UCCD1133

Introduction to Computer Organisation and Architecture

Chapter 5

Program Execution

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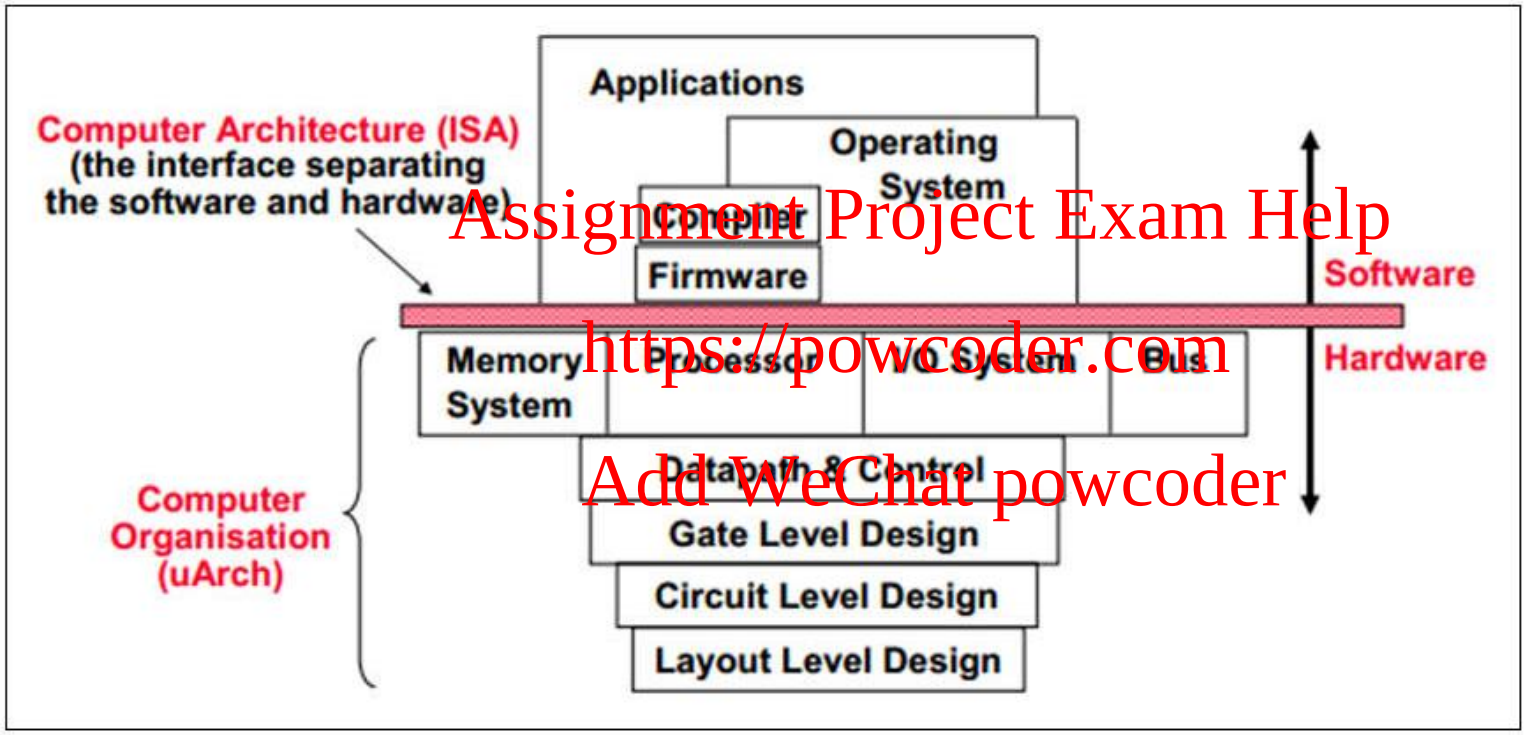
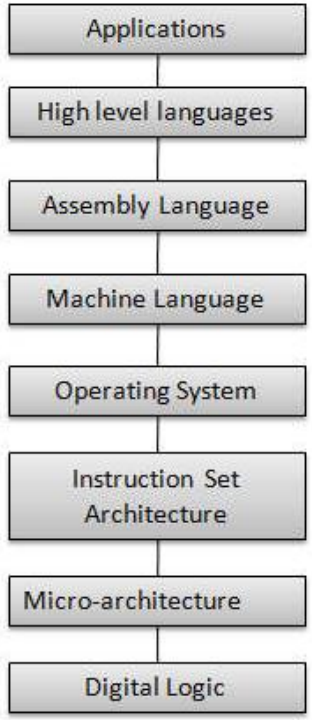
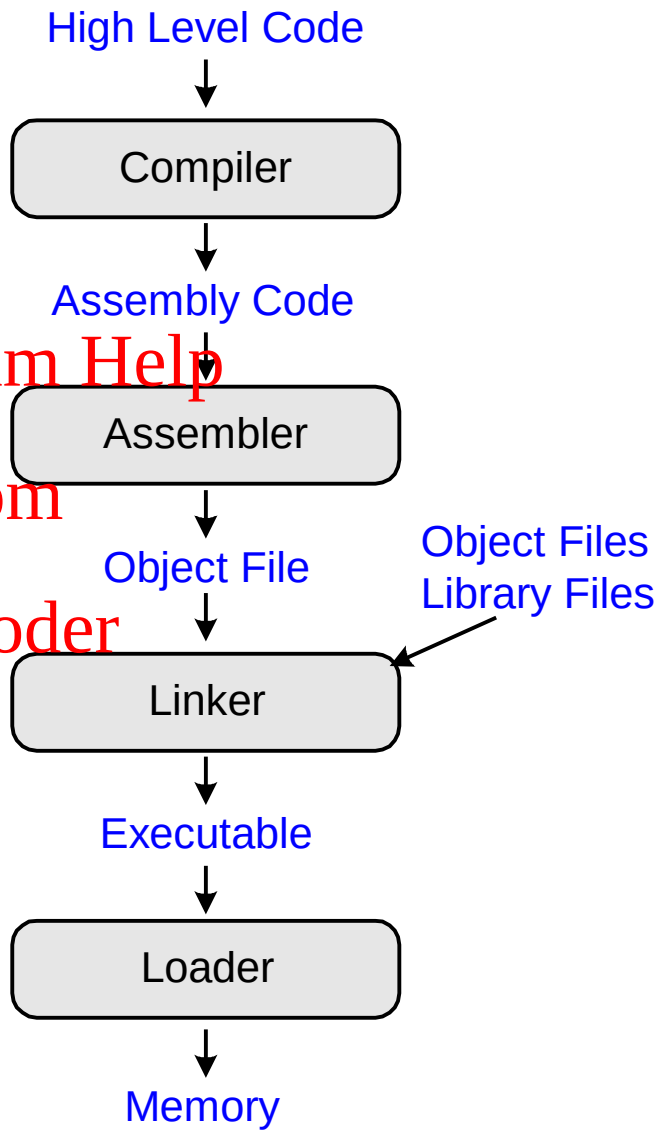
Computer Architecture Levels of Abstraction



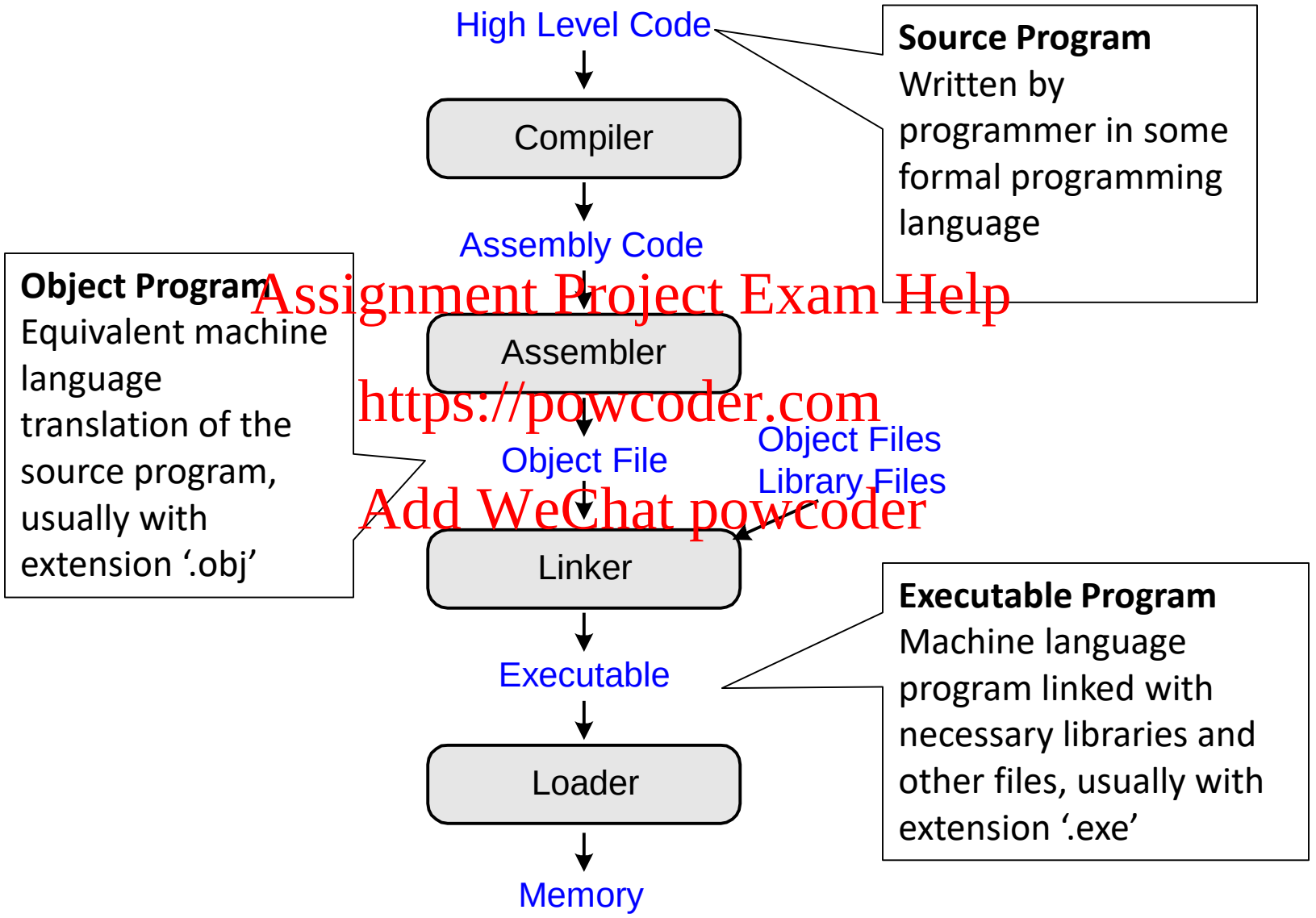


How to Compile & Run a Program

1. **C**ompiler
2. **A**ssembler
3. **L**inker
4. **L**oader



How to Compile & Run a Program



Compiler

- Compiler converts a single HLL file into a single assembly file.
- Example:
  - Input: `foo.c` (C code)
  - Output: `foo.s` (MIPS)

- Programming in HLL
  - Allow the programmer to think in a more natural language for their intended use
    - Fotran for scientific computation
    - Cobol for business programming
    - Lisp for symbol manipulation
    - Java for web programming
  - Improve programmer productivity – more understandable code that is easier to design, debug and validate
  - Improve program maintainability
  - Allow programs to be independent of the computer (compilers and assemblers can translate high-level language programs to the binary instructions of any machine)
  - Emergence of optimizing compilers that produce very efficient assembly code optimized for the target machine

Compiler

- Most programmers don't write assembly code for a number of reasons, including:
  - Readability: HLL's are clearer than assembly.
  - Portability: Assembly code is ISA specific.
  - Productivity: One line of HLL code often takes many lines of assembly, and programmers can write a fixed number of lines of code a day.

- Some reasons to write code in assembly in the real world:

  - To exploit hardware features that have no analogues in HLL
    - there are some things that cannot be expressed in HLL (*e.g.*, I/O, accesses to special registers).

  - Programs with speed- and size-critical, in particular, embedded apps
    - Humans can out code compilers in certain circumstances (performance and code size).

Example Program: C Code

```
int f, g, y;  // global
  variables



int main(void)
{
  f = 2;
  g = 3;
  y = sum(f, g);

  return y;
}



int sum(int a, int b) {
  return (a + b);
}
```

Example Program: MIPS Assembly

```
int f, g, y;  // global variables


int main(void)
{
  f = 2;
  g = 3;
  y = sum(f, g);

  return y;
}


int sum(int a, int b) {
  return (a + b);
}
```

```
.data
f:
g:
y:
.text
main:
  addi $sp, $sp, -4     # stack frame
  sw   $ra, 0($sp)      # store $ra
  addi $a0, $0, 2       # $a0 = 2
  sw   $a0, f           # f = 2
  addi $a1, $0, 3       # $a1 = 3
  sw   $a1, g           # g = 3
  jal  sum              # call sum
  sw   $v0, y           # y = sum()
  lw   $ra, 0($sp)      # restore $ra
  addi $sp, $sp, 4      # restore $sp
  jr   $ra              # return to OS
sum:
  add  $v0, $a0, $a1    # $v0 = a + b
  jr   $ra              # return
```

Assembler

- The assembler convert the assembly language code into an object file containing machine language code.
- An assembler
  - Reads and uses assembler directives, such as
    - `.text`: subsequent items put in user text segment
    - `.data`: subsequent items put in user data segment
    - `.global sym`: declares `sym` as global label
  - Replace pseudoinstructions
  - Assigns instruction addresses
  - Record the addresses of the symbols (labels and global variable names) in the symbol table.
  - Create a relocation table to list the items that needs the address later.
    - Example: `lui $4, l.str`
    - the `l.str` is a label from somewhere, but don't know the value yet.
  - Produce the machine code and stored it in the object file.
- Example:
  - Input: `foo.s` (MIPS)
  - Output: `foo.obj` (Object file)

Assembler

- The translation process has two major parts.

  - During the **first pass**, the assembler
    - Reads each line of an assembly file.
    - If a line begins with a label, records in its ***symbol table*** the name of the label and the address of the memory that the instruction occupies.

  - During the **second pass**, the assembler
    - Use the symbol table to produces ***machine code***.
    - The process is similar to Chapter 4.
    - Instructions and data words that reference an external symbol defined in another file cannot be completely assembled.

Example Program: Symbol Table

```
0x00400000        main:   addi $sp, $sp, -4    # stack frame
0x00400004                sw   $ra, 0($sp)     # store $ra
0x00400008                addi $a0, $0, 2      # $a0 = 2
0x0040000C                sw   $a0, f          # f = 2
0x00400010                addi $a1, $0, 3      # $a1 = 3
0x00400014                sw   $a1, g          # g = 3
0x00400018                jal  sum             # call sum
0x0040001C                sw   $v0, y          # y = sum()
0x00400020                lw   $ra, 0($sp)     # restore $ra
0x00400024                addi $sp, $sp, 4     # restore $sp
0x00400028                jr   $ra             # return to OS
0x0040002C          sum:  add  $v0, $a0, $a1   # $v0 = a + b
0x00400030                jr   $ra             # return
```


Symbol	Address

Example Program: Symbol Table

```
0x00400000        main:  addi $sp, $sp, -4    # stack frame
0x00400004               sw   $ra, 0($sp)     # store $ra
0x00400008               addi $a0, $0, 2      # $a0 = 2
0x0040000C               sw   $a0, f          # f = 2
0x00400010               addi $a1, $0, 3      # $a1 = 3
0x00400014               sw   $a1, g          # g = 3
0x00400018               jal  sum             # call sum
0x0040001C               sw   $v0, y          # y = sum()
0x00400020               lw   $ra, 0($sp)     # restore $ra
0x00400024               addi $sp, $sp, 4     # restore $sp
0x00400028               jr   $ra             # return to OS
0x0040002C        sum:   add  $v0, $a0, $a1   # $v0 = a + b
0x00400030               jr   $ra             # return
```


Symbol	Address
f	0x10000000
g	0x10000004
y	0x10000008
main	0x00400000
sum	0x0040002C

Object File Format

- Object file header: size and position of the other pieces of the object file
- Text segment: the machine code for the routines (instructions) in the source file. Maybe unexecutable because of unresolved references.
- Data segment: binary representation of the data in the source file. The data also may be incomplete because of unresolved references to labels in other files.
- Relocation information: identifies instructions and data that depend on absolute addresses
  - j, jal, and some loads and stores (e.g. lw $t1, 100($zero)) use absolute addresses
  - These references must change if portions of the program are moved in memory.
- Symbol table: addresses with external labels in the source file and lists unresolved reference.
- Debugging information: contains a concise description of the way the program was compiled for debugging purpose.

Object file header	Text segment	Data segment	Relocation information	Symbol table	Debugging information

A UNIX assembler produces an object file with 6 distinct sections.

Linker

- Most programs are very large and consist of several modules. Even small programs use existing code provided by the programming environment called libraries.

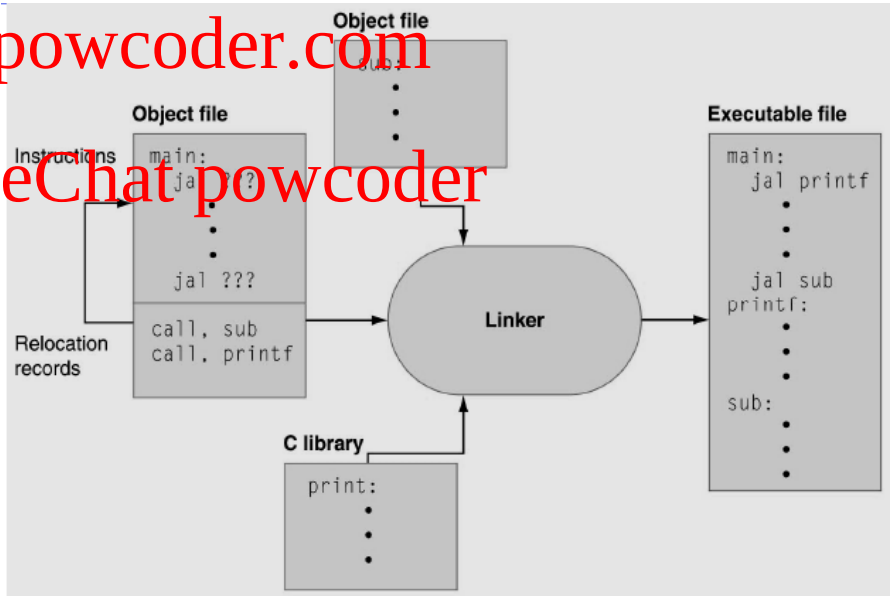
- Assembler only sees one compiled program at a time. It's the job of the linker to link them together.

- A linker combines several object files into a single executable and resolves absolute addresses.
  - It calculates the absolute address of each label to be jumped to (internal or external) and each piece of data being referenced.

- It enables separate compilation of files
  - Changes to one file do not require recompiling of whole program

Linker

- A linker
  - Merge text / data segments
  - Resolve reference
    - Search for reference (data or label) in all symbol tables
    - If not found, search library files (for example, `printf`)
    - Determine the absolute memory addresses
    - Fill in the absolute address in the machine code
- Example:
  - Inputs: foo.obj, lib.obj
  - Output: abc.exe



Executable File Format

Executable file header	Text Size	Data Size
	0x34 (52 bytes)	0xC (12 bytes)
Text segment	**Address**	**Instruction**
	0x00400000	0x23BDFFFC
	0x00400004	0xAFBF0000
	0x00400008	0x20040002
	0x0040000C	0xAF848000
	0x00400010	0x20050003
	0x00400014	0xAF858004
	0x00400018	0x0C10000B
	0x0040001C	0xAF828008
	0x00400020	0x8FBF0000
	0x00400024	0x23BD0004
	0x00400028	0x03E00008
	0x0040002C	0x00851020
	0x00400030	0x03E00008
Data segment	**Address**	**Data**
	0x10000000	f
	0x10000004	g
	0x10000008	y

```
addi $sp, $sp, -4
sw   $ra, 0 ($sp)
addi $a0, $0, 2
sw   $a0, 0x8000 ($gp)
addi $a1, $0, 3
sw   $a1, 0x8004 ($gp)
jal  0x0040002C
sw   $v0, 0x8008 ($gp)
lw   $ra, 0 ($sp)
addi $sp, $sp, -4
jr   $ra
add  $v0, $a0, $a1
jr   $ra
```

Example: Procedure A Object File

```
lw $a0, xxx($gp)
jal B
…
```

refer to the address of data word X

instruction that refer to the addresses of procedures B

Procedure A needs to find the address for the variable labeled X to put in the load instruction and to find the address of procedure B to place in the `jal` instruction.

Object file header			
	Name	Procedure A	
	Text size	100_{hex}	
	Data size	20 hex	
Text segment	Address	Instruction	
	0	lw $a0, 0($gp)	
	4	jal 0	
	…	…	
Data segment	0	(X)	
	…	…	
Relocation information	Address	Instruction type	Dependency
	0	lw	X
	4	jal	B
Symbol table	Label	Address	
	X	–	
	B	–	

Example: Procedure B Object File

```
sw $a1, yyy($gp)
jal A
...
```

refer to the address of data word Y

instruction that refer to the address of procedures A

Procedure B needs the address of the variable labeled Y for the store instruction and the address of procedure A for its `jal` instruction.

Object file header			
	Name	Procedure B	
	Text size	200_{hex}	
	Data size	30_{hex}	
Text segment	Address	Instruction	
	0	sw $a1, 0($gp)	
	4	jal 0	
	...	...	
Data segment	0	(Y)	
	...	...	
Relocation information	Address	Instruction type	Dependency
	0	sw	Y
	4	jal	A
Symbol table	Label	Address	
	Y	–	
	A	–	

Example: Executable File

Procedure A

Object file header			
	Name	Procedure A	
	Text size	100_{hex}	
	Data size	20_{hex}	
Text segment	Address	Instruction	
	0	lw $a0, 0($gp)	
	4	jal 0	
	...	...	
Data segment	0	(X)	
	...	...	
Relocation information	Address	Instruction type	Dependency
	0	lw	X
	4	jal	B
Symbol table	Label	Address	
	X	-	
	B	-	

Procedure B

Object file header			
	Name	Procedure B	
	Text size	200_{hex}	
	Data size	30_{hex}	
Text segment	Address	Instruction	
	0	sw $a1, 0($gp)	
	4	jal 0	
	...	...	
Data segment	0	(Y)	
	...	...	
Relocation information	Address	Instruction type	Dependency
	0	sw	Y
	4	jal	A
Symbol table	Label	Address	
	Y	-	
	A	-	

linker

Executable file header		
	Text size	300_{hex}
	Data size	50_{hex}
Text segment	Address	Instruction
	$0040\ 0000_{hex}$	lw $a0, -8000 hex($gp)
	$0040\ 0004_{hex}$	jal 40 0100 hex
	...	...
	$0040\ 0100_{hex}$	sw $a1, -7980 hex($gp)
	$0040\ 0104_{hex}$	jal 40 0000 hex
	...	...
Data segment	Address	
	$1000\ 0000_{hex}$	(X)
	...	...
	$1000\ 0020_{hex}$	(Y)
	...	...

* `$gp` is initialized to $1000\ 8000_{hex}$
* Recall that MIPS instructions are word aligned, so `jal` drops the right two bits to increase the instruction's address range. Thus, it use 26 bits to create a 28-bit byte address. Hence, the actual address in the lower 26 bits of the `jal` instruction in this example is $10\ 0040_{hex}$, rather than $40\ 0100_{hex}$.

Static vs Dynamically Linked Libraries

- **Statically Linked Library:** fastest way to call library routines.

  Problems:
  - if the library has new release, the program still uses the old version (unless recompile if we have the source files)
  - When the program runs, the *entire* library is loaded including unused parts (library can be larger than the main program)

- An alternative is **dynamically linked libraries (DLL),** common on Windows & UNIX platforms

  - Library routines are not linked and loaded until a routine is called during execution.
  - Only the required routine is linked.

- Use of a dynamic linker-loader.
  - Find the desired routine, remap it, and “link” it to the calling routine

- Overall, dynamic linking adds quite a bit of complexity to the compiler, linker, and operating system.
  - But, advantages more than disadvantages.

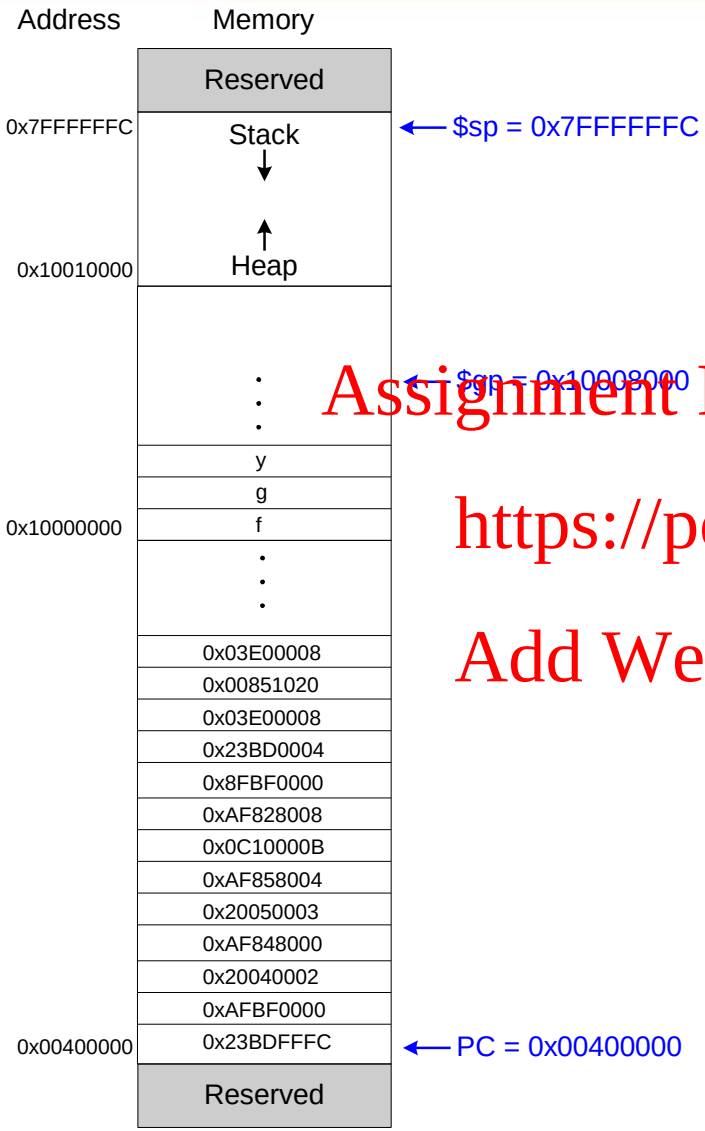
Dynamically Linked Libraries

- Space/time issues
  - + Storing a program requires less disk space
  - + Sending a program requires less time
  - + Executing two programs requires less memory (if they share a library)
  - – At runtime, there's time overhead to do link
- Upgrades
  - + Replacing one file upgrades every program that uses that library
- Microsoft's Windows relies extensively on dynamically linked libraries, and it is also the default when executing programs on UNIX systems today.

Loader

- A program that links without error can be run.
- Before being run, the program resides in a file on secondary storage, such as a disk. It needs to be brought into memory, usually by operating system, to start running.
- The operating system loads a program by:
  - Reads the executable file's header to determine the size of the text and data segments.
  - Creates a new address space for the program.
  - Copies the instruction and data from executable file into the new address space
  - Copies arguments passed to the program onto the stack
  - Initializes the machine registers
    - Most registers are cleared.
    - Sets `$gp` to 0x1000 8000 (the middle of the global data segment)
    - Sets `$sp` to 0x7FFF FFFC (the top of dynamic data segment)
  - Jump to the beginning of the program
    - Perform a `jal` 0x0040 0000.
- Example:
  - Input: abc.exe
  - Output: <program is run>

Example Program: In Memory



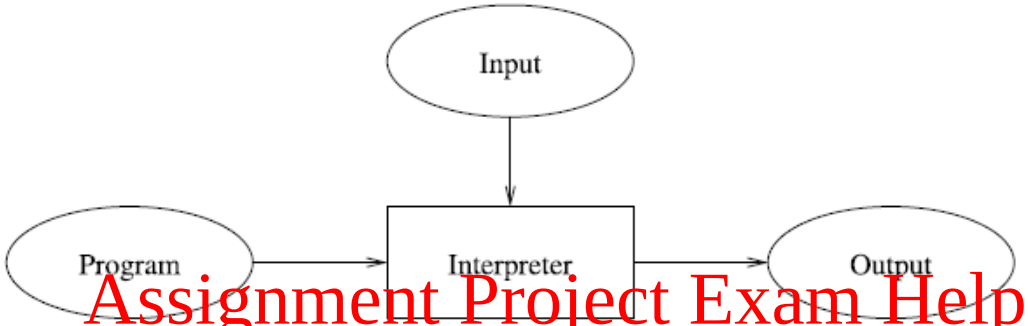
Interpreter vs compiler

- Interpreter and compiler are both translator
  - convert high level language commands into machine code.

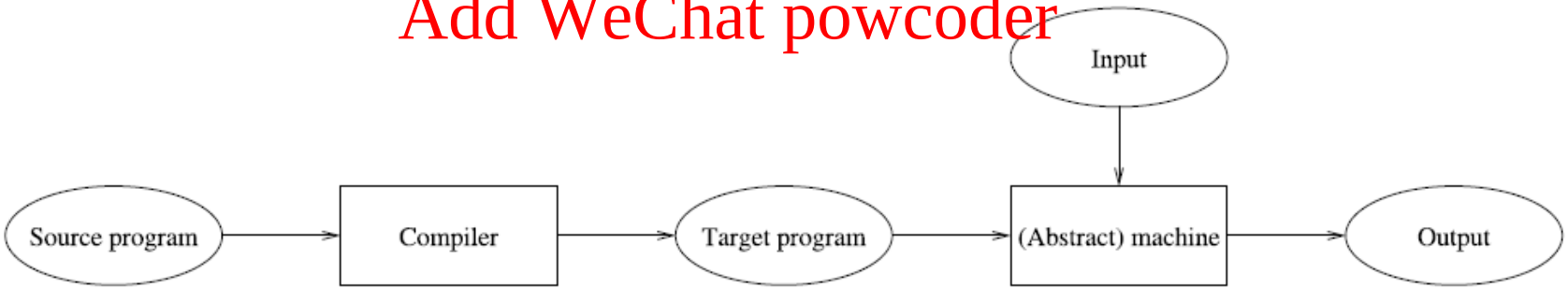
- A compiler translate the whole code into machine code before running the program.
  - Compiled programming languages include Java, Fortran and C++.

- An interpreter translate one instruction at a time. The CPU execute each instruction before the interpreter moves on to the next instruction.
  - Unlike compilation, interpretation has
    - No linking
    - No object code generated
    - Source statements executed line by line
  - Interpreted languages include JavaScript, PHP, Python and Ruby.

Interpreter vs compiler



Interpretation in one stage.



Compilation and execution in two stages.

Advantages and Disadvantages of Compiler

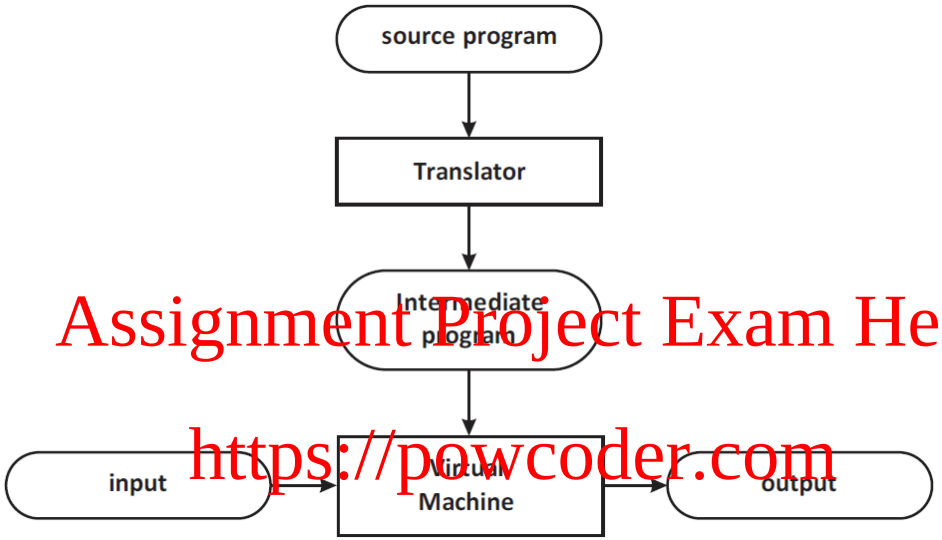
- Advantages
  - Faster Execution
  - Single file to execute
  - Compiler can do better diagnosis of syntax and semantic errors, since it has more info than an interpreter (Interpreter only sees one line at a time)
  - Can find syntax errors before run program
  - Compiler can optimize code
- Disadvantages
  - Harder to debug
  - Takes longer to change source code, recompile and relink

Advantages and Disadvantages of Interpreter

- Advantages
  - Easier to debug
  - Faster development time
  - Interpreter closer to high-level, so can give better error message
  - Provides instruction set independence: can run on any machine

- Disadvantages
  - Slower execution times
  - No optimization
  - Need all of source code available
  - Source code larger than executable for large systems
  - Interpreter must remain installed while the program is interpreted

Hybrid System



- Nearly all Java language processors conform to this hybrid system.
- Java programs are compiled to an intermediate form call bytecodes. Bytecode programs are executed by a Java virtual machine.