - Statically linked executables need to be re-linked
- Some disadvantages
  - Libraries that are updated that break backwards compatibility, might break your executable.
  - Need to have the correct environment.
  - Not necessarily portable, OS and environment need to consistent.

What link errors look like

Static Link Error

```
PROGRAM hello_main

WRITE(*,*) "Hello World!"
CALL some_undefined_routine()

ENDPROGRAM
```

```
$ gfortran -c hello.F90
$ gfortran hello.o -o hello.exe
hello.o: In function `MAIN__':
hello.F90:(.text+0x71): undefined reference to
`some_undefined_routine_'
collect2: ld returned 1 exit status
```

The command given to the linker did not include the library or object
(or the correct path to the library or object) that defines the named symbol.

Dynamic Link Error

```
$ ./some_mpi_program.exe
./mpi_program.exe: error while loading shared
libraries: libmpi.so: cannot open shared object file:
No such file or directory
```

When you attempted to run the executable,
The OS could not find the library using the
information in your current environment

How to trouble shoot link errors

Static Link Error

- Most likely you are missing the correct entries on the following options passed to the linker:
  - `-l<library_name_with_symbol>`
  - `-L<path_to_library>`
- Could also be a typo in your source code
- Generally easy to resolve
  - If you know where the missing library is located.
- Can be difficult if you have no idea why the symbol is trying to be linked (where is it used, where is it defined
  - More likely to happen when you are linking third party libraries

Dynamic Link Error

- Most likely your environment is not the same as when you compiled
  - Check your environment
  - Environment variable is `LD_LIBRARY_PATH`
- Useful command: `ldd`
  - Shows you *exactly* what libraries are dynamically linked to your executable

```
$ ldd ./some_mpi_program.exe
        linux-vdso.so.1 =>  (0x00007ffcf2be8000)
        libmpi.so => not found
        libc.so.6 => /lib/x86_64-linux-gnu/libc.so.6
(0x00007f4d12878000)
        /lib64/ld-linux-x86-64.so.2 (0x00007f4d12c38000)
```

Dynamic Loading: Linking in code at run time

- Start your executable then load a library into memory.
  - Use case is "plugins". An example might be linking proprietary correlations for material properties.
  - Can be done interactively. User could specify library name and function name as an input.
  - Challenging to list "available symbols" in library, although this can be done. But basically need to know what routine you want to call
- In Linux requires "dl" library.

```
#include <dlfcn.h>

void* sdl_library = dlopen("libSDL.so", RTLD_LAZY);
if (sdl_library == NULL) {
   // report error ...
} else {
   void* initializer = dlsym(sdl_library,"SDL_Init"); //extract library contents
   if (initializer == NULL) {
      // report error ...
   } else {
      // cast initializer to its proper type and use
      typedef void (*sdl_init_function_type)(void);
      sdl_init_function_type init_func = (sdl_init_function_type) initializer;
   }
}
```

https://en.wikipedia.org/wiki/Dynamic_loading

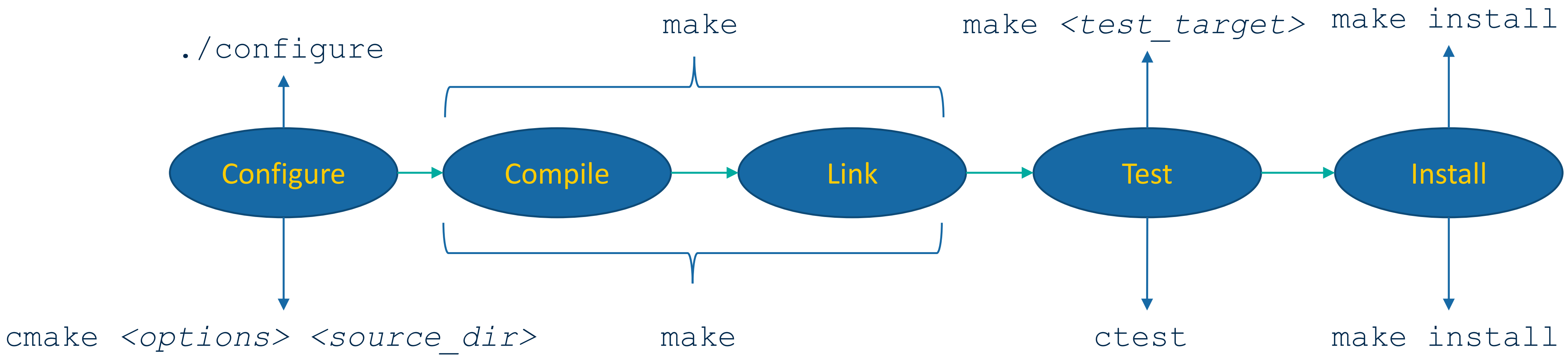
Multi-language Programs

- **The key is linking!**
  - Linker does not care what high-level language produced your object code. It could have been generated from Fortran or C or C++.
    - Linker just has to resolve symbols in object code.
  - Well one subtlety, you must have a compatible application binary interface (ABI)
    - Usually not an issue unless you are compiling on one machine and linking on another.
- If a programming language or environment (e.g. Python) supports linking of C interfaces than you can link any code that provides a C interface
  - Most languages support C interfaces (because they were probably implemented in C or the compiler was)
  - Therefore, *C is the de-factor language of interoperability*.
- By “C interface” I mean a binary symbol that is producible from the C high-level language and a C compiler.

Linking Hands-on Example

Summary: Using the Toolchain

Autotools



CMake