Computers
Compilation Environment & System Libraries

Grau en Ciència i Enginyeria de Dades

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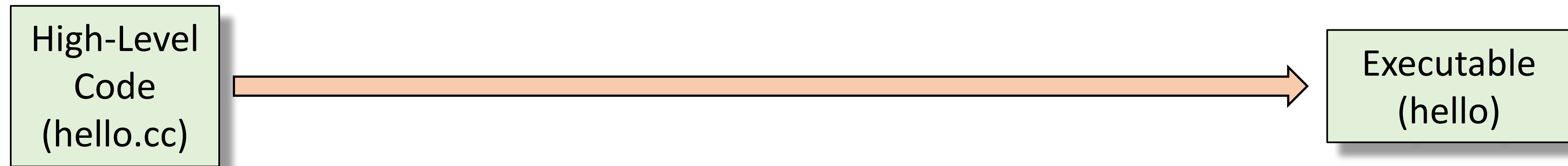
From High-Level code to program execution

- **How can we transform the high-level source code to an executable file?**



- **Executable file:** program that can be executed on a computer.

Example: C/C++ code (similar to Lab S3 example)

- From high-level code to program execution

```
#include <unistd.h>
#include <stdio.h>

int global = 4;

int main(int argc, char **argv){
        char buf[512];
        int num;

        num = sprintf(buf, "Hello World %d!\n", global);
        write(1, buf, num);

        return 0;
}
```

High-Level Code (hello.cc)

High Level Language Code specified in a file that cannot be understood by the CPU to be executed right away

Example: C/C++ code (similar to Lab S3 example)

```
#include <unistd.h>
#include <stdio.h>
```

Including Header Files

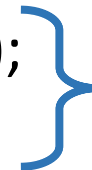
```
int global = 4;
```

Global Variable

```
int main(int argc, char **argv){
        char buf[512];
        int num;
```

Local Variables

```
        num = sprintf(buf, "Hello World %d!\n", global);
        write(1, buf, num);
```



Calling to external functions

```
        return 0;
}
```

Return the exit status of the program,
Indicating success(0) or some failure(1)

Header files contain required information for the compiler about external components used in this code, such as “sprintf” and “write” functions

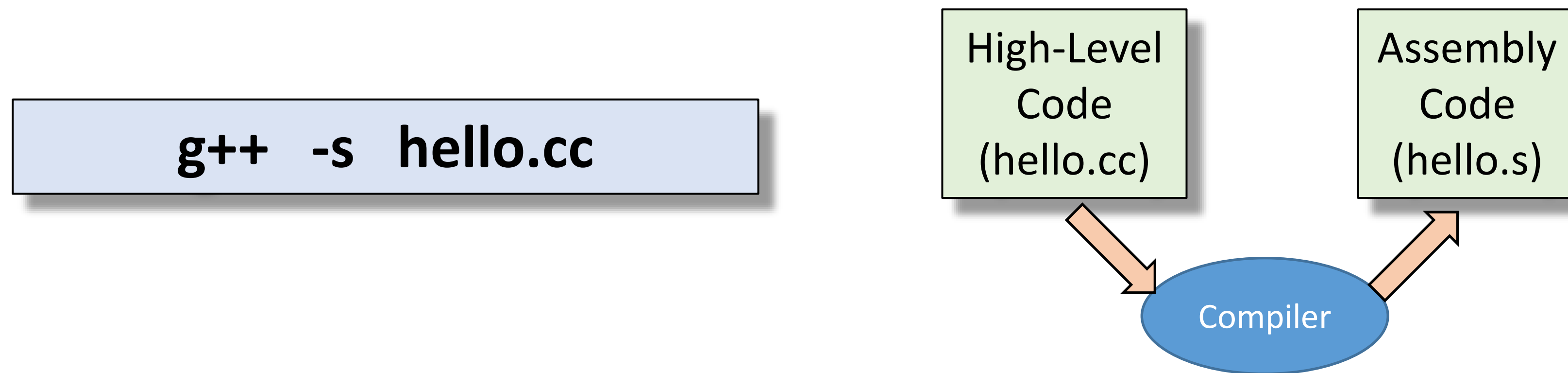
Example of Header Files provided by Libraries

- Many services are reused by [all] applications
  - Operating system interface
  - Basic Math operations
  - Language support
  - Input/output
  - Memory management
  - Character & string manipulation
  - Filesystem
  - ...
  - Parallelism support
  - Message passing
  - ...

C header	/ C++ header
stdio.h, unistd.h, stdlib.h, fcntl.h, sys/types.h, sys/stat.h…	
math.h	/ cmath
stdio.h	/ iostream
	/ stdc++
malloc.h	/ new
string.h	/ string
pthread.h	/ thread
omp.h	/ omp.h
mpi.h	/ mpi.h

Basic Concepts: Compiler

- **Compiler:** software that translates a given code into another language
  - It usually translates high-level code into lower-level code



  - **Assembly Language:** symbolic language that can be translated into binary machine language

Assembly Code (intermediate code)

- cat hello.s

```
    .text
    .globl   main
    .type    main,@function
main:
.LFB12:
    .cfi_startproc
    subq    $520, %rsp                  // buf,num
    .cfi_def_cfa_offset 528
    movl    global(%rip), %edx    // global
    movl    $.LC0, %esi              // string
    movq    %rsp, %rdi               // buf
    movb    $0, %al     // num. floating point args
    call    sprintf
```

```
movslq   %eax, %rdx       // num
movq     %rsp, %rsi       // buf
movl     $1, %edi         // 1
call     write
movl     $0, %eax         // 0
addq     $520, %rsp
.cfi_def_cfa_offset 8
ret
```

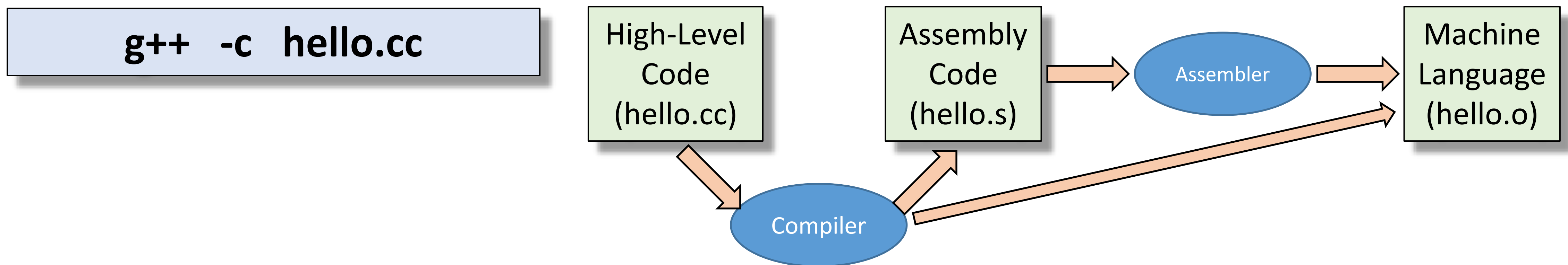
Assembly Code (intermediate code)

- cat hello.s (cont)

```
        .section        .rodata.str1.1,"aMS",@progbits,1
.LC0:
        .string "Hello World %d!\n“
        .globl  global
        .data
        .align  4
        .type   global,@object
        .size   global, 4
global:
        .long   4
```

From High-Level code to program execution

- **Assembler:** software that translates assembly code into machine language
  - The output is also known as **object file** (with **.o** extension)



- **Object File:** is a combination of machine language instructions, data, and information needed to place instructions properly in memory

Compiler Optimizations

- -O**x** where x is a numerical digit indicating the optimization type
- Assuming we are focused on gcc/g++ compiler
  - -O0: no optimizations. Thus, it reduces compilation time and preserves debugging behaviour
  - -O1: tries to reduce code size and execution time, without performing any optimizations that take a great deal of compilation time
  - -O2: performs nearly all supported optimizations that do not involve a space-speed tradeoff. As compared to –O1, this option increases both compilation time and the performance of the generated code
  - -O3: turns on all above optimizations and also turns on advanced optimizations: function inlining, register renaming and loop unrolling among others

https://gcc.gnu.org/onlinedocs/gcc/Optimize-Options.html

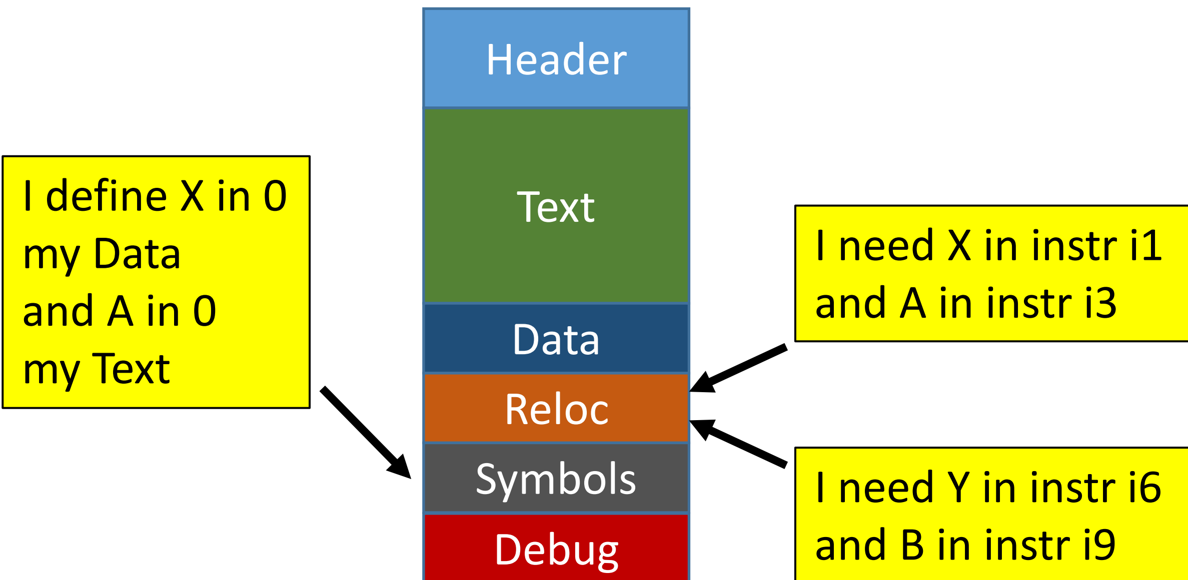
Object file (machine code)

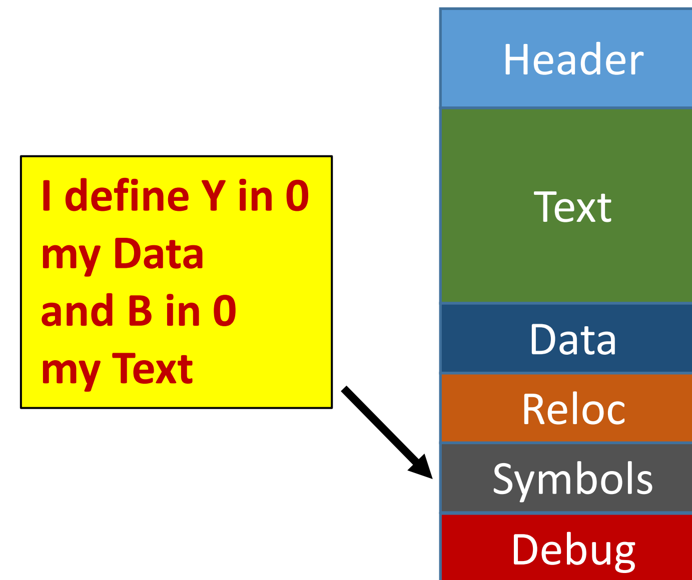
- Object file for UNIX-like OSes includes:
  1) **Object file header:** size and position of other pieces of the object file
  2) **Text segment:** the machine language code
  3) **Static data segment:** data allocated for the whole life of the program (e.g. global variables)
  4) **Relocation information/records:** information about addresses referenced in the object file. The linker adjust them once the final memory allocation is resolved
  5) **Symbol Table:** a table of memory location and variable or function that can be called from other object files
  6) **Debugging information:** additional data for a software (called debugger) to associate machine instructions to high-level language code

- The assembler keeps track of labels used in branches and data transfer instructions to generate the executable

Relocation Info vs Symbol Table (I)

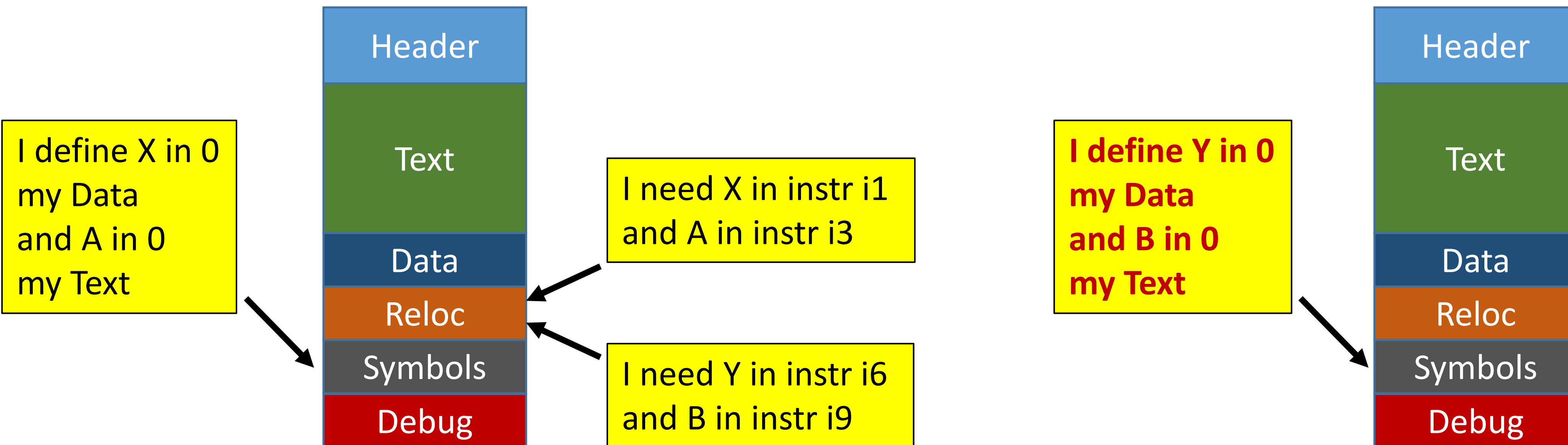
Pass 1: *read in section sizes, compute final memory layout. Also, read in all symbols, create complete symbol table in memory.*





Object Files are relocatable files with symbols not associated to addresses
Symbol Table: symbols have no address assigned yet
Relocation information: one entry per reference to symbols

Relocation Info vs Symbol Table (I)

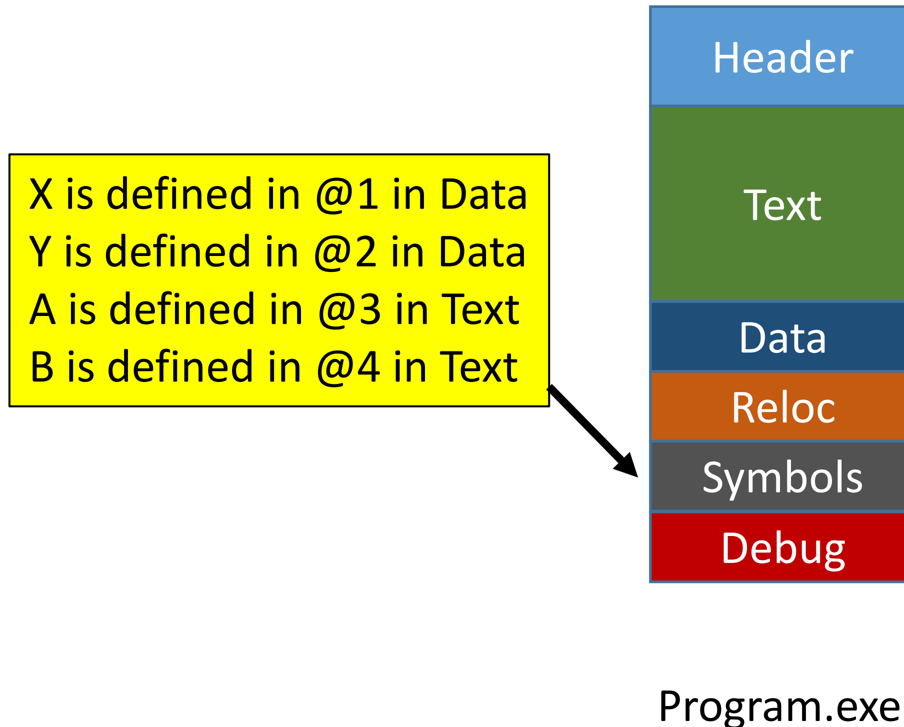


How to relocate:

- Overwrite with final address of symbol
- Add final address of symbol to current contents; used for accessing element of record: external symbol + offset (known from a header file)
- Add difference between final and original addresses of symbol to current contents

Relocation Info vs Symbol Table (II)

Pass 2: *read in section and relocation information, update addresses, write out new file.*



Program.exe

Executable Files are relocatable files with symbols associated to addresses → it can be loaded into memory
Symbol Table: symbols have address assigned
The linker has resolved undefined addresses, except dynamic linked libraries

Object file (machine code)

- Contents of hello.o (od –t x1c hello.o)

```
0000000  7f  45  4c  46  02  01  01  00  00  00  00  00  00  00  00  00
        177   E   L   F 002 001 001  \0  \0  \0  \0  \0  \0  \0  \0  \0
0000020  01  00  3e  00  01  00  00  00  00  00  00  00  00  00  00  00
        001  \0   >  \0 001  \0  \0  \0  \0  \0  \0  \0  \0  \0  \0  \0
0000040  00  00  00  00  00  00  00  00  20  03  00  00  00  00  00  00
         \0  \0  \0  \0  \0  \0  \0  \0     003  \0  \0  \0  \0  \0  \0
0000060  00  00  00  00  40  00  00  00  00  00  40  00  0d  00  0c  00
         \0  \0  \0  \0   @  \0  \0  \0  \0  \0   @  \0  \r  \0  \f  \0
0000100  ...
0000200  48  65  6c  6c  6f  20  57  6f  72  6c  64  20  25  64  21  0a
          H   e   l   l   o       W   o   r   l   d       %   d   !  \n
0000220  00  00  47  43  43  3a  20  28  53  55  53  45  20  4c  69  6e
         \0  \0   G   C   C   :       (   S   U   S   E       L   i   n
0000240  75  78  29  20  38  2e  31  2e  30  00  00  00  00  00  00  00
          u   x   )       8   .   1   .   0  \0  \0  \0  \0  \0  \0  \0
0000260  14  00  00  00  00  00  00  00  01  7a  52  00  01  78  10  01
        024  \0  \0  \0  \0  \0  \0  \0 001   z   R  \0 001   x 020 001
```

Object file (machine code)

- objdump -xs hello.o

```
Contents of section .text:
 0000 4881ec08 0200008b 15000000 00be0000  H...............
 0010 00004889 e7b000e8 00000000 4863d048  ..H.........Hc.H
 0020 89e6bf01 000000e8 00000000 b8000000  ................
 0030 004881c4 08020000 c3                 .H.......
Contents of section .data:
 0000 04000000                             ....
Contents of section .rodata.str1.1:
 0000 48656c6c 6f20576f 726c6420 2564210a  Hello World %d!.
 0010 00                                   .
Contents of section .comment:
 0000 00474343 3a202853 55534520 4c696e75  .GCC: (SUSE Linu
 0010 78292038 2e312e30 00                 x) 8.1.0.
Contents of section .eh_frame:   // exception support
 0000 14000000 00000000 017a5200 01781001  .........zR..x..
```

Object file (machine code)

- objdump -xs hello.o

```
Contents of section .text:
 0000 4881ec08 0200008b 15000000 00be0000  H...............
 0010 00004889 e7b000e8 00000000 4863d048  ..H.........Hc.H
 0020 89e6bf01 000000e8 00000000 b8000000  ................
 0030 004881c4 08020000 c3                 .H.......
Contents of section .data:
 0000 04000000                             ....
Contents of section .rodata.str1.1:
 0000 48656c6c 6f20576f 726c6420 2564210a  Hello World %d!.
 0010 00                                   .
Contents of section .comment:
 0000 00474343 3a202853 55534520 4c696e75  .GCC: (SUSE Linu
 0010 78292038 2e312e30 00                 x) 8.1.0.
Contents of section .eh_frame:    // exception support
 0000 14000000 00000000 017a5200 01781001  .........zR..x..
```

Unfortunately object files are not self-contained

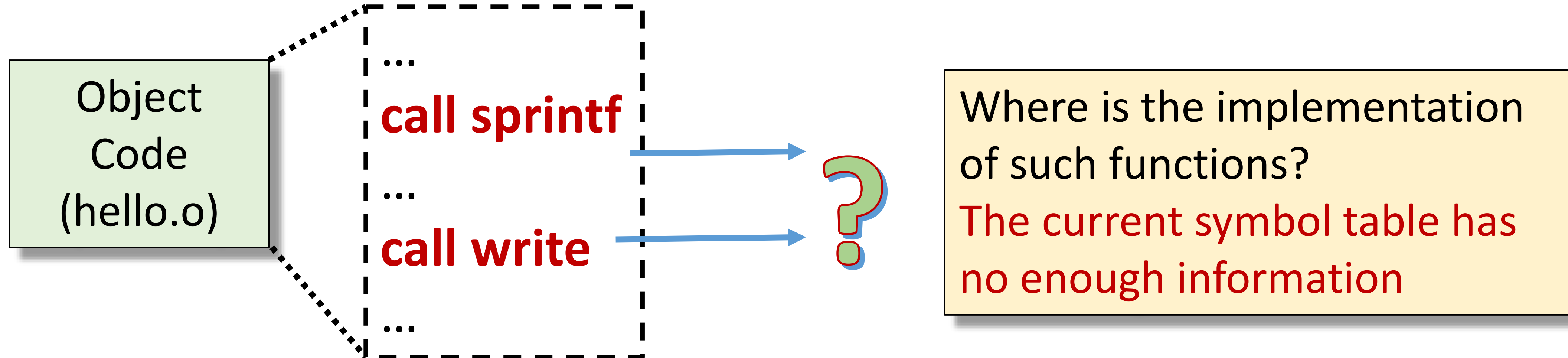
For example, there are calls to functions not defined in our object file:

- Sprintf
- Write

We need their code!!!

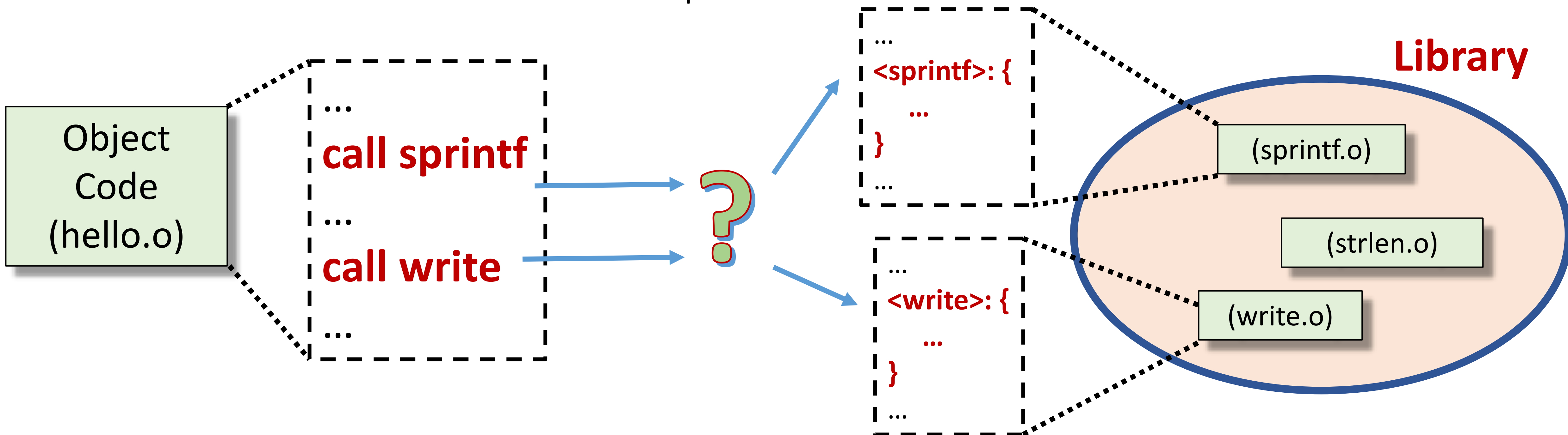
From High-Level code to program execution

- The same problem happens when the code calls to functions implemented in other object files, although they are not in a library



From High-Level code to program execution

- **Library:** a file that encapsulates a set of object files
  - Libraries grant **independency**
    - A high-level code is independent of **OS** and **Hw architecture**, but …
    - … executables are created for a particular **OS** and **Hw architecture**



From High-Level code to program execution

- Language Libraries
  - Bind a language to a particular OS, but independently of the hardware architecture
  - Provide functions of the programming language
  - Sometimes they are self-contained (e.g. **math**): independent of OS
  - Sometimes they request services to the OS (e.g. **sprintf**, cin, cout…)

- System Libraries
  - Bind an OS to a particular Hw architecture (independent of the high-level code)
  - Include functions that invoke services/routines of the OS (e.g. **write**, open, …)
  - Depends on the type of Operating System and the architecture of the CPU

- Examples of incompatibility:
  - Linux 32 vs 64 bits, CPU Intel vs ARM, Ubuntu vs OpenSUSE, …

Linux i386 (32bits) vs Linux x64 (64bits)

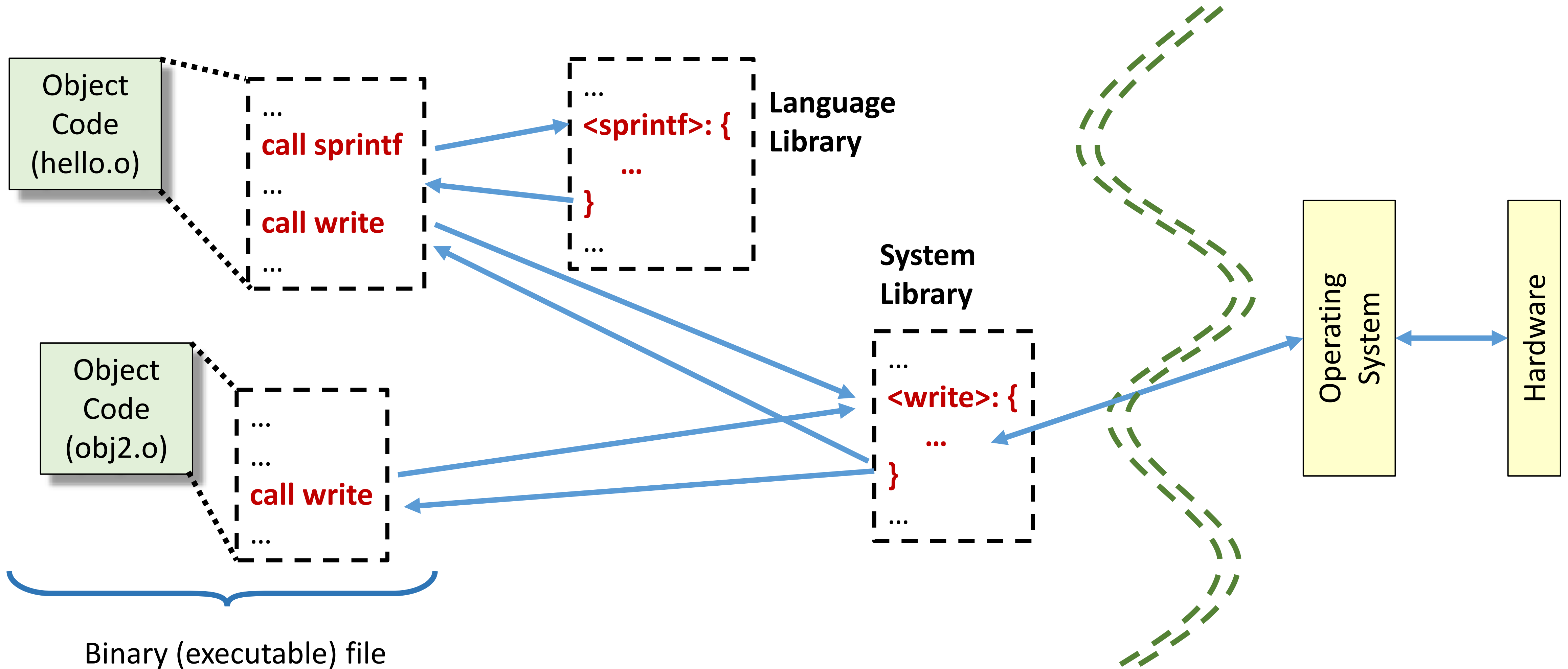
Linux i386

```
...
movl   $4, %eax   ; use the write syscall
movl   $1, %ebx   ; write to stdout
movl   $msg, %ecx ; use string "Hello ..."
movl   $14, %edx  ; write 14 characters
int    $0x80      ; make syscall
...
```

Linux x64

```
...
movq   $1, %rax   ; use the write syscall
movq   $1, %rdi   ; write to stdout
movq   $msg, %rsi ; use string "Hello ..."
movq   $14, %rdx  ; write 14 characters
syscall           ; make syscall
...
```

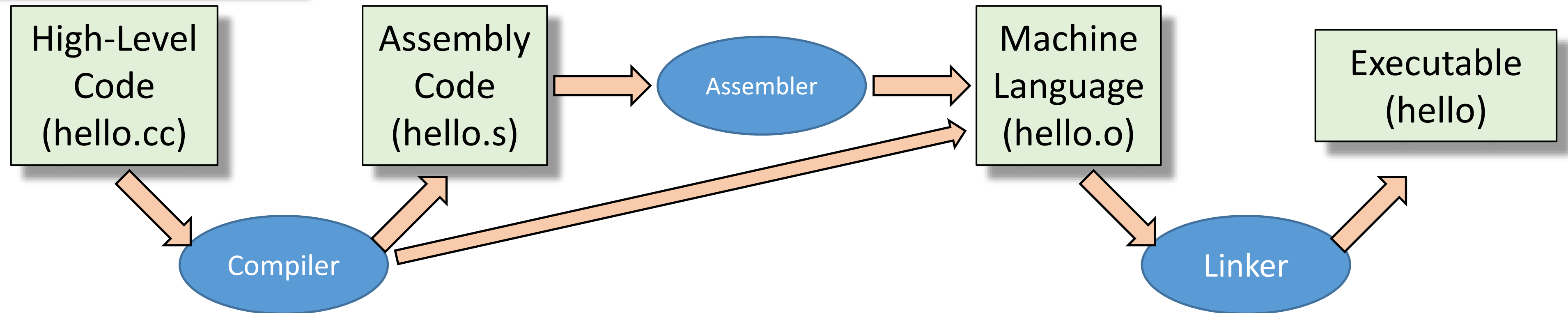
From High-Level code to program execution



From High-Level code to program execution

- **Linker:** a software that combines independent codes (object files) and resolves all undefined labels into an executable

```
g++   -o hello   hello.o
```



- **Executable file:** program that can be executed on a computer. It has the format of an object file, but all references are resolved. There are no undefined labels
  - It is posible to have partially linked files (unresolved addresses of some library routines)

Static versus Dinamically linking

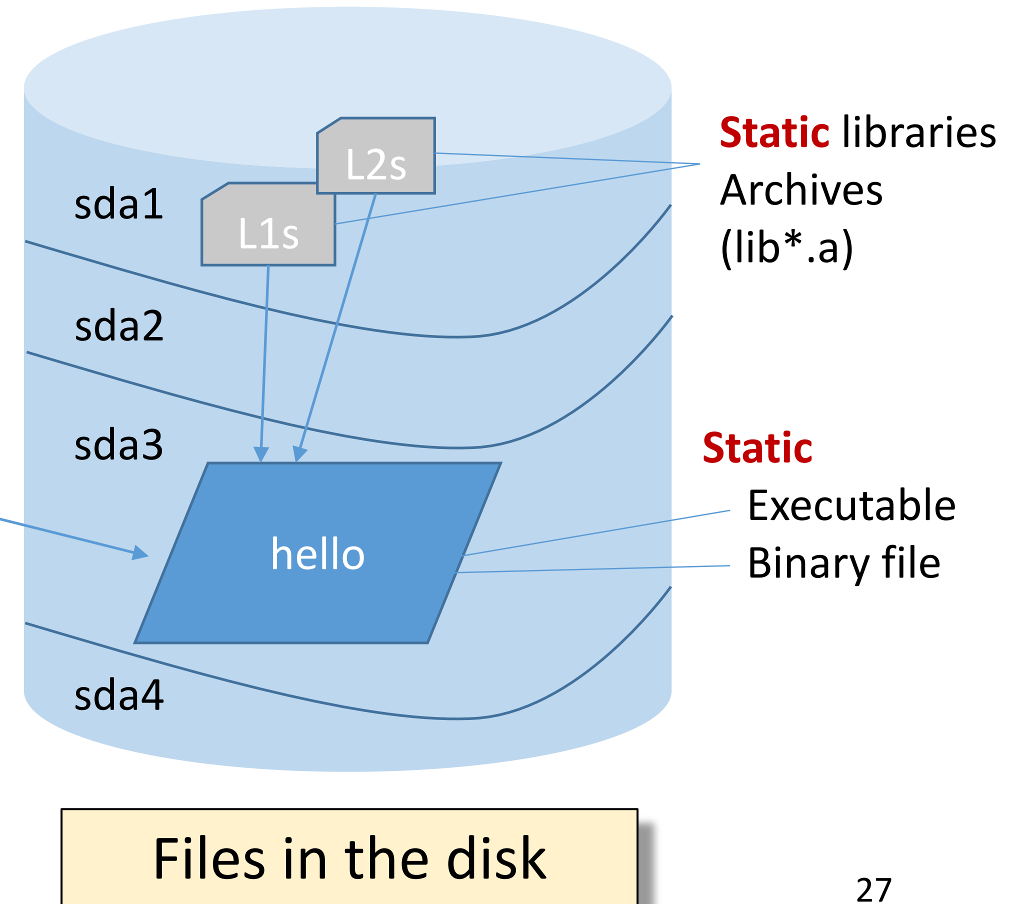
- Static linking
  - The codes of libraries are included INSIDE the executable
  - Waste of space (in disk when stored, and in memory when running)
    - Different programs may use the same libraries
  - Static libraries: "**.a**" in UNIX-like OS; "**.lib**" in Windows-like OS
- Dynamic linking
  - The linking stage is delayed to run-time. Thus, the code is not included in the program
  - Save space in both disk and memory
    - Different programs can access to a shared library loaded in memory
  - Dynamic libraries: "**.so**" in UNIX-like OS; "**.dll**" in Windows-like OS

Static linking

- Static compilation and linking phases

```
#include <unistd.h>
#include <stdio.h>

int global = 4;

int main(int argc, char **argv){
		char buf[512];
		int num;

		num = sprintf(buf, "Hello World %d!", global);
		write(1, buf, num);

		return 0;
}
```

g++ **-static** -o hello hello.o
(compile & link)

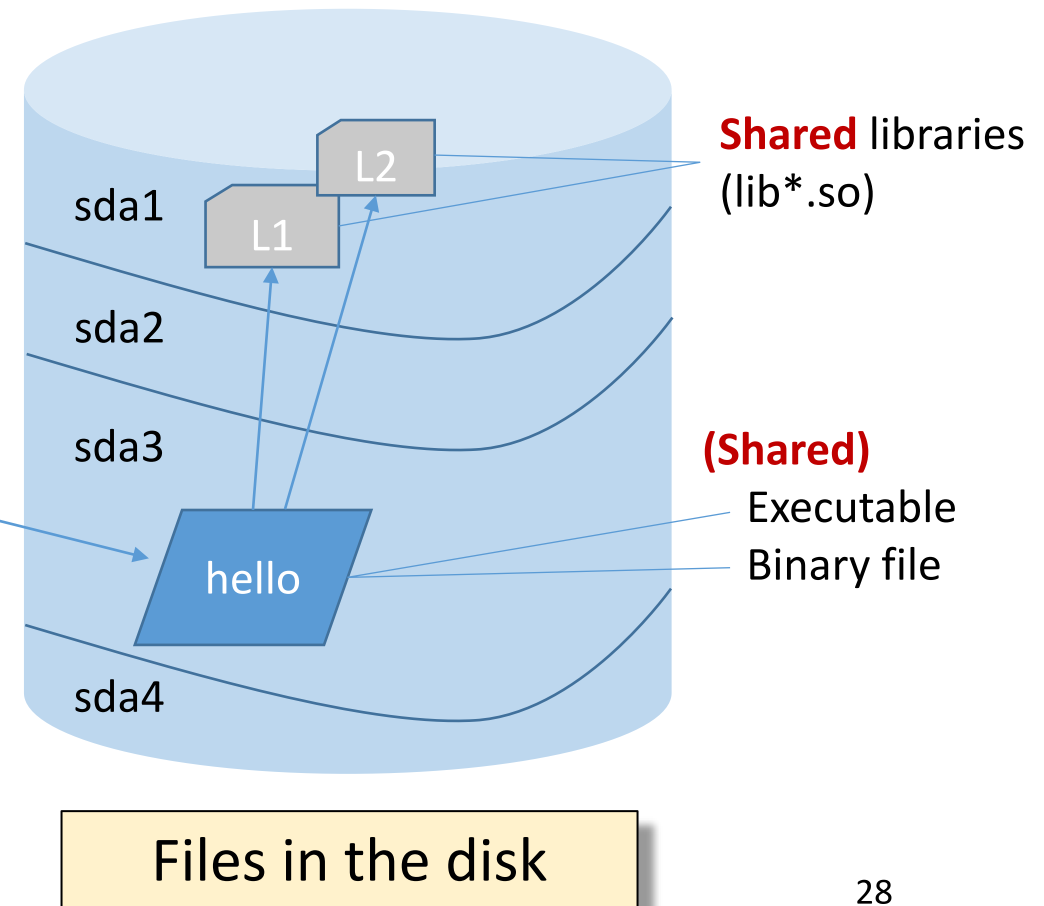


Dinamically linking

- Dynamic compilation and linking phases

```
#include <unistd.h>
#include <stdio.h>

int global = 0;

int main(int argc, char **argv){
        char buf[512];
        int num;

        num = sprintf(buf, "Hello World %d!", global);
        write(1, buf, num);

        return 0;
}
```

g++ -o hello hello.o
(compile & link)



Executable / binary files

- Files that contain the program code, data, symbols, debug info…
- Generated by the process of compiling and linking
- Specific structure depends on the Operating System
  - Windows – PE32 Portable Executable, PE32+ for 64 bits
  - Linux – ELF Executable and Linkable Format
    - x86_64 64-bits data and 64-bits addresses
    - x32 64-bits data and 32-bits addresses
    - i386 32-bits data and 32-bits addresses (compatible with 32-bits systems)

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

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

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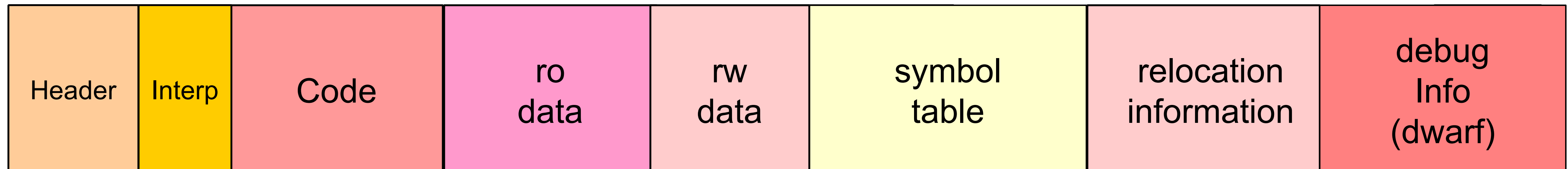
Executable File Format

- Contains an arbitrary number of sections:
  - Code: machine language code
  - Data (read-only, read-write): constants and global variables
  - Symbol table: labels and their already resolved addresses
  - Relocations: values that depend on the address where the file is loaded into mem
  - Debug information: associate machine data/instructions to high-level source code
    - File names (*.c, *.cxx, *.h...) and line numbers
    - Data types, classes, structures, unions, variables...



Executable File Format

- File header
  - Contains information about the executable
  - Used by...
    - The ELF utilities to read/understand/write this type of files
    - The Operating System to load **binary** files and **libraries** for execution

Executable File Format

```
ELF Header:
  Magic:   7f 45 4c 46 02 01 01 00 00 00 00 00 00 00 00 00
  Class:                             ELF64
  Data:                              2's complement, little endian
  Version:                           1 (current)
  OS/ABI:                            UNIX - System V
  ABI Version:                       0
  Type:                              EXEC (Executable file)
  Machine:                           Advanced Micro Devices X86-64
  Version:                           0x1
  Entry point address:               0x400470
  Start of program headers:          64 (bytes into file)
  Start of section headers:          6672 (bytes into file)
  Flags:                             0x0
  Size of this header:               64 (bytes)
  Size of program headers:           56 (bytes)
  Number of program headers:         9
  Size of section headers:           64 (bytes)
  Number of section headers:         31
  Section header string table index: 28
```

Executable File Format

- Interpreter: refers to a support library for loading the executable file onto memory (e.g. /lib64/ld-linux-x86-64.so.2)
- Code: contains the executable instructions
- Data: contains the global variables
  - Read-only data: constant values pre-initialized in the program
    - const int val = 10;
  - Read-write data: variables pre-initialized in the program
    - double degrees = -273.15;
- BSS: Block Started by Symbol. It holds non initialized global variables
  - int x, y, z;

Executable File Format

- Symbol table: local and exported symbols to find/resolve every “label”

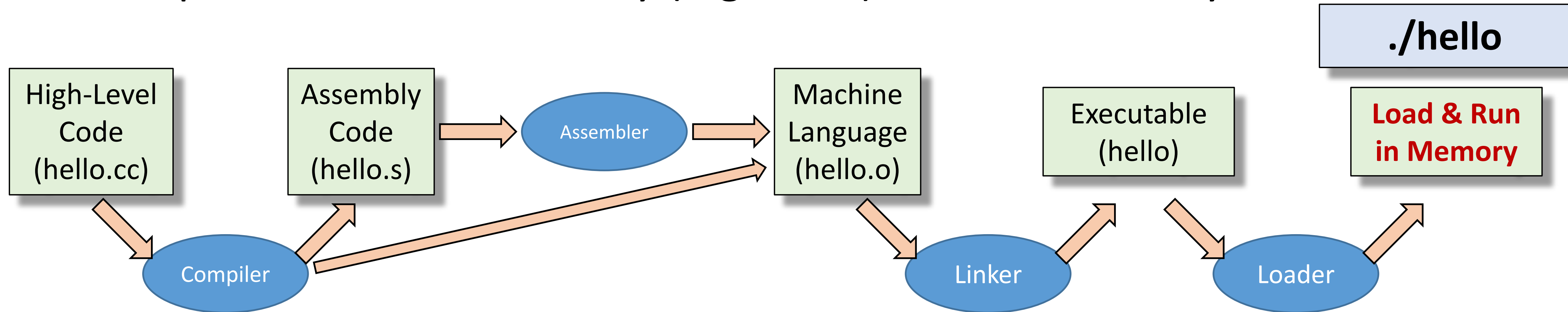
  - <address> <size> function1
  - <address> <size> x
  - <address> <size> fahrenheit_degrees
  - ...

Executable File Format

- Debugging information
  - DWARF (http://dwarfstd.org): to keep fantasy from ELF
    - Debugging With Attributed Record Formats
  - Generated by the –g option to gcc/g++
  - Multiple subsections
    - Source code line numbers
    - Macro information
    - Call frame information
    - Data types
    - Enumerations
    - Strings
    - Structures, unions, classes
    - Functions
    - ...

From High-Level code to program execution

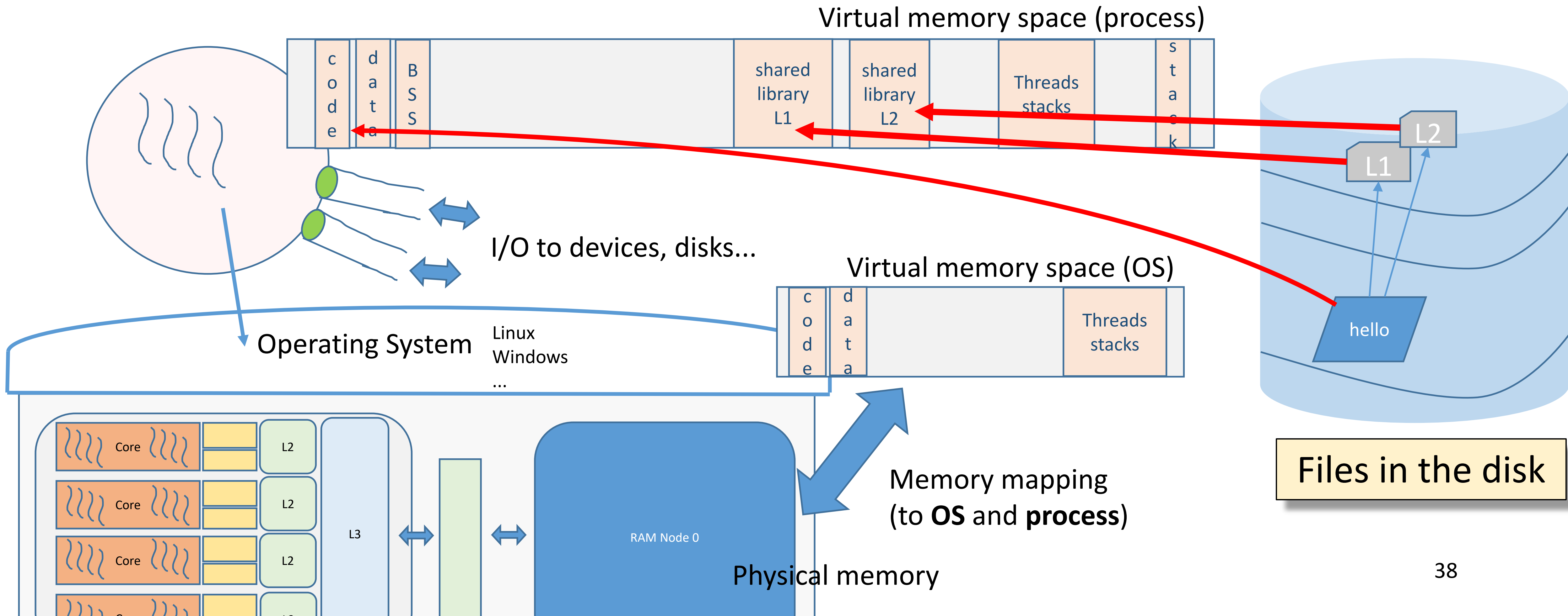
- **Loader:** a system program that reads a program from a storage device and place it in main memory (e.g. RAM) so that it is ready to execute



- The details about how to start executing the program in memory will be studied in the next lesson (focused on the OS)

Sharing services among applications

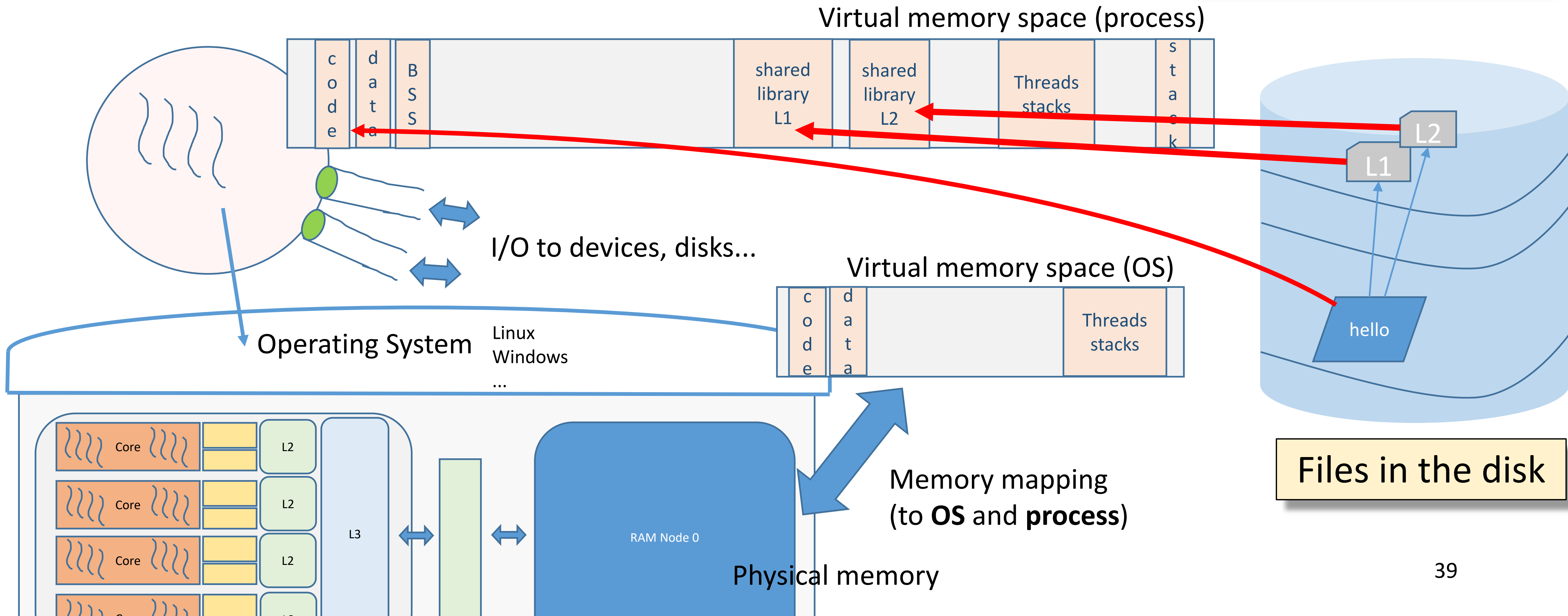
- Execution phase (with shared libraries)



Sharing services among applications

Virtual memory space is the location used when the program is loaded by the OS

- Execution phase (with shared libraries)



Sharing services among applications

Virtual memory space is the location used when the program is loaded by the OS

- Execution phase (with static libraries)

Virtual memory space (process)

code | data | BSS | Threads stacks | stack

I/O to devices, disks...

Virtual memory space (OS)

code | data | Threads stacks

Operating System

Linux
Windows
...

Core | L2 | L3 | RAM Node 0

Memory mapping
(to **OS** and **process**)

Physical memory

hello

Files in the disk

Binary format utilities (GNU Linux)

- We will play with them in Lab Sessions
  - ld – linker... gets ELF **Object** files and
    generates ELF **Binary** files or **Shared Libraries**
  - ar – archive... gets ELF **Object** files and generates **Static Libraries**
  - nm – namelist... lists file symbols and some debugging information
  - size – reports various code/data/bss sizes
  - strings – shows the strings present in the ELF files
  - strip – deletes the debugging information from ELF files
  - addr2line – translates addresses to source code line numbers

Binary format utilities (GNU Linux)

- c++filt – demangle C++ names

```
$ c++filt __Z9reductionRSt6vectorIfSaIfEE
reduction(std::vector<float, std::allocator<float> >&)
```

- objdump – full access to the ELF files contents
  - ELF header
  - File sections
  - Local and dynamic symbols
  - Relocations
  - List code instructions
  - Debugging information
  - Can support several different architectures and specific file formats

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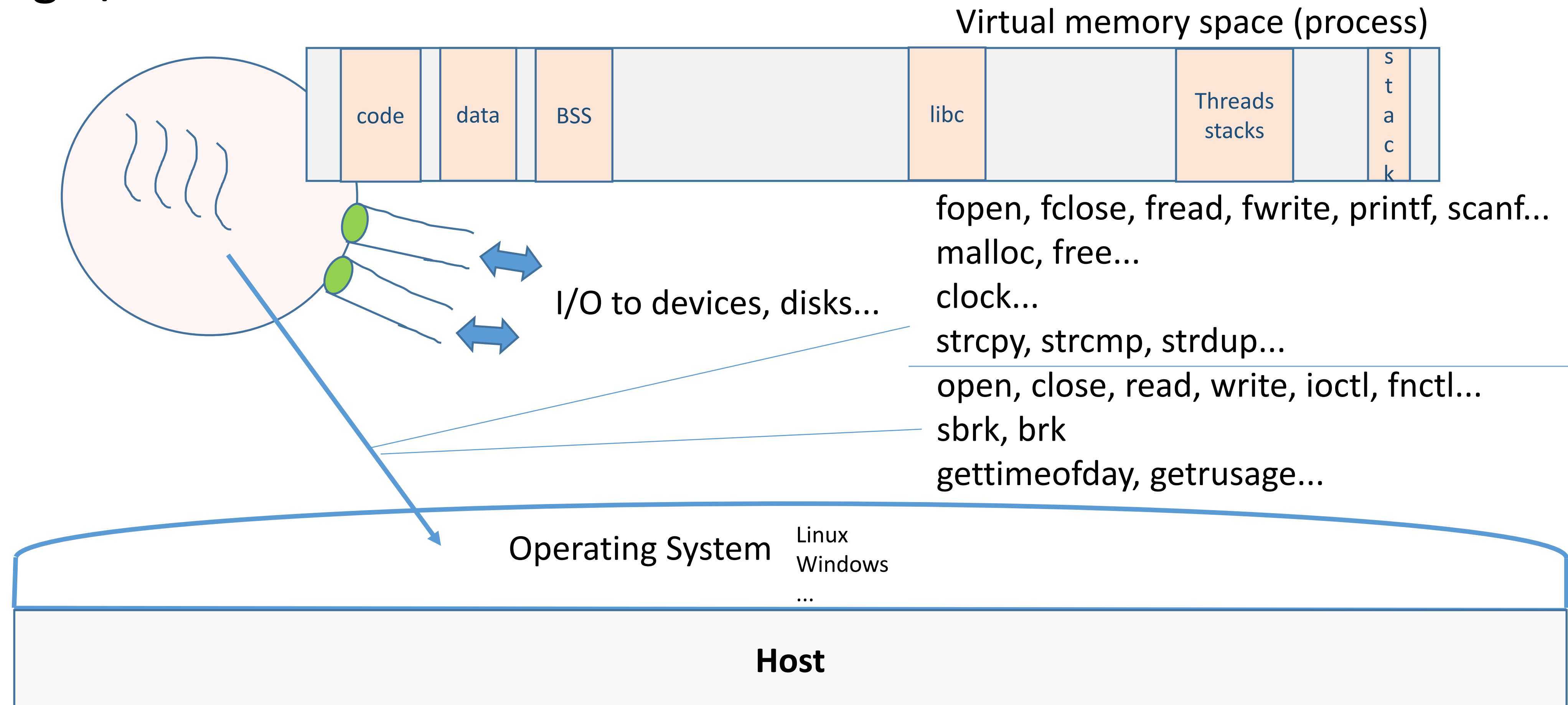
System libraries

- High / low levels



System libraries: C Library

- The basic library to Access Operating System services directly
- It follows the ISO C standard

  https://www.iso.org/obp/ui/#iso:std:iso-iec:9899:ed-3:v1:en

- Used by all applications
- Usually in **/lib/x86_64-linux-gnu/libc.so** (shared)
  /usr/lib/x86_64-linux-gnu/libc.a (static)

- Provides access to the low-level services offered by the Operating System
  - Process and memory management, files, directories, I/O…
- Provides higher level functions
  - Easier to use

Standard C++ library

- Dynamic memory management: new, delete
- Error handling, exceptions
- Strings, wide characters, Unicode
- Containers: array, vector, deque, list, stack, queue, set, map
- Iterators
- Common math functions
- Input/output: iostream
- Localization library

Standard C++ library

- Regular expressions
- Thread support, atomics, mutex, condition variables
- Filesystem (C++17)
- Experimental
- C compatibility headers

Table of Contents

- Introduction
  - From high-level code to program execution
- Compilers and the translation mechanism
- Executable file structure
  - File header, sections
  - How programs are executed
  - Software utilities
- System libraries
- Interpreters

Combining Interpreter & Compiler

- AOT: Ahead-of-Time
  - Compile the program before it is running: at compile time
- JIT: Just-in-Time
  - Compile the program while it is running: at runtime
- Steps to run a program

Source code →AOT→ **Bytecode** (intermediate code) →JIT→ **Native code**

Combining Interpreter & Compiler

- Use cases
  - Java
    - Java code -> Compiled to -> Java Bytecode -> Interpreted by: Java Virtual Machine
  - Python
    - Python -> Compiled to -> CPython -> Interpreted by: Python Interpreter
  - Microsoft .NET
    - Any .NET language -> Compiled to -> CIL (Common Intermediate Language) -> Interpreted by: CLR (Common Language Runtime)

Interpreter vs Compiler

- Interpreter
  - It directly executes instructions from the source code (through different approaches)
  - Less time to analyze the source code, but slower execution
  - No object file is generated
  - Executes until the first error → easy debugging
  - E.g. Python, MATLAB, Javascript
- Compiler
  - Scans the whole code and translates it into machine code
  - Long time to analyze the source code, but faster execution
  - Generates object file
  - Error messages after scanning the whole program
  - E.g. C, C++

E.g. Standard Library for interpreted language

- Distributed with the Python execution environment
  - Strings
  - Numbers and math
  - File and directory access
  - File formats and data compression
  - Operating System services
  - Communications & protocols
  - Internationalization
  - ...

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Next steps

- Support to the programming environment
  - Operating System
  - Programming Foundations