Assemblers, Linkers, and Loaders

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CS 3410, Spring 2015

Computer Science

Cornell University

See: P&H Appendix A1-2, A.3-4 and 2.12

Announcement

Upcoming agenda

- PA1 due yesterday

- PA2 available and discussed during lab section this week
- PA2 Work-in-Progress due Monday, March 16th
- PA2 due Thursday, March 26th

- HW2 available next week, due before Prelim2 in April

- Spring break: Saturday, March 28th to Sunday, April 5th

Goal for Today: Putting it all Together

Brief review of calling conventions

Compiler output is assembly files

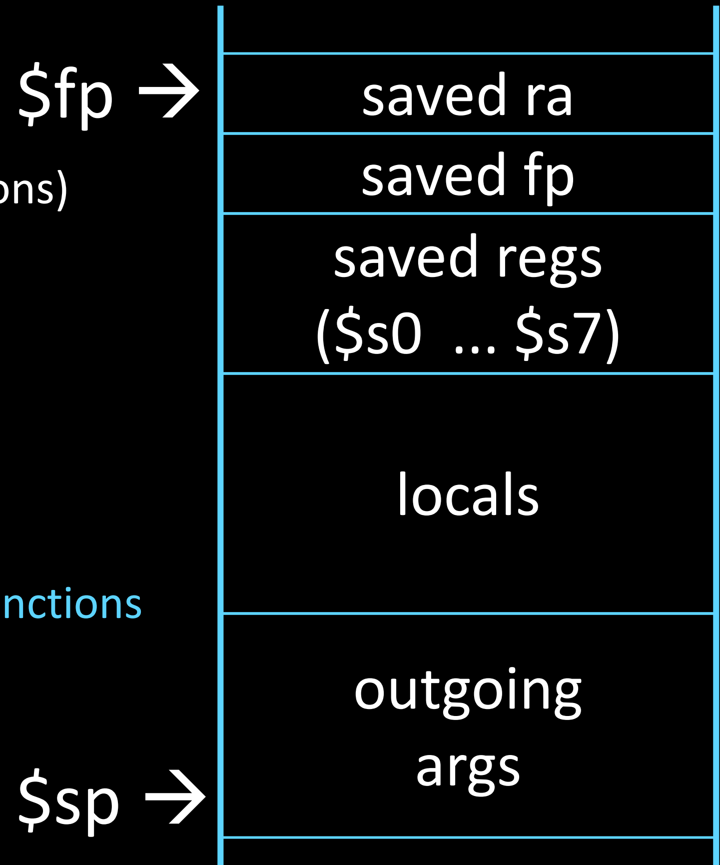
Assembler output is obj files

Linker joins object files into one executable

Loader brings it into memory and starts execution

Recap: Calling Conventions

- first four arg words passed in \$a0, \$a1, \$a2, \$a3
- remaining arg words passed in parent's stack frame
- return value (if any) in \$v0, \$v1
- stack frame at \$sp
  - contains \$ra (clobbered on JAL to sub-functions)
  - contains \$fp
  - contains local vars (possibly clobbered by sub-functions)
  - contains extra arguments to sub-functions (i.e. argument "spilling)
  - contains space for first 4 arguments to sub-functions
- callee save regs are preserved
- caller save regs are not preserved
- Global data accessed via \$gp

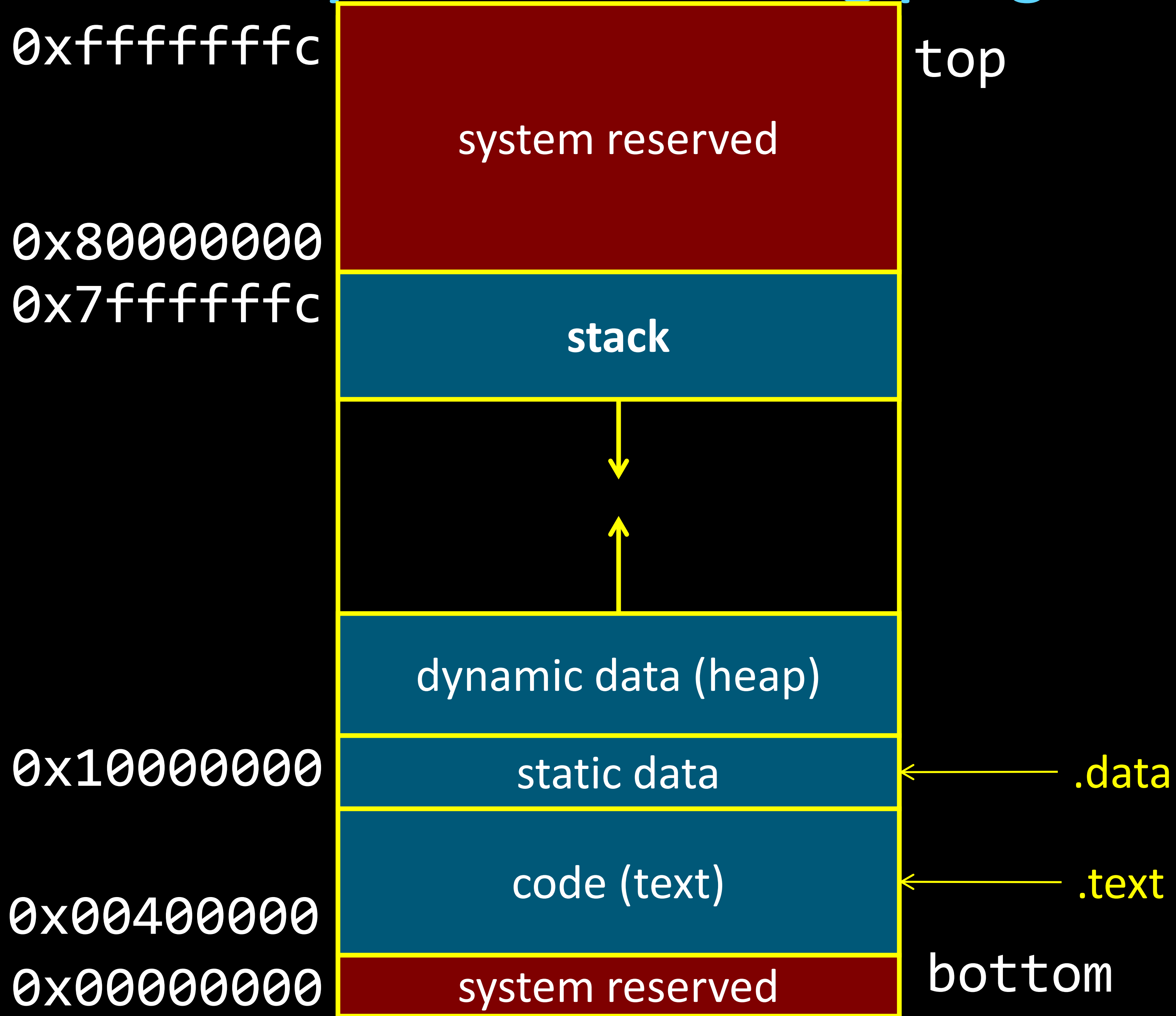


Warning: There is no one true MIPS calling convention.
lecture != book != gcc != spim != web

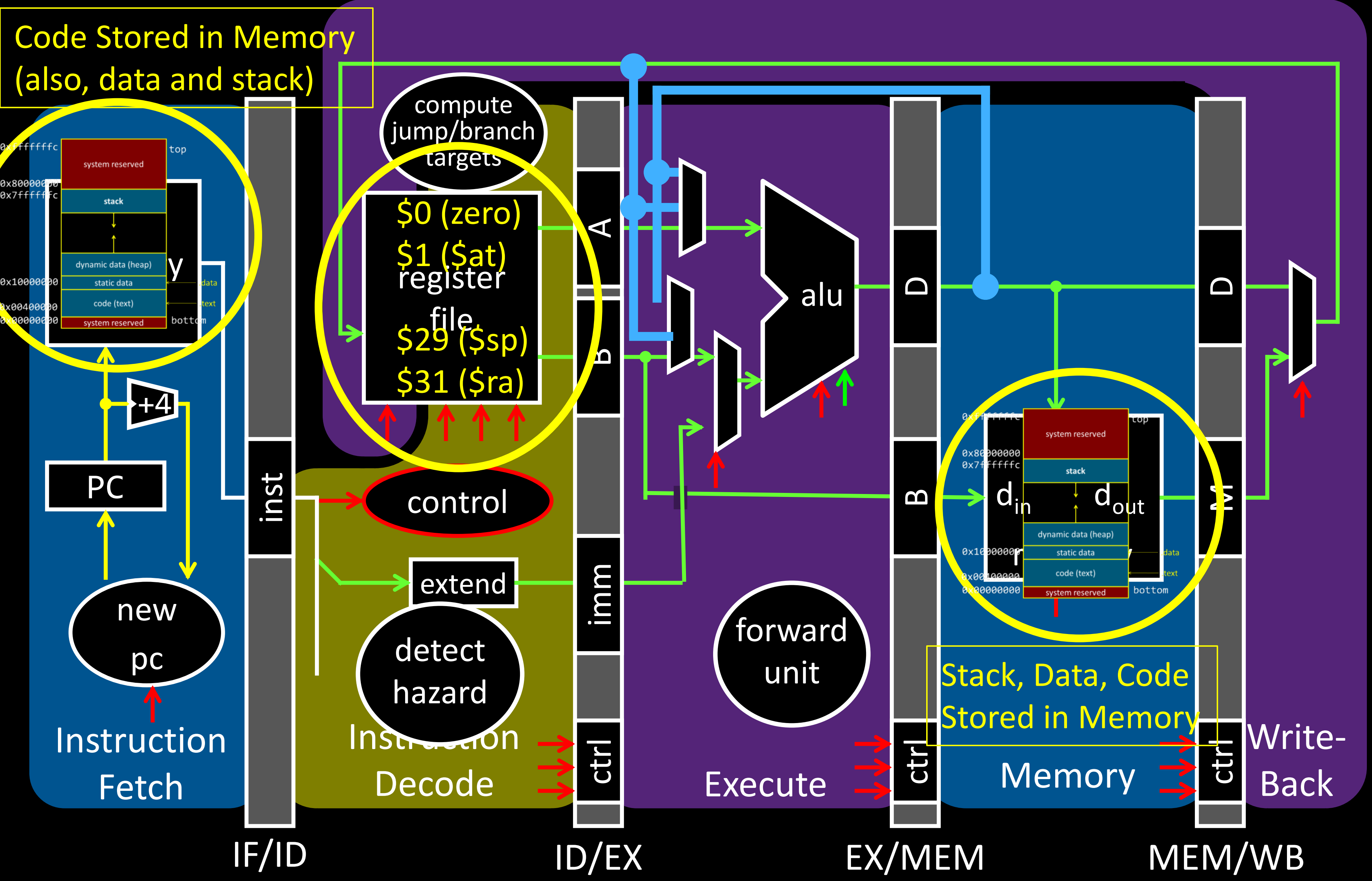
MIPS Register Conventions

Register	Name	Use
r0	$zero	zero
r1	$at	assembler temp
r2	$v0	function return values
r3	$v1	
r4	$a0	function arguments
r5	$a1	
r6	$a2	
r7	$a3	
r8	$t0	**temps (caller save)**
r9	$t1	
r10	$t2	
r11	$t3	
r12	$t4	
r13	$t5	
r14	$t6	
r15	$t7	
r16	$s0	**saved (callee save)**
r17	$s1	
r18	$s2	
r19	$s3	
r20	$s4	
r21	$s5	
r22	$s6	
r23	$s7	
r24	$t8	**more temps (caller save)**
r25	$t9	
r26	$k0	reserved for kernel
r27	$k1	
r28	$gp	global data pointer
r29	$sp	stack pointer
r30	$fp	frame pointer
r31	$ra	return address

Anatomy of an executing program



Anatomy of an executing program



Activity #4: Debugging

init():	0x400000
printf(s, …):	0x4002B4
vnorm(a,b):	0x40107C
main(a,b):	0x4010A0
pi:	0x10000000
str1:	0x10000004

CPU:
$pc=0x004003C0
$sp=0x7FFFFFAC
$ra=0x00401090

0x00000000
0x0040010c
0x7FFFFFF4
0x00000000
0x00000000
0x00000000
0x00000000
0x004010c4
0x7FFFFFDC
0x00000000
0x00000000
0x00000015
0x10000004 (0x7FFFFFB0)
0x00401090

What func is running?

Who called it?

Has it called anything?

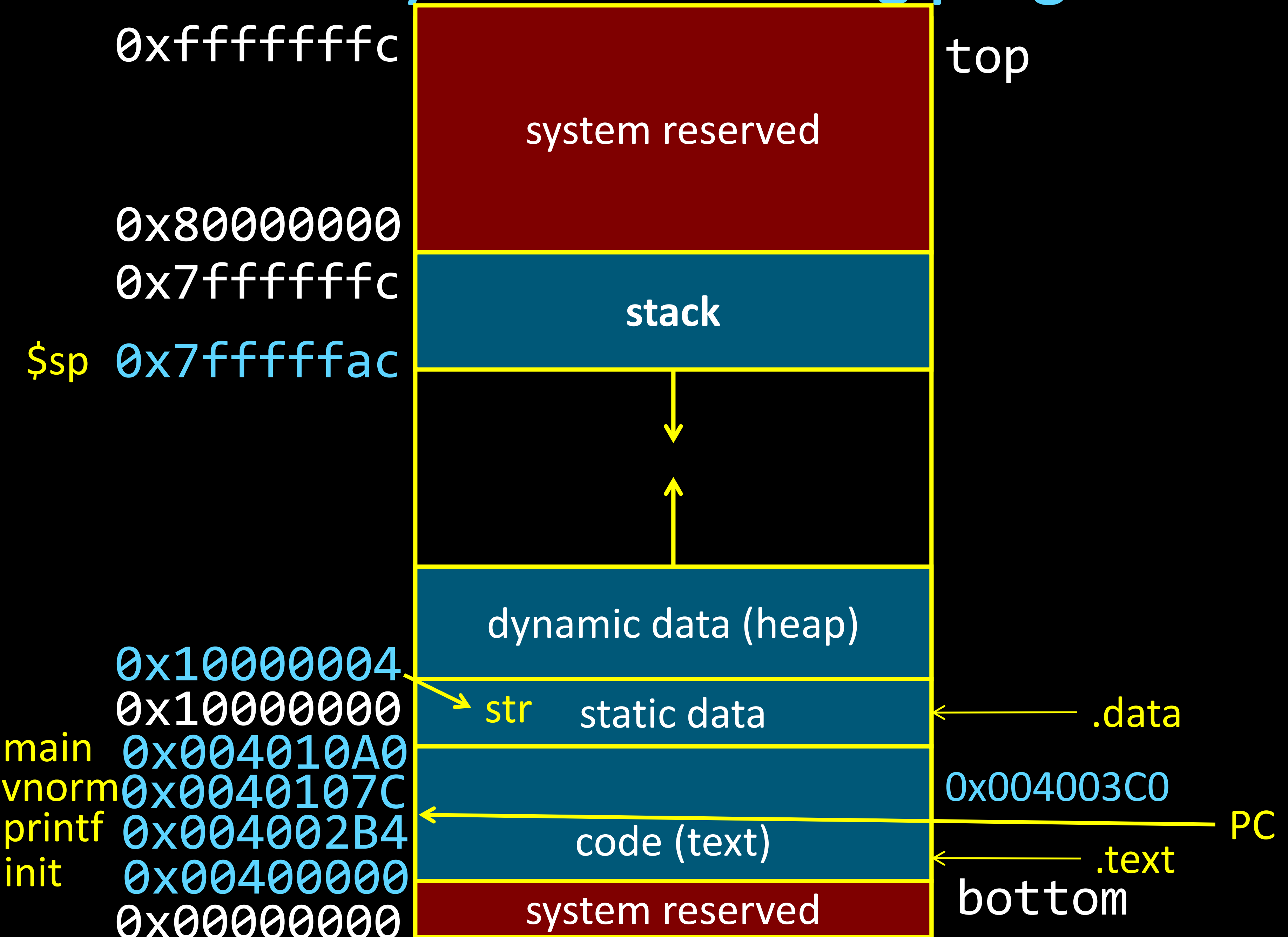
Will it?

Args?

Stack depth?

Call trace?

Anatomy of an executing program



Activity #4: Debugging

init(): 0x400000
printf(s, ...): 0x4002B4
vnorm(a,b): 0x40107C
main(a,b): 0x4010A0
pi: 0x10000000
str1: 0x10000004

CPU:
$pc=0x004003C0
$sp=0x7FFFFFAC
$ra=0x00401090

What func is running? printf

Who called it? vnorm

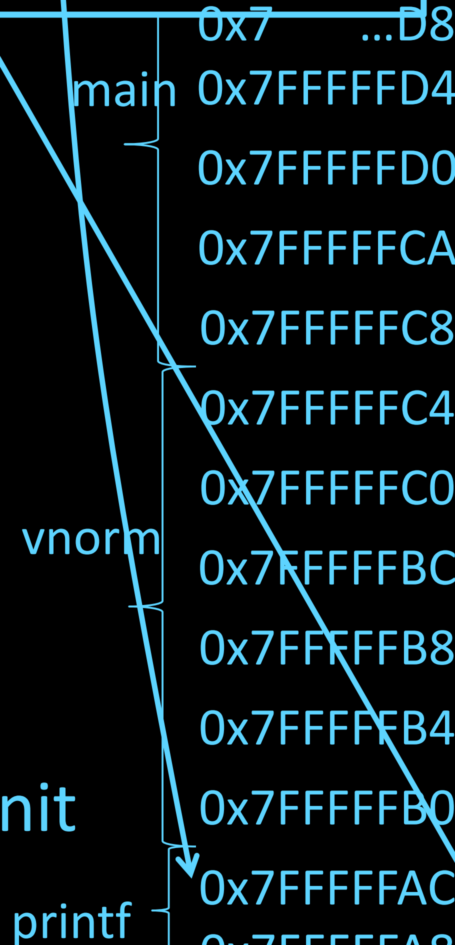
Has it called anything? no

Will it? no b/c no space for outgoing args

Args? Str1 and 0x15

Stack depth? 4

Call trace? printf, vnorm, main, init



Memory

Address	Value	
...F4		ra
...F0		fp
EA		a3
E8		a2
E4		a1
E0	0x00000000	a0
DC	0x0040010c	ra
0x7 ...D8	0x7FFFFFF4	fp
0x7FFFFFD4	0x00000000	a3
0x7FFFFFD0	0x00000000	a2
0x7FFFFFCA	0x00000000	a1
0x7FFFFFC8	0x00000000	a0
0x7FFFFFC4	0x004010c4	ra
0x7FFFFFC0	0x7FFFFFDC	fp
0x7FFFFFBC	0x00000000	a3
0x7FFFFFB8	0x00000000	a2
0x7FFFFFB4	0x00000015	a1
0x7FFFFFB0	0x10000004	a0
0x7FFFFFAC	0x00401090	ra
0x7FFFFFA8	0x7FFFFFC4	

Takeaway

We need a calling convention to coordinate use of registers and memory. Registers exist in the Register File. Stack, Code, and Data exist in memory. Both instruction memory and data memory accessed through cache (modified harvard architecture) and a shared bus to memory (Von Neumann).

Compilers and Assemblers

Next Goal

How do we compile a program from source to assembly to machine object code?

Big Picture

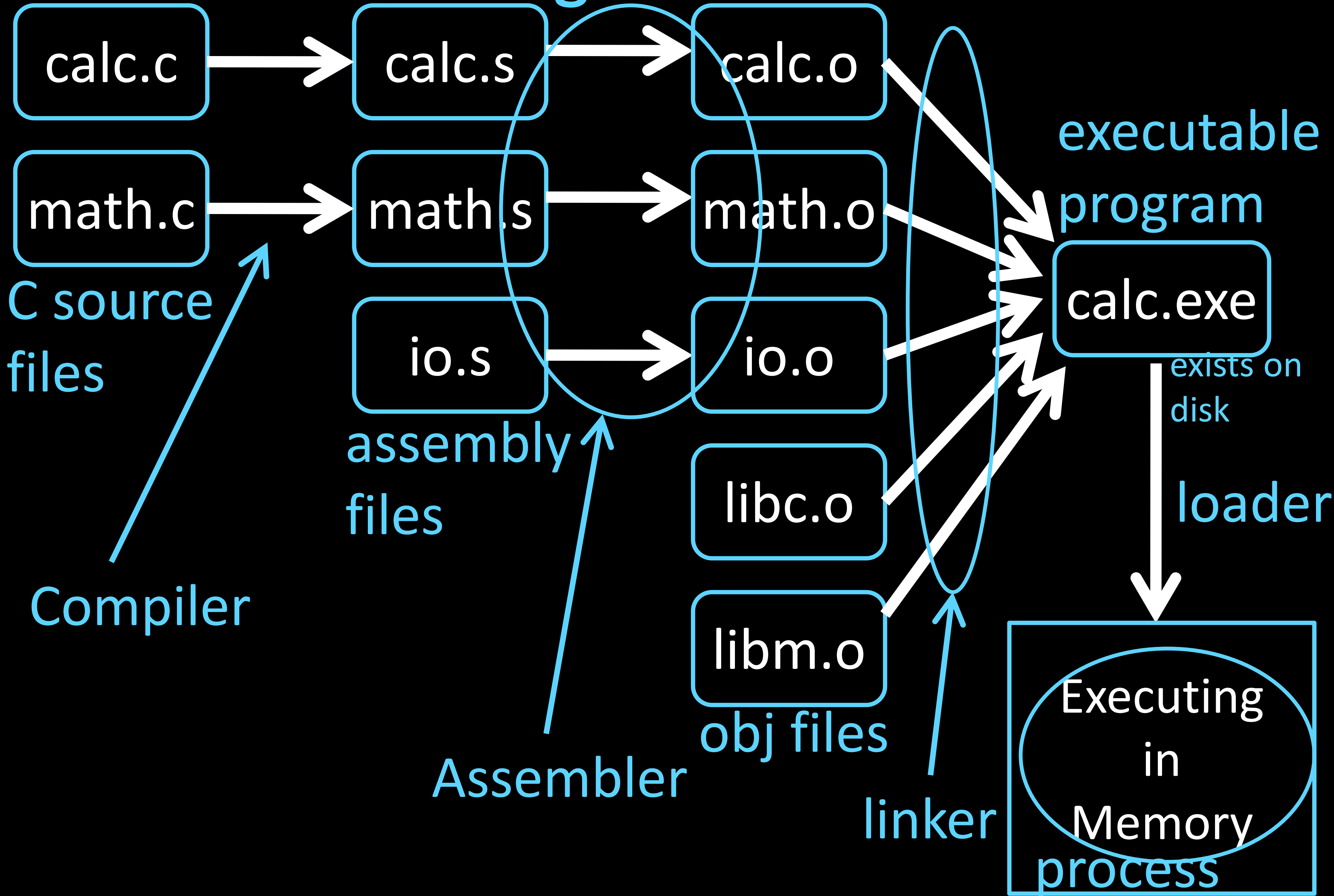
Compiler output is assembly files

Assembler output is obj files

Linker joins object files into one executable

Loader brings it into memory and starts execution

Big Picture



Next Goal

How do we (as humans or compiler) program on top of a given ISA?

Assembler

Translates text *assembly language* to binary machine code

Input: a text file containing MIPS instructions in human readable form

```
addi r5, r0, 10
muli r5, r5, 2
addi r5, r5, 15
```

Output: an object file (.o file in Unix, .obj in Windows) containing MIPS instructions in executable form

```
00100000000001010000000000001010
00000000000001010010100001000000
00100000101001010000000000001111
```

Assembly Language

Assembly language is used to specify programs at a low-level

Will I program in assembly?

A: I do...

- For CS 3410 (and some CS 4410/4411)
- For kernel hacking, device drivers, GPU, etc.
- For performance (but compilers are getting better)
- For highly time critical sections
- For hardware without high level languages
- For new & advanced instructions: rdtsc, debug registers, performance counters, synchronization, ...

Assembly Language

Assembly language is used to specify programs at a low-level

What does a program consist of?

- MIPS instructions
- Program data (strings, variables, etc)

Assembler

Assembler:

Input:

assembly instructions

+ psuedo-instructions

+ data and layout directives

Output:

Object File

Slightly higher level than plain assembly

e.g: takes care of delay slots

(will reorder instructions or insert nops)

Assembler

Assembler:

Input:

assembly instructions

+ psuedo-instructions

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Object File

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MIPS Assembly Language Instructions

Arithmetic/Logical

- ADD, ADDU, SUB, SUBU, AND, OR, XOR, NOR, SLT, SLTU
- ADDI, ADDIU, ANDI, ORI, XORI, LUI, SLL, SRL, SLLV, SRLV, SRAV, SLTI, SLTIU
- MULT, DIV, MFLO, MTLO, MFHI, MTHI

Memory Access

- LW, LH, LB, LHU, LBU, LWL, LWR
- SW, SH, SB, SWL, SWR

Control flow

- BEQ, BNE, BLEZ, BLTZ, BGEZ, BGTZ
- J, JR, JAL, JALR, BEQL, BNEL, BLEZL, BGTZL

Special

- LL, SC, SYSCALL, BREAK, SYNC, COPROC

Assembler

Assembler:

Input:

assembly instructions

+ psuedo-instructions

+ data and layout directives

Output:

Object file

Slightly higher level than plain assembly

e.g: takes care of delay slots

(will reorder instructions or insert nops)

Pseudo-Instructions

Pseudo-Instructions

NOP # do nothing

- SLL r0, r0, 0

MOVE reg, reg # copy between regs

- ADD r2, r0, r1 # copies contents of r1 to r2

LI reg, imm # load immediate (up to 32 bits)

LA reg, label # load address (32 bits)

B label # unconditional branch

BLT reg, reg, label # branch less than

- SLT r1, rA, rB # r1 = 1 if R[rA] < R[rB]; o.w. r1 = 0
- BNE r1, r0, label # go to address label if r1!=r0; i.t. rA < rB

Assembler

Assembler:

Input:

assembly instructions

+ psuedo-instructions

+ data and layout directives

Output:

Object file

Slightly higher level than plain assembly

e.g: takes care of delay slots

(will reorder instructions or insert nops)

Program Layout

Programs consist of segments used for different purposes

- Text: holds instructions
- Data: holds statically allocated program data such as variables, strings, etc.

data

"cornell cs"

13

25

text

add r1,r2,r3

ori r2, r4, 3

...

Assembling Programs

```
.text
  .ent main
main: la $4, Larray
  li $5, 15
  ...
  li $4, 0
  jal exit
  .end main
.data
Larray:
  .long 51, 491, 3991
```

Assembly files consist of a mix of

+ instructions

+ pseudo-instructions

+ assembler (data/layout) directives

(Assembler lays out binary values in memory based on directives)

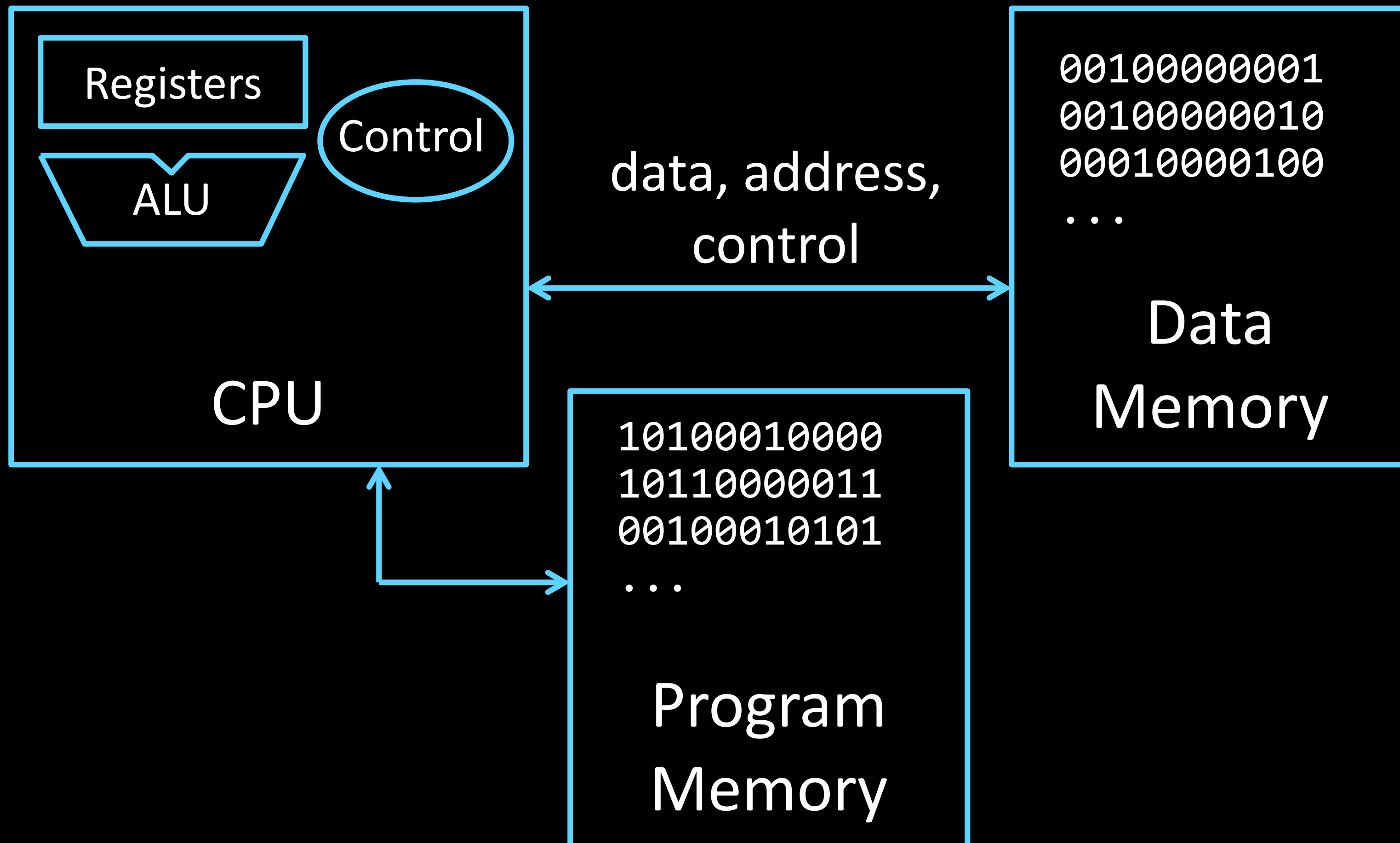
Assembled to an Object File

- Header
- Text Segment
- Data Segment
- Relocation Information
- Symbol Table
- Debugging Information

Assembling Programs

Assembly using a (modified) Harvard architecture

- Need segments since data and program stored together in memory



Takeaway

Assembly is a low-level task

- Need to assemble assembly language into machine code binary. Requires
  - Assembly language instructions
  - *pseudo-instructions*
  - And Specify layout and data using *assembler directives*

- Today, we use a modified Harvard Architecture (Von Neumann architecture) that mixes data and instructions in memory

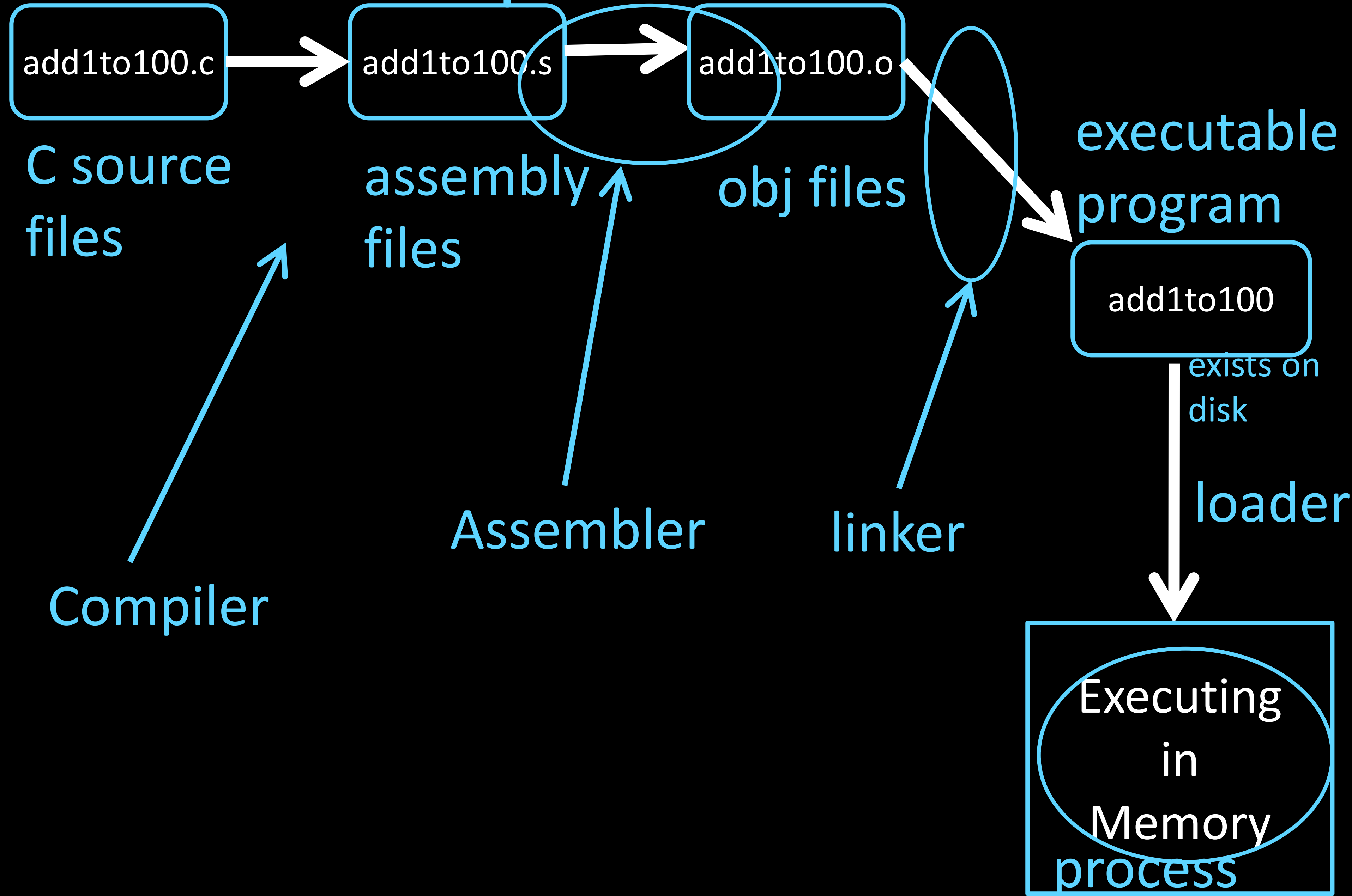
  … but kept in separate *segments*

  … and has separate caches

Next Goal

Put it all together: An example of compiling a program from source to assembly to machine object code.

Example: Add 1 to 100



Example: Add 1 to 100

```
int n = 100;

int main (int argc, char* argv[ ]) {
        int i;
        int m = n;
        int sum = 0;

        for (i = 1; i <= m; i++)
           sum += i;

        printf ("Sum 1 to %d is %d\n", n, sum);
}
```

export PATH=${PATH}:/courses/cs3410/mipsel-linux/bin:/courses/cs3410/mips-sim/bin
or
setenv PATH ${PATH}:/courses/cs3410/mipsel-linux/bin:/courses/cs3410/mips-sim/bin

```
# Compile
[csug03] mipsel-linux-gcc –S add1To100.c
```

Example: Add 1 to 100

```
        .data
        .globl  n
        .align  2
n:      .word   100
        .rdata
        .align  2
$str0:  .asciiz
           "Sum 1 to %d is %d\n"
        .text
        .align  2
        .globl  main
main:   addiu   $sp,$sp,-48
        sw      $31,44($sp)
        sw      $fp,40($sp)
        move    $fp,$sp
        sw      $4,48($fp)
        sw      $5,52($fp)
        la      $2,n
        lw      $2,0($2)
        sw      $2,28($fp)
        sw      $0,32($fp)
        li      $2,1
        sw      $2,24($fp)
$L2:    lw      $2,24($fp)
        lw      $3,28($fp)
        slt     $2,$3,$2
        bne     $2,$0,$L3
        lw      $3,32($fp)
        lw      $2,24($fp)
        addu    $2,$3,$2
        sw      $2,32($fp)
        lw      $2,24($fp)
        addiu   $2,$2,1
        sw      $2,24($fp)
        b       $L2
$L3:    la      $4,$str0
        lw      $5,28($fp)
        lw      $6,32($fp)
        jal     printf
        move    $sp,$fp
        lw      $31,44($sp)
        lw      $fp,40($sp)
        addiu   $sp,$sp,48
        j       $31
```

Example: Add 1 to 100

```
        .data
        .globl  n√
        .align  2
n:      .word   100
        .rdata
        .align  2
$str0:  .asciiz
           "Sum 1 to %d is %d\n"
        .text
        .align  2
        .globl  main√
main:   addiu       $sp,$sp,-48
        sw          $31,44($sp)
        sw          $fp,40($sp)     prologue
        move        $fp,$sp
        sw     $a0  $4,48($fp)
        sw     $a1  $5,52($fp)
        la     $v0  $2,n
        lw          $2,0($2)   $v0=100
        sw          $2,28($fp) m=100
        sw          $0,32($fp) sum=0
        li          $2,1
        sw          $2,24($fp) i=1
```

```
$L2:    lw     $v0  $2,24($fp)  i=1
        lw     $v1  $3,28($fp)  m=100
        slt         $2,$3,$2    if(m < i)
        bne         $2,$0,$L3   100 < 1
        lw          $3,32($fp)  v1=0(sum)
        lw          $2,24($fp)  v0=1(i)
        addu        $2,$3,$2    v0=1(0+1)
        sw          $2,32($fp)  sum=1
        lw          $2,24($fp)  i=1
        addiu       $2,$2,1     i=2 (1+1)
        sw          $2,24($fp)  i=2
        b           $L2
$L3:    la     $a0  $4,$str0    str
printf  lw     $a1  $5,28($fp)  m=100
        lw     $a2  $6,32($fp)  sum
        jal         printf
        move        $sp,$fp
        lw          $31,44($sp)     epilogue
        lw          $fp,40($sp)
        addiu       $sp,$sp,48
        j           $31
```

Example: Add 1 to 100

```
# Assemble
[csug01] mipsel-linux-gcc –c add1To100.s

# Link
[csug01] mipsel-linux-gcc –o add1To100 add1To100.o
${LINKFLAGS}
# -nostartfiles –nodefaultlibs
# -static -mno-xgot -mno-embedded-pic
-mno-abicalls -G 0 -DMIPS -Wall

# Load
[csug01] simulate add1To100
Sum 1 to 100 is 5050
MIPS program exits with status 0 (approx. 2007
instructions in 143000 nsec at 14.14034 MHz)
```

Globals and Locals

Variables	Visibility	Lifetime	Location
Function-Local i, m, sum	w/in func	func invocation	stack
Global n, str	whole prgm	prgm execution	.data
Dynamic A	? Anywhere that has a ptr	b/w malloc and free	heap

```
int n = 100;
int main (int argc, char* argv[ ]) {
        int i, m = n, sum = 0;  int* A = malloc(4*m + 4);
        for (i = 1; i <= m; i++) { sum += i; A[i] = sum; }
        printf ("Sum 1 to %d is %d\n", n, sum);
}
```

Globals and Locals

Variables	Visibility	Lifetime	Location
Function-Local i, m, sum	w/in func	func invocation	stack
Global n, str	whole prgm	prgm execution	.data
Dynamic A	Anywhere that has a ptr	b/w malloc and free	heap

C Pointers can be trouble

Globals and Locals

Variables	Visibility	Lifetime	Location
Function-Local i, m, sum	w/in func	func invocation	stack
Global n, str	whole prgm	prgm execution	.data
Dynamic A	Anywhere that has a ptr	b/w malloc and free	heap

C Pointers can be trouble

```
int *trouble()
{ int a; …; return &a; }
char *evil()
{ char s[20]; gets(s); return s; }
int *bad()
{ s = malloc(20); … free(s); … return s; }
```

“addr of” something on the stack!

Invalid after return

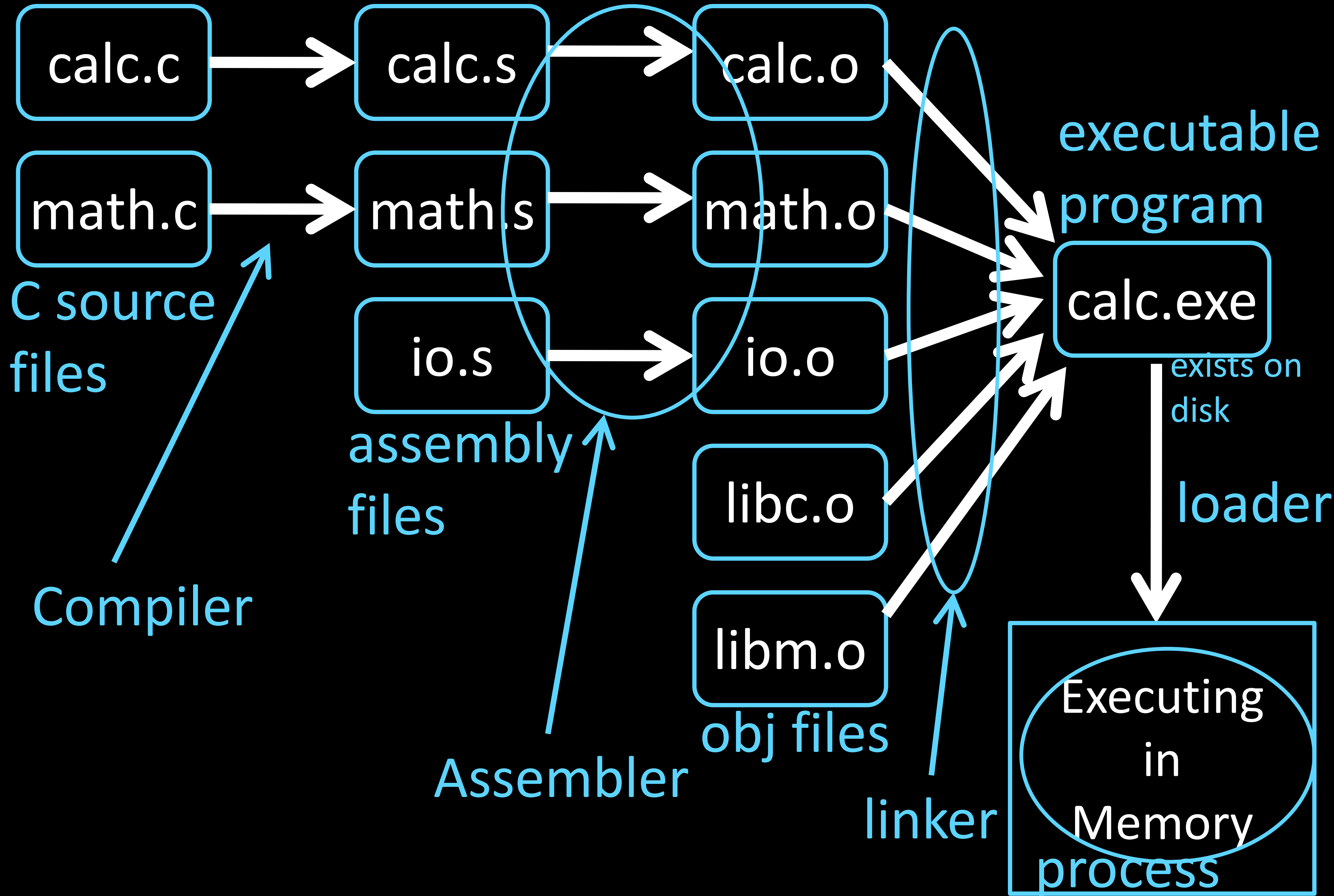
Buffer overflow

Allocated on the heap

But freed (i.e. a dangling ptr)

(Can’t do this in Java, C#, ...)

Example #2: Review of Program Layout

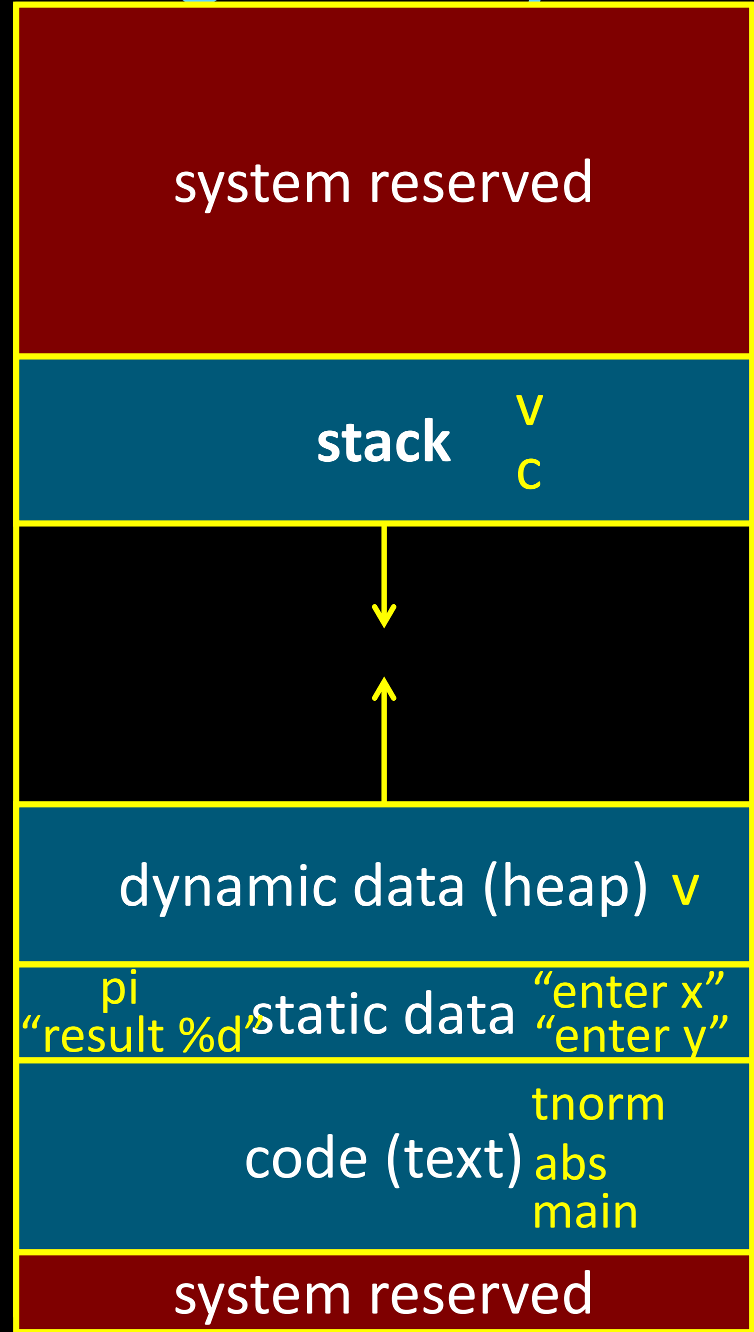


Example #2: Review of Program Layout

calc.c
```
vector* v = malloc(8);
v->x = prompt("enter x");
v->y = prompt("enter y");
int c = pi + tnorm(v);
print("result %d", c);
```

math.c
```
int tnorm(vector* v) {
 return abs(v->x)+abs(v->y);
}
```

lib3410.o
```
global variable: pi
entry point: prompt
entry point: print
entry point: malloc
```



Takeaway

Compiller produces assembly files

- (contain MIPS assembly, pseudo-instructions, directives, etc.)

Assembler produces object files

- (contain MIPS machine code, missing symbols, some layout information, etc.)

Linker produces executable file

- (contains MIPS machine code, no missing symbols, some layout information)

Loader puts program into memory and jumps to first instruction

- (machine code)

Recap

Compiler output is assembly files

Assembler output is obj files

Next Time

Linker joins object files into one executable

Loader brings it into memory and starts execution