Assemblers, Linkers, and Loaders

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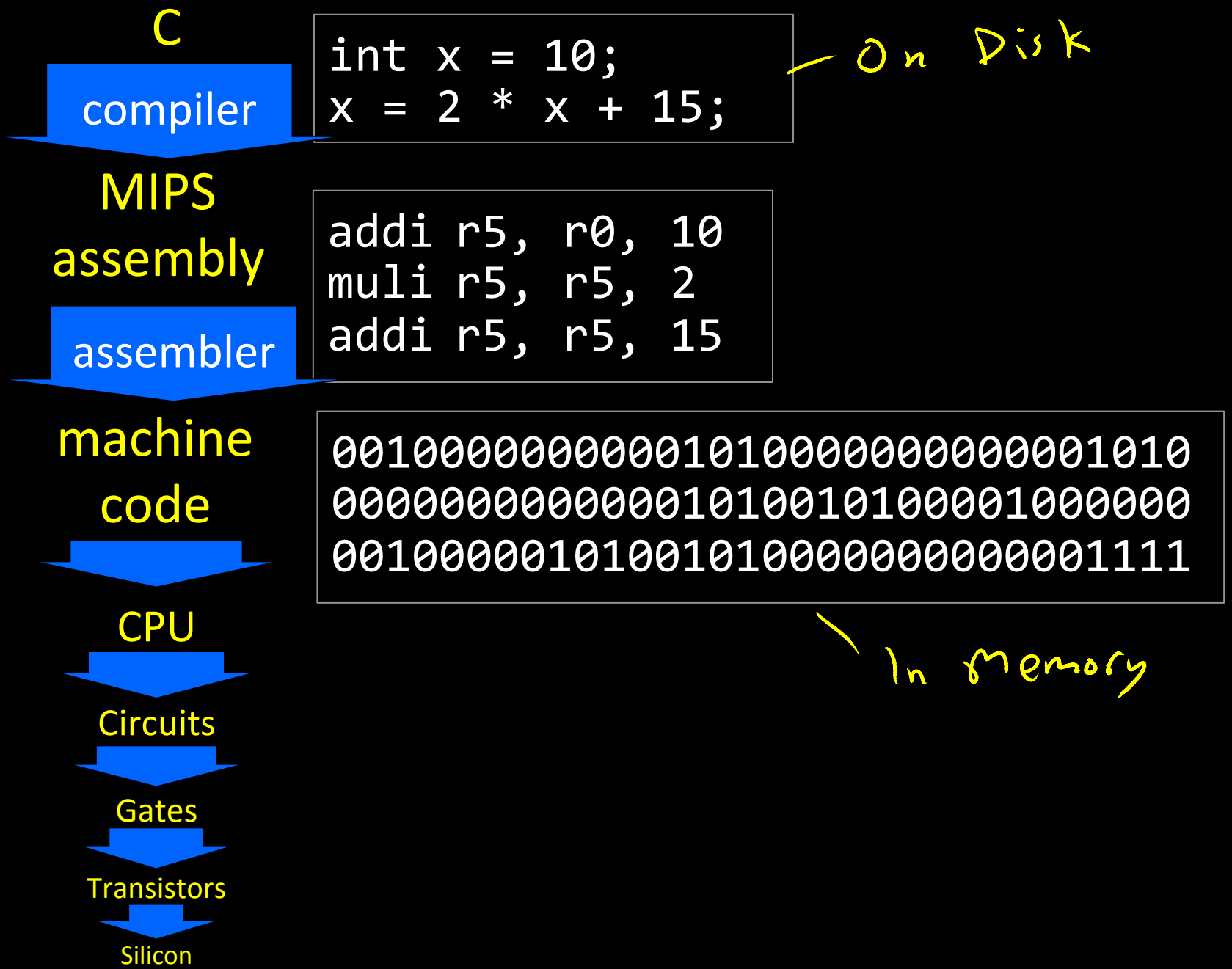
See: P&H Appendix B.3-4


C
compiler
int x = 10;
x = 2 * x + 15;
On Disk
MIPS assembly
assembler
addi r5, r0, 10
muli r5, r5, 2
addi r5, r5, 15
machine code
00100000000001010000000000001010
00000000000001010010100001000000
00100000101001010000000000001111
In memory
CPU
Circuits
Gates
Transistors
Silicon

calc.c

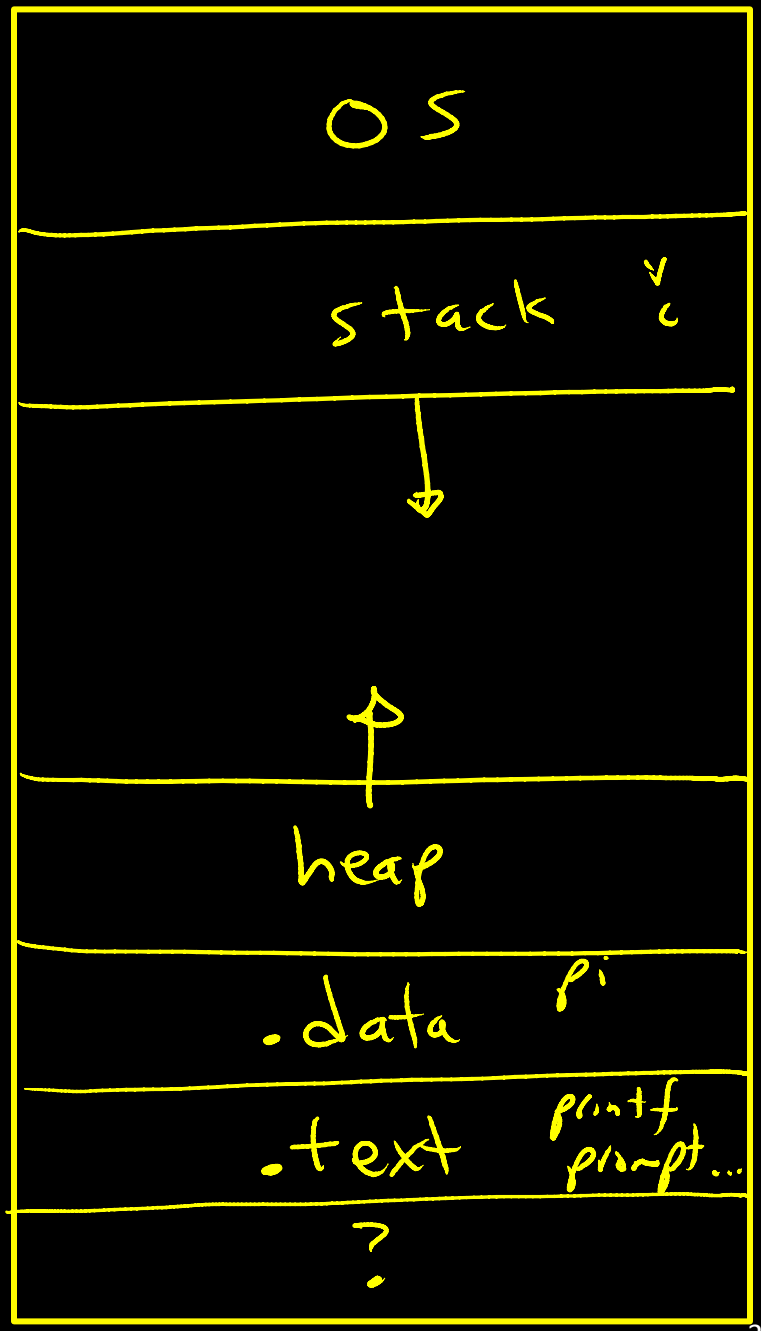
```
vector v = malloc(8);
v->x = prompt("enter x");
v->y = prompt("enter y");
int c = pi + tnorm(v);
print("result", c);
```

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
```



```
int n = 100;

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

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

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

```
[csug01] mipsel-linux-gcc –S add1To100.c
```

```
        .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
```

n

constant strings

prolog

call printf.

epilog

Variables	Visibility	Lifetime	Location
Function-Local i, m, count, A, argc, argv	within function	function invocation	stack
Global n	whole program	program execution	.data
Dynamic *A	?	between malloc and free	heap

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

Variables	Visibility	Lifetime	Location
Function-Local i, m, count, A, argc, argv	within function	function invocation	stack
Global n	whole program	program execution	.data
Dynamic *A	?	between 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; }
```

"address of" something on stack!

also on stack! Both invalid after return!

points to free space in heap

(Can't do this in Java, C#, …)

Variables	Visibility	Lifetime	Location
Function-Local i, m, count, A, argc, argv	within function	function invocation	stack
Global n	whole program	program execution	.data
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C Pointers can be trouble

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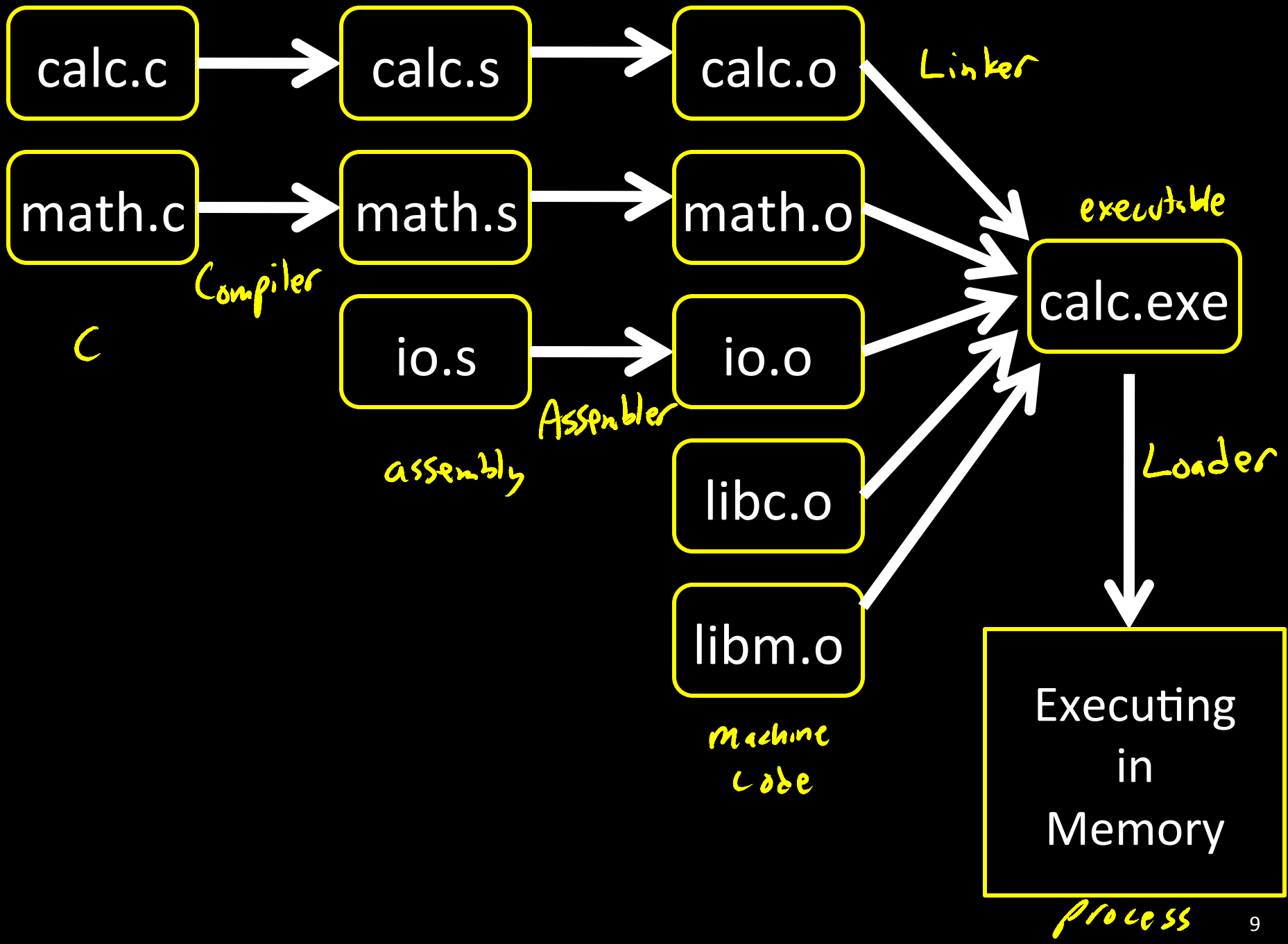
int *trouble()
{ int a; …; return &a; }
char *evil()
{ char s[20]; gets(s); return s;}
int *bad()
{ s = malloc(20); … free(s); … return s; }
```

Banned in Java, …

(Can't do this in Java, C#, …)


calc.c
calc.s
calc.o
Linker
math.c
math.s
math.o
executable
Compiler
C
calc.exe
io.s
io.o
Assembler
assembly
Loader
libc.o
libm.o
Machine Code
Executing in Memory
Process

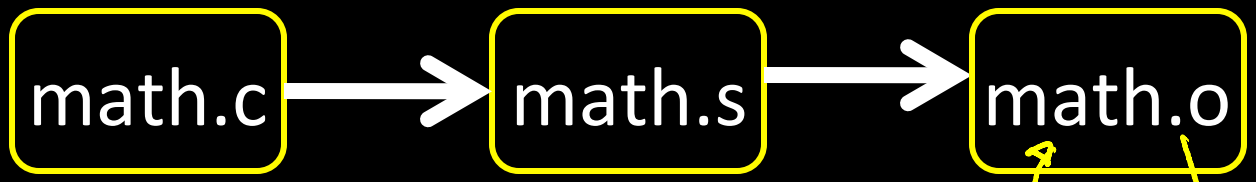
Compiler output is assembly files

Assembler output is obj files

Linker joins object files into one executable

Loader brings it into memory and starts execution

Compilers and Assemblers



- .o = linux
- .obj = Windows

- Call to exported function
- reference to exported var

- Call to extern function
- reference extern variable

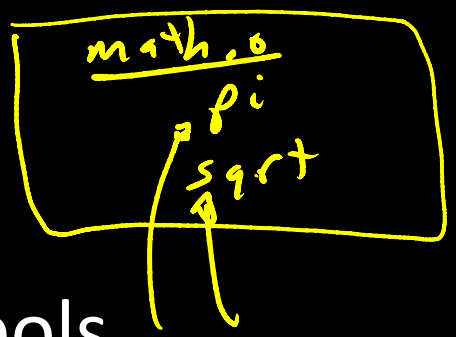
Output is obj files

- Binary machine code, but not executable
- May refer to external symbols
- Each object file has illusion of its own address space
  - Addresses will need to be fixed later

- Code starts at 0x0
- data starts at 0x0

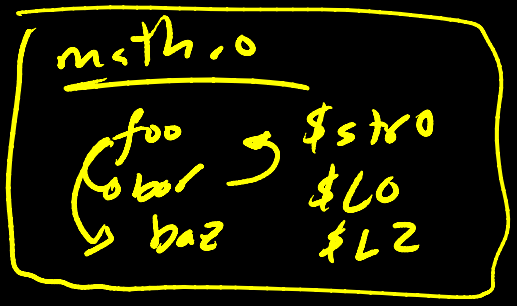
Global labels: Externally visible "exported" symbols

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



Local labels: Internal visible only symbols

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



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

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 only

Defined in some other file

global

local

global

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

compiler

assembler

List symbols

reverse assembler

```
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)
  ...
```

addresses

Mem[8]

This is wrong address — Need to fix to point to data section!

prolog

Body:

epilog

v0 = 0
v0 = mem[8 + v0]
= mem[8 + 0]
= mem[8]
= 0x03a0f021

should be return random val

v0 = 7

?!

symbol

```
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

SYMBOL TABLE:

l = local
g = global

section

size

symbol

F = function
O = var

external references

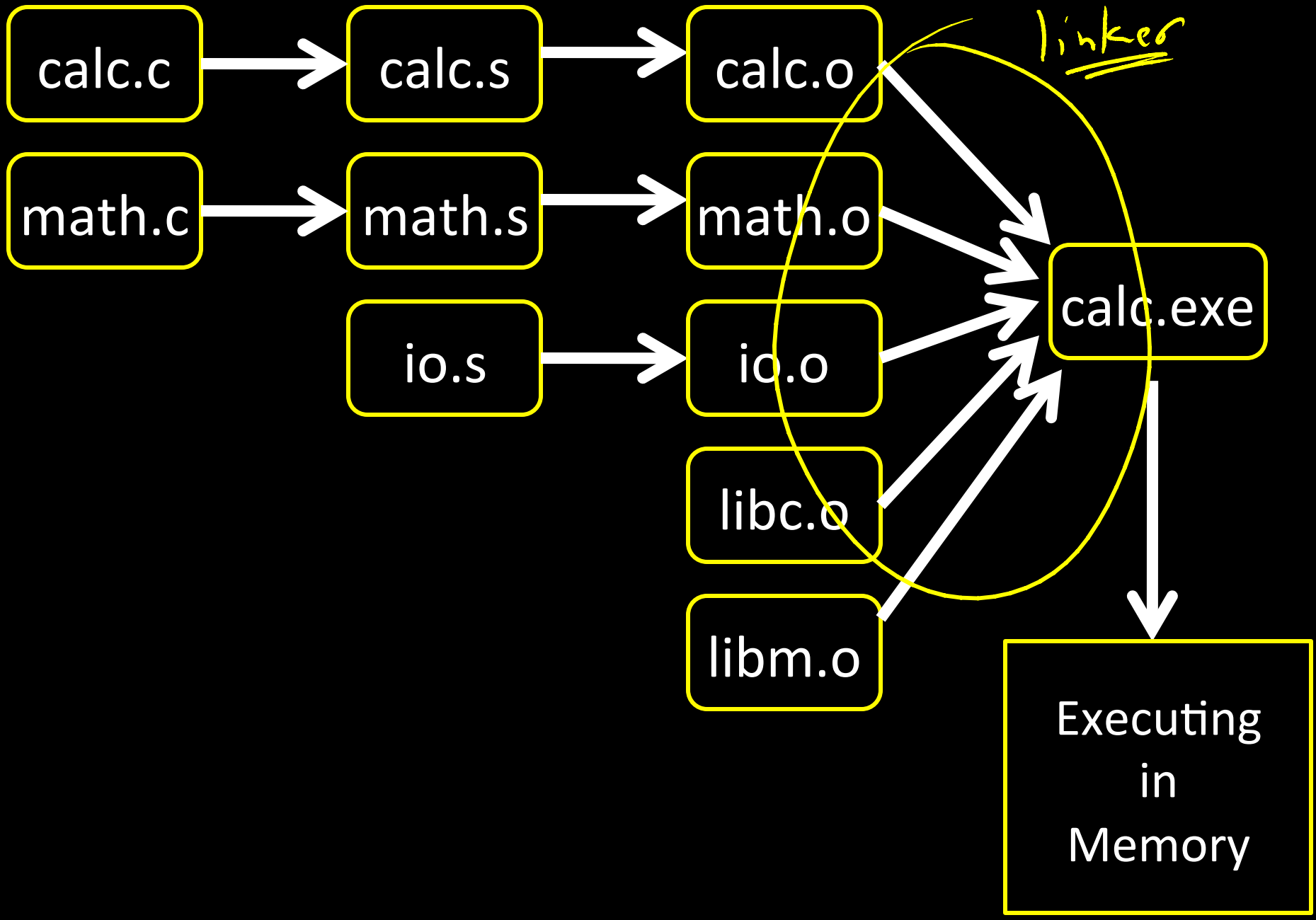
static/local function @ address 60 code size = 28

global 4 byte variable @ address 4

Q: Why separate compile/assemble and linking steps?

A: Can recompile one object, then just relink.

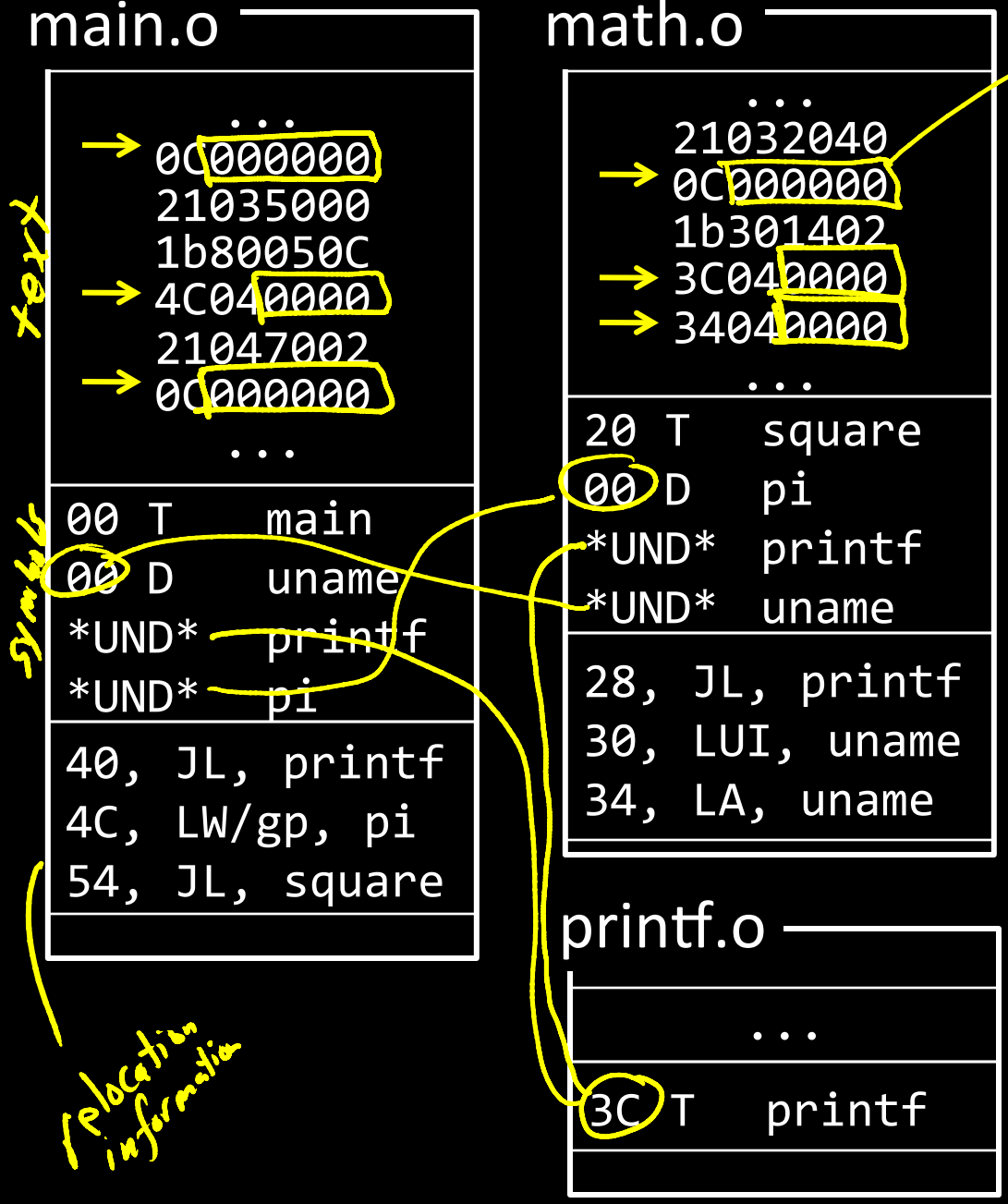
Linkers

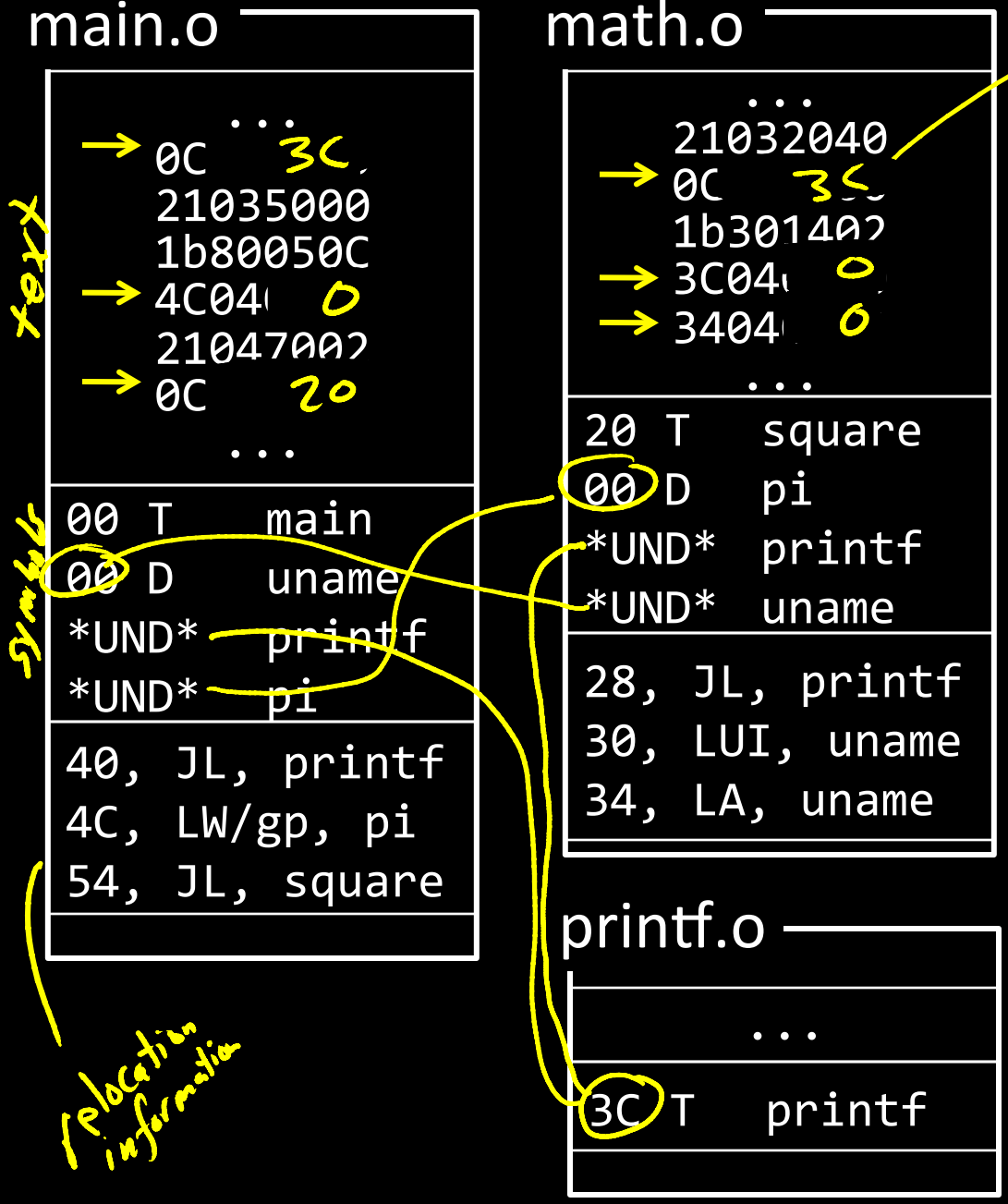

calc.c
calc.s
calc.o
linker
math.c
math.s
math.o
calc.exe
io.s
io.o
libc.o
libm.o
Executing
in
Memory

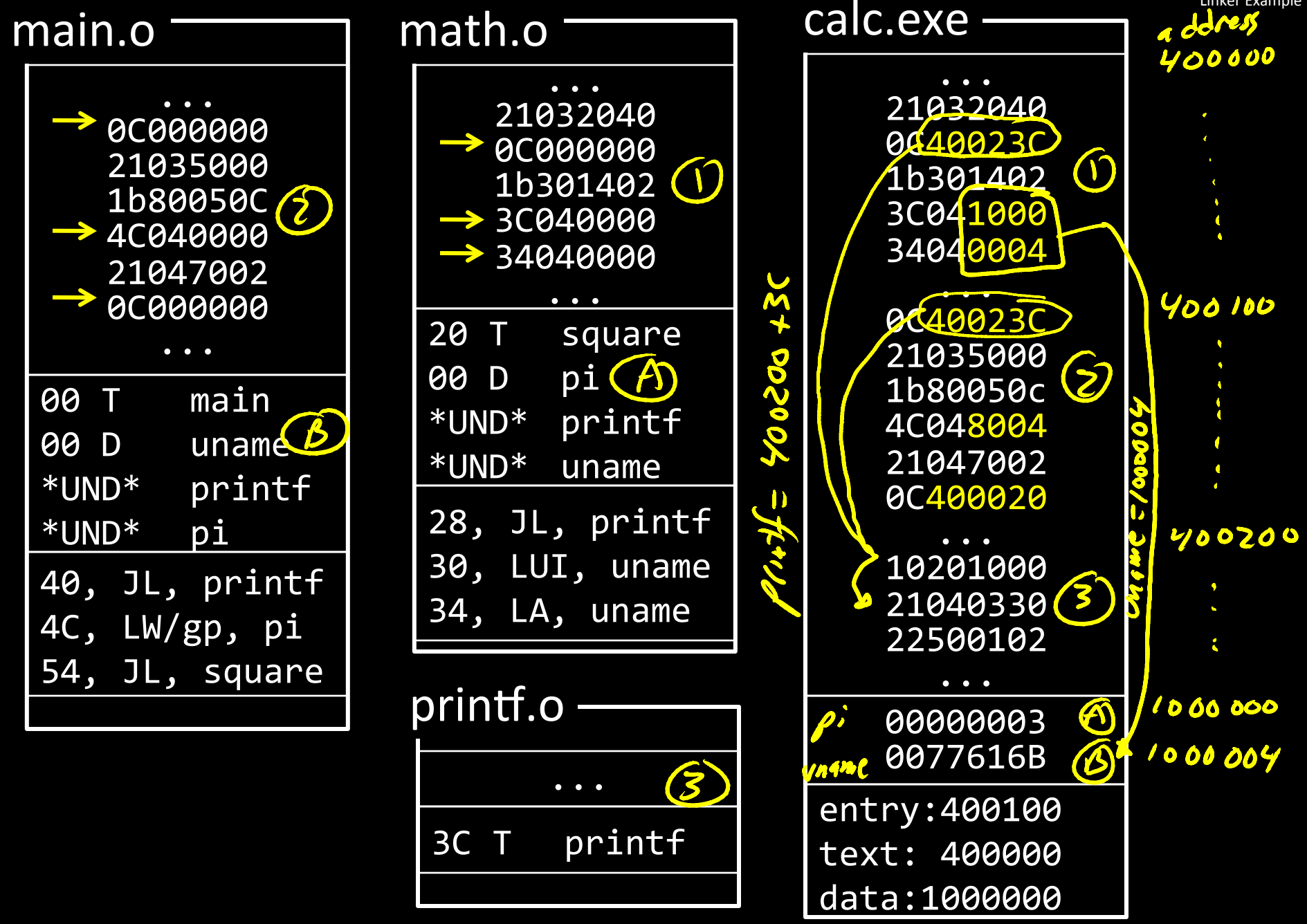
Linker combines object files into an executable file

- 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


main.o
...
0C000000
21035000
1b80050C
4C040000
21047002
0C000000
...
text
00 T main
00 D uname
UND printf
UND pi
symbols
40, JL, printf
4C, LW/gp, pi
54, JL, square
relocation information
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
lots of ∅ bytes - these are external references, need to be fixed
(1) Find UND symbols in other tables


main.o
...
0C 3C
21035000
1b80050C
4C04 0
21047002
0C 20
...
text
00 T main
00 D uname
UND printf
UND pi
symbols
40, JL, printf
4C, LW/gp, pi
54, JL, square
relocation information
math.o
...
21032040
0C 3C
1b301402
3C04 0
3404 0
...
20 T square
00 D pi
UND printf
UND uname
28, JL, printf
30, LUI, uname
34, LA, uname
printf.o
...
3C T printf
lots of ∅ bytes - these are external references, need to be fixed
(1) Find UND symbols in other tables
(2) Patch Code
→ Addresses collide
uname @ 0
pi @ 0
main @ 0
square @ 20
...
→ Need to relocate first


main.o
...
0C000000
21035000
1b80050C
4C040000
21047002
0C000000
...
00 T main
00 D uname
UND printf
UND pi
40, JL, printf
4C, LW/gp, pi
54, 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
calc.exe
...
21032040
0C40023C
1b301402
3C041000
34040004
...
0C40023C
21035000
1b80050c
4C048004
21047002
0C400020
...
10201000
21040330
22500102
...
pi 00000003
uname 0077616B
entry:400100
text: 400000
data:1000000
printf = 400200 +3C
uname = 1000004
address
400000
400100
400200
1000000
1000004

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

Unix

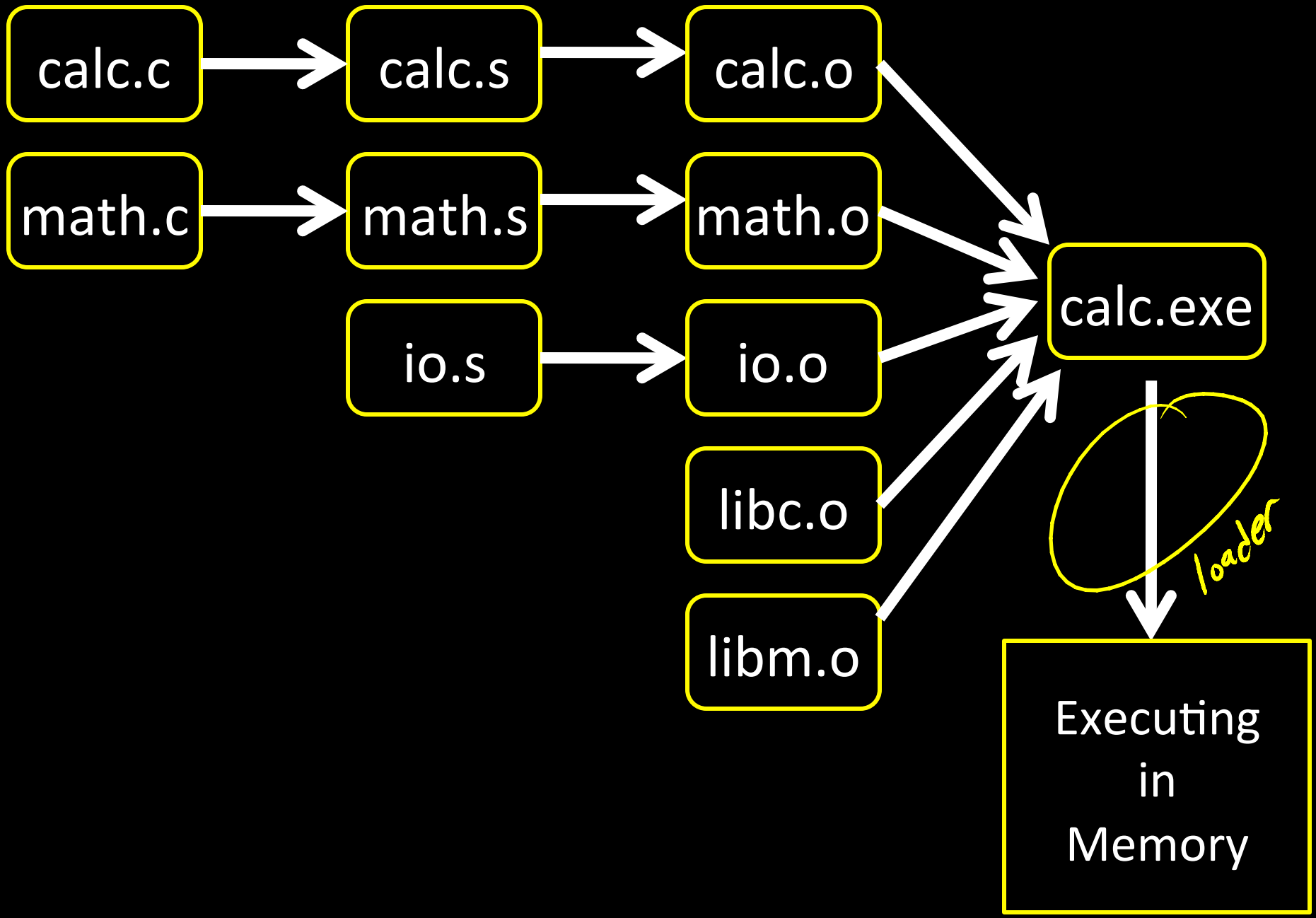
- a.out — older
- COFF: Common Object File Format
- ELF: Executable and Linking Format
- …

Windows

- PE: Portable Executable

All support both executable and object files

Loaders and Libraries


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

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

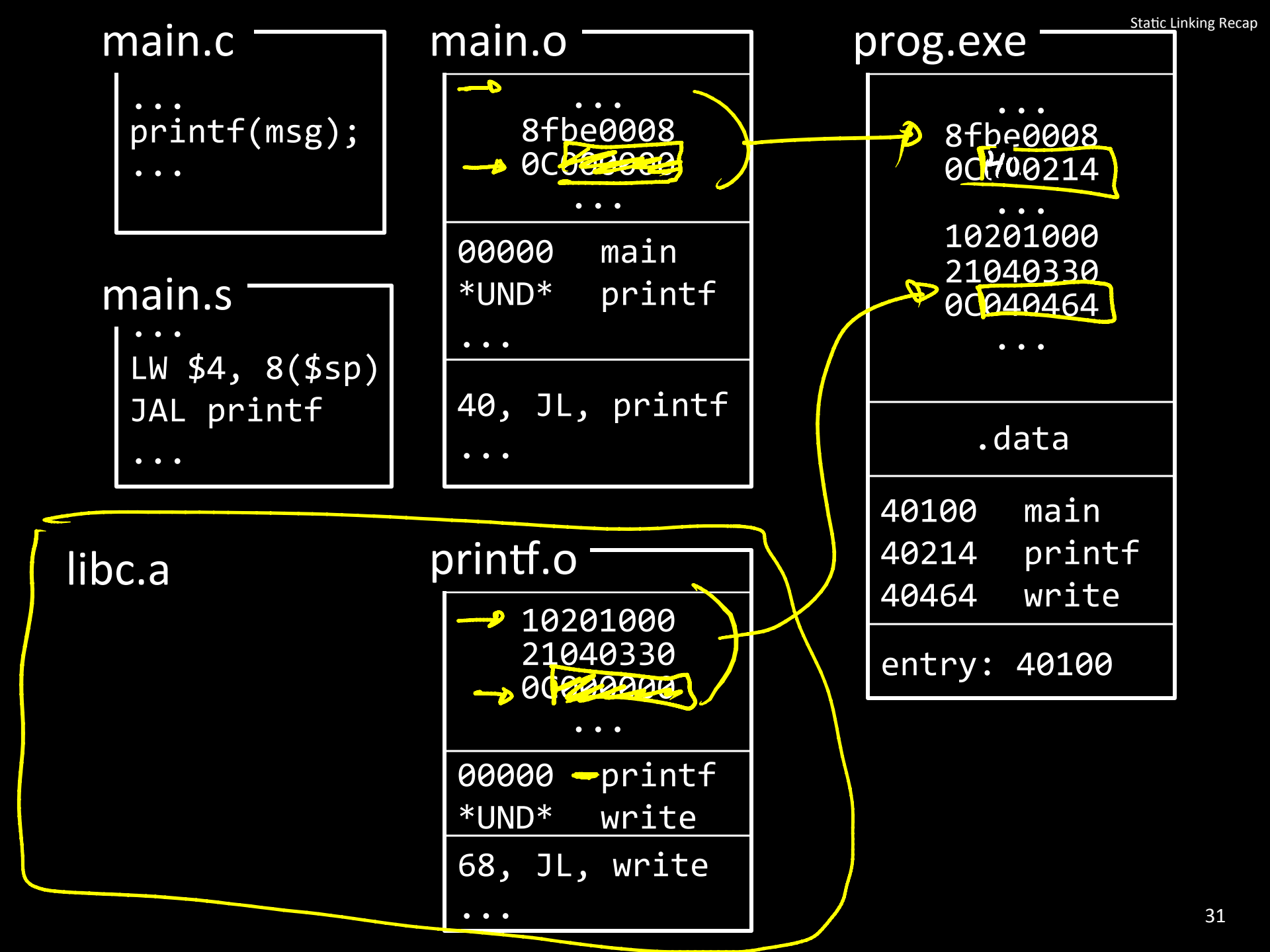
- .a = linux
- .lib = windows

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, ….


main.c
...
printf(msg);
...
main.s
...
LW $4, 8($sp)
JAL printf
...
main.o
...
8fbe0008
0C000000
...
00000 main
UND printf
...
40, JL, printf
...
prog.exe
...
8fbe0008
0C100214
...
10201000
21040330
0C040464
...
.data
40100 main
40214 printf
40464 write
entry: 40100
libc.a
printf.o
10201000
21040330
0C000000
...
00000 printf
UND write
68, JL, write
...

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 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

```
00400010 <main>:
   L:W temp, GOT[0]
   jal 0x00400330
   JALR temp
   ...
   jal 0x00400620
   ...
   jal 0x00400330
   ...
00400330 <printf>:
   ...
00400620 <gets>:
   ...
```

GOT: global offset table

printf	400330
gets	400620

Indirect call:

```
00400010 <main>:
   ...
   lw t9, -32708(gp)
   jalr t9
   ...
   lw t9, ? # gets
   jalr t9
   ...
00400330 <printf>:
   ...
00400620 <gets>:
   ...
```

```
# data segment
   ...
   ...
# global offset table
# to be loaded
# at -32712(gp)
.got
-712 .word 00400010 # main
-708 .word 00400330 # printf
-704 .word 00400620 # gets
   ...
```

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
```

RA

if (!loaded)
load printf and fix table
call printf
return

Indirect call with on-demand dynamic linking:

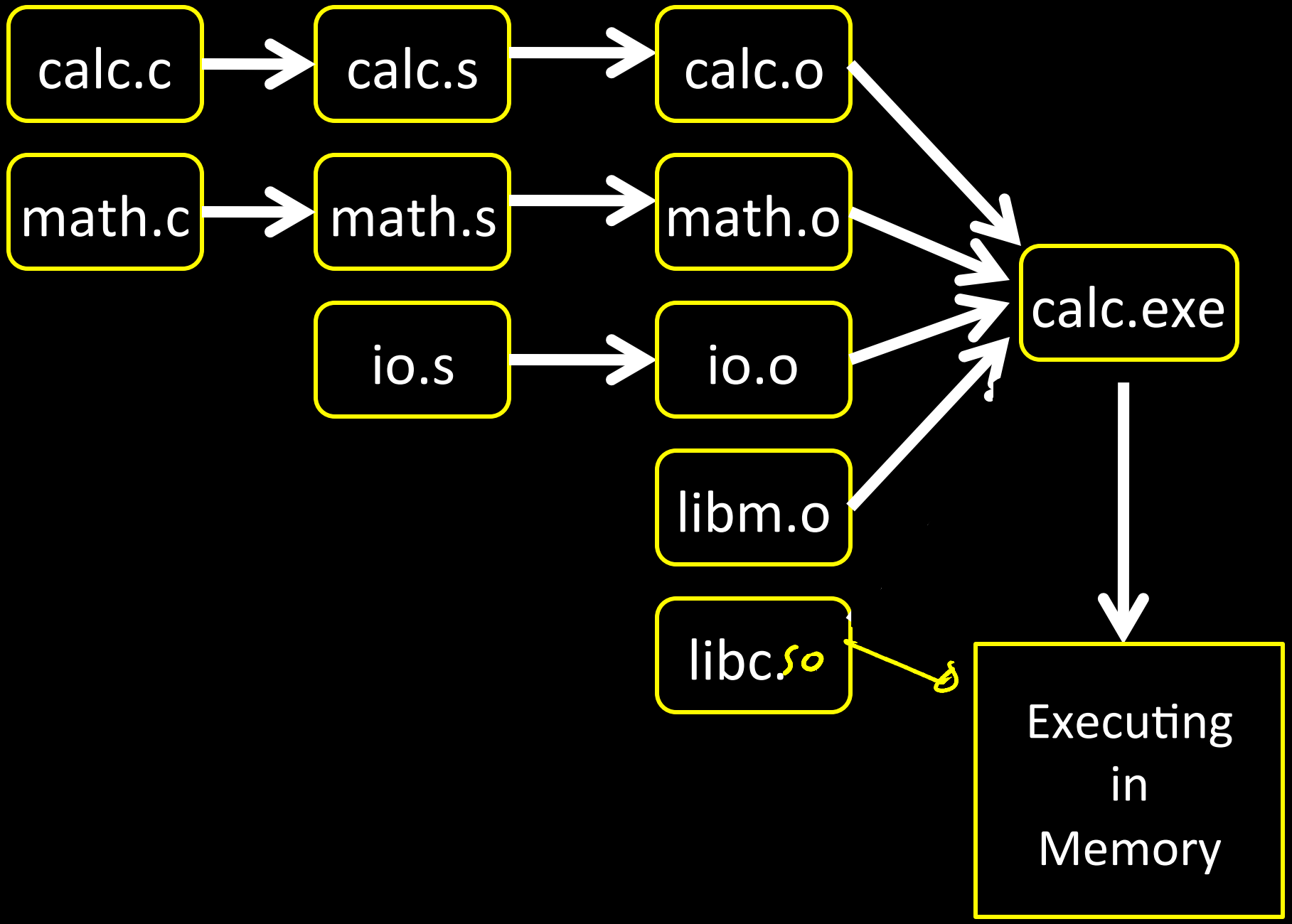
```
00400010 <main>:
   ...
   # load address of prints
   # from .got[1]
   lw t9, -32708(gp)
   # also load the index 1
   li t8, 1
   # now call it
   jalr t9
   ...
.got
   .word 00400888 # open
   .word 00400888 # prints
   .word 00400888 # gets
   .word 00400888 # foo
```

```
   ...
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
```


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

Windows: dynamically loaded library (DLL)

- PE format

Unix: dynamic shared object (DSO) .so

- 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 linking

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

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 faster to load initial code)
- But dll code is probably already in memory
- And can do the linking incrementally, on-demand