Assemblers, Linkers, and Loaders

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CS 3410, Spring 2014

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 17th
- PA2 due next week, Thursday, March 27th

- HW2 available, due before Prelim2 in April

- Spring break: Saturday, March 29th to Sunday, April 6th

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?

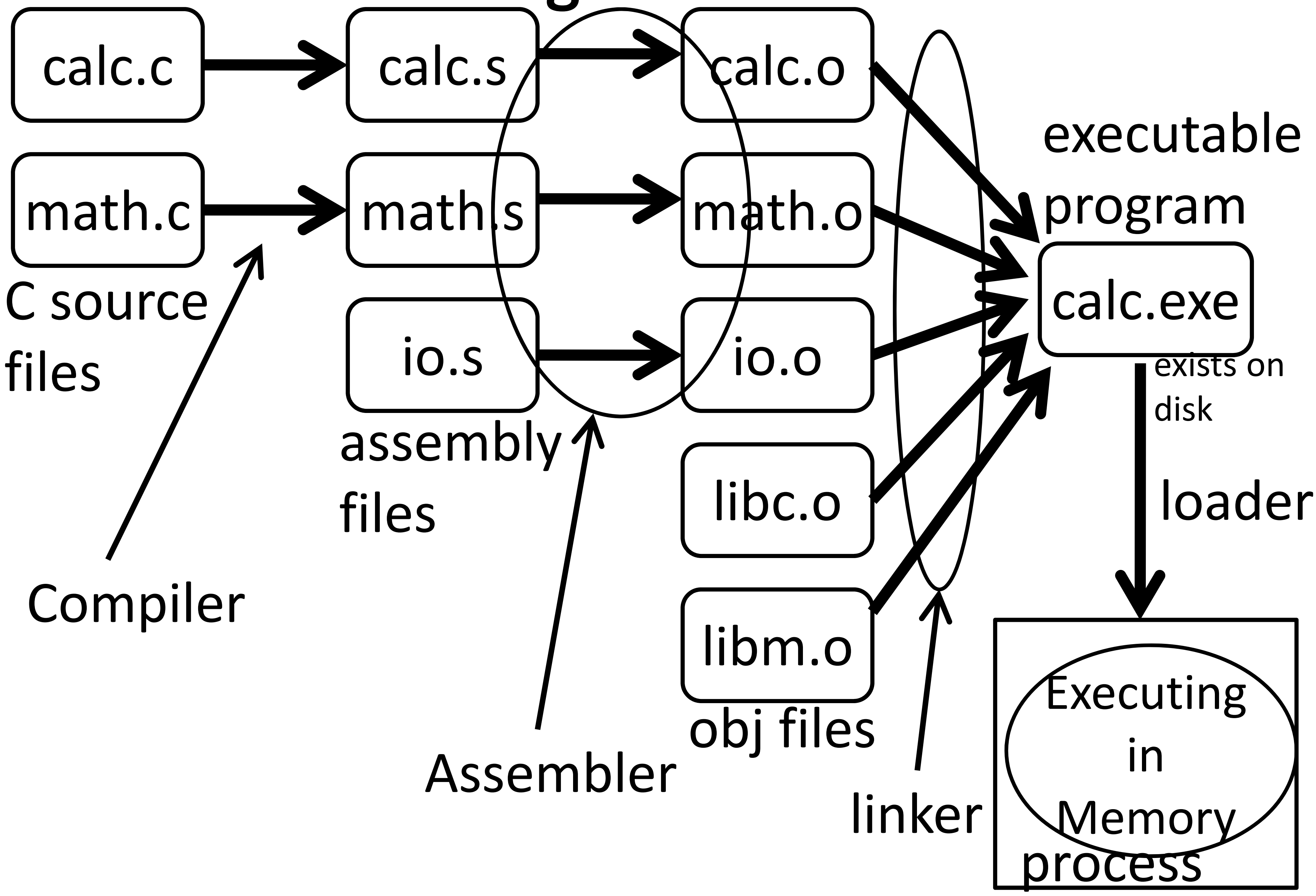
Linker joins object files into one executable

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

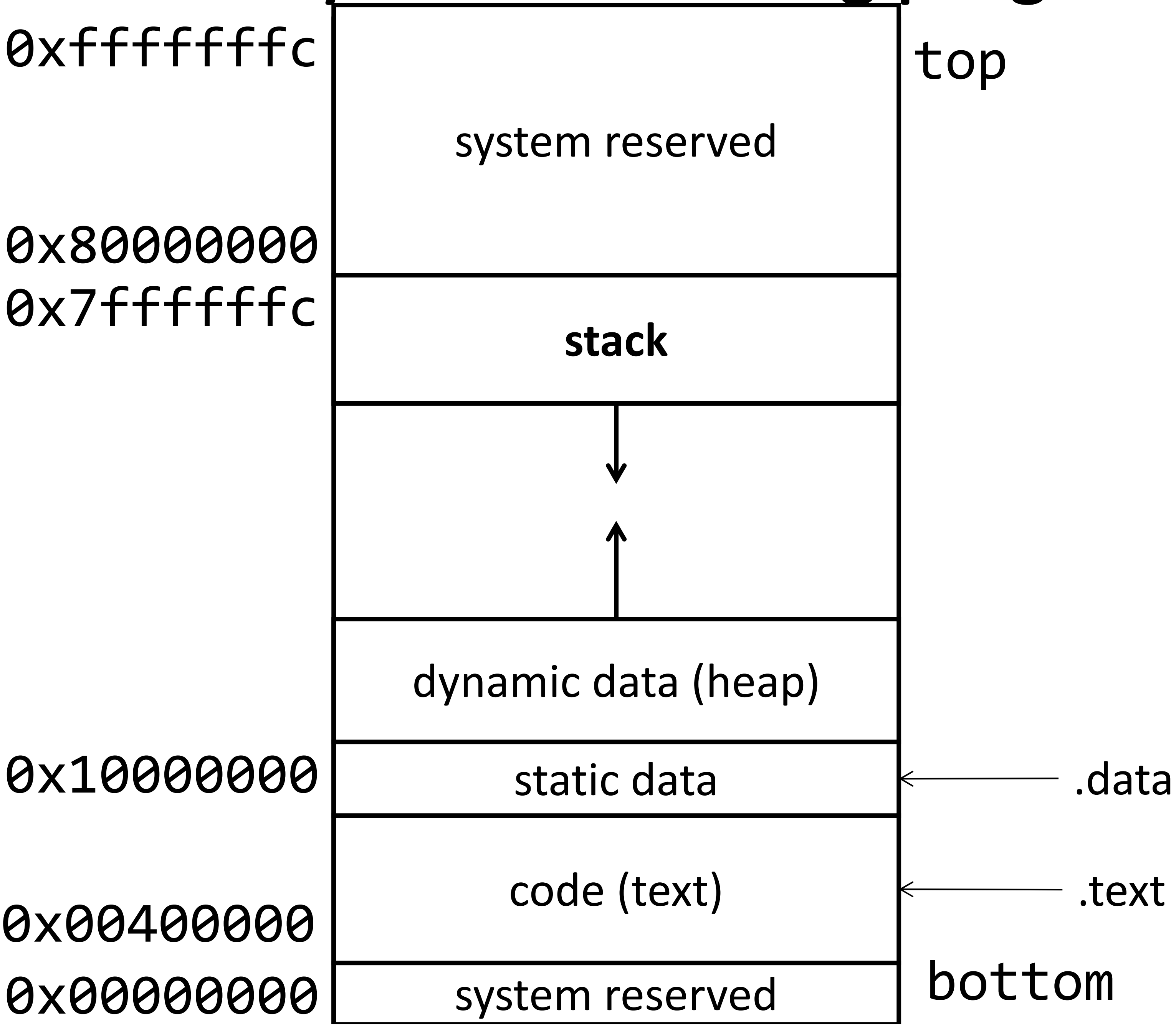
Loader brings it into memory and starts execution

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

Big Picture


calc.c
math.c
C source files
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: Review of Program Layout

calc.c

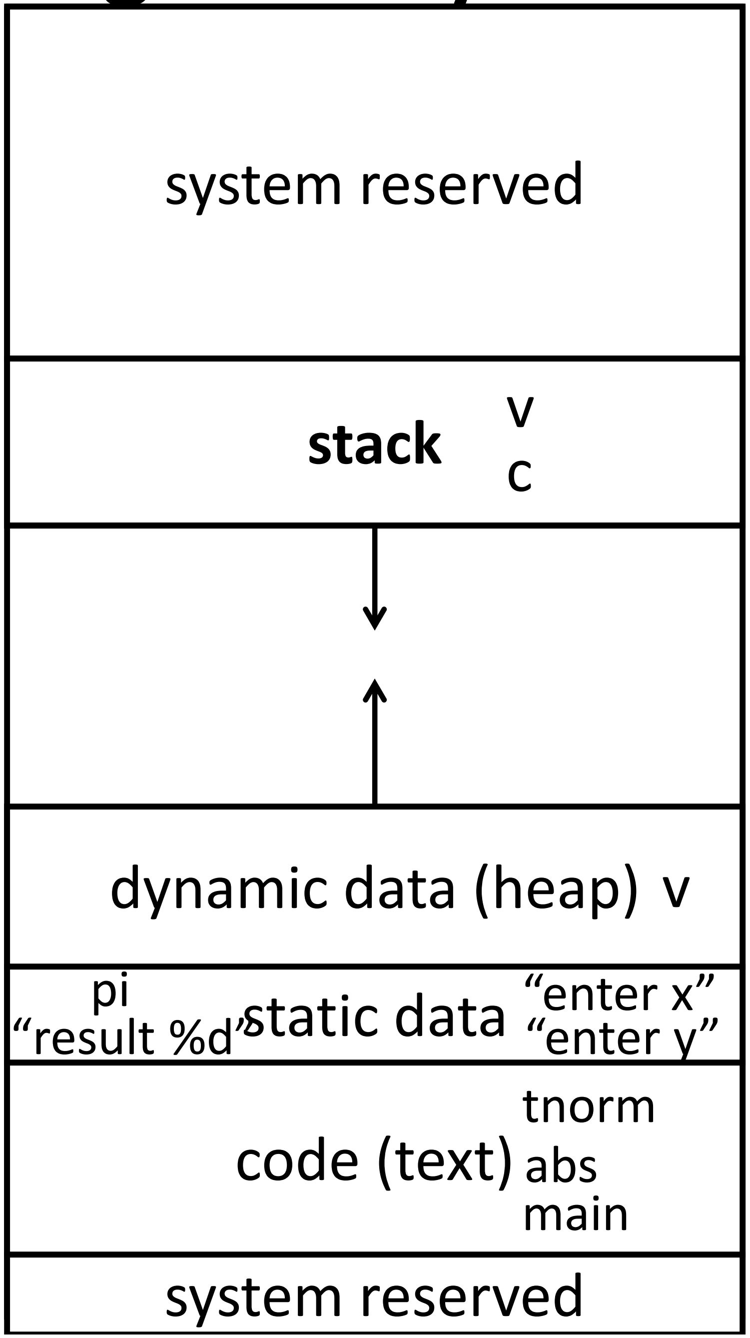
```
vector* v = malloc(8);
v->x = prompt("enter x");
v->y = prompt("enter y");
int c = pi + tnorm(v);
print("result %d", c);
```

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
```



system reserved

stack v c

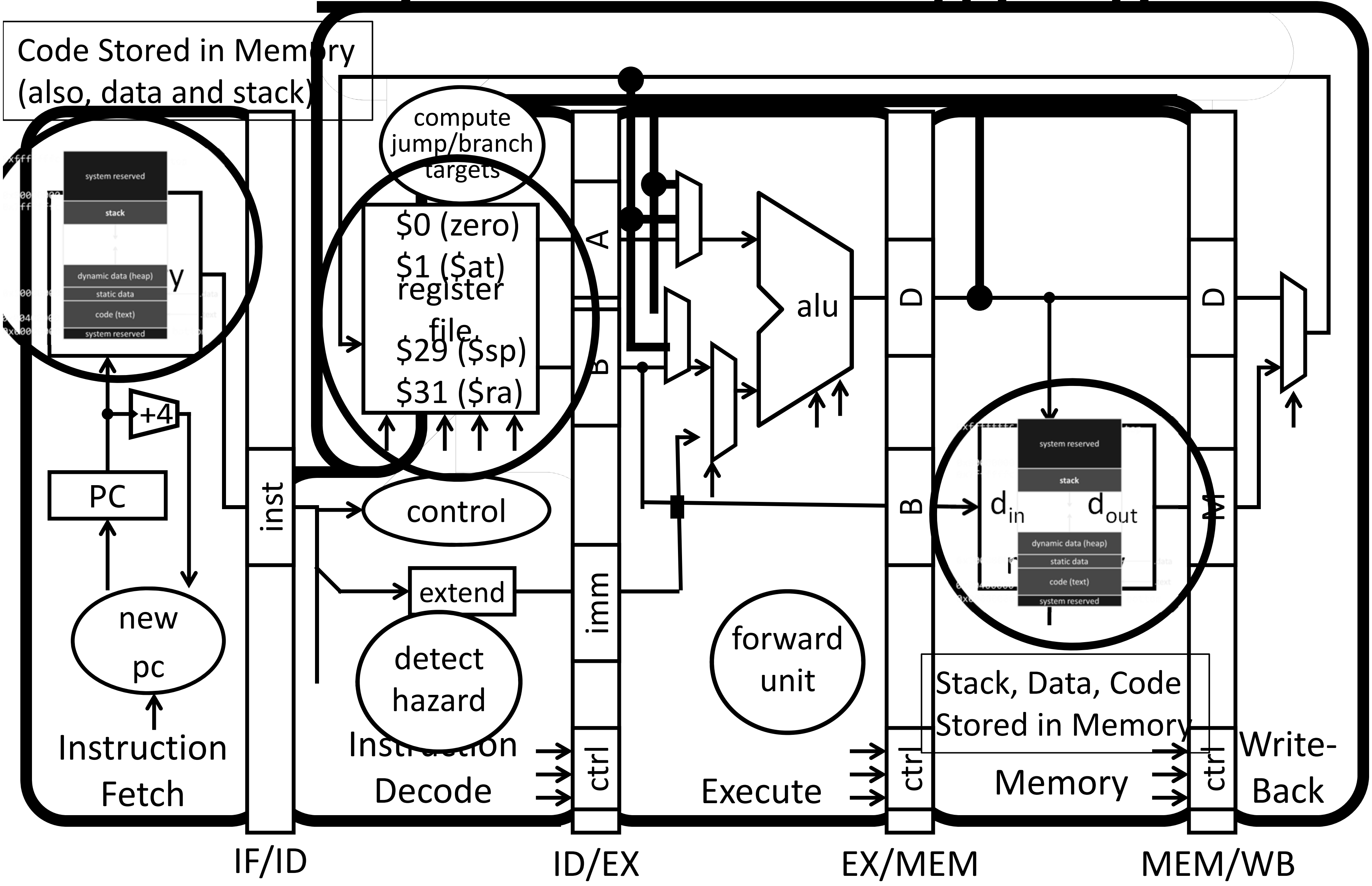
dynamic data (heap) v

pi "result %d" static data "enter x" "enter y"

code (text) tnorm abs main

system reserved

Anatomy of an executing program



Code Stored in Memory (also, data and stack)

Stack, Data, Code Stored in Memory

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
  ```

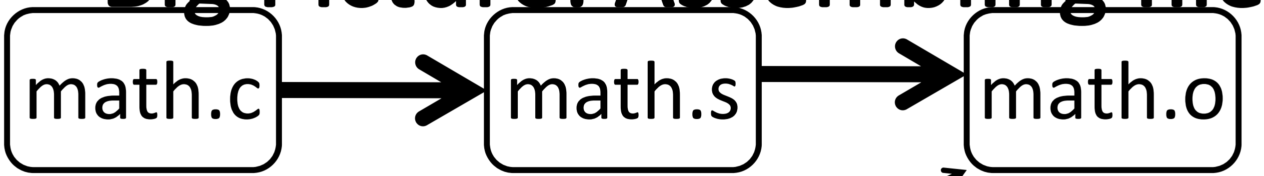
The assembler will change this to

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

Final machine code

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

Big Picture: Assembling file separately



.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

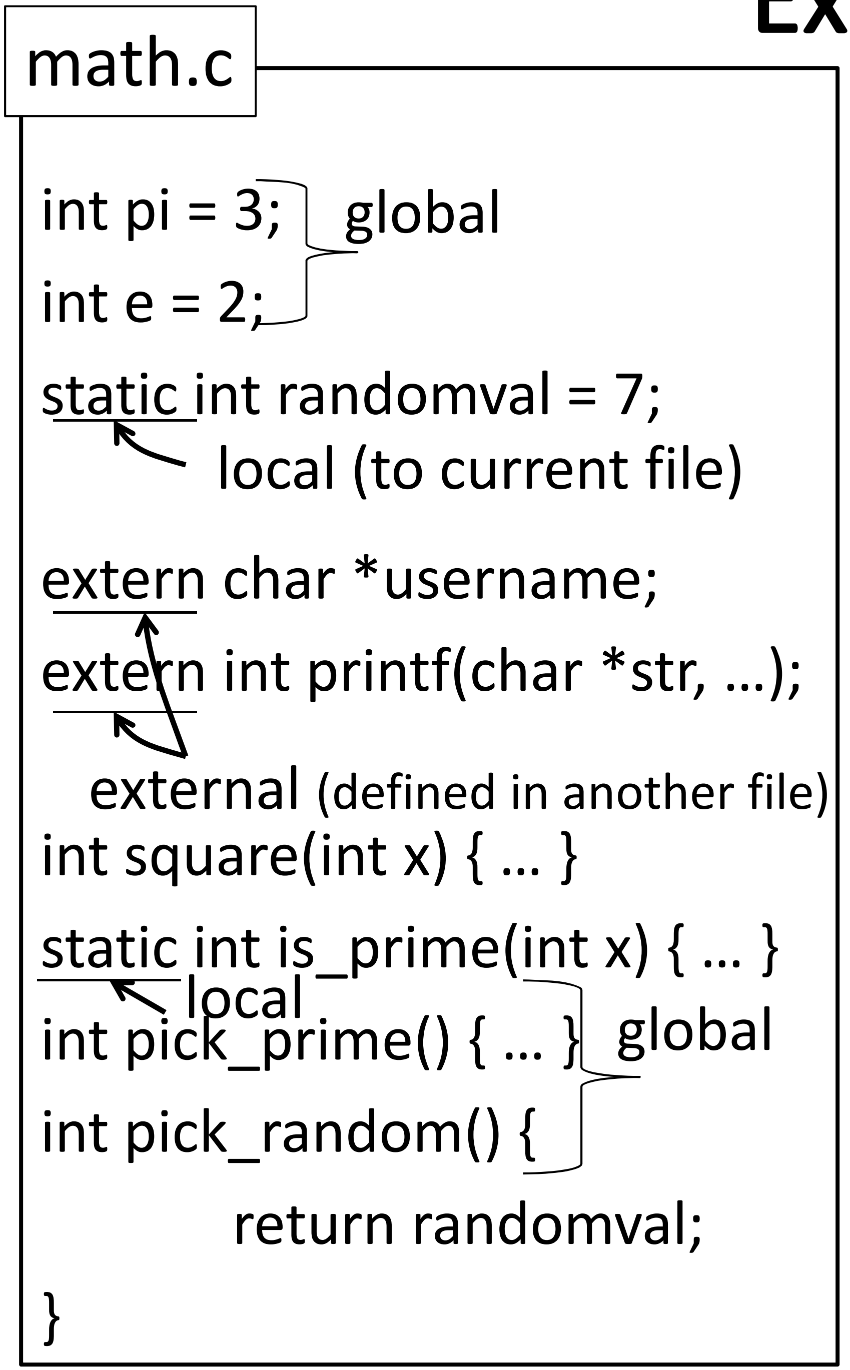
e.g.
$str
$L0
$L2

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;
}
```

```
gcc -S … math.c
gcc -c … math.s
objdump --disassemble math.o
objdump --syms math.o
```

Compiler

Assembler

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

```
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Disassembly of section .text:
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   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
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  30:     03a0f021        move    s8,sp
  34:     afc40008        sw      a0,8(s8)
```

Address

instruction

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

prologue

body

epilogue

resolved (fixed) later

symbol

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
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
```

Address

l: local

g: global

segment

segment size

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

f: func

O: obj

external reference

Separate Compilation

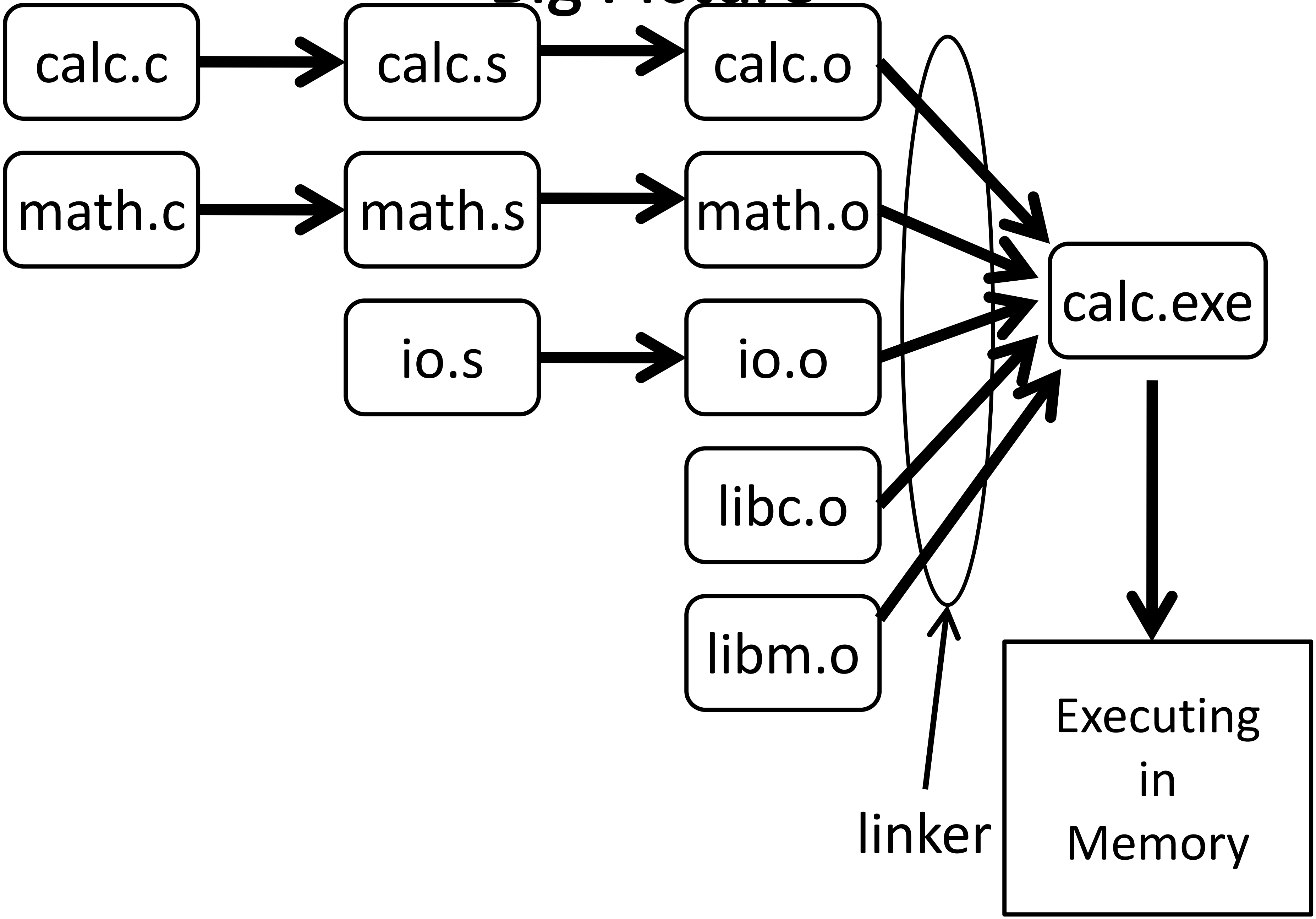
Q: Why separate compile/assemble and linking steps?

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
linker
Executing in Memory

Linkers

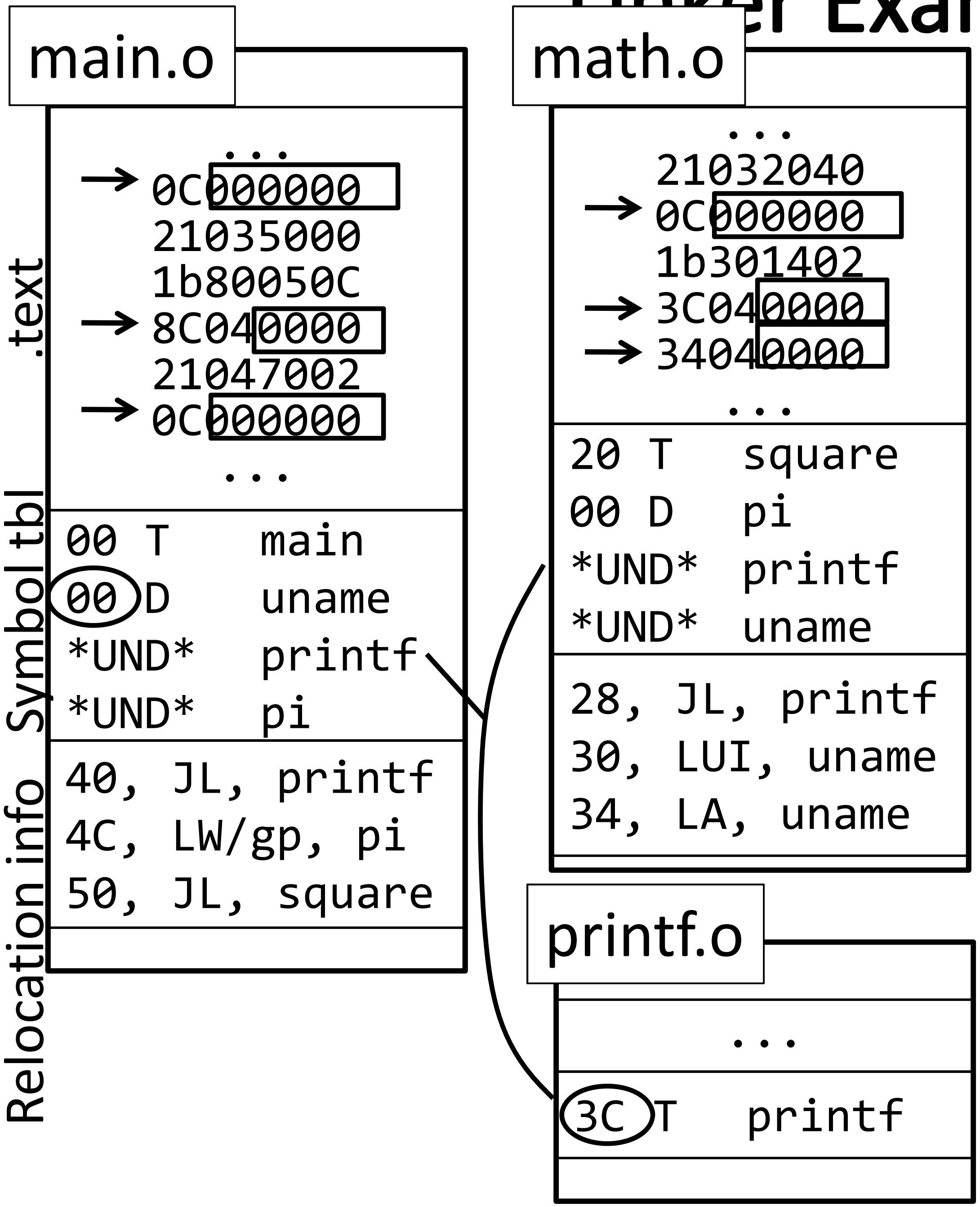
Linker combines object files into an executable file

- 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

```
        ...
→ 0C000000
  21035000
  1b80050C
→ 8C040000
  21047002
→ 0C000000
        ...
00 T     main
00 D     uname
*UND*    printf
*UND*    pi
40, JL, printf
4C, LW/gp, pi
50, JL, square
```

math.o

```
        ...
  21032040
→ 0C000000
  1b301402
→ 3C040000
→ 34040000
        ...
20 T   square
00 D   pi
*UND*  printf
*UND*  uname
28, JL, printf
30, LUI, uname
34, LA, uname
```

printf.o

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

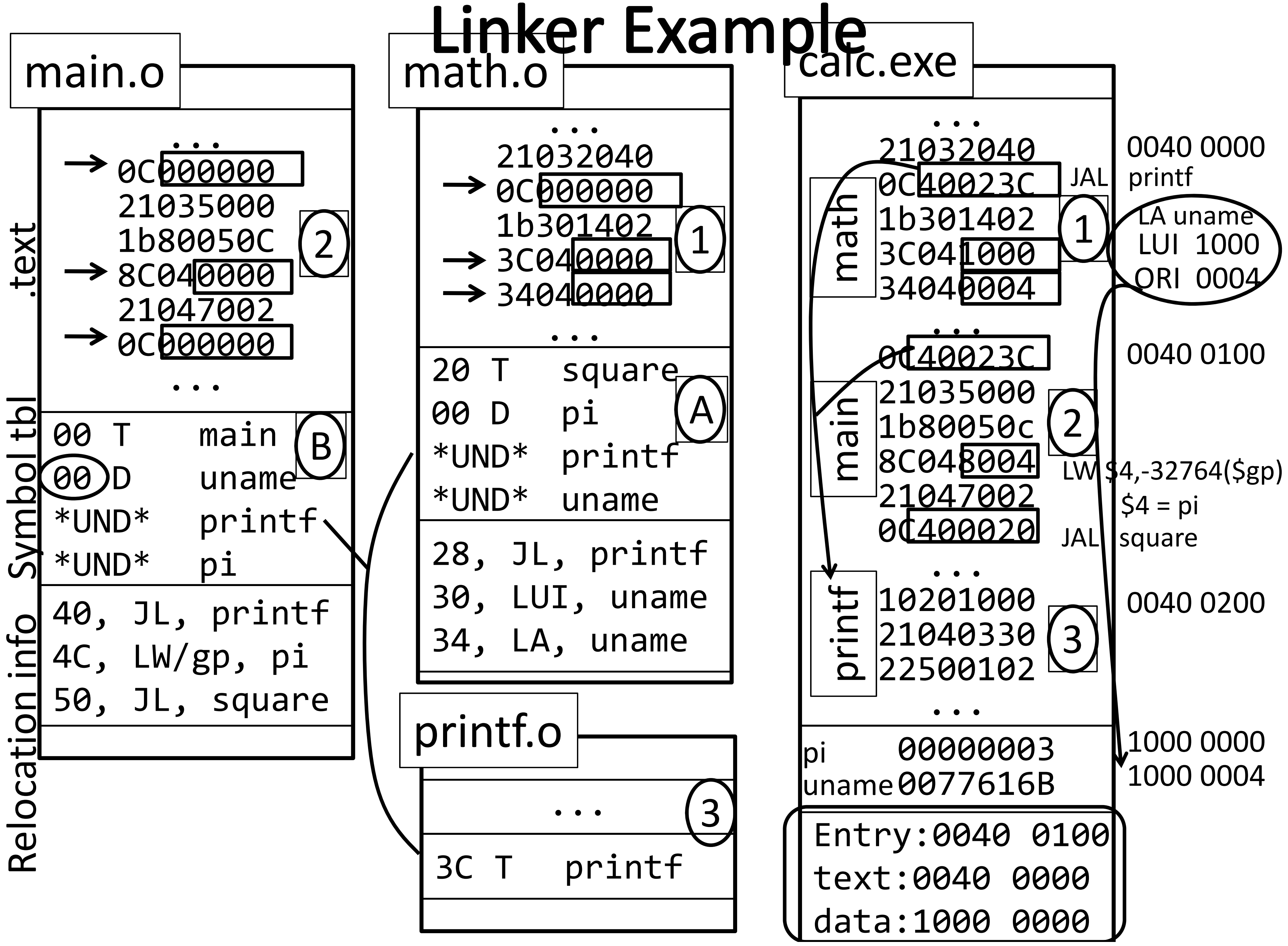
External references need to be resolved (fixed)

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      (2)
→ 8C040000
  21047002
→ 0C000000
      ...
Symbol tbl
00     T     main       (B)
00     D     uname
*UND*        printf
*UND*        pi
Relocation info
40, JL, printf
4C, LW/gp, pi
50, JL, square
```

math.o

```
      ...
  21032040
→ 0C000000
  1b301402      (1)
→ 3C040000
→ 34040000
      ...
20 T    square
00 D    pi          (A)
*UND*   printf
*UND*   uname
28, JL, printf
30, LUI, uname
34, LA, uname
```

printf.o

```
      ...       (3)
3C T   printf
```

calc.exe

```
          ...                    0040 0000
      21032040
math  0C40023C  JAL   printf
      1b301402  (1)    LA uname
      3C041000         LUI  1000
      34040004         ORI  0004
          ...
      0C40023C                   0040 0100
      21035000
main  1b80050c  (2)
      8C048004  LW $4,-32764($gp)
      21047002        $4 = pi
      0C400020  JAL   square
          ...
printf 10201000                  0040 0200
      21040330  (3)
      22500102
          ...
pi      00000003                 1000 0000
uname   0077616B                 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
- …

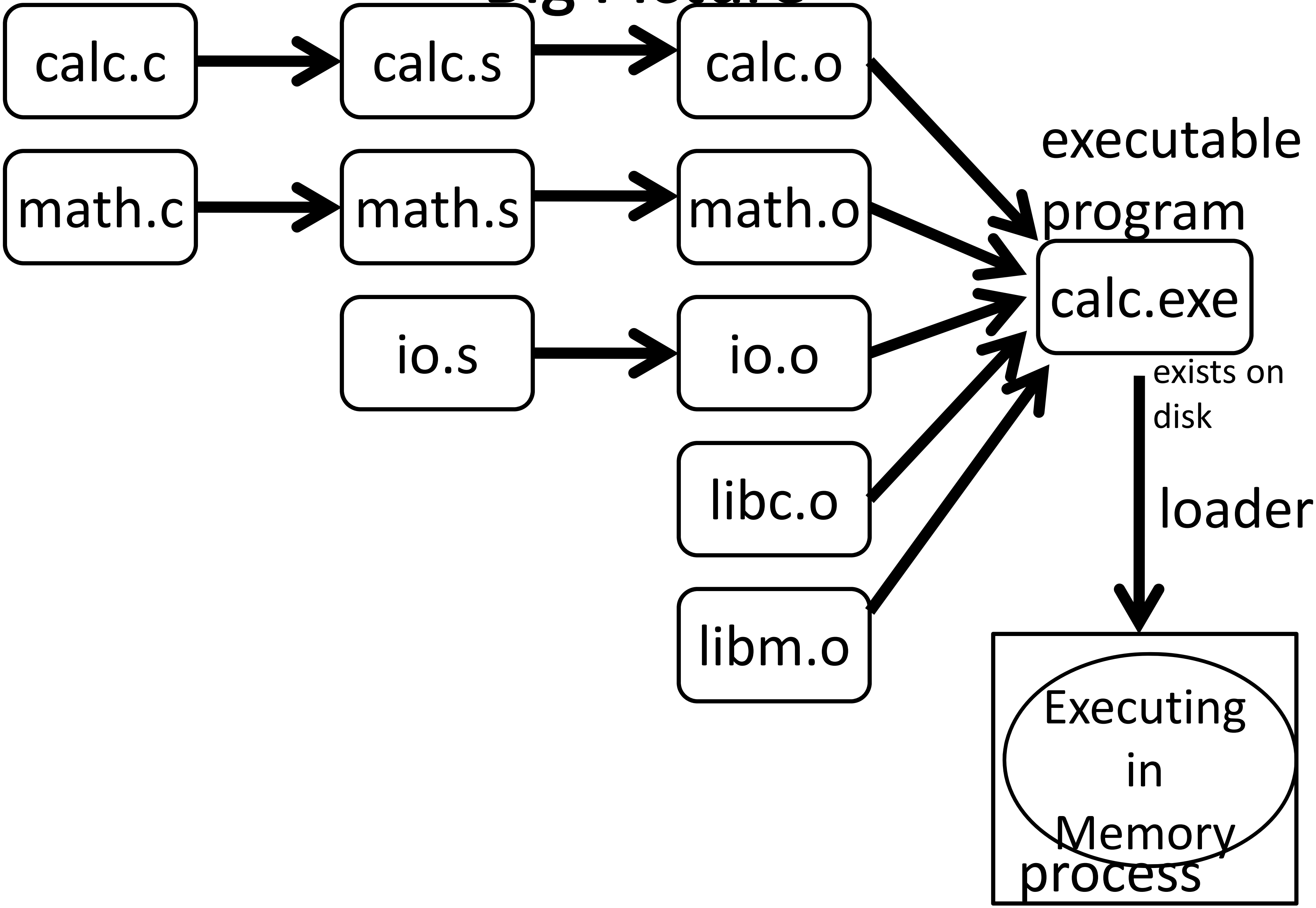
Windows

- PE: Portable Executable

All support both executable and object files

Loaders and Libraries

Big Picture



calc.c

calc.s

calc.o

math.c

math.s

math.o

io.s

io.o

libc.o

libm.o

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, …)

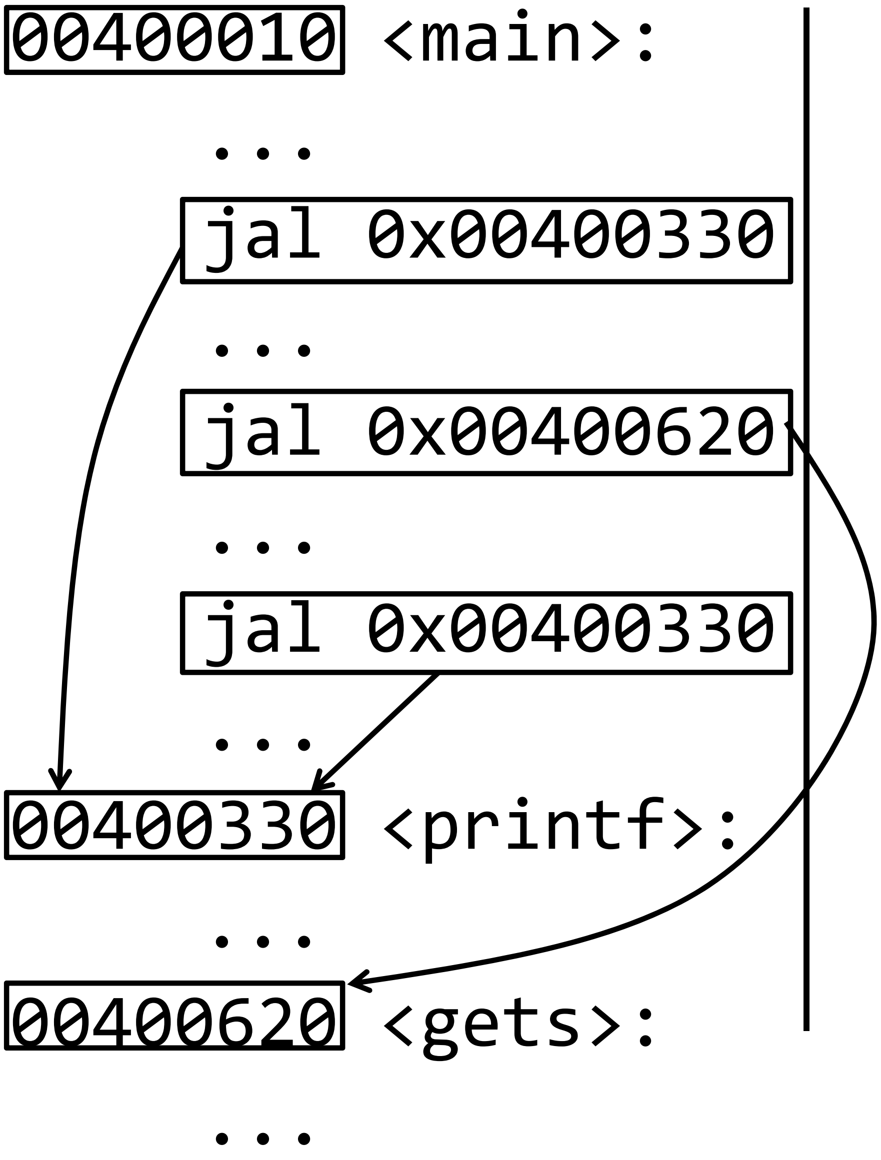
Idea:

Put all symbols in a single "global offset table"

Code does lookup as needed

Indirect Function Calls

Indirect call:

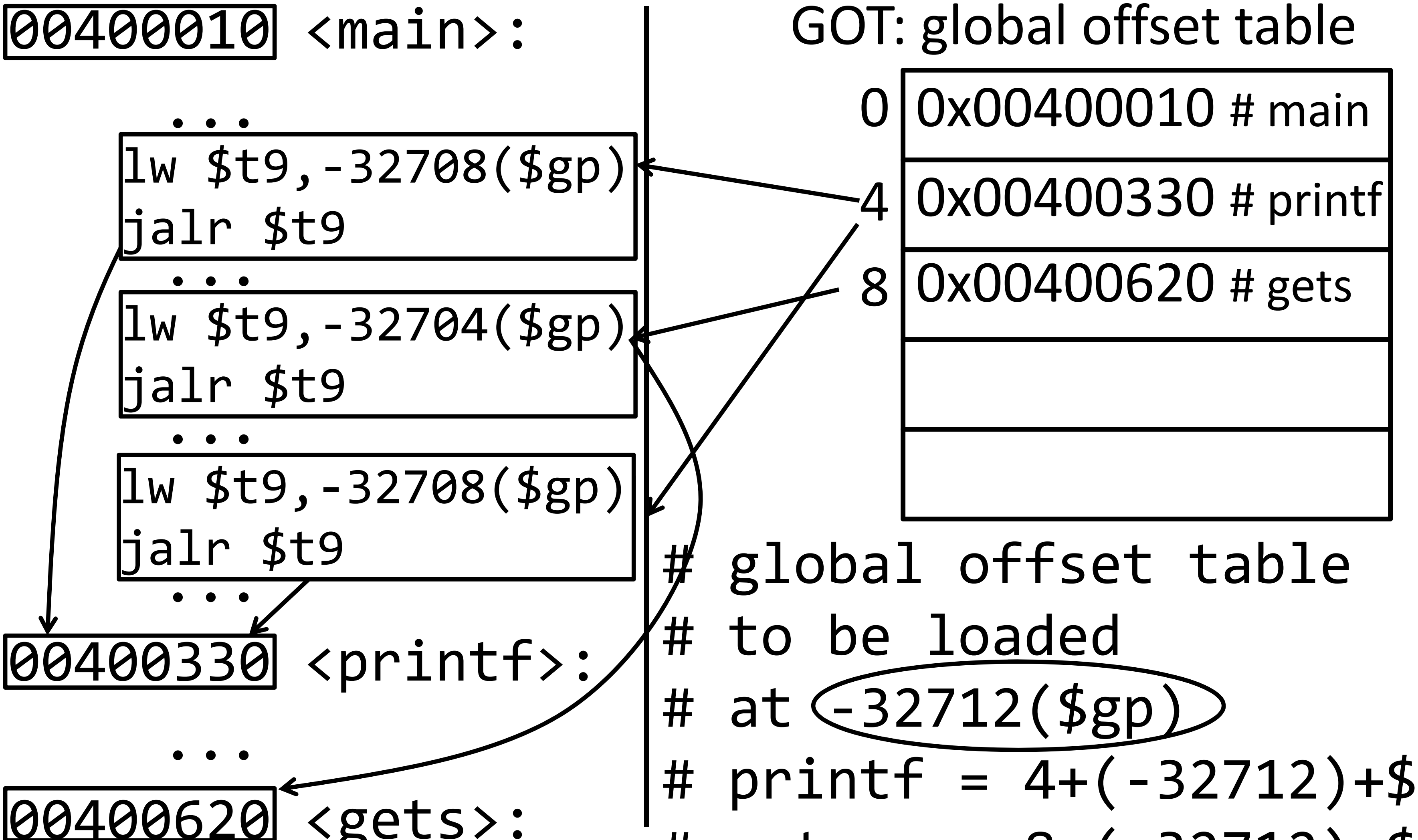


```
00400010 <main>:
      ...
      jal 0x00400330
      ...
      jal 0x00400620
      ...
      jal 0x00400330
      ...
00400330 <printf>:
      ...
00400620 <gets>:
      ...
```

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
```

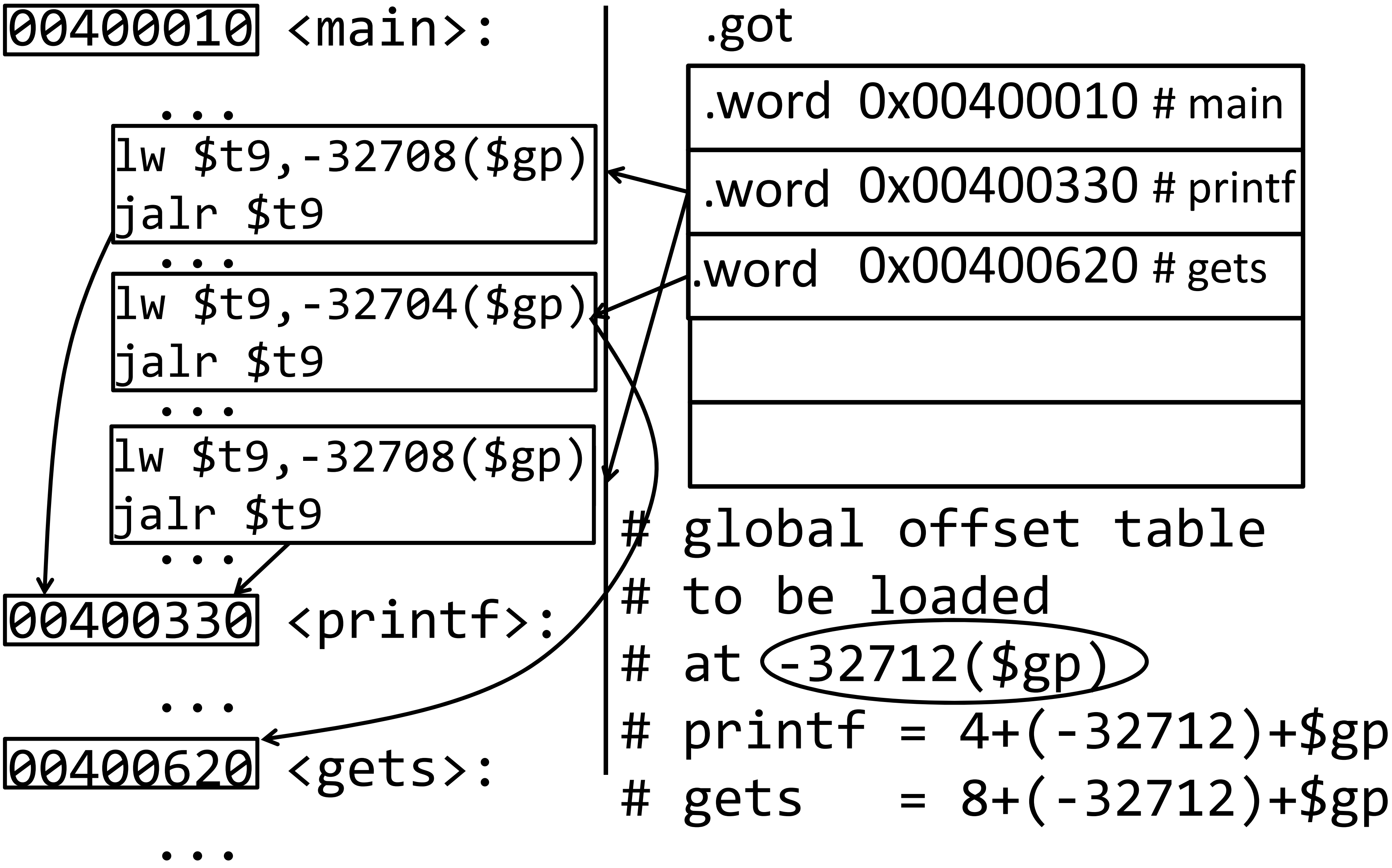
GOT: global offset table

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
```

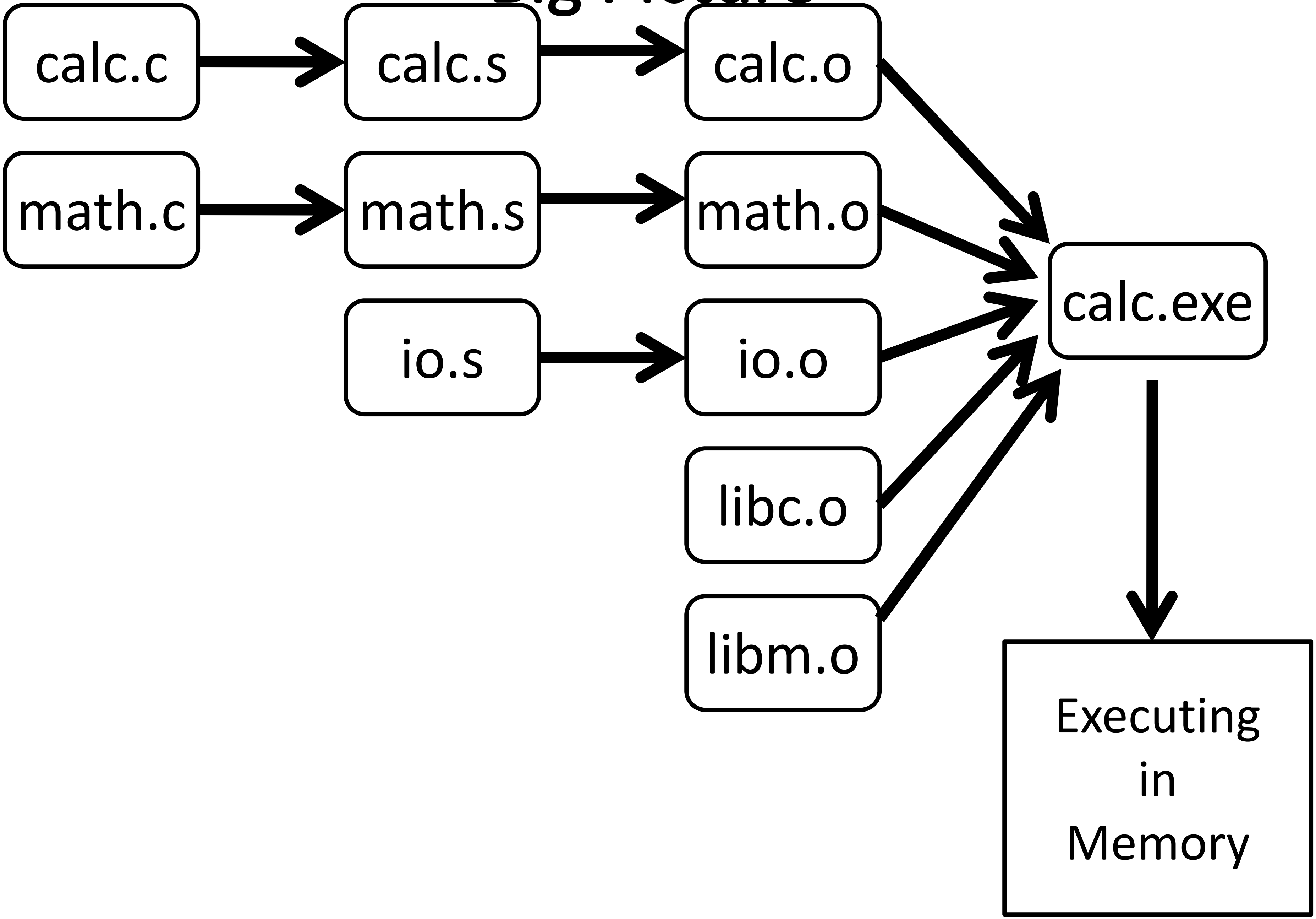
```
   ...
00400888 <dlresolve>:
   # t9 = 0x400888
   # t8 = index of func that
   #    needs to be loaded

   # 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


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

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