Workshop on High Performance Computing (HPC) Architecture and Applications in the ICTP

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Compiling and Linking with Static and Shared Libraries Using Multiple Programming Languages

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Pre-process / Compile / Link

- Creating an executable includes multiple steps
- The “compiler” (gcc) is a wrapper for several commands that are executed in succession
- The “compiler flags” similarly fall into categories and are handed down to the respective tools
- The “wrapper” selects the compiler language from source file name, but links “its” runtime
- We will look into a C example first, since this is the language the OS is (mostly) written in
A simple C Example

- Consider the minimal C program 'hello.c':

```c
#include <stdio.h>
int main(int argc, char **argv) {
    printf("hello world\n");
    return 0;
}
```

- i.e.: what happens, if we do:

  > gcc -o hello hello.c
  (try: gcc -v -o hello hello.c)
Step 1: Pre-processing

- Pre-processing is mandatory in C (and C++)
- Pre-processing will handle '#' directives
  - File inclusion with support for nested inclusion
  - Conditional compilation and Macro expansion
- In this case: /usr/include/stdio.h
  - and all files are included by it - are inserted and the contained macros expanded
- Use -E flag to stop after pre-processing:
  > cc -E -o hello.pp.c hello.c
Step 2: Compilation

- Compiler converts a high-level language into the specific instruction set of the target CPU
- Individual steps:
  - Parse text (lexical + syntactical analysis)
  - Do language specific transformations
  - Translate to internal representation units (IRs)
  - Optimization (reorder, merge, eliminate)
  - Replace IRs with pieces of assembler language
- Try: `gcc -S hello.c` (produces `hello.s`)
Compilation cont'd

```assembly
.file "hello.c"
.section .rodata

.LC0:
.string "hello, world!"
.text
.globl main
.type main, @function
main:
pushl %ebp
movl %esp, %ebp
andl $-16, %esp
subl $16, %esp
movl $.LC0, (%esp)
call puts
movl $0, %eax
leave
ret
.size main, -.main
.ident "GCC: (GNU) 4.5.1 20100924 (Red Hat 4.5.1-4)"
.section .note.GNU-stack,"",@progbits
```

gcc replaced printf with puts

try: gcc -fno-built-in -S hello.c

```c
#include <stdio.h>
int main(int argc,
    char **argv)
{
    printf("hello world\n");
    return 0;
}
```
Step 3: Assembler / Step 4: Linker

- Assembler (as) translates assembly to binary
  - Creates so-called object files (in ELF format)
    Try: > gcc -c hello.c
    Try: > nm hello.o
    000000000 T main
    U puts
- Linker (ld) puts binary together with startup code and required libraries
- Final step, result is executable.
  Try: > gcc -o hello hello.o
Adding Libraries

- Example 2: exp.c

```c
#include <math.h>
#include <stdio.h>
int main(int argc, char **argv)
{
    double a=2.0;
    printf("exp(2.0)=%f\n", exp(a));
    return 0;
}
```

- `gcc -o exp exp.exp.c`
  Fails with “undefined reference to 'exp'”. Add: -lm

- `gcc -03 -o exp exp.exp.c`
  Works due to inlining at high optimization level.
Symbols in Object Files & Visibility

- Compiled object files have multiple sections and a symbol table describing their entries:
  - “Text”: this is executable code
  - “Data”: pre-allocated variables storage
  - “Constants”: read-only data
  - “Undefined”: symbols that are used but not defined
  - “Debug”: debugger information (e.g. line numbers)
- Entries in the object files can be inspected with either the “nm” tool or the “readelf” command
Example File: visibility.c

```c
static const int val1 = -5;
const int val2 = 10;
static int val3 = -20;
int val4 = -15;
extern int errno;

static int add_abs(const int v1, const int v2) {
    return abs(v1)+abs(v2);
}

int main(int argc, char **argv) {
    int val5 = 20;
    printf("%d / %d / %d\n",
            add_abs(val1,val2),
            add_abs(val3,val4),
            add_abs(val1,val5));
    return 0;
}
```

What Happens During Linking?

- Historically, the linker combines a “startup object” (crt1.o) with all compiled or listed object files, the C library (libc) and a “finish object” (crtn.o) into an executable (a.out)
- With current compilers it is more complicated
- The linker then “builds” the executable by matching undefined references with available entries in the symbol tables of the objects
- crt1.o has an undefined reference to “main” thus C programs start at the main() function
Static Libraries

- Static libraries built with the “ar” command are collections of objects with a global symbol table.
- When linking to a static library, object code is copied into the resulting executable and all direct addresses recomputed (e.g. for “jumps”).
- Symbols are resolved “from left to right”, so circular dependencies require to list libraries multiple times or use a special linker flag.
- When linking only the name of the symbol is checked, not whether its argument list matches.
Shared Libraries

- Shared libraries are more like executables that are missing the main() function.
- When linking to a shared library, a marker is added to load the library by its “generic” name (soname) and the list of undefined symbols.
- When resolving a symbol (function) from shared library all addresses have to be recomputed (relocated) on the fly.
- The shared linker program is executed first and then loads the executable and its dependencies.
Differences When Linking

- Static libraries are fully resolved “left to right”; circular dependencies are only resolved between explicit objects or inside a library -> need to specify libraries multiple times or use: `-WI,--start-group (...) -WI,--end-group`

- Shared libraries symbols are **not** fully resolved at link time, only checked for symbols required by the object files. **Full check** only at runtime.

- Shared libraries may depend on other shared libraries whose symbols will be globally visible
Semi-static Linking

- Fully static linking is a bad idea with GNU libc; it requires matching shared objects for NSS.
- Dynamic linkage of add-on libraries requires a compatible version to be installed (e.g. MKL).
- Static linkage of individual libs via linker flags -Wl,-Bstatic,-lfftw3,-Bdynamic.
- Can be combined with grouping, example:
  -Wl,--start-group,-Bstatic
  -lMKL_gf_lp64 -lMKL_sequential
  -lMKL_core -Wl,--end-group,-Bdynamic
Meta-Libraries

- The GNU linker supports linker scripts a library
- Can be used to build a library-of-libraries:
  ```
  [~]$ cat libscalapack.a
  GROUP (-lscalapack_gnu -lblacsF77 -lblacs -llapack -lf77blas)
  ```
- To link the entire sequence of libraries only the flag `-lscalapack` is needed
- Useful to hide implementation details or handle library dependencies for static libraries (not an issue with shared libraries, since the shared library is linked to its dependencies)
Dynamic Linker Properties

- Linux defaults to dynamic libraries:
  > ldd hello
  linux-gate.so.1 => (0x0049d000)
  libc.so.6 => /lib/libc.so.6
  (0x005a0000)
  /lib/ld-linux.so.2 (0x0057b000)
- /etc/ld.so.conf, LD_LIBRARY_PATH define where to search for shared libraries
- gcc -Wl,-rpath,/some/dir will encode /some/dir into the binary for searching
Using LD_PRELOAD

- Using the LD_PRELOAD environment variable, symbols from a shared object can be preloaded into the global object table and will override those in later resolved shared libraries => replace specific functions in a shared library

- Example: override log() with a faster version:
  
  ```c
  #include "amdlibm.h"
  double log(double x) { return amd_log(x); }
  gcc -shared -o fasterlog.so faster.c -lamdlibm
  ```

- LD_PRELOAD=../fasterlog.so ./myprog-with
Before LD_PRELOAD

<table>
<thead>
<tr>
<th>samples</th>
<th>pcnt</th>
<th>function</th>
<th>DSO</th>
</tr>
</thead>
<tbody>
<tr>
<td>53462.00</td>
<td>52.2%</td>
<td>ieee754_log</td>
<td>/lib64/libm-2.12.so</td>
</tr>
<tr>
<td>10490.00</td>
<td>10.3%</td>
<td>R_binary</td>
<td>/opt/binf/R-2.13.0/lib64/R/bin/exec/R</td>
</tr>
<tr>
<td>8764.00</td>
<td>8.5%</td>
<td>clear_page_c</td>
<td>[kernel.kallsyms]</td>
</tr>
<tr>
<td>5737.00</td>
<td>5.6%</td>
<td>_ieee754_exp</td>
<td>/lib64/libm-2.12.so</td>
</tr>
<tr>
<td>4645.00</td>
<td>4.5%</td>
<td>mathl</td>
<td>/lib64/libm-2.12.so</td>
</tr>
<tr>
<td>3070.00</td>
<td>3.0%</td>
<td>__log</td>
<td>/lib64/libm-2.12.so</td>
</tr>
<tr>
<td>3020.00</td>
<td>3.0%</td>
<td>__isnan</td>
<td>/lib64/libc-2.12.so</td>
</tr>
<tr>
<td>2094.00</td>
<td>2.0%</td>
<td>_R_gc_internal</td>
<td>/opt/binf/R-2.13.0/lib64/R/bin/exec/R</td>
</tr>
<tr>
<td>1643.00</td>
<td>1.6%</td>
<td>do_summary</td>
<td>/opt/binf/R-2.13.0/lib64/R/bin/exec/R</td>
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<tr>
<td>1251.00</td>
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<tr>
<td>1210.00</td>
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<td>/opt/binf/R-2.13.0/lib64/R/bin/exec/R</td>
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<tr>
<td>1161.00</td>
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<td>__GI__exp</td>
<td>/lib64/libm-2.12.so</td>
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<tr>
<td>754.00</td>
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<td>__isnan</td>
<td>/lib64/libm-2.12.so</td>
</tr>
<tr>
<td>739.00</td>
<td>0.7%</td>
<td>R_log</td>
<td>/opt/binf/R-2.13.0/lib64/R/bin/exec/R</td>
</tr>
<tr>
<td>553.00</td>
<td>0.5%</td>
<td>_kernel_standard</td>
<td>/lib64/libm-2.12.so</td>
</tr>
<tr>
<td>550.00</td>
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</tr>
<tr>
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</tr>
<tr>
<td>439.00</td>
<td>0.4%</td>
<td>coerceToReal</td>
<td>/opt/binf/R-2.13.0/lib64/R/bin/exec/R</td>
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<tr>
<td>413.00</td>
<td>0.4%</td>
<td>finite</td>
<td>/lib64/libm-2.12.so</td>
</tr>
<tr>
<td>358.00</td>
<td>0.3%</td>
<td>log@plt</td>
<td>/opt/binf/R-2.13.0/lib64/R/bin/exec/R</td>
</tr>
<tr>
<td>182.00</td>
<td>0.2%</td>
<td>get_page_from_freelist</td>
<td>[kernel.kallsyms]</td>
</tr>
<tr>
<td>120.00</td>
<td>0.1%</td>
<td>__alloc_pages_nodemask</td>
<td>[kernel.kallsyms]</td>
</tr>
</tbody>
</table>
After LD_PRELOAD

PerfTop: 8020 irqs/sec kernel:17.2% exact: 0.0% [1000Hz cycles], (all, 8 CPUs)

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<tr>
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</tr>
</thead>
<tbody>
<tr>
<td>24702.00</td>
<td>19.5%</td>
<td>__amd_bas64_log</td>
<td>/opt/libs/fastermath-0.1/libamdlibm.so</td>
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<tr>
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<td>/opt/binf/R-2.13.0/lib64/R/bin/exec/R</td>
</tr>
<tr>
<td>18463.00</td>
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<td>clear_page_c</td>
<td>[kernel.kallsyms]</td>
</tr>
<tr>
<td>10480.00</td>
<td>8.3%</td>
<td>__ieee754_exp</td>
<td>/lib64/libm-2.12.so</td>
</tr>
<tr>
<td>9834.00</td>
<td>7.8%</td>
<td>mathl</td>
<td>/opt/binf/R-2.13.0/lib64/R/bin/exec/R</td>
</tr>
<tr>
<td>9155.00</td>
<td>7.2%</td>
<td>log</td>
<td>/opt/libs/fastermath-0.1/fasterlog.so</td>
</tr>
<tr>
<td>6269.00</td>
<td>5.6%</td>
<td>__isnan</td>
<td>/lib64/libc-2.12.so</td>
</tr>
<tr>
<td>4214.00</td>
<td>3.3%</td>
<td>R_gc_internal</td>
<td>/opt/binf/R-2.13.0/lib64/R/bin/exec/R</td>
</tr>
<tr>
<td>3074.00</td>
<td>2.4%</td>
<td>do_summary</td>
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<td>1.8%</td>
<td>real_relop</td>
<td>/opt/binf/R-2.13.0/lib64/R/bin/exec/R</td>
</tr>
<tr>
<td>2257.00</td>
<td>1.8%</td>
<td>__isnan@plt</td>
<td>/opt/binf/R-2.13.0/lib64/R/bin/exec/R</td>
</tr>
<tr>
<td>2076.00</td>
<td>1.6%</td>
<td>__GI__exp</td>
<td>/lib64/libm-2.12.so</td>
</tr>
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<td>1346.00</td>
<td>1.1%</td>
<td>R_log</td>
<td>/opt/binf/R-2.13.0/lib64/R/bin/exec/R</td>
</tr>
<tr>
<td>1213.00</td>
<td>1.0%</td>
<td>do_abs</td>
<td>/opt/binf/R-2.13.0/lib64/R/bin/exec/R</td>
</tr>
<tr>
<td>1075.00</td>
<td>0.8%</td>
<td>__kernel_standard</td>
<td>/lib64/libm-2.12.so</td>
</tr>
<tr>
<td>894.00</td>
<td>0.7%</td>
<td>coerceToReal</td>
<td>/opt/binf/R-2.13.0/lib64/R/bin/exec/R</td>
</tr>
<tr>
<td>780.00</td>
<td>0.6%</td>
<td>__mul</td>
<td>/lib64/libm-2.12.so</td>
</tr>
<tr>
<td>756.00</td>
<td>0.6%</td>
<td>finite</td>
<td>/lib64/libm-2.12.so</td>
</tr>
<tr>
<td>729.00</td>
<td>0.6%</td>
<td>amd_log@plt</td>
<td>/opt/libs/fastermath-0.1/fasterlog.so</td>
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<tr>
<td>706.00</td>
<td>0.6%</td>
<td>amd_log</td>
<td>/opt/libs/fastermath-0.1/libamdlibm.so</td>
</tr>
<tr>
<td>674.00</td>
<td>0.5%</td>
<td>log@plt</td>
<td>/opt/binf/R-2.13.0/lib64/R/bin/exec/R</td>
</tr>
</tbody>
</table>
Difference Between C and Fortran

- Basic compilation principles are the same => preprocess, compile, assemble, link
- In Fortran, symbols are case insensitive => most compilers translate them to lower case
- In Fortran symbol names may be modified to make them different from C symbols (e.g. append one or more underscores)
- Fortran entry point is not “main” (no arguments) PROGRAM => MAIN__ (in gfortran)
- C-like main() provided as startup (to store args)
Pre-processing in C and Fortran

- Pre-processing is **mandatory** in C/C++
- Pre-processing is **optional** in Fortran
- Fortran pre-processing enabled implicitly via file name: name.F, name.F90, name.FOR
- Legacy Fortran packages often use /lib/cpp:
  /lib/cpp -C -P -traditional -o name.f name.F
  -C : keep comments (may be legal Fortran code)
  -P : no '#line' markers (not legal Fortran syntax)
  -traditional : don't collapse whitespace (incompatible with fixed format sources)
Fortran Symbols Example

SUBROUTINE GREET
  PRINT*, 'HELLO, WORLD!'
END SUBROUTINE GREET

program hello
  call greet
end program

- “program” becomes symbol “MAIN__” (compiler dependent)
- “subroutine” name becomes lower case with '_' appended
- several “undefineds” with '_gfortran' prefix
  => calls into the Fortran runtime library, libgfortran
- cannot link object with “gcc” alone, need to add -lgfortran
  => cannot mix and match Fortran objects from different compilers
Fortran 90+ Modules

• When subroutines or variables are defined inside a module, they have to be hidden

```fortran
module func
  integer :: val5, val6
contains
  integer function add_abs(v1,v2)
    integer, intent(in) :: v1, v2
    add_abs = iabs(v1)+iabs(v2)
  end function add_abs
end module func
```

• `gfortran` creates the following symbols:

```plaintext
000000000 T __func_MOD_add_abs
000000000 B __func_MOD_val5
000000004 B __func_MOD_val6
```
The Next Level: C++

- In C++ functions with different number or type of arguments can be defined (overloading) => encode prototype into symbol name:
  Example: symbol for `int add_abs(int, int)` becomes: `_ZL7add_absii`
- Note: the return type is **not** encoded
- C++ symbols are no longer compatible with C => add 'extern "C"' qualifier for C style symbols
- C++ symbol encoding is **compiler specific**
C++ Namespaces and Classes vs. Fortran 90 Modules

- Fortran 90 modules share functionality with classes and namespaces in C++
- C++ namespaces are encoded in symbols
  Example: `int func::add_abs(int,int)` becomes: `_ZN4funcL7add_absEii`
- C++ classes are encoded the same way
- Figuring out which symbol to encode into the object as undefined is the job of the compiler
- When using the gdb debugger use '::' syntax
Why We Need Header or Module Files

- The linker is “blind” for any **language specific** properties of a symbol => checking of the validity of the **interface** of a function is only possible during **compilation**
- A header or module file contains the **prototype** of the function (not the implementation) and the compiler can compare it to its use
- Important: header/module has to match library => Problem with FFTW-2.x: cannot tell if library was compiled for single or double precision
Calling C from Fortran 77

- Need to make C function look like Fortran 77
  - Append underscore (except on AIX, HP-UX)
  - Call by reference conventions
  - Best only used for “subroutine” constructs (cf. MPI) as passing return value of functions varies a lot:
    ```c
    void add_abs_(int *v1,int *v2,int *res){
      *res = abs(*v1)+abs(*v2);
    }
    ```
- Arrays are always passed as “flat” 1d arrays by providing a pointer to the first array element
- Strings are tricky (no terminal 0, length added)
void sum_abs_(int *in, int *num, int *out) {
    int i, sum;
    sum = 0;
    for (i=0; i < *num; ++i) { sum += abs(in[i]);}
    *out = sum;
    return;
}

/* fortran code:
  integer, parameter :: n=200
  integer :: s, data(n)

  call SUM_ABS(data, n, s)
  print*, s
  */
Calling Fortran 77 from C

- Inverse from previous, i.e. need to add underscore and use lower case (usually)
- Difficult for anything but Fortran 77 style calls since Fortran 90+ features need extra info
  - Shaped arrays, optional parameters, modules
- Arrays need to be “flat”, C-style multi-dimensional arrays are lists of pointers to individual pieces of storage, which may not be consecutive
  => use 1d and compute position
Calling Fortran 77 From C Example

```fortran
subroutine sum_abs(in, num, out)
    integer, intent(in) :: num, in(num)
    integer, intent(out) :: out
    Integer :: i, sum
    sum = 0
    do i=1,num
        sum = sum + ABS(in(i))
    end do
    out = sum
end subroutine sum_abs
```

?? c code:
! const int n=200;
! int data[n], s;
! sum_abs_(data, &n, &s);
! printf("%d\n", s);
Modern Fortran vs C Interoperability

• Fortran 2003 introduces a standardized way to tell Fortran how C functions look like and how to make Fortran functions have a C-style ABI
• Module “iso_c_binding” provides kind definition: e.g. C_INT, C_FLOAT, C_SIGNED_CHAR
• Subroutines can be declared with “BIND(C)”
• Arguments can be given the property “VALUE” to indicate C-style call-by-value conventions
• String passing tricky, needs explicit 0-terminus
Calling C from Fortran 03 Example

```c
int sum_abs(int *in, int num) {
    int i, sum;
    for (i=0, sum=0; i<num; ++i) {sum += abs(in[i]);}
    return sum;
}

/* fortran code: */
use iso_c_binding, only: c_int
interface
    integer(c_int) function sum_abs(in, num) bind(C)
    use iso_c_binding, only: c_int
    integer(c_int), intent(in) :: in(*)
    integer(c_int), value :: num
    end function sum_abs
end interface
integer(c_int), parameter :: n=200
integer(c_int) :: data(n)
print*, SUM_ABS(data,n)  */
```
Calling Fortran 03 From C Example

```
subroutine sum_abs(in, num, out) bind(c)
  use iso_c_binding, only : c_int
  integer(c_int), intent(in) :: num,in(num)
  integer(c_int), intent(out) :: out
  integer(c_int), :: i, sum
  sum = 0
  do i=1,num
    sum = sum + ABS(in(i))
  end do
  out = sum
end subroutine sum_abs

!! c code:
! const int n=200;
! int data[n], s;
! sum_abs(data, &n, &s);
! printf("%d\n", s);
```
Linking Multi-Language Binaries

- Inter-language calls via mutual C interface only due to name “mangling” of C++ / Fortran 90+ => extern “C”, ISO_C_BINDING, C wrappers
- Fortran “main” requires fortran compiler for link
- Global static C++ objects require C++ for link => avoid static objects (good idea in general)
- Either language requires its runtime for link => GNU: -lstdc++ and -lgfortran
  => Intel: “its complicated” (use -# to find out) more may be needed (-lgomp, -lpthread, -lm)