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

- .

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?

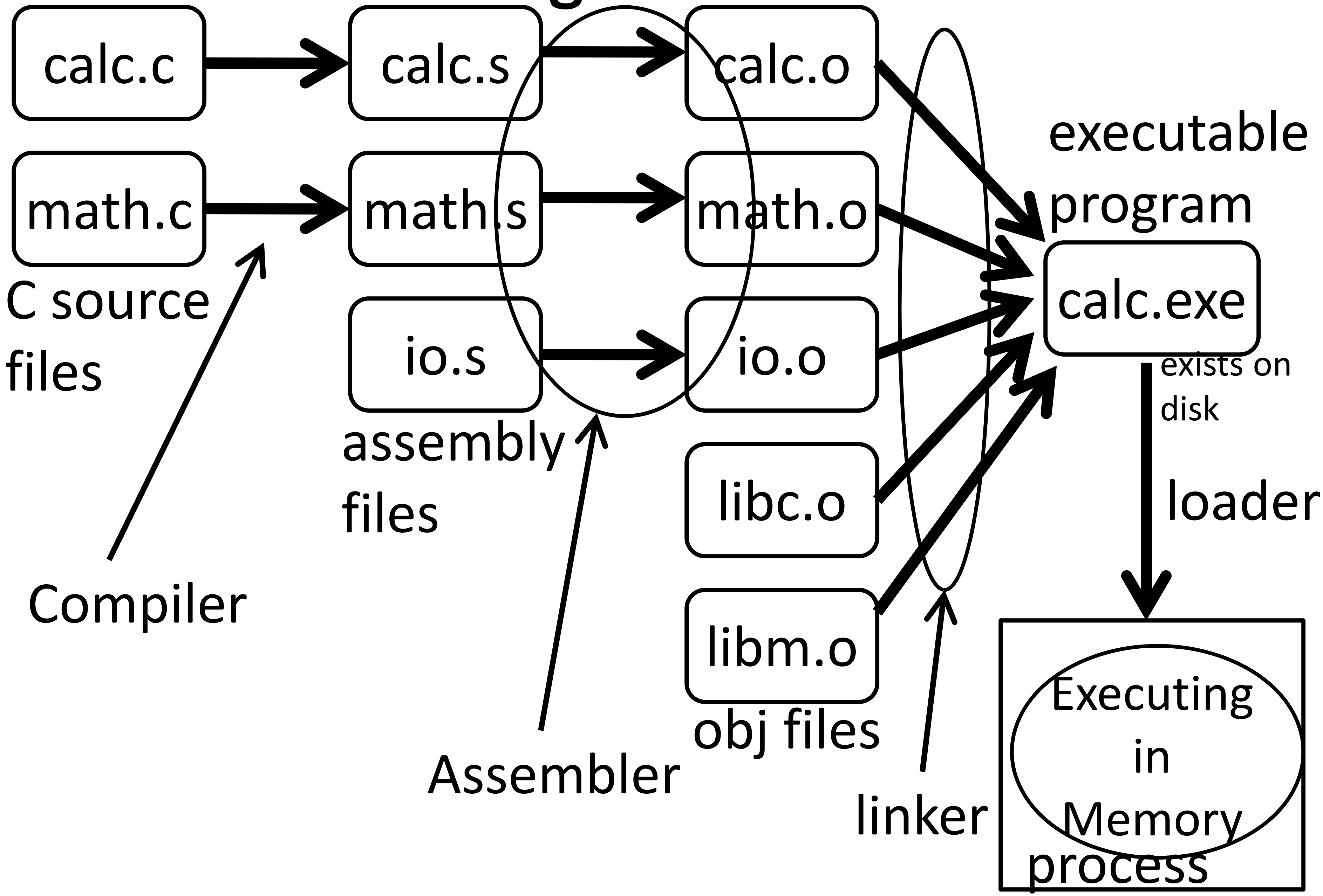
Linker joins object files into one executable

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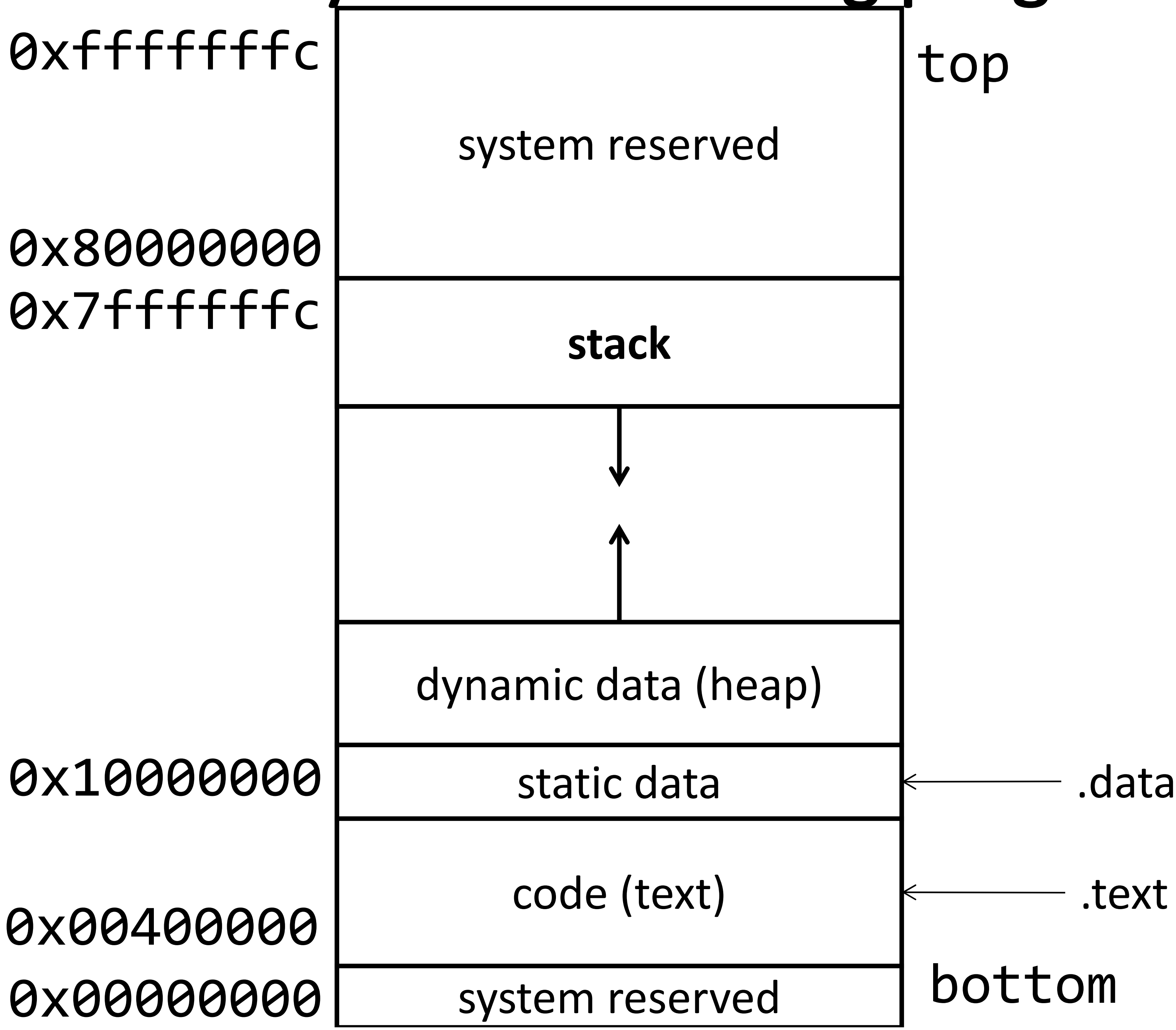
libc.o
libm.o
obj files
linker
executable program
calc.exe
exists on disk
loader
Executing in Memory
process

Anatomy of an executing program



Example: Review of Program Layout

calc.c

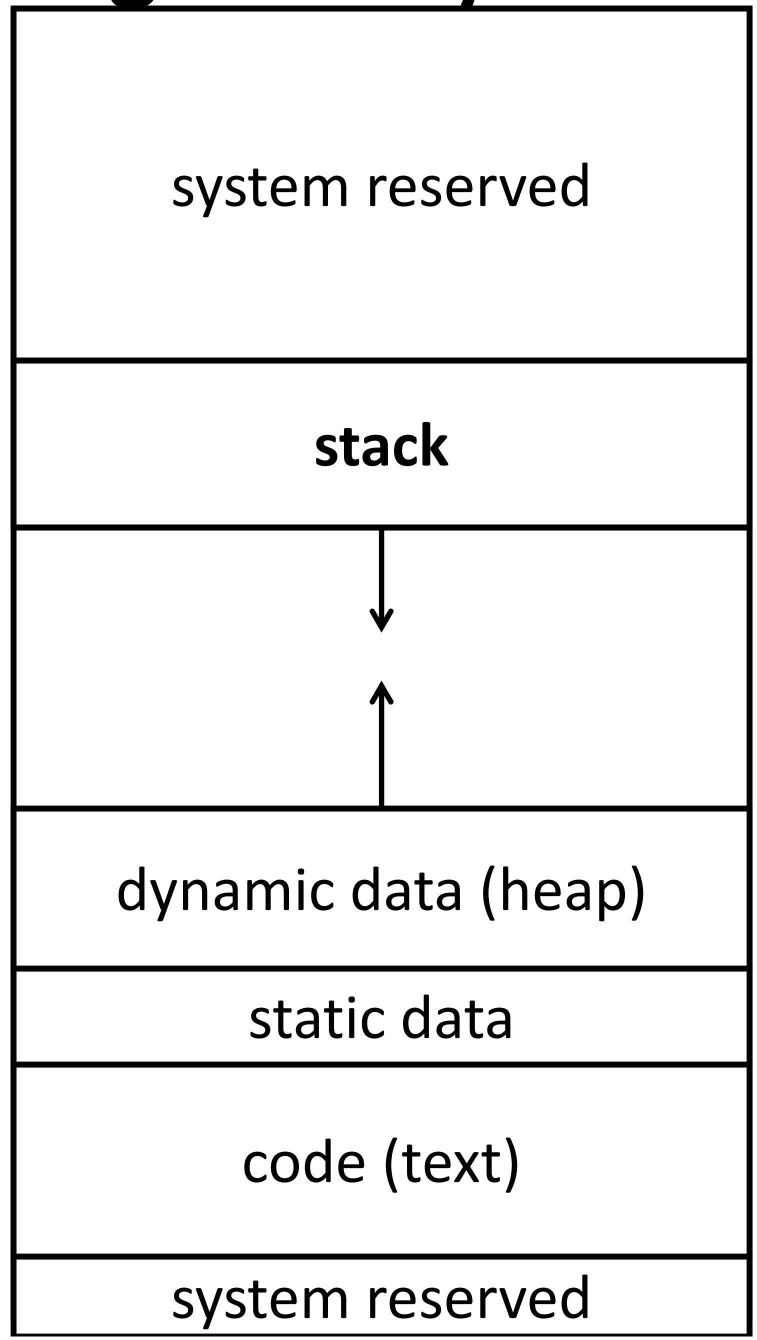
```
vector* v = malloc(8);
v->x = prompt("enter x");
v->y = prompt("enter y");
int c = pi + tnorm(v);
print("result %d", c);
```

math.c

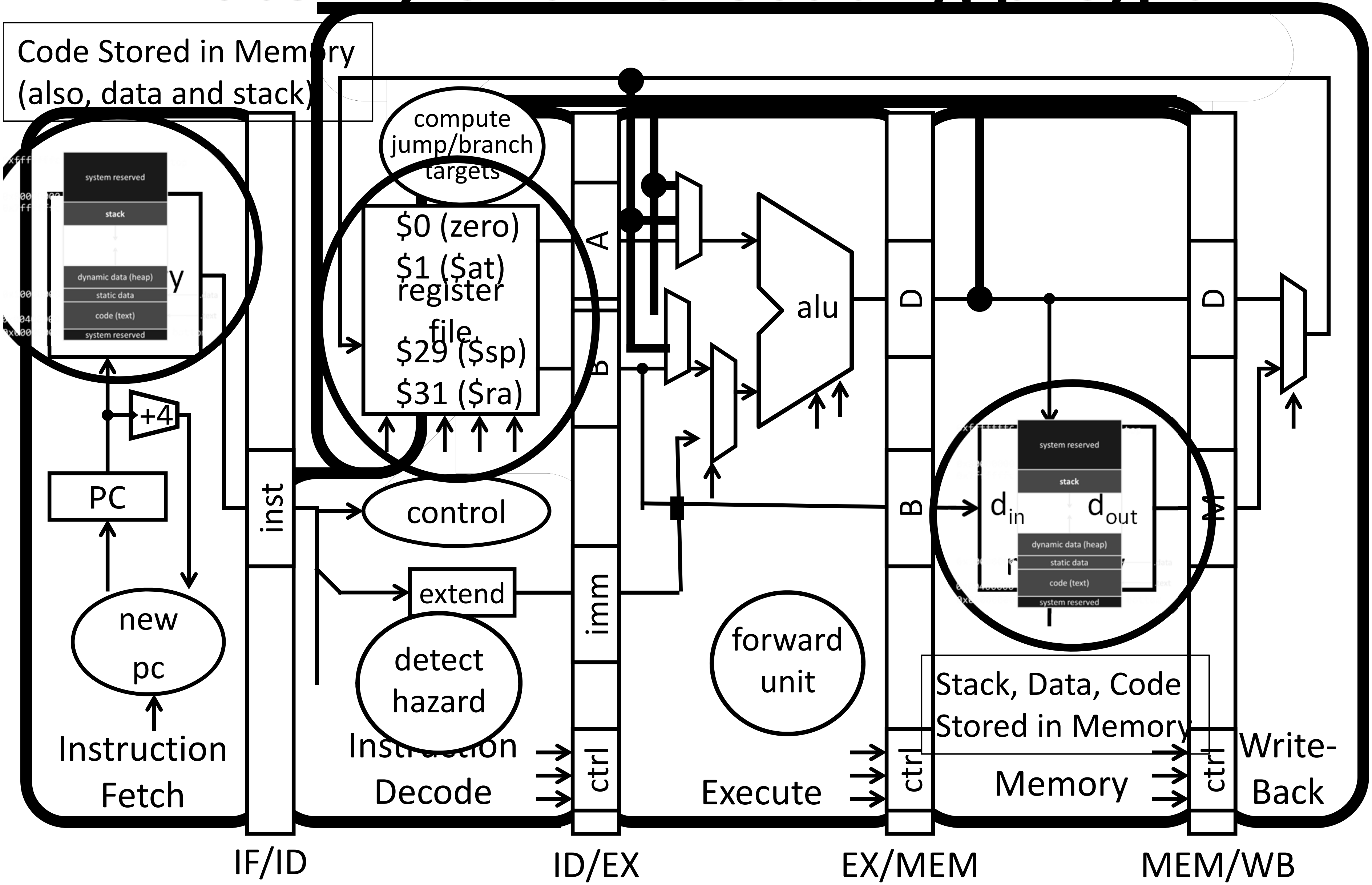
```
int tnorm(vector* v) {
 return abs(v->x)+abs(v->y);
}
```

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 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
  ```
  ```

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 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
```

Separate Compilation

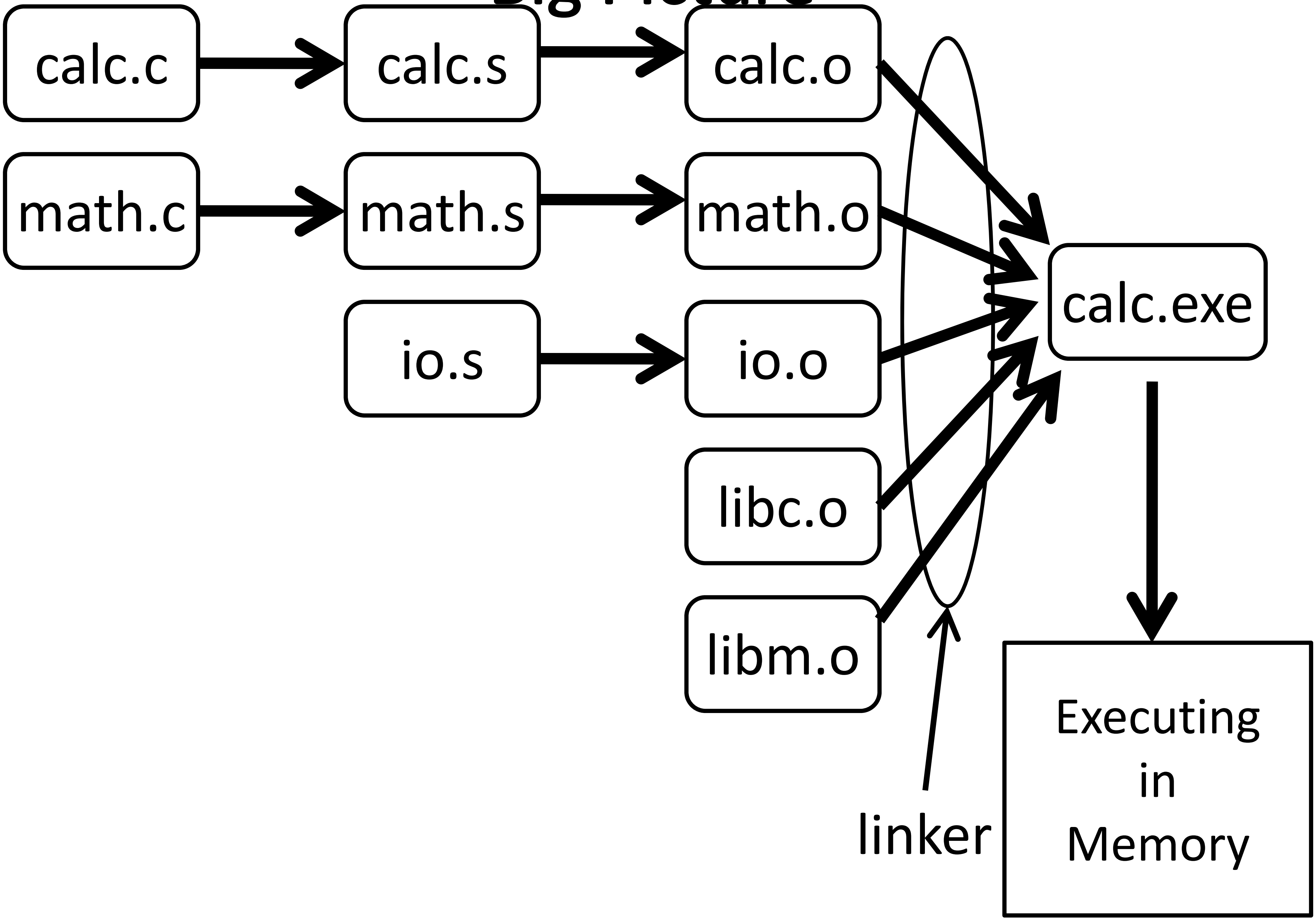
Q: Why separate compile/assemble and linking steps?

Linkers

Next Goal

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

Big Picture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libm.o
calc.exe
linker
Executing in Memory

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
```

calc.exe

```
...
21032040
0C40023C
1b301402
3C041000
34040004
...
0C40023C
21035000
1b80050c
8C048004
21047002
0C400020
...
10201000
21040330
22500102
...
```

```
00000003
0077616B
```

```
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
- …

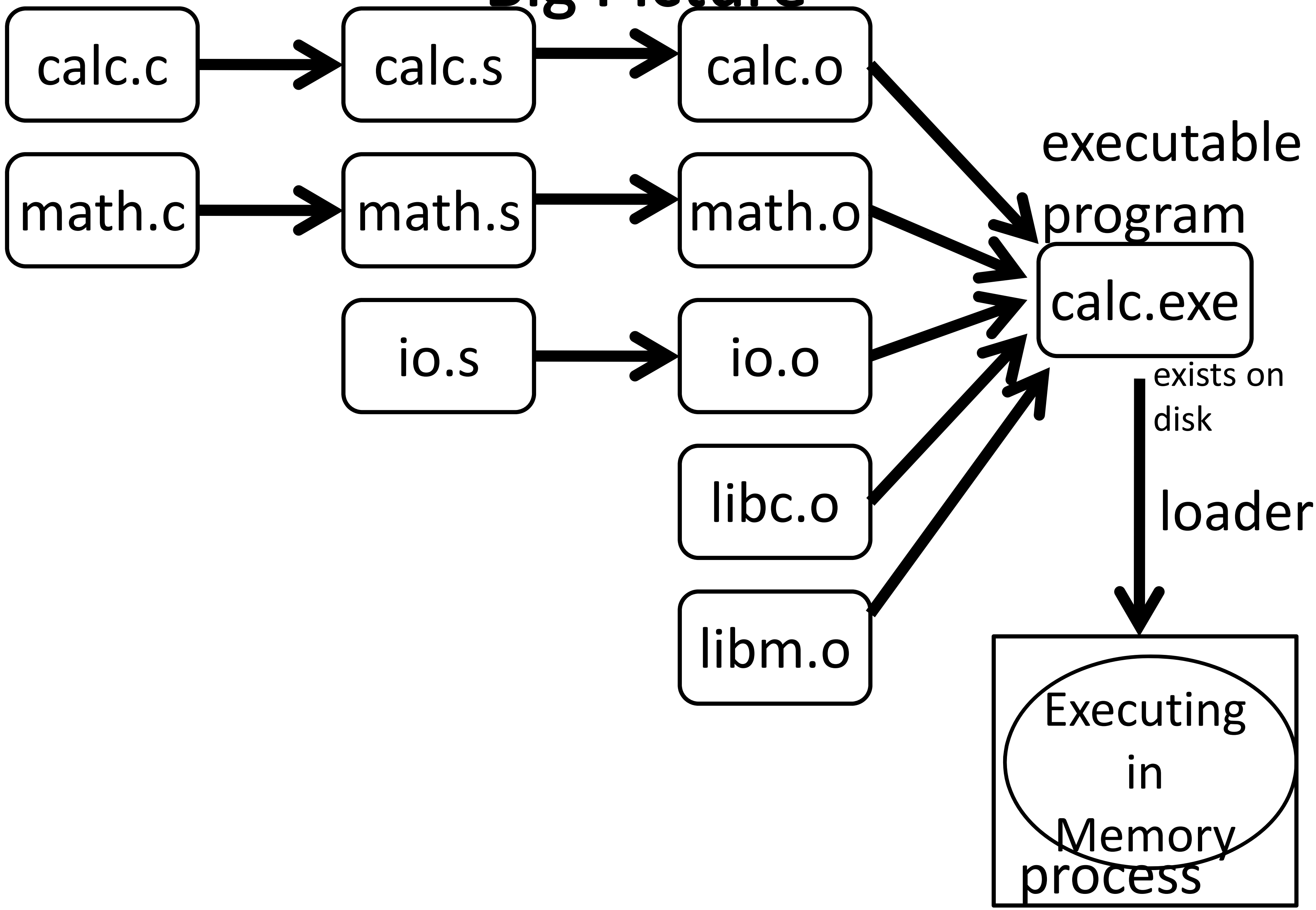
Windows

- PE: Portable Executable

All support both executable and object files

Loaders and Libraries

Big Picture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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
```

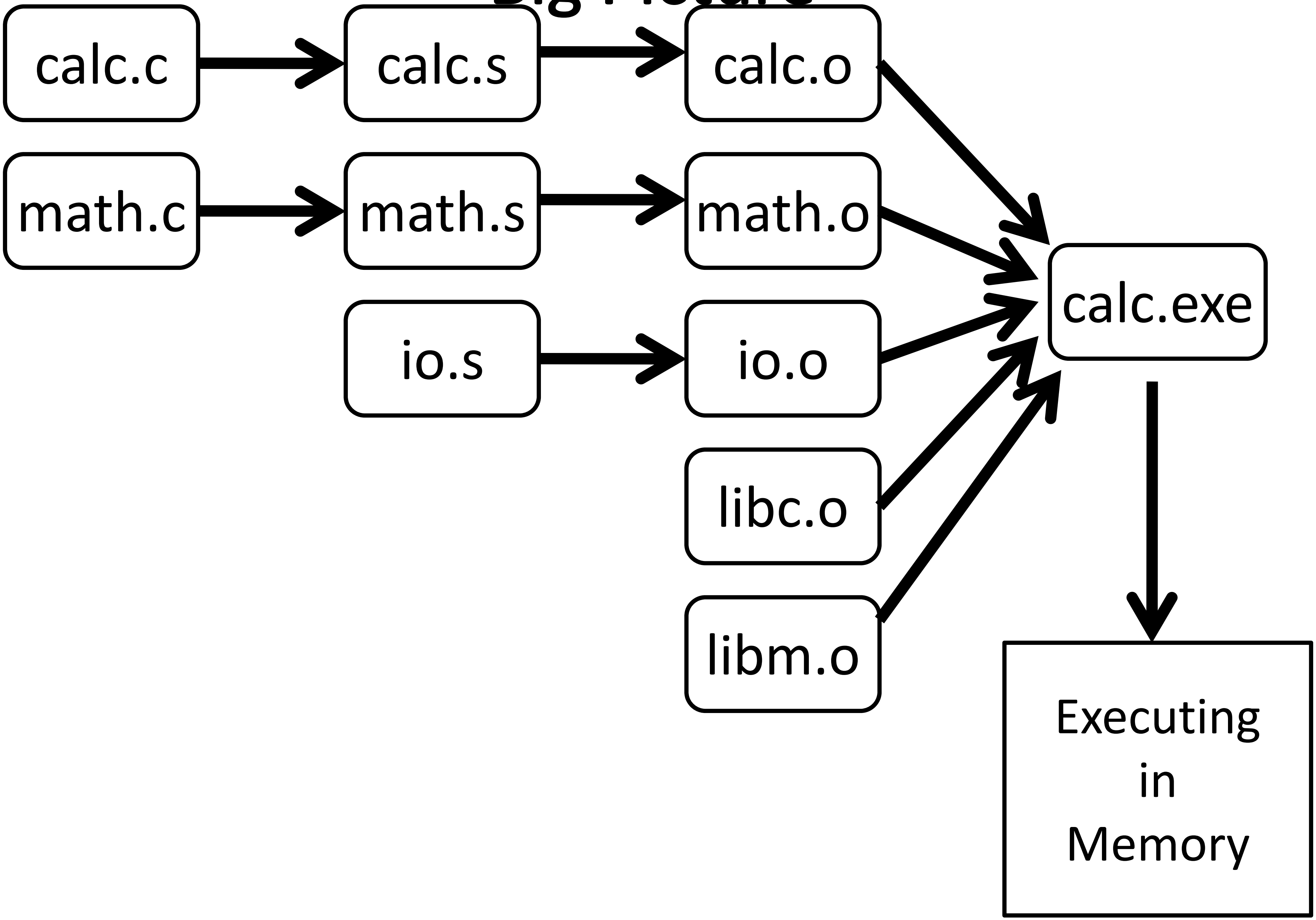
```
   ...
00400888 <dlresolve>:
   # t9 = 0x400888
   # t8 = index of func that
   #    needs to be loaded

   # 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