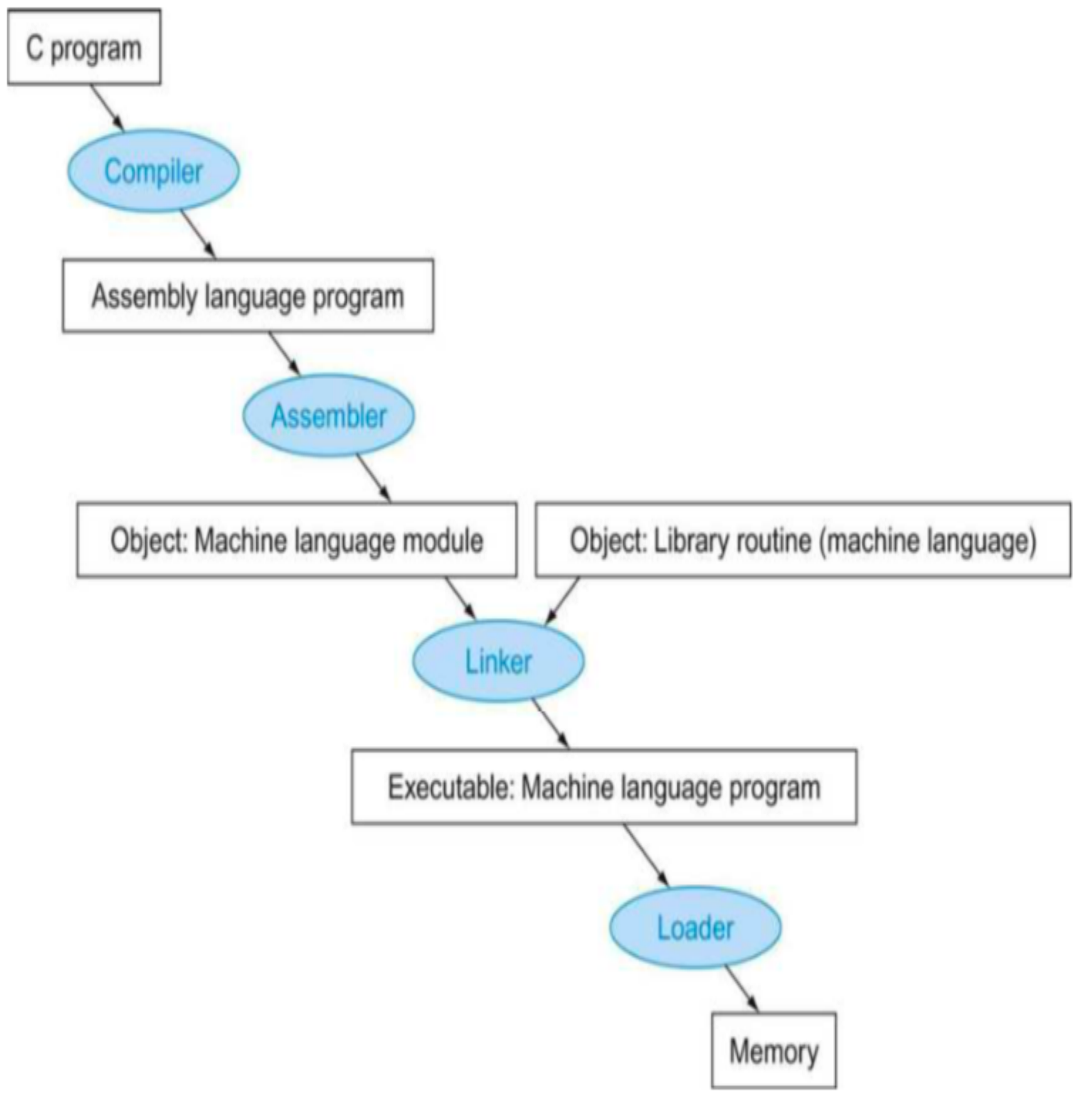
Chapter 2.12: Compilation, Assembling, Linking and Program Execution

ITSC 3181 Introduction to Computer Architecture
https://passlab.github.io/ITSC3181/

Department of Computer Science
Yonghong Yan
yyan7@uncc.edu
https://passlab.github.io/yanyh/

A Translation Hierarchy for C



Compilation Process in C

- Compilation process: gcc hello.c -o hello
  - Constructing an executable image for an application
  - **Multiple stages**
  - Command:
    gcc <options> <source_file.c>

- Compiler Tool
  - gcc (GNU Compiler)
    - man gcc (on Linux m/c)

  - icc (Intel C compiler)

4 Stages of Compilation Process

Preprocessing
gcc -E hello.c -o hello.i
hello.c → hello.i

Compilation (after preprocessing)

gcc -S hello.i -o hello.s

Assembling (after compilation)

gcc -c hello.s -o hello.o

Linking object files

gcc hello.o -o hello

Output → Executable (a.out)
Run → ./hello (Loader)

4 Stages of Compilation Process

1. Preprocessing (Those with # …)
   - Expansion of Header files (#include …)
   - Substitute macros and inline functions (#define …)
2. Compilation
   - Generates assembly language, .s file
   - Verification of functions usage using prototypes
   - Header files: Prototypes declaration
3. Assembling
   - Generates re-locatable object file (contains m/c instructions), .o file
   - nm app.o

     ```
     0000000000000000 T main
                      U puts
     ```
   - nm or objdump tool used to view object files

4 Stages of Compilation Process (contd..)

4. Linking
   - Generates executable file (nm tool used to view exe file)
   - Binds appropriate libraries
     - Static Linking
     - Dynamic Linking (default)

- Loading and Execution (of an executable file)
  - Evaluate size of code and data segment
  - Allocates address space in the user mode and transfers them into memory
  - Load dependent libraries needed by program and links them
  - Invokes Process Manager → Program registration

Compiling a C Program

- *gcc <options> program_name.c*

Four stages into one

- Options:

  -Wall: Shows all warnings

  -o output_file_name: By default a.out executable file is created when we compile our program with gcc. Instead, we can specify the output file name using "**-o**" option.

  -g: Include debugging information in the binary.

- man gcc

Preprocessing

- Things with #
  - #include <stdio.h>
  - #define REAL float
  - Others
- Processes the C source files BEFORE handing it to compiler.
  - `Pre`-process
  - gcc –E
  - cpp

File Inclusion

- Recall : #include <*filename*>
  - #include <foo.h>
    - System directories
  - #include “foo.h”
    - Current directories
  - gcc -I/usr/include to specify where to search those header files
    - gcc -I/usr/include sum_full.c -o sum

- Preprocessing replaces the line “#include <foo.h>” with the content of the file foo.h

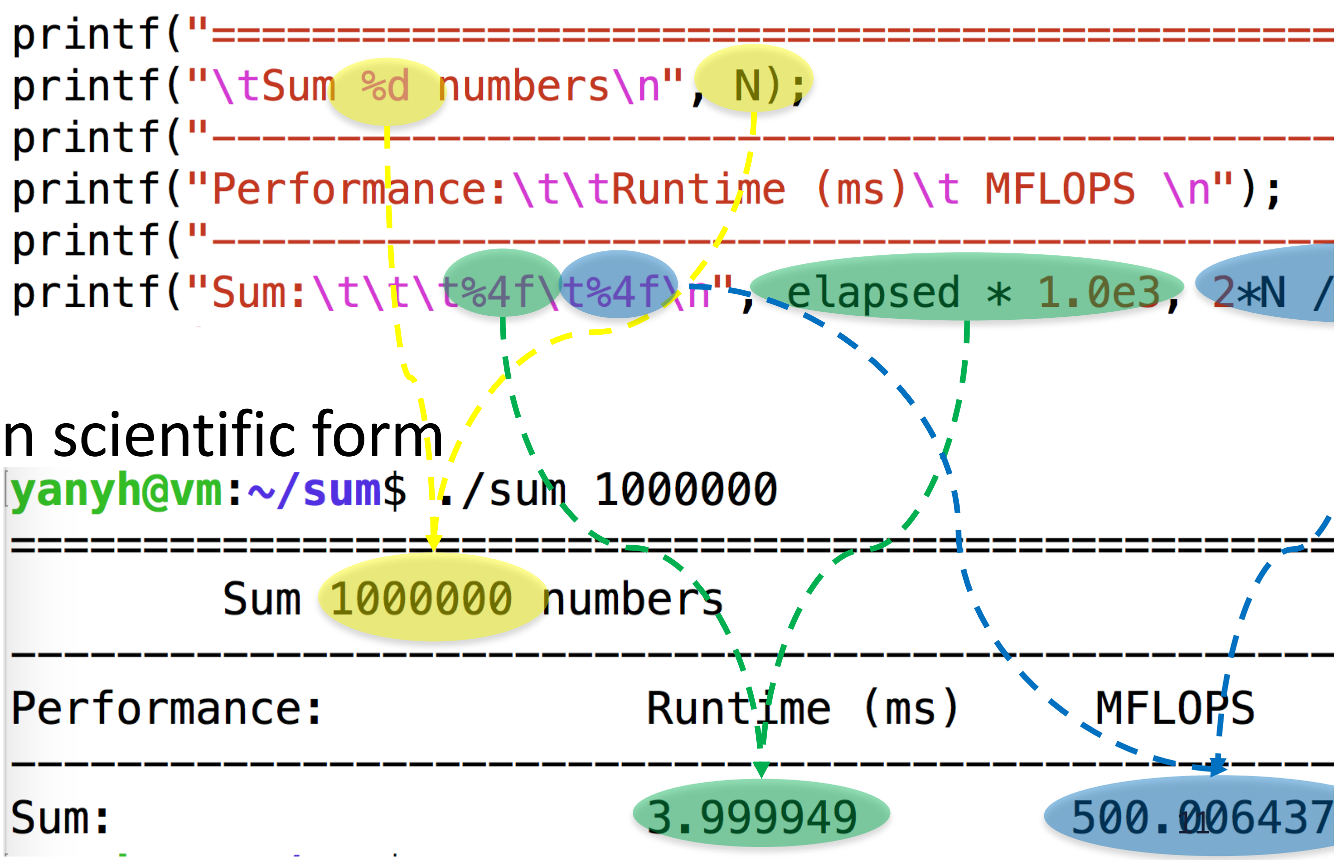
Macros

- Define and replaced by preprocessing
  - Every occurrence of **REAL** will be replaced with **float** before compilation.

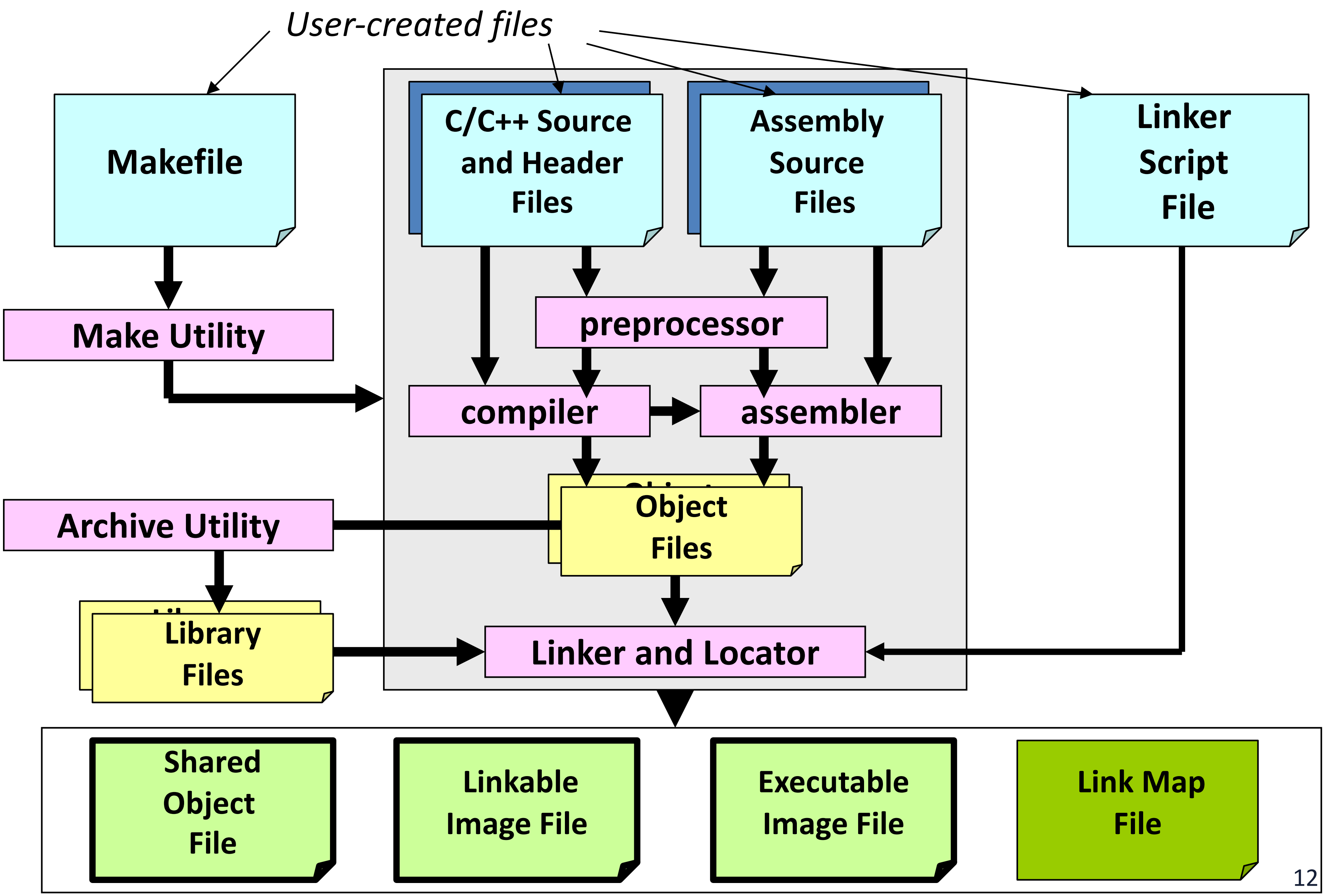
```c
#define REAL float

REAL sum(int N, REAL X[], REAL a) {
    int i;
    REAL result = 0.0;
    for (i = 0; i < N; ++i)
        result += a * X[i];
    return result;
}
```

About printf in C

- `printf("format string",vars);`
- Format string?
  - `"This year is %d\n"`
  - `"Your score is %d\n"`
- Conversion by `%`
  - `%d` : int
  - `%f` : float, double
  - `%c` : char
  - `%s` : char *, string
  - `%e` : float, double in scientific form

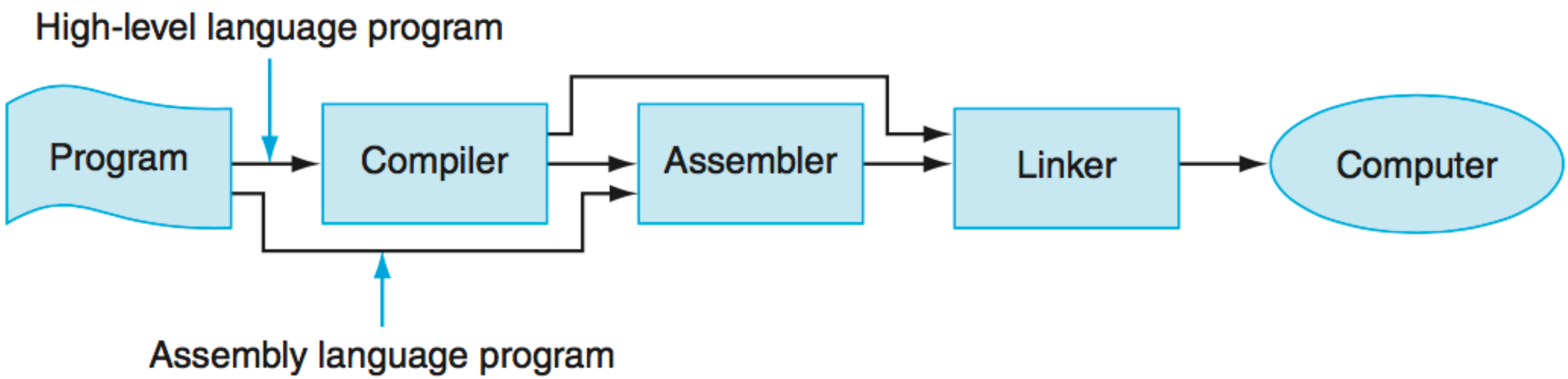


Tools and Steps for Program Execution



Code Can be in Assembly Language

- Assembly language either is written by a programmer or is the output of a compiler.



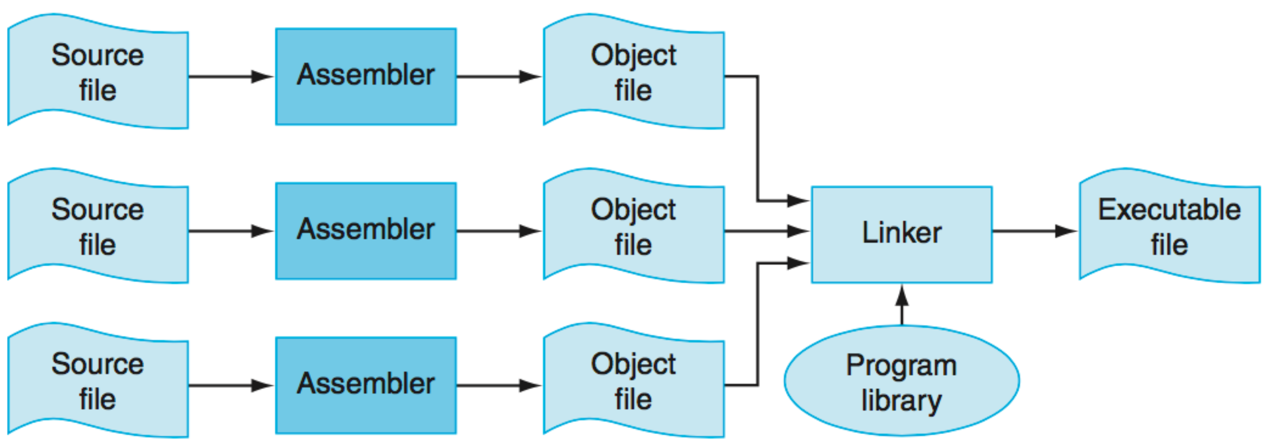


FIGURE A.1.1 The process that produces an executable file. An assembler translates a file of assembly language into an object file, which is linked with other files and libraries into an executable file.

High-Level Program, Assembly Code and Binary

```c
#include <stdio.h>
int main (int argc, char * argv[])
{
  int i;
  int sum = 0;
  for (i = 0; i <= 100; i = i + 1) sum = sum + i * i;
  printf ("The sum from 0 .. 100 is %d\n", sum);
}
```

```
addiu   $29, $29, -32
sw      $31, 20($29)
sw      $4, 32($29)
sw      $5, 36($29)
sw      $0, 24($29)
sw      $0, 28($29)
lw      $14, 28($29)
lw      $24, 24($29)
multu   $14, $14
addiu   $8, $14, 1
slti    $1, $8, 101
sw $8,  28($29)
mflo    $15
addu    $25, $24, $15
bne     $1, $0, -9
sw      $25, 24($29)
lui     $4, 4096
lw      $5, 24($29)
jal     1048812
addiu   $4, $4, 1072
lw      $31, 20($29)
addiu   $29, $29, 32
jr      $31
move    $2, $0
```

```
        .text
        .align  2
        .globl  main
main:
        subu    $sp, $sp, 32
        sw      $ra, 20($sp)
        sd      $a0, 32($sp)
        sw      $0,  24($sp)
        sw      $0,  28($sp)
loop:
        lw      $t6, 28($sp)
        mul     $t7, $t6, $t6
        lw      $t8, 24($sp)
        addu    $t9, $t8, $t7
        sw      $t9, 24($sp)
        addu    $t0, $t6, 1
        sw      $t0, 28($sp)
        ble     $t0, 100, loop
        la      $a0, str
        lw      $a1, 24($sp)
        jal     printf
        move    $v0, $0
        lw      $ra, 20($sp)
        addu    $sp, $sp, 32
        jr      $ra

        .data
        .align  0
str:
        .asciiz "The sum from 0 .. 100 is %d\n"
```

```
00100111101111011111111111100000
10101111101111110000000000010100
10101111101001000000000000100000
10101111101001010000000000100100
10101111101000000000000000011000
10101111101000000000000000011100
10001111101011100000000000011100
10001111101110000000000000011000
00000001110011100000000000011001
00100101110010000000000000000001
00101001000000010000000001100101
10101111101010000000000000011100
00000000000000000111100000010010
00000011000011111100100000100001
00010100001000001111111111110111
10101111101110010000000000011000
00111100000001000001000000000000
10001111101001010000000000011000
00001100000100000000000011101100
00100100100001000000010000110000
10001111101111110000000000010100
00100111101111010000000000100000
00000011111000000000000000001000
00000000000000000001000000100001
```

FIGURE A.1.2 MIPS machine language code f
of the squares of integers between 0 and 100.

Hand-On, sum x86_64

https://passlab.github.io/ITSC3181/exercises/sum/sum_full.c

https://passlab.github.io/ITSC3181/exercises/sum/sum_full_x86.s

```c
REAL sum(int N, REAL X[], REAL a) {
    int i;
    REAL result = 0.0;
    for (i = 0; i < N; ++i)
        result += a * X[i];
    return result;
}
```

- A method in assembly
  - .globl: **a global symbol**
  - .type
  - .cfi_startproc
  - .cfi_endproc
  - ret: **return**
- for loop
  - check i<N, if true continue, else goto end;
  - loop body
  - i++
  - end

```
        .cfi_def_cfa 7, 8
        ret
        .cfi_endproc
.LFE4:
        .size   init, .-init
        .globl  sum
        .type   sum, @function
sum:
.LFB5:
        .cfi_startproc
        pushq   %rbp
        .cfi_def_cfa_offset 16
        .cfi_offset 6, -16
        movq    %rsp, %rbp
        .cfi_def_cfa_register 6
        movl    %edi, -20(%rbp)
        movq    %rsi, -32(%rbp)
        movss   %xmm0, -24(%rbp)
        pxor    %xmm0, %xmm0
        movss   %xmm0, -4(%rbp)
        movl    $0, -8(%rbp)
        jmp     .L11
.L12:
        movl    -8(%rbp), %eax
        cltq
        leaq    0(,%rax,4), %rdx
        movq    -32(%rbp), %rax
        addq    %rdx, %rax
        movss   (%rax), %xmm0
        mulss   -24(%rbp), %xmm0
        movss   -4(%rbp), %xmm1
        addss   %xmm1, %xmm0
        movss   %xmm0, -4(%rbp)
        addl    $1, -8(%rbp)
.L11:
        movl    -8(%rbp), %eax
        cmpl    -20(%rbp), %eax
        jl      .L12
        movss   -4(%rbp), %xmm0
        popq    %rbp
        .cfi_def_cfa 7, 8
        ret
        .cfi_endproc
.LFE5:
        .size   sum, .-sum
        .section        .rodata
.LC2:
        .string "Usage: sum <n> (default %d)\n"
        .align 8
```

Sum, RISC-V and MIPS

- Mainly different instructions

```c
REAL sum(int N, REAL X[], REAL a) {
    int i;
    REAL result = 0.0;
    for (i = 0; i < N; ++i)
        result += a * X[i];
    return result;
}
```

- for loop
  - check i<N, if true, continue, else goto end;
  - loop body
  - i++
  - end

RISC-V Version

```
        .globl  sum
        .type   sum, @function
sum:
        addi    sp,sp,-48
        sd      s0,40(sp)
        addi    s0,sp,48
        mv      a5,a0
        sd      a1,-48(s0)
        fsw     fa0,-40(s0)
        sw      a5,-36(s0)
        sw      zero,-24(s0)
        sw      zero,-20(s0)
        j       .L9
.L10:
        lw      a5,-20(s0)
        slli    a5,a5,2
        ld      a4,-48(s0)
        add     a5,a4,a5
        flw     fa4,0(a5)
        flw     fa5,-40(s0)
        fmul.s  fa5,fa4,fa5
        flw     fa4,-24(s0)
        fadd.s  fa5,fa4,fa5
        fsw     fa5,-24(s0)
        lw      a5,-20(s0)
        addiw   a5,a5,1
        sw      a5,-20(s0)
.L9:
        lw      a4,-20(s0)
        lw      a5,-36(s0)
        sext.w  a4,a4
        sext.w  a5,a5
        blt     a4,a5,.L10
        flw     fa5,-24(s0)
        fmv.s   fa0,fa5
        ld      s0,40(sp)
        addi    sp,sp,48
        jr      ra
        .size   sum, .-sum
        .section        .rodata
        .align  3
```

MIPS Version

```
        sw      $6,32($fp)
        sw      $0,12($fp)
        sw      $0,8($fp)
        b       $L9
        nop

$L10:
        lw      $2,8($fp)
        nop
        sll     $2,$2,2
        lw      $3,28($fp)
        nop
        addu    $2,$3,$2
        lwc1    $f2,0($2)
        lwc1    $f0,32($fp)
        nop
        mul.s   $f0,$f2,$f0
        lwc1    $f2,12($fp)
        nop
        add.s   $f0,$f2,$f0
        swc1    $f0,12($fp)
        lw      $2,8($fp)
        nop
        addiu   $2,$2,1
        sw      $2,8($fp)
$L9:
        lw      $3,8($fp)
        lw      $2,24($fp)
        nop
        slt     $2,$3,$2
        bne     $2,$0,$L10
        nop

        lwc1    $f0,12($fp)
        move    $sp,$fp
        lw      $fp,20($sp)
        addiu   $sp,$sp,24
        j       $31
        nop
```

Sum, x86_64

- Number of instructions per loop iteration
  - Count it

```c
REAL sum(int N, REAL X[], REAL a) {
    int i;
    REAL result = 0.0;
    for (i = 0; i < N; ++i)
        result += a * X[i];
    return result;
}
```

$$\text{CPU Time}(s) = \frac{\#\ \text{Instructions}}{\text{Program}} \times \frac{\#\ \text{Clock cycles}}{\text{Instruction}} \times \frac{\text{Seconds}}{\text{Clock cycle}}$$

```
        .cfi_def_cfa 7, 8
        ret
        .cfi_endproc
.LFE4:
        .size   init, .-init
        .globl  sum
        .type   sum, @function
sum:
.LFB5:
        .cfi_startproc
        pushq   %rbp
        .cfi_def_cfa_offset 16
        .cfi_offset 6, -16
        movq    %rsp, %rbp
        .cfi_def_cfa_register 6
        movl    %edi, -20(%rbp)
        movq    %rsi, -32(%rbp)
        movss   %xmm0, -24(%rbp)
        pxor    %xmm0, %xmm0
        movss   %xmm0, -4(%rbp)
        movl    $0, -8(%rbp)
        jmp     .L11
.L12:
        movl    -8(%rbp), %eax
        cltq
        leaq    0(,%rax,4), %rdx
        movq    -32(%rbp), %rax
        addq    %rdx, %rax
        movss   (%rax), %xmm0
        mulss   -24(%rbp), %xmm0
        movss   -4(%rbp), %xmm1
        addss   %xmm1, %xmm0
        movss   %xmm0, -4(%rbp)
        addl    $1, -8(%rbp)
.L11:
        movl    -8(%rbp), %eax
        cmpl    -20(%rbp), %eax
        jl      .L12
        movss   -4(%rbp), %xmm0
        popq    %rbp
        .cfi_def_cfa 7, 8
        ret
        .cfi_endproc
.LFE5:
        .size   sum, .-sum
        .section        .rodata
.LC2:
        .string "Usage: sum <n> (default %d)\n"
        .align 8
```

When to Use Assembly Language

- Advantage: Speed, size and predictable
  - No compiler middle-man
  - Fit for mission-critical, embedded domain, e.g. space shuttle or car control
- Hybrid approach
  - Non-critical part in high-level language
  - Critical part in assembly language
- Explore special instructions
  - E.g. those special-purpose instructions that can do more than one thing

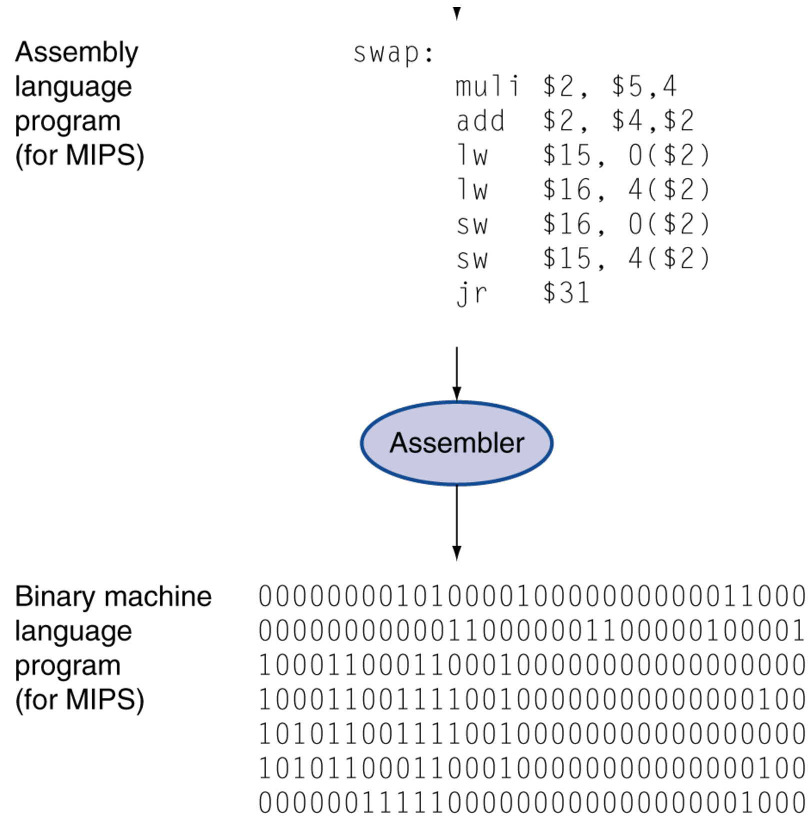
Drawbacks of Assembly Language

Assembly language has many (and more) disadvantages that strongly argue against its wide-spread use.

- Machine-specific code, i.e. assembly code are not portable
  - Rewrite for new or different architectures
- Harder than high level language to write large code or software
  - Harder to keep a high-level software structure
  - Harder to read and debug
- Most compilers are good enough to convince that you do not need to write assembly code for general-purpose applications
  - Except embedded or IoT domain

Assembler

- Translates file of assembly language statements into a file of binary machine instructions and binary data.
- Two main steps:
  - Find memory address for symbols (e.g. functions).
  - Translate each assembly statement by combining the numeric equivalents of opcodes, register specifiers, and labels into a legal instruction
    - Binary
- Produce object files



Object File

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

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

FIGURE A.2.1 Object file. A UNIX assembler produces an object file with six distinct sections.

```
#include <stdio.h>

int a[10]={0,1,2,3,4,5,6,7,8,9};
int b[10];

int main(int argc, char* argv[]){
   int i;
   static int k = 3;

   for(i = 0; i < 10; i++) {
      printf("%d\n",a[i]);
      b[i] = k*a[i];
   }
}
```

Contents of Object File for the Sample C program

Offset	*Contents*	*Comment*
Header section		
0	124	number of bytes of Machine code section
4	44	number of bytes of initialized data section
8	40	number of bytes of Uninitialized data section (array **`b[]`**) (*not part of this object module*)
12	60	number of bytes of Symbol table section
16	44	number of bytes of Relocation information section
Machine code section (124 bytes)		
20	X	code for the top of the **`for`** loop (36 bytes)
56	X	code for call to **`printf()`** (22 bytes)
68	X	code for the assignment statement (10 bytes)
88	X	code for the bottom of the **`for`** loop (4 bytes)
92	X	code for exiting **`main()`** (52 bytes)
Initialized data section (44 bytes)		
144	0	beginning of array **`a[]`**
148	1	
:		
176	8	
180	9	end of array **`a[]`** (40 bytes)
184	3	variable **`k`** (4 bytes)
Symbol table section (60 bytes)		
188	X	array **`a[]`** : offset 0 in Initialized data section (12 bytes)
200	X	variable **`k`** : offset 40 in Initialized data section (10 bytes)
210	X	array **`b[]`** : offset 0 in Uninitialized data section (12 bytes)
222	X	**`main`** : offset 0 in Machine code section (12 bytes)
234	X	**`printf`** : external, used at offset 56 of Machine code section (14 bytes)
Relocation information section (44 bytes)		
248	X	relocation information

Some Terms

- Object file vs Executable
  - Object file is the file for binary format of machine instructions, not linked with others, nor positioned (in memory) for execution
  - Executable is binary format of object files that are linked and positioned ready for execution.
- Symbol
  - Names, e.g. global function name, variable name
- Library
  - Archive or package of multiple object files

Inspect an ELF Object File or Executable

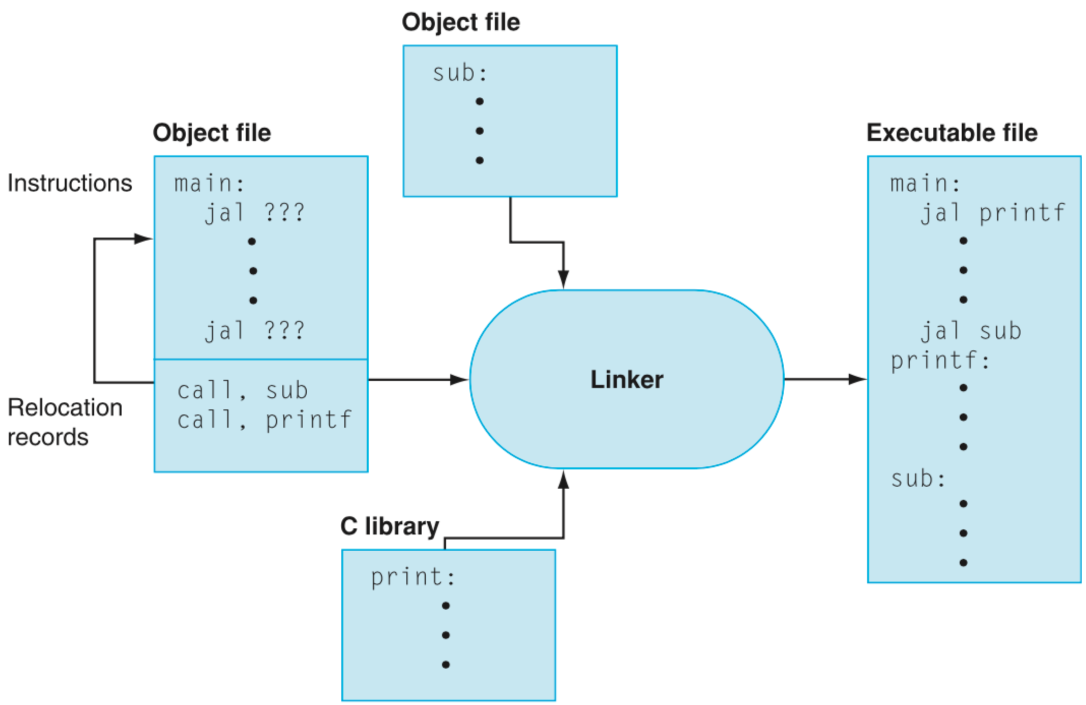
- Executable and Linkable Format (ELF)
  - https://en.wikipedia.org/wiki/Executable_and_Linkable_Format
- readelf and objdump command in Linux to inspect object/executable file or disassembly
  - Only objdump can do disassembly

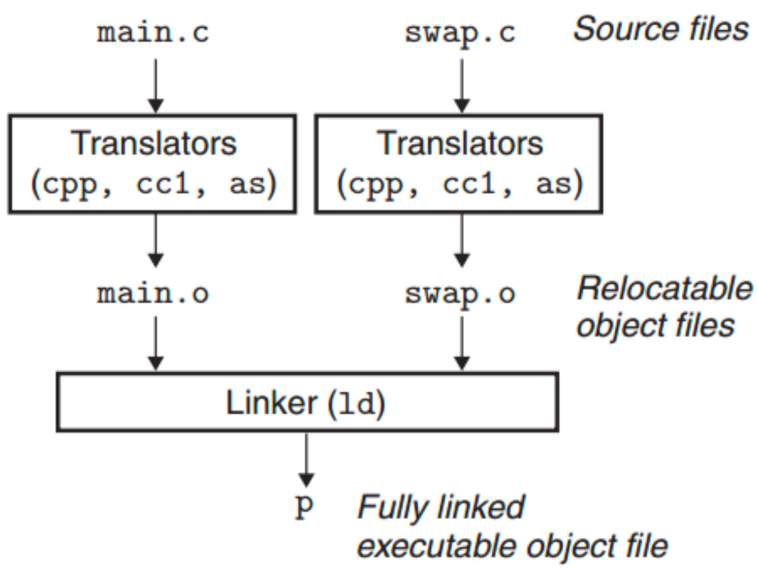
- nm command to display symbol information

- Try sum_full.o and sum example
  - sum_full.o is an object file
  - sum is an executable

Linking

- Linker (ld command) searches a collection of object files and program libraries to find nonlocal routines used in a program, combines them into a single executable file, and resolves references between routines in different files.





Linking Multiple files to make executable file

- Two programs, prog1.c and prog2.c for one single task
  - To make single executable file using following instructions

    First, compile these two files with option "**-c**"
    gcc -c prog1.c
    gcc -c prog2.c

    -c: Tells gcc to compile and assemble the code, but not link.

    We get two files as output, prog1.o and prog2.o
    Then, we can link these object files into single executable file using below instruction.

    gcc -o prog prog1.o prog2.o

    Now, the output is prog executable file.
    We can run our program using
    ./prog

Linking with other libraries

- Normally, compiler will read/link libraries from /usr/lib directory to our program during compilation process.
  - Library are precompiled object files

- To link our programs with libraries like pthreads and realtime libraries (rt library).
  - gcc <options> program_name.c -**lpthread -lrt**

    -lpthread: Link with pthread library → **libpthread.so** file
    -lrt: Link with rt library → **librt.so** file
    Option here is **"-l<library>"**

    Another option **"-L<dir>"** used to tell gcc compiler search for library file in given <dir> directory.

Compile Multiple Files and Link to One Executable

- Split the sum_full.c into two files
  - sum.c that only contains the definition of sum method
    - Also the “#define REAL float” line on top
  - Remove the sum definition from sum_full.c, but still keep sum method declaration (referred too as function signature)
  - Compile both together and generate sum executable

- **Compile in one step: gcc sum_full.c sum.c -o sum**
  - **The command compiles each *.c file one by one into object files and then link the two object files into one executable**
- **Compile in multiple steps: compile each .c file one by one and link together**

Compile in One Step

```
yanyh@vm:~/sum$ ls
sum.c  sum_full.c
yanyh@vm:~/sum$ gcc sum.c sum_full.c -o sum
yanyh@vm:~/sum$ ls
sum  sum.c  sum_full.c
yanyh@vm:~/sum$ ./sum 1000000
====================================================
        Sum 1000000 numbers
----------------------------------------------------
Performance:            Runtime (ms)     MFLOPS
----------------------------------------------------
Sum:                    3.999949        500.006437
```

Compile in Multiple Steps

```
yanyh@vm:~/sum$ gcc -c sum.c
yanyh@vm:~/sum$ ls
sum  sum.c  sum_full.c  sum.o
yanyh@vm:~/sum$ gcc -c sum_full.c
yanyh@vm:~/sum$ ls
sum  sum.c  sum_full.c  sum_full.o  sum.o
yanyh@vm:~/sum$ gcc sum.o sum_full.o -o sum
yanyh@vm:~/sum$ ls
sum  sum.c  sum_full.c  sum_full.o  sum.o
yanyh@vm:~/sum$ ./sum 1000000
==================================================
        Sum 1000000 numbers
--------------------------------------------------
Performance:                Runtime (ms)     MFLOPS
--------------------------------------------------
Sum:                        9.999990        200.000191
```

Try readelf

```
yanyh@vm:~/sum$ readelf -a sum
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)
```

```
yanyh@vm:~/sum$ readelf -a sum.o
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:                              REL (Relocatable file)
  Machine:                           Advanced Micro Devices X86-64
  Version:                           0x1
```

Try objdump for both object file and executable

```
yanyh@vm:~/sum$ objdump -x sum.o

sum.o:     file format elf64-x86-64
sum.o
architecture: i386:x86-64, flags 0x00000011:
HAS_RELOC, HAS_SYMS
start address 0x0000000000000000

Sections:
Idx Name          Size      VMA               LMA
  0 .text         00000060  0000000000000000  0000000000000000
                  CONTENTS, ALLOC, LOAD, READONLY, CODE
  1 .data         00000000  0000000000000000  0000000000000000
                  CONTENTS, ALLOC, LOAD, DATA
  2 .bss          00000000  0000000000000000  0000000000000000
```

“objdump -D” to disassembly: convert binary object code back to symbolic assembly code

```
yanyh@vm:~/sum$ objdump -D sum

sum:     file format elf64-x86-64


Disassembly of section .interp:

0000000000400238 <.interp>:
  400238:       2f                      (bad)
  400239:       6c                      insb   (%dx),%es:(%rdi)
  40023a:       69 62 36 34 2f 6c 64    imul   $0x646c2f34,0x36(%rdx),%esp
  400241:       2d 6c 69 6e 75          sub    $0x756e696c,%eax
  400246:       78 2d                   js     400275 <_init-0x37b>
  400248:       78 38                   js     400282 <_init-0x36e>
  40024a:       36 2d 36 34 2e 73       ss sub $0x732e3436,%eax
  400250:       6f                      outsl  %ds:(%rsi),(%dx)
  400251:       2e 32 00                xor    %cs:(%rax),%al
```

nm: list symbols from object files

- T: define a symbol
- U: undefined symbol
  - Linker to link
- Address are relative

```
yanyh@vm:~/sum$ nm sum.o
0000000000000000 T sum
yanyh@vm:~/sum$ nm sum_full.o
                 U atoi
                 U drand48
                 U fprintf
                 U ftime
00000000000000ca T init
0000000000000119 T main
                 U malloc
                 U printf
                 U puts
0000000000000000 T read_timer
0000000000000065 T read_timer_ms
                 U srand48
                 U __stack_chk_fail
                 U stderr
                 U sum
yanyh@vm:~/sum$ nm sum
                 U atoi@@GLIBC_2.2.5
0000000000602078 B __bss_start
0000000000602088 b completed.7588
0000000000602068 D __data_start
0000000000602068 W data_start
0000000000400700 t deregister_tm_clones
0000000000400780 t __do_global_dtors_aux
0000000000601e18 t __do_global_dtors_aux
                 U drand48@@GLIBC_2.2.5
```

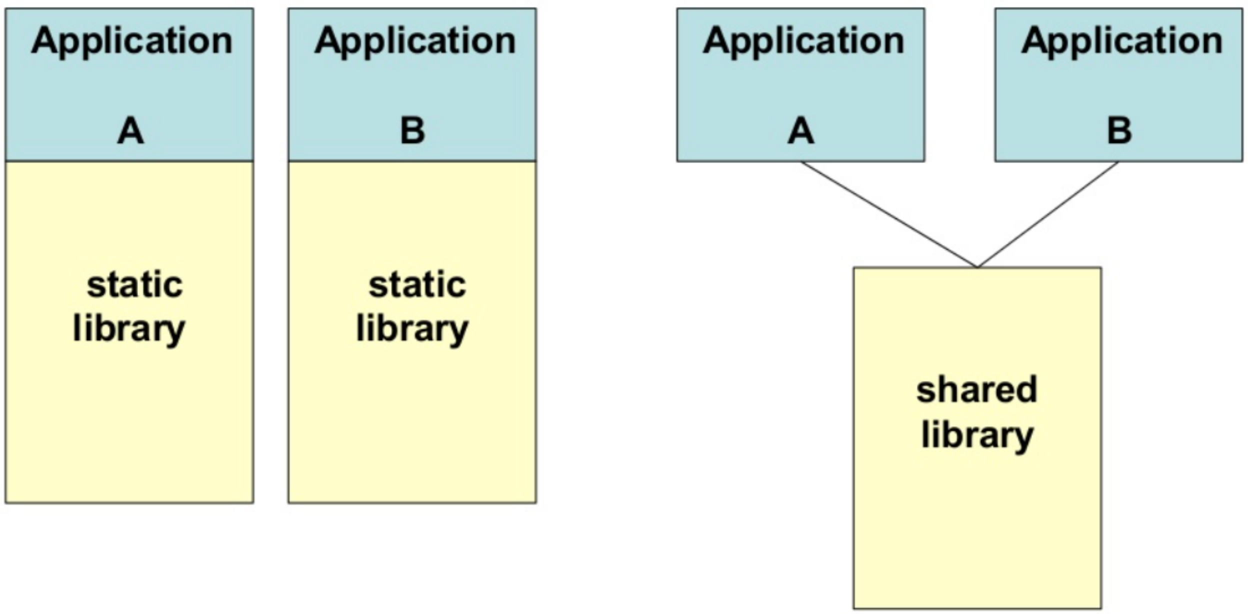
Static Linking

- If multiple program want to use read_timer functions
  - They all include the full definition in their source code
    - Duplicate: If the function changes, we need to change each file
  - Separate reader_timer in a new file, compile and statically linked with other object files to create executables
    - Duplicate the same object in multiple executables.

- Dynamic linking at the runtime
  - Create a dynamic library that provides reader_timer implementation
  - Tell ld to link the library at the runtime
  - Runtime load and link them on the fly and execute

Static Library vs Shared (Dynamic) Library

- Static library needs to be duplicated in every executable
  - Bigger code size, better optimized
- Shared library are loaded on the fly during the execution
  - Smaller code size, performance hits of loading shared memory



- Combine both

Hands-On for dynamic linking

- Sum example for static and dynamic linking: from sum.c and sum_full.c created in the last exercise,
  - Create a new file read_timer.c that includes the read_timer and read_timer_ms definition in the file
  - Leave only the read_timer and read_timer_ms declaration in the sum_full.c
    - They are the interface of the two methods.
  - Compile read_timer.c into a dynamic library
    - The library name is my_read_timer, and the library file is libmy_read_timer.so. You can choose any name.
  - Compile sum.c and sum_full.c and link with lib my_read_timer
    - gcc sum_full.c sum.c -o sum -L. -lmy_read_timer
  - Use ldd command to list dependent libraries

Build Steps with Dynamic Library

```
yanyh@vm:~/sum$ ls
read_timer.c  sum.c  sum_full.c
yanyh@vm:~/sum$ gcc -shared -fPIC -o libmy_read_timer.so read_timer.c
yanyh@vm:~/sum$ ls
libmy_read_timer.so  read_timer.c  sum.c  sum_full.c
yanyh@vm:~/sum$ gcc sum.c sum_full.c -o sum
/tmp/ccqjRuag.o: In function `main':
sum_full.c:(.text+0x108): undefined reference to `read_timer'
sum_full.c:(.text+0x13e): undefined reference to `read_timer'
collect2: error: ld returned 1 exit status
yanyh@vm:~/sum$
yanyh@vm:~/sum$ gcc sum.c sum_full.c -o sum -lmy_read_timer
/usr/bin/ld: cannot find -lmy_read_timer
collect2: error: ld returned 1 exit status
yanyh@vm:~/sum$
yanyh@vm:~/sum$ gcc sum.c sum_full.c -o sum -L. -lmy_read_timer
yanyh@vm:~/sum$ ls
libmy_read_timer.so  read_timer.c  sum  sum.c  sum_full.c
yanyh@vm:~/sum$ ./sum 1000000
```

Linking error: cannot find reader_timer implementation when linking from sum_full.o

Linking error: do not know where to find the libread_timer.so file.

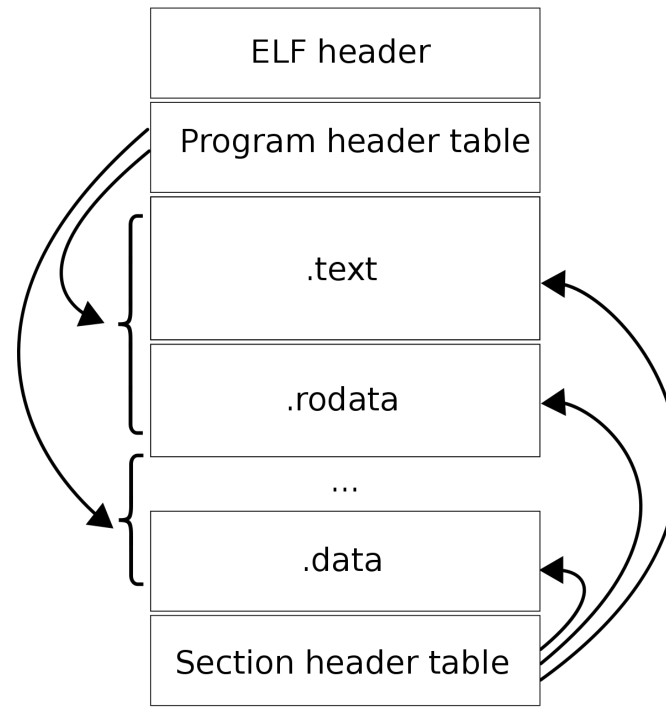
-L<...>: to tell where to find the library file, in this case, the current folder (.)
-l<...>: to tell the library file name, which will be expanded to lib<...>.so file

ldd command to list the dependent libraries

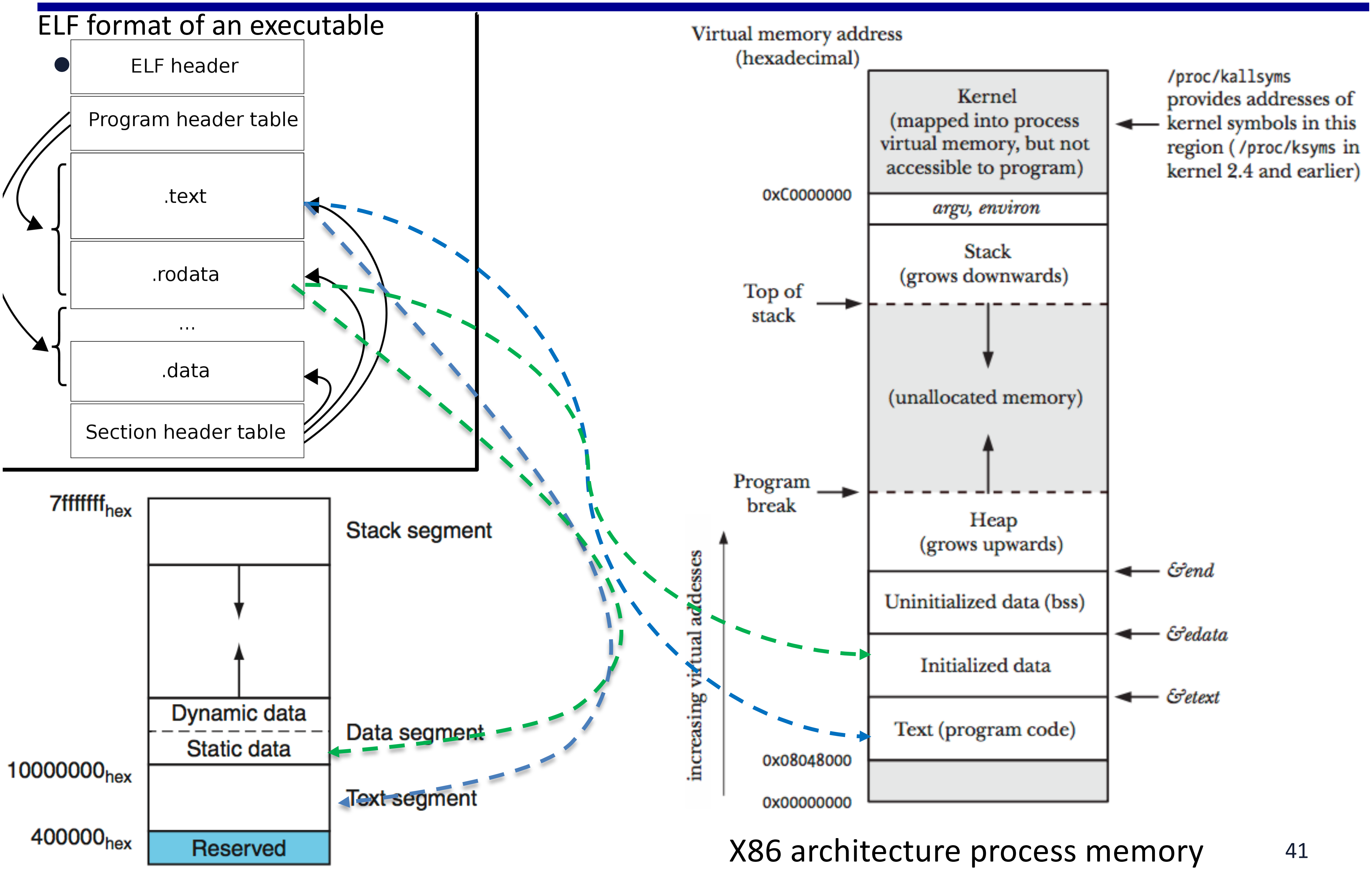
```
yanyh@vm:~/sum$ ldd sum
        linux-vdso.so.1 =>  (0x00007fff8b382000)
        libmy_read_timer.so (0x00007f437c0ae000)
        libc.so.6 => /lib/x86_64-linux-gnu/libc.so.6 (0x00007f437bce4000)
        /lib64/ld-linux-x86-64.so.2 (0x00007f437c2b0000)
```

Loading a File for Execution

- Steps:
  - It reads the executable's header to determine the size of the text and data segments.
  - It creates a new address space for the program. is address space is large enough to hold the text and data segments, along with a stack segment (see Section A.5).
  - It copies instructions and data from the executable into the new address space.
  - It copies arguments passed to the program onto the stack.
  - It initializes the machine registers. In general, most registers are cleared, but the stack pointer must be assigned the address of the rst free stack location (see Section A.5).
  - It jumps to a start-up routine that copies the program's arguments from the stack to registers and calls the program's **main** routine. If the **main** routine returns, the start-up routine terminates the program with the exit system call.



Memory Layout of A Process



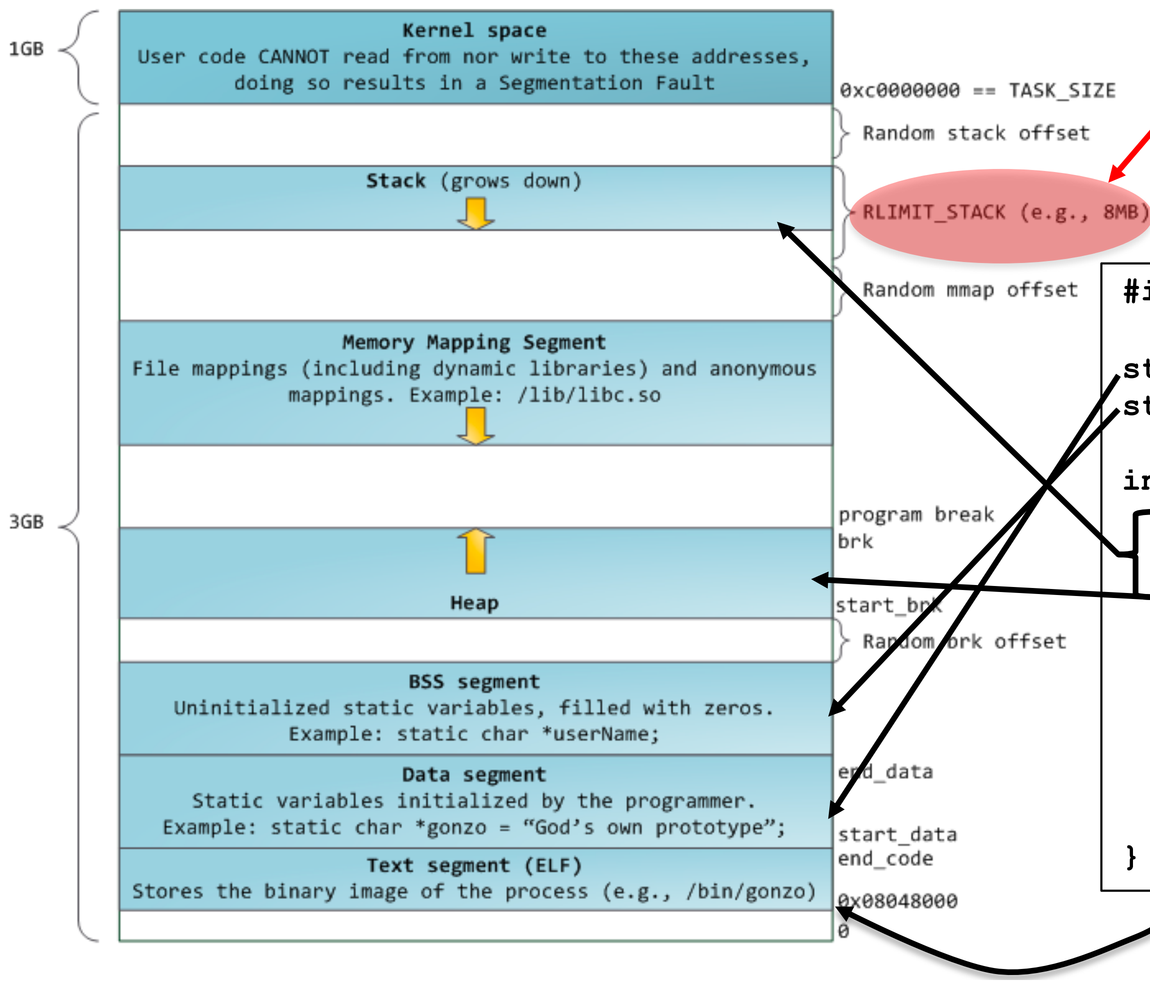
MIPS architecture process memory

X86 architecture process memory

Linux Process Memory in 32-bit System (4G space)

- Code (machine instructions) → Text segment
- Static variables → Data or BSS segment
- Function variables → stack (i, A[100] and B)
  - A is a variable that stores memory address, the memory for A's 100 int elements is in the stack
  - B is a memory address, it is stored in stack, but the memory B points to is in heap (100 int elements)
- Dynamic allocated memory using malloc or C++ "new" → heap (B[100)

Stack size limit. If 8MB, "int A[10,000,000]" won't work.




```
#include <stdio.h>

static char *gonzo = "God's own prototype";
static char *userName;

int main(int argc, char* argv[]){
  int i; /* stack */
  int A[100]; /* stack */
  int *B = (int*)malloc(sizeof(int)*100); //heap

  for(i = 0; i < 100; i++) {
    A[i] = i*i;
    B[i] = A[i] * 20;
    printf("A[i]: %d, B[i]: %d\n",A[i], B[i]);
  }
}
```

Check the Memory Map of a Process

- Given a process ID:
  - pmap <pid>
  - cat /proc/<pid>/maps

```
yanyh@vm:~$ pmap 7153
7153:   -bash
0000000000400000    976K r-x-- bash
00000000006f3000      4K r---- bash
00000000006f4000     36K rw--- bash
00000000006fd000     24K rw---   [ anon ]
0000000001a31000   3224K rw---   [ anon ]
00007f03653f3000     44K r-x-- libnss_file
00007f03653fe000   2044K ----- libnss_file
00007f03655fd000      4K r---- libnss_file
00007f03655fe000      4K rw--- libnss_file
00007f03655ff000     24K rw---   [ anon ]
```

```
yanyh@vm:~$ cat /proc/7153/maps
00400000-004f4000 r-xp 00000000 08:02 794409                             /bin/bash
006f3000-006f4000 r--p 000f3000 08:02 794409                             /bin/bash
006f4000-006fd000 rw-p 000f4000 08:02 794409                             /bin/bash
006fd000-00703000 rw-p 00000000 00:00 0
01a31000-01d57000 rw-p 00000000 00:00 0                                  [heap]
7f03653f3000-7f03653fe000 r-xp 00000000 08:02 917692                     /lib/x86_6
-gnu/libnss_files-2.23.so
7f03653fe000-7f03655fd000 ---p 0000b000 08:02 917692                     /lib/x86_6
-gnu/libnss_files-2.23.so
7f03655fd000-7f03655fe000 r--p 0000a000 08:02 917692                     /lib/x86_6
-gnu/libnss_files-2.23.so
```