Assemblers, Linkers, and Loaders

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CS 3410, Spring 2015

Computer Science

Cornell University

See: P&H Appendix A.1-2, A.3-4 and 2.12

Administrivia

Upcoming agenda

- PA2 Work-in-Progress due yesterday, Monday, March 16th
- PA2 due next week, Thursday, March 26th

- HW2 available later today, due before Prelim2 in April

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

Academic Integrity

All submitted work must be your own

- OK to study together, ***but do NOT share soln's***

e.g. CANNOT email soln, look at screen, writ soln for others

- ***Cite your (online) sources***
- "Crowd sourcing" your problem/soln same as copying

Project groups submit joint work

- Same rules apply to projects at the group level
- Cannot use of someone else' s soln

Closed-book exams, no calculators

- Stressed? Tempted? Lost?
  - Come see me ***before*** due date!

Plagiarism in any form will not be tolerated

Academic Integrity

"Black Board" Collaboration Policy

- Can discuss approach together on a "black board"
- Leave and write up solution independently
- Do not copy solutions

Plagiarism in any form will not be tolerated

Goal for Today: Putting it all Together

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

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Goal for Today: Putting it all Together

Compiler output is assembly files

Assembler output is obj files

- How does the assembler resolve references/labels?
- How does the assembler resolve external references?

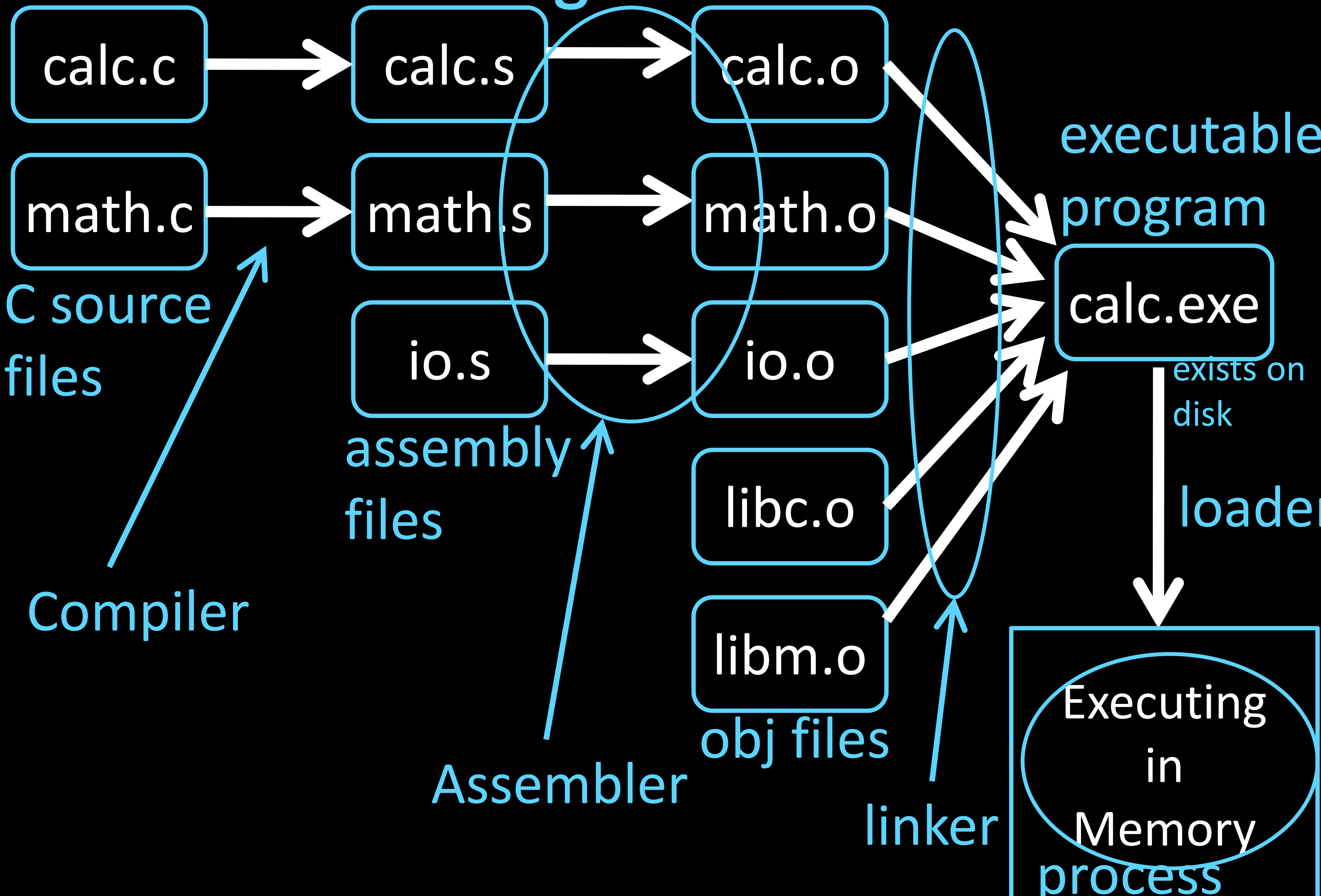
Linker joins object files into one executable

- How does the linker combine separately compiled files?
- How does linker resolve unresolved references?
- How does linker relocate data and code segments

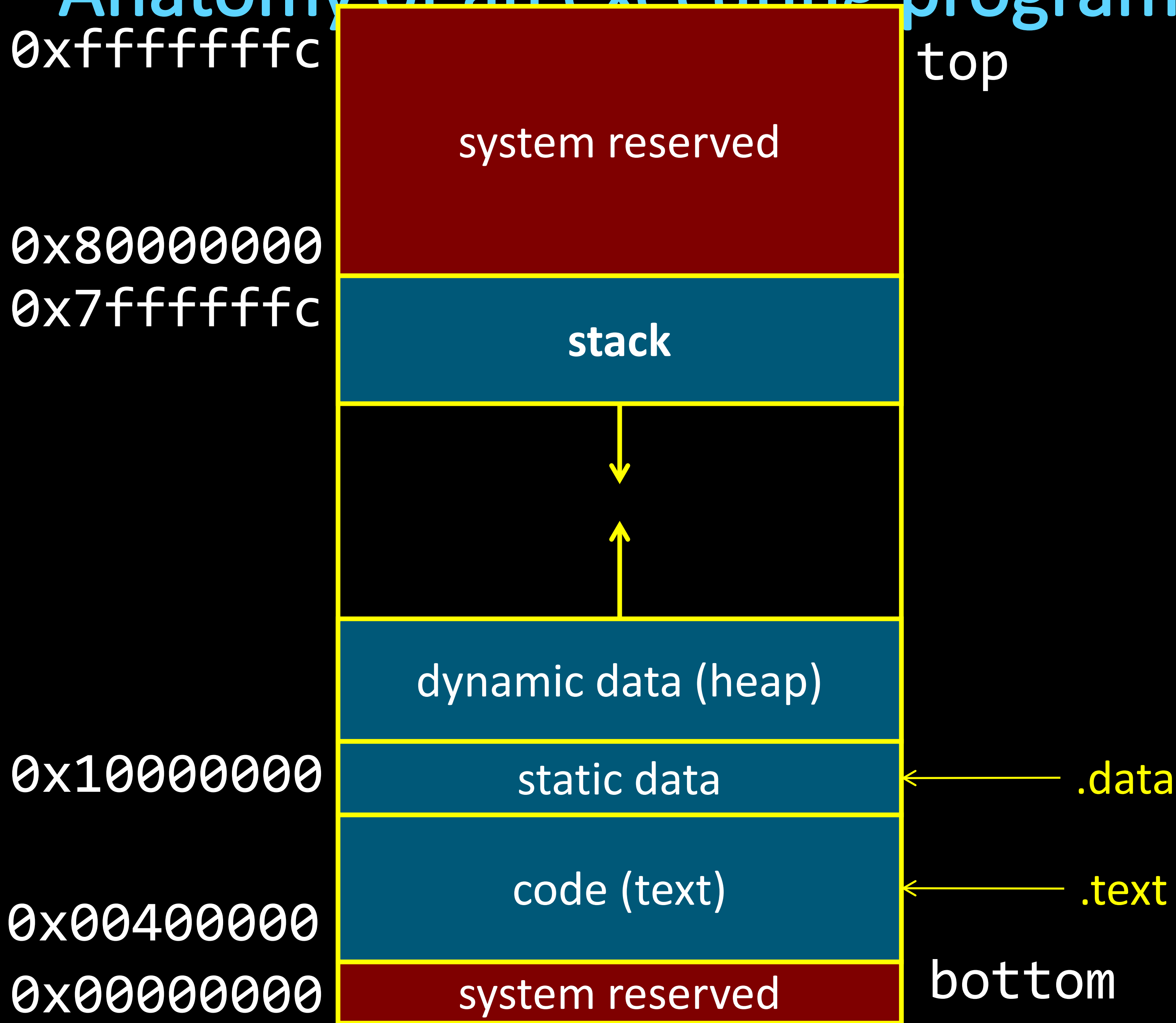
Loader brings it into memory and starts execution

- How does the loader start executing a program?
- How does the loader handle shared libraries?

Big Picture


calc.c
math.c
C source files
calc.s
math.s
io.s
assembly files
calc.o
math.o
io.o
libc.o
libm.o
obj files
executable program
calc.exe
exists on disk
loader
Executing in Memory
process
Compiler
Assembler
linker

Anatomy of an executing program



Example #2: Review of Program Layout

calc.c

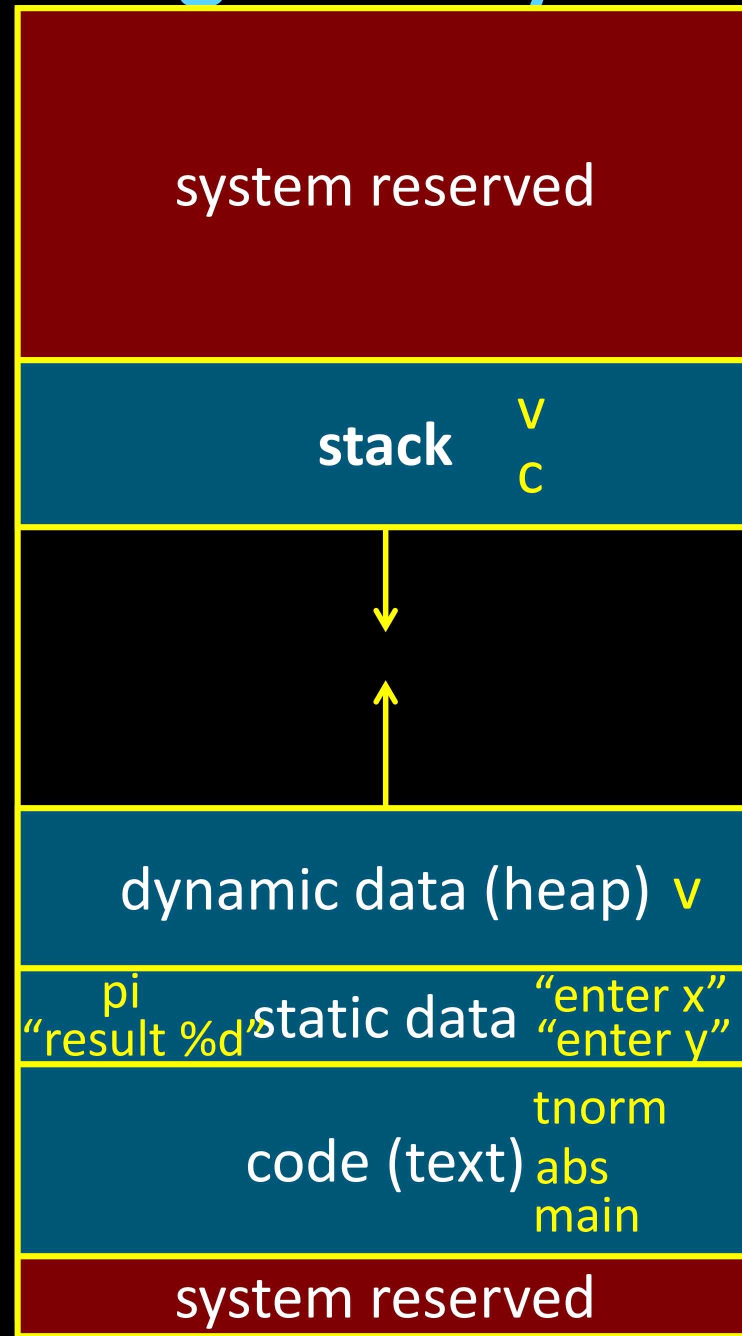
```
vector* v = malloc(8);
v->x = prompt("enter x");
v->y = prompt("enter y");
int c = pi + tnorm(v);
print("result %d", c);
```

math.c

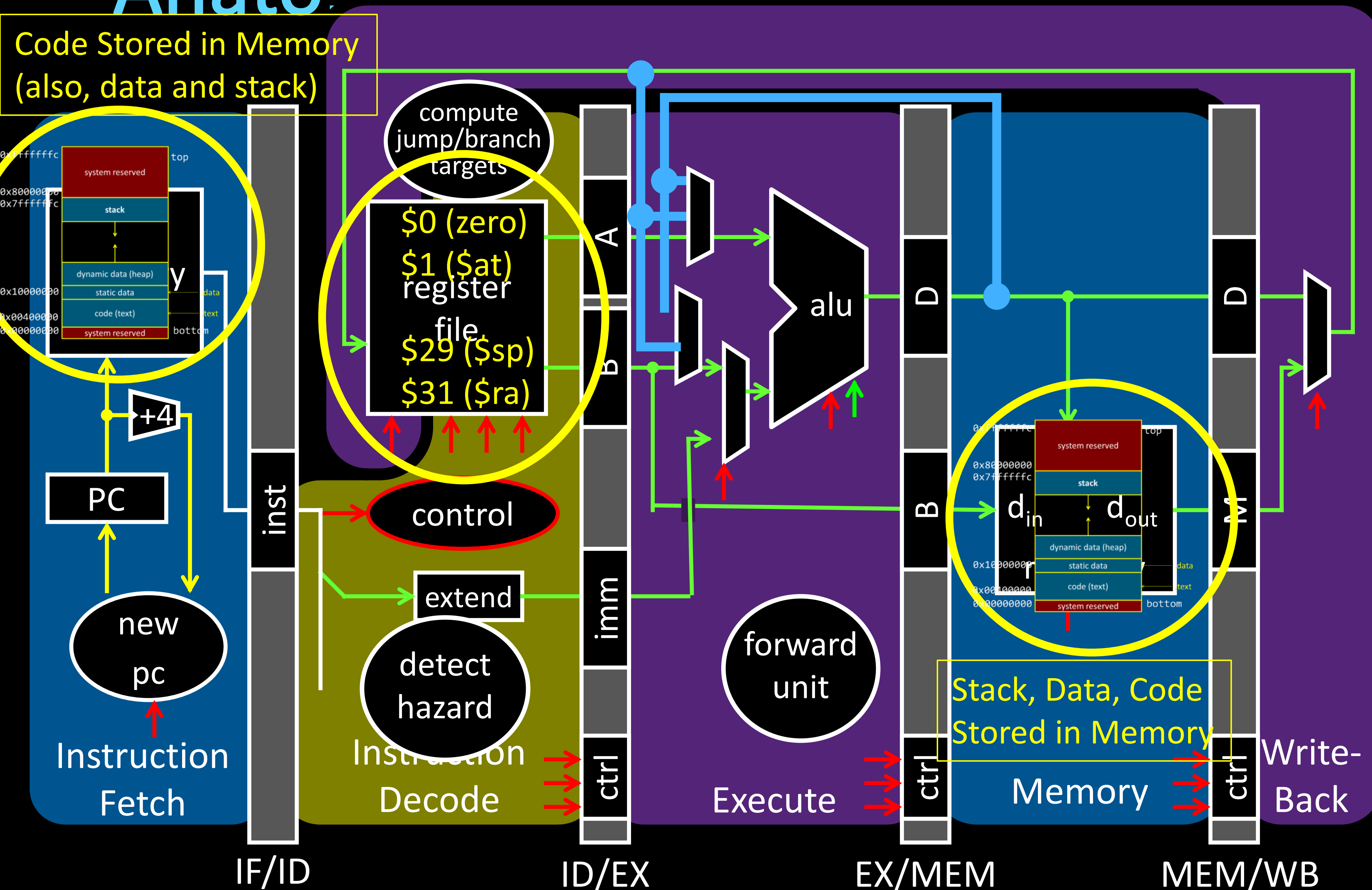
```
int tnorm(vector* v) {
 return abs(v->x)+abs(v->y);
}
```

lib3410.o

```
global variable: pi
entry point: prompt
entry point: print
entry point: malloc
```



Anatomy of an executing program



Big Picture: Assembling file separately

math.c → math.s → math.o

.o = Linux
.obj Windows

Output of assembler is a object files

- Binary machine code, but not executable
- How does assembler handle forward references?

Next Goal

How does the assembler handle local references

How does Assembler handle forward references

Two-pass assembly

- Do a pass through the whole program, allocate instructions and lay out data, thus determining addresses
- Do a second pass, emitting instructions and data, with the correct label offsets now determined

One-pass (or backpatch) assembly

- Do a pass through the whole program, emitting instructions, emit a 0 for jumps to labels not yet determined, keep track of where these instructions are
- Backpatch, fill in 0 offsets as labels are defined

How does Assembler handle forward references

Example:

- bne $1, $2, L
  sll $0, $0, 0

L: addiu $2, $3, 0x2

The assembler will change this to

- bne $1, $2, +1
  sll $0, $0, 0
  addiu $2, $3, $0x2

Final machine code

- 0X14220001 # bne
  0x00000000 # sll
  0x24620002 # addiu

How does Assembler handle forward references

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  sll $0, $0, 0

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Final machine code

- 0X14220001 # bne
  0x00000000 # sll
  0x24620002 # addiu

000101	00001	00010	0000000000000001		
000000	00000	00000	00000	00000	000000
001001	00011	00010	0000000000000010		

How does Assembler handle forward references

Example:

- bne $1, $2, L
  sll $0, $0, 0

L: addiu $2, $3, 0x2

The assembler will change this to

- bne $1, $2, +1
  sll $0, $0, 0
  addiu $2, $3, $0x2

Final machine code

- 0X14220001 # bne
  0x00000000 # sll
  0x24620002 # addiu

1	4	2	2	0	0	0	1
0	0	0	0	0	0	0	0
2	4	6	2	0	0	0	2

Big Picture: Assembling file separately

math.c → math.s → math.o

.o = Linux
.obj Windows

Output of assembler is a object files

- Binary machine code, but not executable
- How does assembler handle forward references?
- May refer to external symbols i.e. Need a “symbol table”
- Each object file has illusion of its own address space
  - Addresses will need to be fixed later

    e.g. .text (code) starts at addr 0x00000000
    .data starts @ addr 0x00000000

Next Goal

How does the assembler handle external references

Symbols and References

Global labels: Externally visible “exported” symbols

- Can be referenced from other object files
- Exported functions, global variables

e.g. pi
(from a couple of slides ago)

Local labels: Internal visible only symbols

- Only used within this object file
- static functions, static variables, loop labels, …

e.g.
static foo
static bar
static baz

e.g.
$str
$L0
$L2

Object file

Object File

Header

- Size and position of pieces of file

Text Segment

- instructions

Data Segment

- static data (local/global vars, strings, constants)

Debugging Information

- line number → code address map, etc.

Symbol Table

- External (exported) references
- Unresolved (imported) references

Example

math.c

```
int pi = 3;
int e = 2;
static int randomval = 7;

extern char *username;
extern int printf(char *str, ...);

int square(int x) { ... }
static int is_prime(int x) { ... }
int pick_prime() { ... }
int pick_random() {
        return randomval;
}
```

global

local (to current file)

external (defined in another file)

local

global

gcc -S ... math.c — Compiler

gcc -c ... math.s — Assembler

objdump --disassemble math.o

objdump --syms math.o

Objdump disassembly

```
csug01 ~$ mipsel-linux-objdump --disassemble math.o
math.o:     file format elf32-tradlittlemips
Disassembly of section .text:

00000000 <pick_random>:
  0:   27bdfff8   addiu  sp,sp,-8
  4:   afbe0000   sw     s8,0(sp)
  8:   03a0f021   move   s8,sp
  c:   3c020000   lui    v0,0x0
 10:   8c420008   lw     v0,8(v0)
 14:   03c0e821   move   sp,s8
 18:   8fbe0000   lw     s8,0(sp)
 1c:   27bd0008   addiu  sp,sp,8
 20:   03e00008   jr     ra
 24:   00000000   nop

00000028 <square>:
 28:   27bdfff8   addiu  sp,sp,-8
 2c:   afbe0000   sw     s8,0(sp)
 30:   03a0f021   move   s8,sp
 34:   afc40008   sw     a0,8(s8)
```

Objdump disassembly

```
csug01 ~$ mipsel-linux-objdump --disassemble math.o
math.o:     file format elf32-tradlittlemips
Disassembly of section .text:
```

Address   instruction   Mem[8] = instruction 0x03a0f021 (move s8,sp)

```
00000000 <pick_random>:
   0:   27bdfff8    addiu   sp,sp,-8
   4:   afbe0000    sw      s8,0(sp)
   8:   03a0f021    move    s8,sp
   c:   3c020000    lui     v0,0x0
  10:   8c420008    lw      v0,8(v0)
  14:   03c0e821    move    sp,s8
  18:   8fbe0000    lw      s8,0(sp)
  1c:   27bd0008    addiu   sp,sp,8
  20:   03e00008    jr      ra
  24:   00000000    nop
```

prologue

resolved (fixed) later

body

epilogue

symbol

```
00000028 <square>:
  28:   27bdfff8    addiu   sp,sp,-8
  2c:   afbe0000    sw      s8,0(sp)
  30:   03a0f021    move    s8,sp
  34:   afc40008    sw      a0,8(s8)
```

Objdump symbols

```
csug01 ~$ mipsel-linux-objdump --syms math.o
math.o:     file format elf32-tradlittlemips

SYMBOL TABLE:
00000000 l    df *ABS*          00000000 math.c
00000000 l    d  .text          00000000 .text
00000000 l    d  .data          00000000 .data
00000000 l    d  .bss           00000000 .bss
00000000 l    d  .mdebug.abi32  00000000 .mdebug.abi32
00000008 l     O .data          00000004 randomval
00000060 l     F .text          00000028 is_prime
00000000 l    d  .rodata        00000000 .rodata
00000000 l    d  .comment       00000000 .comment
00000000 g     O .data          00000004 pi
00000004 g     O .data          00000004 e
00000000 g     F .text          00000028 pick_random
00000028 g     F .text          00000038 square
00000088 g     F .text          0000004c pick_prime
00000000         *UND*          00000000 username
00000000         *UND*          00000000 printf
```

Objdump symbols

```
csug01 ~$ mipsel-linux-objdump --syms math.o
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SYMBOL TABLE:
00000000 l    df *ABS*        00000000 math.c
00000000 l    d  .text        00000000 .text
00000000 l    d  .data        00000000 .data
00000000 l    d  .bss         00000000 .bss
00000000 l    d  .mdebug.abi32 00000000 .mdebug.abi32
00000008 l     O .data        00000004 randomval
00000060 l     F .text        00000028 is_prime
00000000 l    d  .rodata      00000000 .rodata
00000000 l    d  .comment     00000000 .comment
00000000 g     O .data        00000004 pi
00000004 g     O .data        00000004 e
00000000 g     F .text        00000028 pick_random
00000028 g     F .text        00000038 square
00000088 g     F .text        0000004c pick_prime
00000000         *UND*        00000000 username
00000000         *UND*        00000000 printf
```

Address

l: local

g: global

segment

segment size

Static local func @ addr=0x60 size=0x28 byte

f: func

O: obj

external reference

Separate Compilation

Q: Why separate compile/assemble and linking steps?

a) Removes the need to recompile the whole program

b) Need to just recompile a small module

c) Separation of concern: Linker coalesces object files

d) All the above

e) None of the above

Separate Compilation

Q: Why separate compile/assemble and linking steps?

A: Separately compiling modules and linking them together obviates the need to recompile the whole program every time something changes

- Need to just recompile a small module

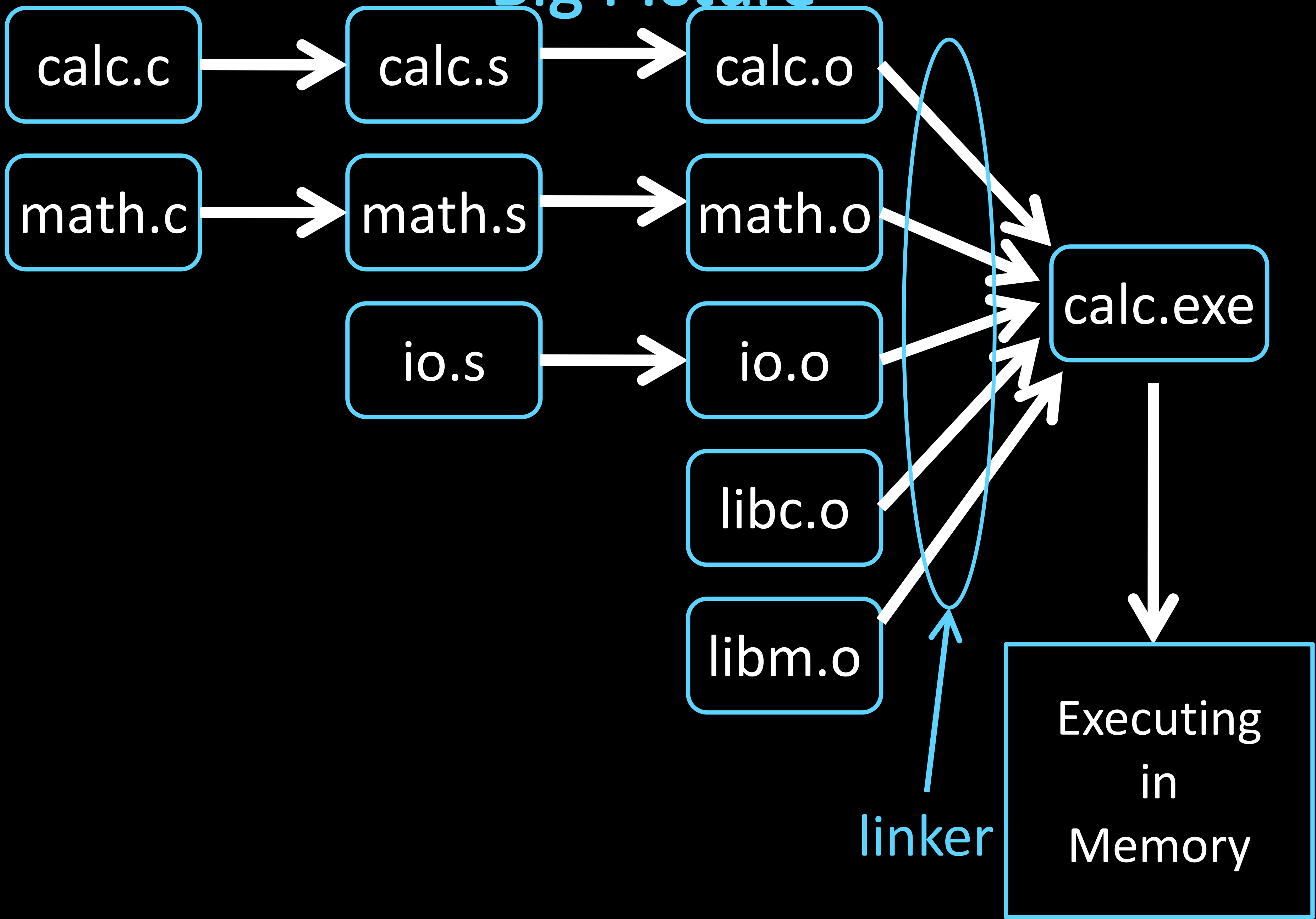
- A linker coalesces object files together to create a complete program

Linkers

Next Goal

How do we link together separately compiled and assembled machine object files?

Big Picture


calc.c
calc.s
calc.o
math.c
math.s
math.o
io.s
io.o
libc.o
libm.o
calc.exe
Executing in Memory
linker

Linkers

Linker combines object files into an executable file

- Relocate each object's text and data segments
- Resolve as-yet-unresolved symbols
- Record top-level entry point in executable file

End result: a program on disk, ready to execute

- E.g.

./calc	Linux
./calc.exe	Windows
simulate calc	Class MIPS simulator

Linker Example

main.o

.text
```
...
0C000000
21035000
1b80050C
8C040000
21047002
0C000000
...
```

Symbol tbl
```
00 T      main
00 D      uname
*UND*     printf
*UND*     pi
```

Relocation info
```
40,JAL, printf
4C,LW/gp, pi
50,JAL, square
```

math.o

```
...
21032040
0C000000
1b301402
3C040000
34040000
...
```

```
20 T    square
00 D    pi
*UND*   printf
*UND*   uname
```

```
28,JAL, printf
30,LUI, uname
34,LA,  uname
```

printf.o

```
...
```

```
3C T    printf
```

External references need to be resolved (fixed)

Steps

1) Find UND symbols in symbol table
2) Relocate segments that collide

e.g. uname @0x00
pi @ 0x00
square @ 0x00
main @ 0x00

Linker Example

main.o

.text

```
...
0C000000
21035000
1b80050C
8C040000
21047002
0C000000
...
```

Symbol tbl

```
00    T     main
00    D     uname
*UND*       printf
*UND*       pi
```

Relocation info

```
40,JAL, printf
4C,LW/gp, pi
50,JAL, square
```

2

B

math.o

```
...
21032040
0C000000
1b301402
3C040000
34040000
...
```

```
20    T   square
00    D   pi
*UND*     printf
*UND*     uname
```

```
28,JAL, printf
30,LUI, uname
34,LA,  uname
```

1

A

printf.o

```
...
3C  T   printf
```

3

calc.exe

math

```
...
21032040
0C40023C
1b301402
3C041000
34040004
...
```

JAL printf

1

LA uname
LUI 1000
ORI 0004

0040 0000

main

```
0C40023C
21035000
1b80050c
8C048004
21047002
0C400020
...
```

2

LW $4,-32764($gp)
$4 = pi
JAL square

0040 0100

printf

```
10201000
21040330
22500102
...
```

3

0040 0200

```
pi     00000003
uname  0077616B
```

1000 0000
1000 0004

```
Entry:0040 0100
text:0040 0000
data:1000 0000
```

Object file

Object File

Header

- location of main entry point (if any)

Text Segment

- instructions

Data Segment

- static data (local/global vars, strings, constants)

Relocation Information

- Instructions and data that depend on actual addresses
- Linker patches these bits after relocating segments

Symbol Table

- Exported and imported references

Debugging Information

Object File Formats

Unix

- a.out
- COFF: Common Object File Format
- ELF: Executable and Linking Format
- …

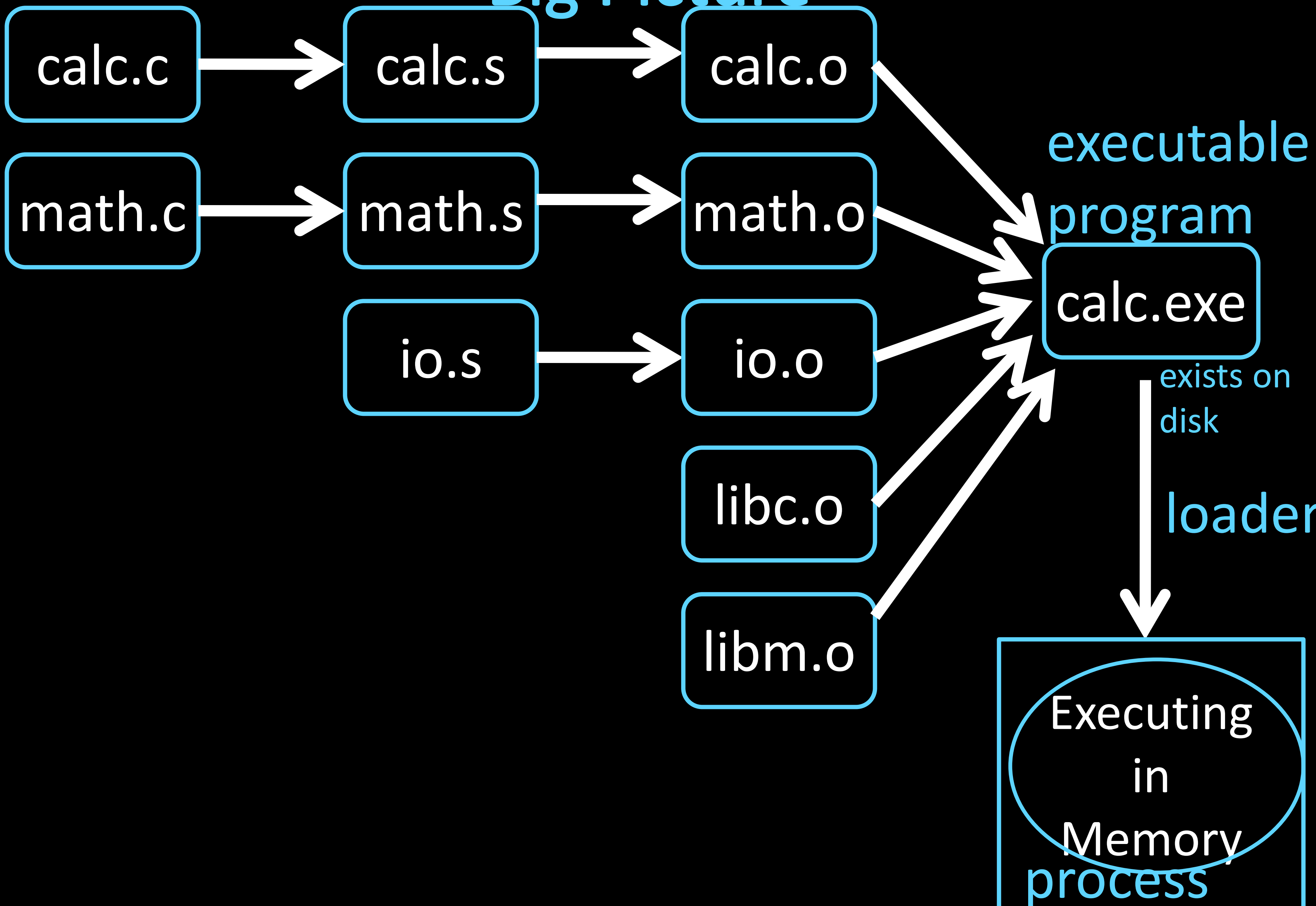
Windows

- PE: Portable Executable

All support both executable and object files

Loaders and Libraries

Big Picture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executable program
calc.exe
exists on disk
loader
Executing in Memory
process

Loaders

Loader reads executable from disk into memory

- Initializes registers, stack, arguments to first function
- Jumps to entry-point

Part of the Operating System (OS)

Static Libraries

Static Library: Collection of object files
(think: like a zip archive)

Q: But every program contains entire library!

A: Linker picks only object files needed to resolve undefined references at link time

e.g. libc.a contains many objects:

- printf.o, fprintf.o, vprintf.o, sprintf.o, snprintf.o, …
- read.o, write.o, open.o, close.o, mkdir.o, readdir.o, …
- rand.o, exit.o, sleep.o, time.o, ….

Shared Libraries

Q: But every program still contains part of library!

A: shared libraries

- executable files all point to single *shared library* on disk
- final linking (and relocations) done by the loader

Optimizations:

- Library compiled at fixed non-zero address

- Jump table in each program instead of relocations
- Can even patch jumps on-the-fly

Direct Function Calls

Direct call:

```
00400010 <main>:
    ...
    jal 0x00400330
    ...
    jal 0x00400620
    ...
    jal 0x00400330
    ...
00400330 <printf>:
    ...
00400620 <gets>:
    ...
```

Drawbacks:

Linker or loader must edit every use of a symbol (call site, global var use, ...)

Idea:

Put all symbols in a single "global offset table"

Code does lookup as needed

Indirect Function Calls

Indirect call:

```
00400010 <main>:
      ...
      jal 0x00400330
      ...
      jal 0x00400620
      ...
      jal 0x00400330
      ...
00400330 <printf>:
      ...
00400620 <gets>:
      ...
```

GOT: global offset table

0x00400010 # main
0x00400330 # printf
0x00400620 # gets

Indirect Function Calls

Indirect call:

```
00400010 <main>:
    ...
  lw $t9,-32708($gp)
  jalr $t9
    ...
  lw $t9,-32704($gp)
  jalr $t9
    ...
  lw $t9,-32708($gp)
  jalr $t9
    ...
00400330 <printf>:

    ...
00400620 <gets>:

    ...
```

```
# data segment
```

GOT: global offset table

0	0x00400010 # main
4	0x00400330 # printf
8	0x00400620 # gets

```
# global offset table
# to be loaded
# at -32712($gp)
# printf = 4+(-32712)+$gp
# gets   = 8+(-32712)+$gp
```

Indirect Function Calls

Indirect call:

```
00400010 <main>:
    ...
    lw $t9,-32708($gp)
    jalr $t9
    ...
    lw $t9,-32704($gp)
    jalr $t9
    ...
    lw $t9,-32708($gp)
    jalr $t9
    ...
00400330 <printf>:

    ...
00400620 <gets>:

    ...
```

```
# data segment
    .got
    .word 0x00400010 # main
    .word 0x00400330 # printf
    .word 0x00400620 # gets



# global offset table
# to be loaded
# at -32712($gp)
# printf = 4+(-32712)+$gp
# gets   = 8+(-32712)+$gp
```

Dynamic Linking

Indirect call with on-demand dynamic linking:

```
00400010 <main>:
    ...
    # load address of prints
    # from .got[1]
    lw t9, -32708(gp)


    # now call it
    jalr t9
    ...
.got
    .word 00400888 # open
    .word 00400888 # prints
    .word 00400888 # gets
    .word 00400888 # foo
```

Dynamic Linking

Indirect call with on-demand dynamic linking:

```
00400010 <main>:
    ...
    # load address of prints
    # from .got[1]
    lw t9, -32708(gp)
    # also load the index 1
    li t8, 1
    # now call it
    jalr t9
    ...
.got
    .word 00400888 # open
    .word 00400888 # prints
    .word 00400888 # gets
    .word 00400888 # foo
```

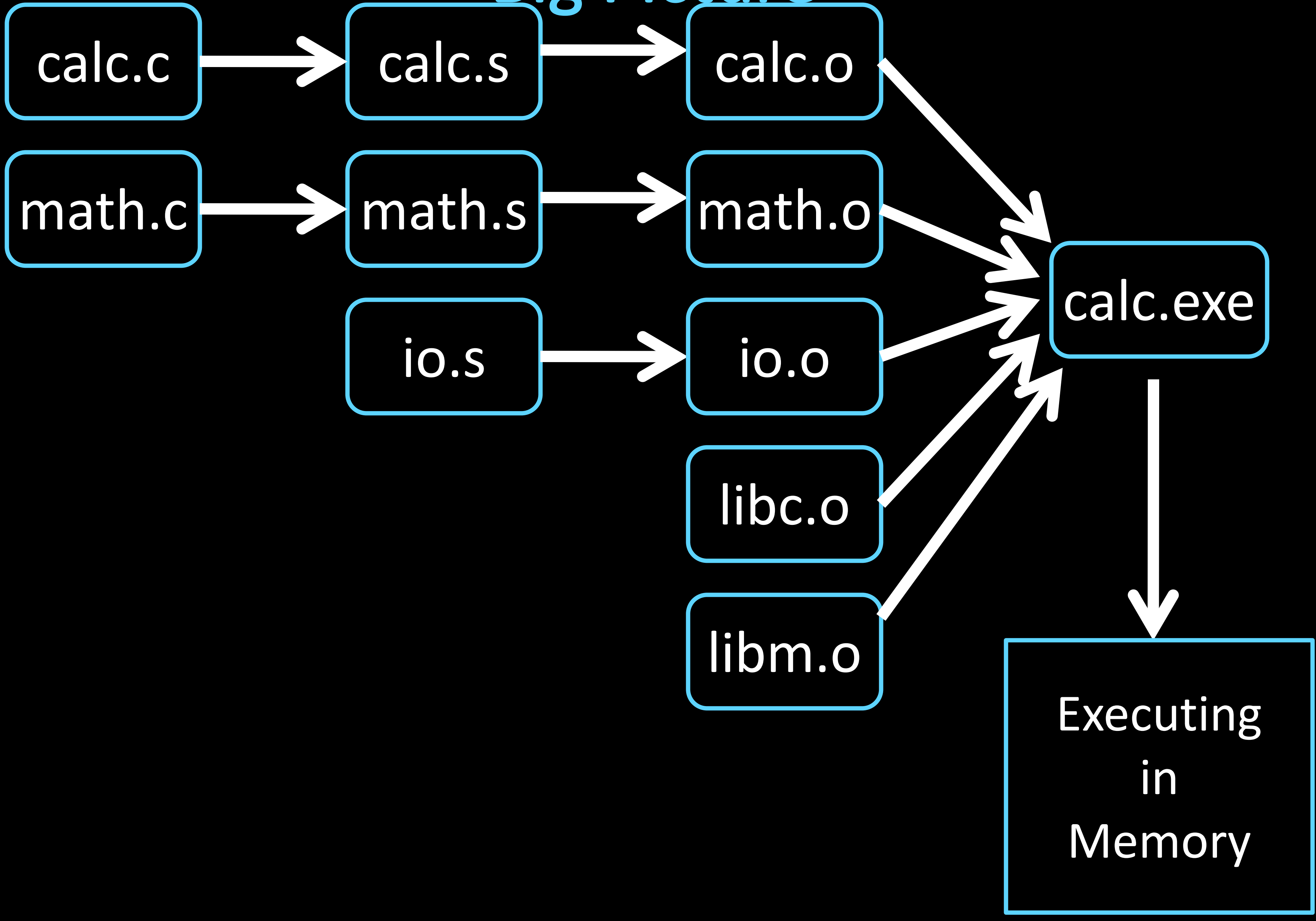
```
    ...
00400888 <dlresolve>:
    # t9 = 0x400888
    # t8 = index of func that
    #      needs to be loaded

    # load that func
    ... # t7 = loadfromdisk(t8)

    # save func's address so
    # so next call goes direct
    ... # got[t8] = t7

    # also jump to func
    jr t7
    # it will return directly
    # to main, not here
```

Big Picture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Executing
in
Memory

Dynamic Shared Objects

Windows: dynamically loaded library (DLL)

- PE format

Unix: dynamic shared object (DSO)

- ELF format

Unix also supports Position Independent Code (PIC)

- – Program determines its current address whenever needed (no absolute jumps!)
- – Local data: access via offset from current PC, etc.
- – External data: indirection through Global Offset Table (GOT)
- – … which in turn is accessed via offset from current PC

Static and Dynamic Linking

Static linking

- Big executable files (all/most of needed libraries inside)
- Don’t benefit from updates to library
- No load-time linking

Dynamic linking

- Small executable files (just point to shared library)
- Library update benefits all programs that use it
- Load-time cost to do final linking
  - But dll code is probably already in memory
  - And can do the linking incrementally, on-demand

Recap

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