Assemblers, Linkers, and Loaders

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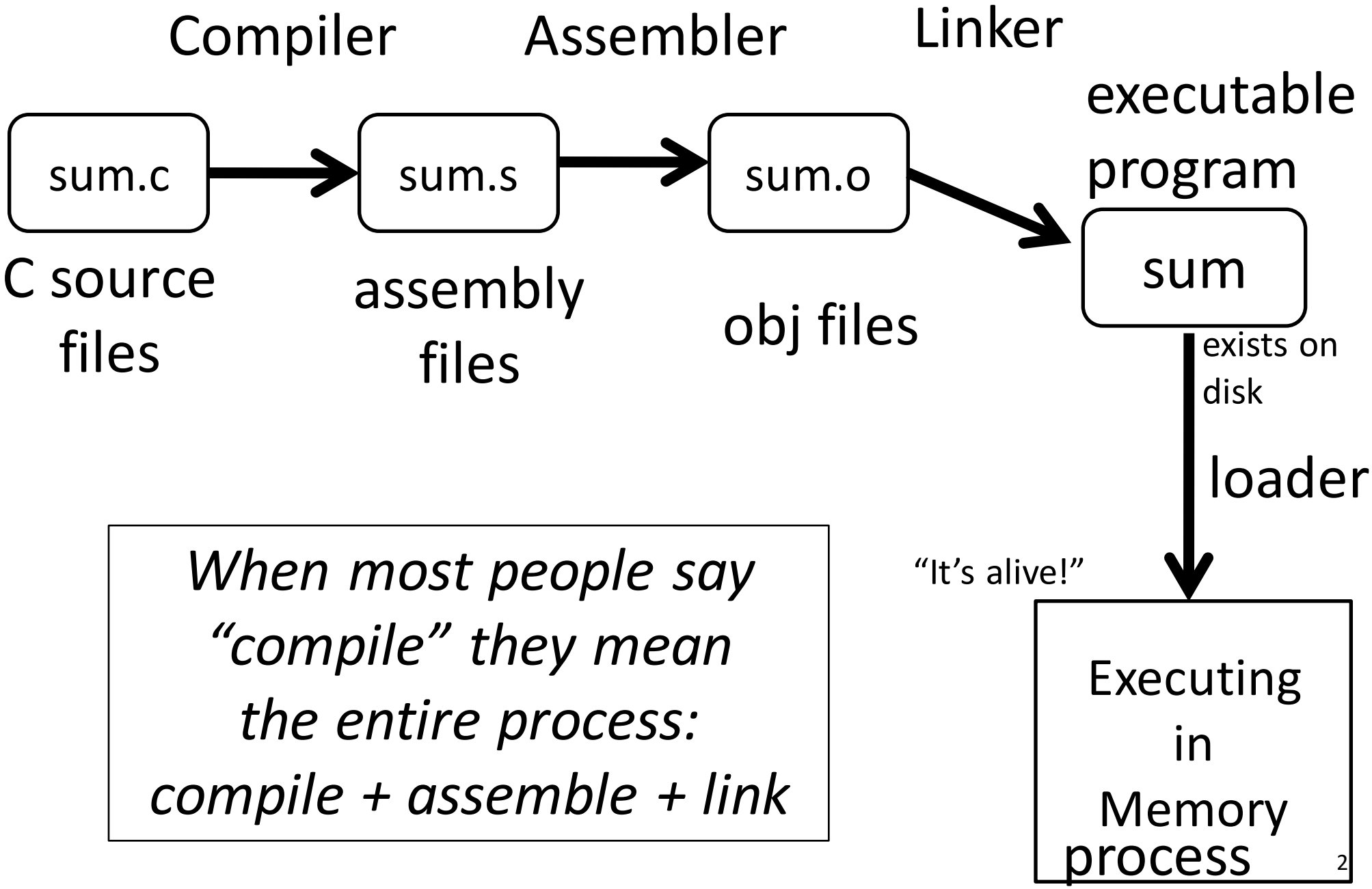
The slides are the product of many rounds of teaching CS 3410 by Professors Weatherspoon, Bala, Bracy, McKee, and Sirer.

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

From Writing to Running



When most people say "compile" they mean the entire process: compile + assemble + link

From Writing to Running: Command Line

```
# Compile
csug01> mipsel-linux-gcc –S sum.c

# Assemble
csug01> mipsel-linux-gcc –c sum.s

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

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

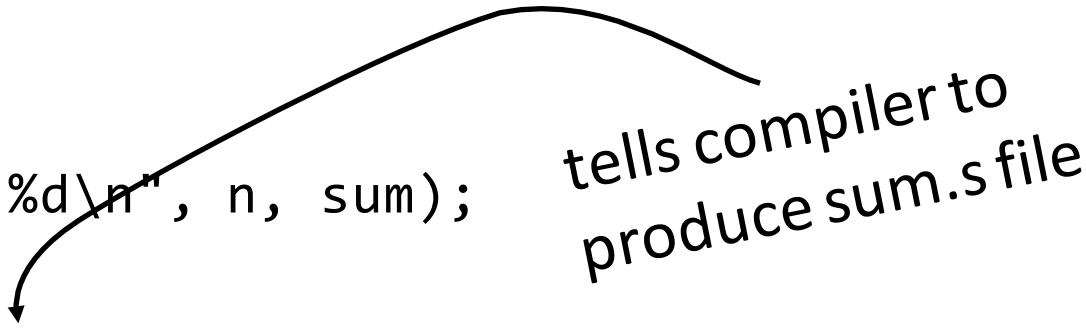
sum.c

```
#include <stdio.h>

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);
}
```




```
csug03> mipsel-linux-gcc –S sum.c
```

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

sum.s

```
        .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
```

sum.s

```
        .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   $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       $2,24($fp)  i=1
        lw       $3,28($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
        lw   $a1 $5,28($fp)  m=100
        lw   $a2 $6,32($fp)  sum
        jal      printf
        move     $sp,$fp
        lw       $31,44($sp)
        lw       $fp,40($sp)
        addiu    $sp,$sp,48
        j        $31
```

prologue

call printf

epilogue

Assembler

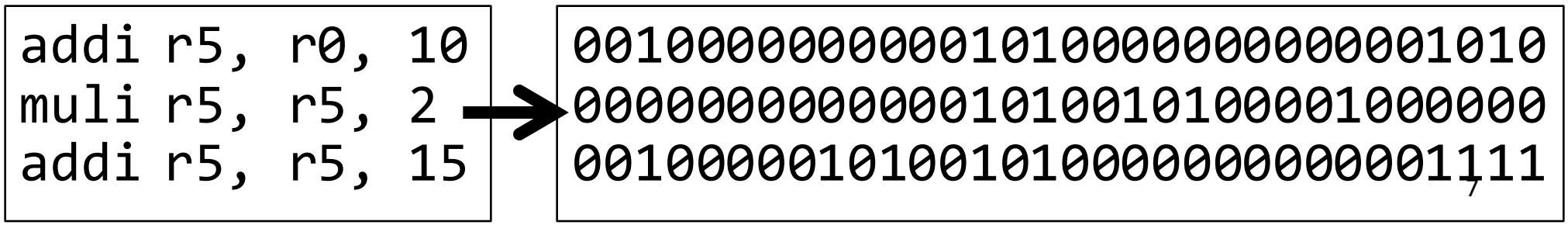
Input: Assembly File (.s)

- assembly instructions, pseudo-instructions
- program data (strings, variables), layout directives

Output: Object File in binary machine code

MIPS instructions in executable form

(.o file in Unix, .obj in Windows)



MIPS Assembly 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

Pseudo-Instructions

Assembly shorthand, technically not machine instructions, but easily converted into 1+ instructions that are

Pseudo-Insns	Actual Insns	Functionality
NOP	SLL r0, r0, 0	# do nothing
MOVE reg, reg	ADD r2, r0, r1	# copy between regs
LI reg, 0x45678	LUI reg, 0x4 ORI reg, reg, 0x5678	#load immediate
BLT reg, reg, label	SLT r1, rA, rB BNE r1, r0, label	# branch less than

+ a few more…

Symbols and References

math.c

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

        (external == defined in another file)
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 labels: Externally visible "exported" symbols

- Can be referenced from other object files
- Exported functions, global variables
- Examples: pi, e, username, printf, pick_prime, pick_random

Local labels: Internally visible only symbols

- Only used within this object file
- static functions, static variables, loop labels, …
- Examples: randomval, is_prime

Handling forward references

Example:

```
    bne $1, $2, L          Looking for L
    sll $0, $0, 0
L:  addiu $2, $3, 0x2      Found L
```

The assembler will change this to

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

Final machine code

```
0X14220001 # bne    00010100001000100000000000000001
0x00000000 # sll    00000000000000000000000000000000
0x24620002 # addiu  00100100011000100000000000000010
```

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

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

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
```

prologue

body

epilogue

unresolved symbol (see symbol table next slide)

```
static int randomval = 7;
int pick_random() {   return randomval;  }
```

Objdump symbols

[F]unction
[O]bject
[l]ocal
[g]lobal

```
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
```

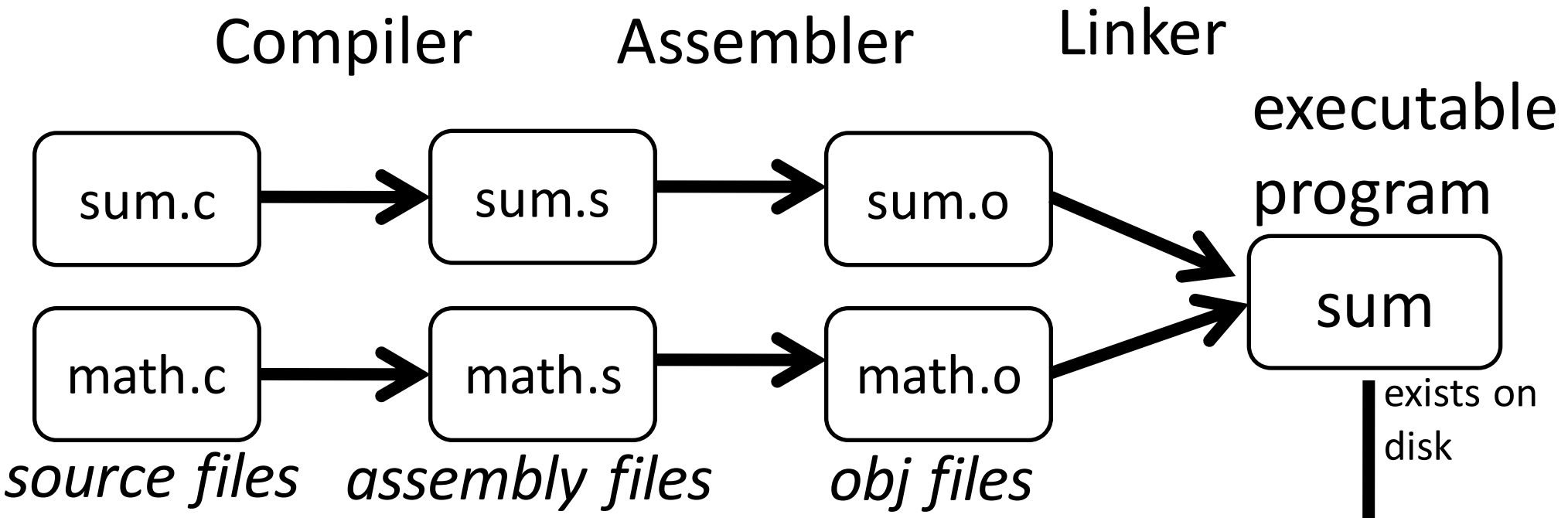
segment

segment size

← static local function @ address 0x60 Size = x28 bytes

external references (undefined)

Separate Compilation & Assembly



http://xkcd.com/303/

small change ?

→ recompile one module only

Executing in Memory process

Linkers

Linker combines object files into an executable file

- Resolve as-yet-unresolved symbols
- Each has illusion of own address space

  → Relocate each object's text and data segments
- Record top-level entry point in executable file

End result: a program on disk, ready to execute

- E.g.

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

Static Libraries

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

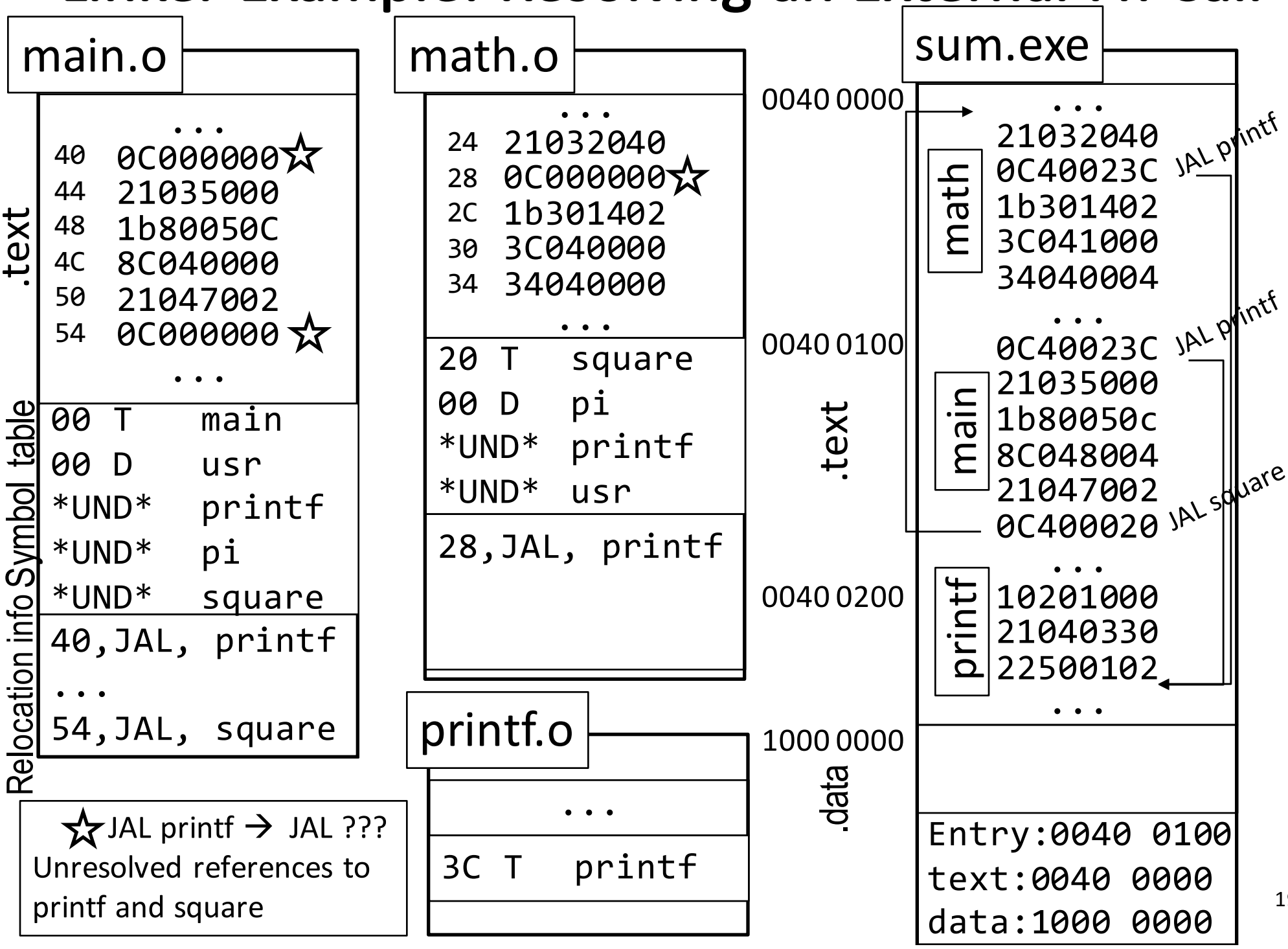
Q: Every program contains the entire library?!?

A: No, Linker picks only object files needed to resolve undefined references at link time

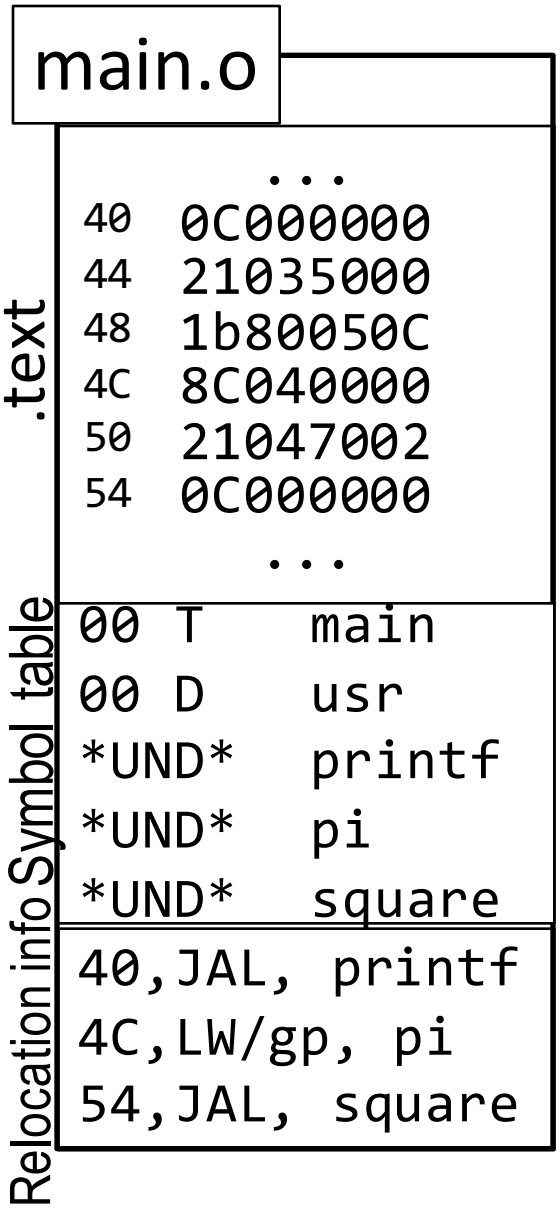
e.g. libc.a contains many objects:

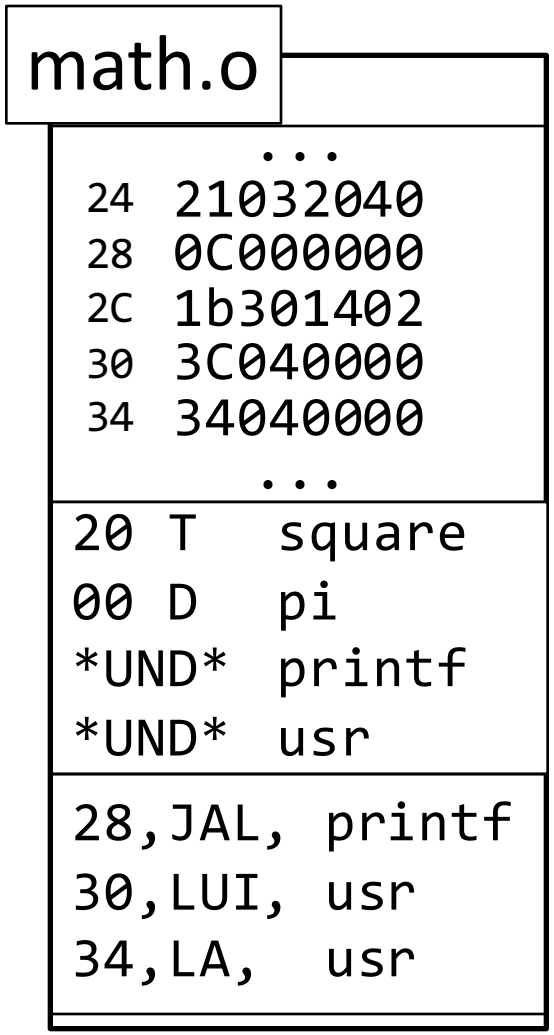
- printf.o, fprintf.o, vprintf.o, sprintf.o, snprintf.o, …
- read.o, write.o, open.o, close.o, mkdir.o, readdir.o, …
- rand.o, exit.o, sleep.o, time.o, ….

Linker Example: Resolving an External Fn Call



iClicker Question

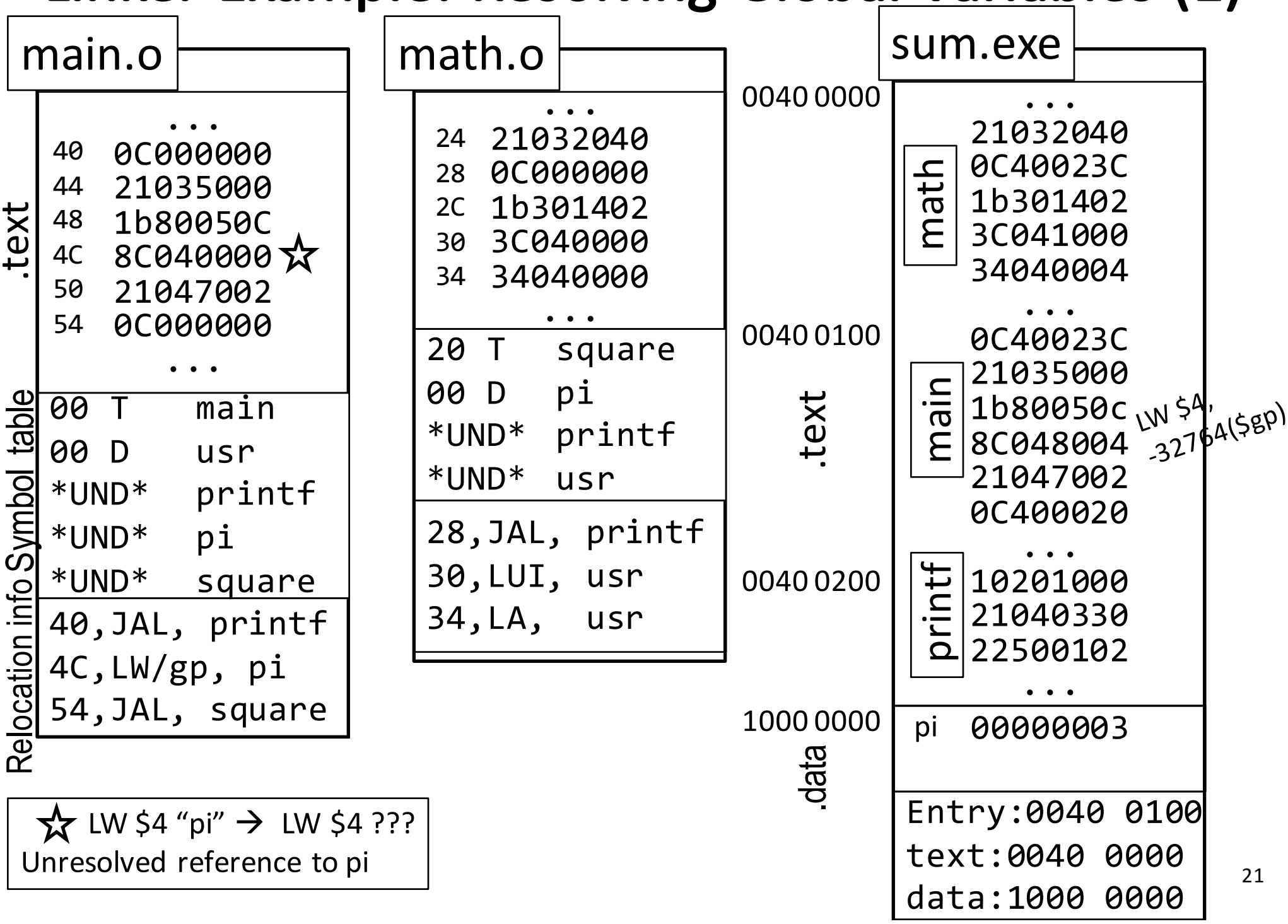




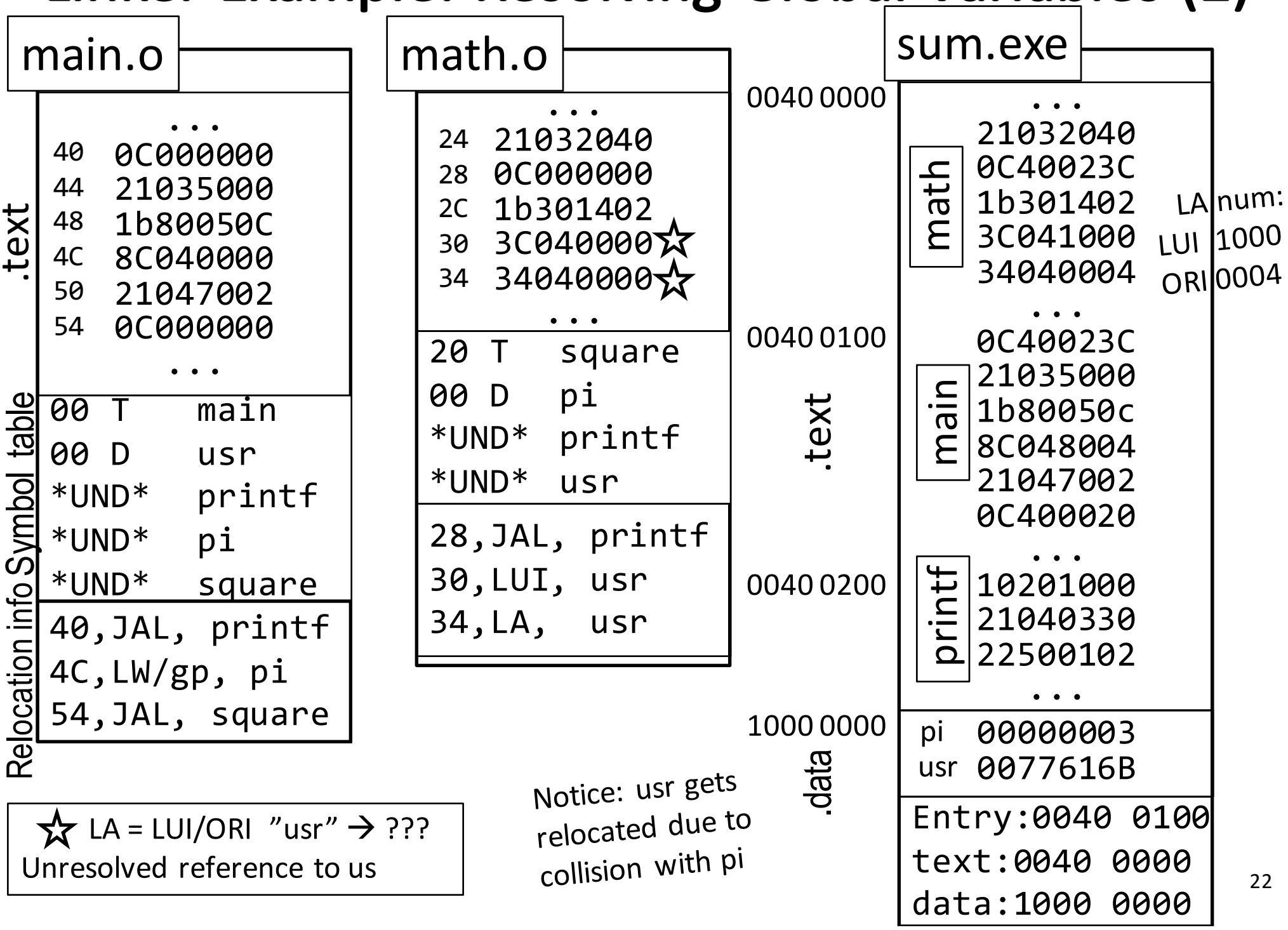
Which symbols are undefined according to both main.o and math.o's symbol table?

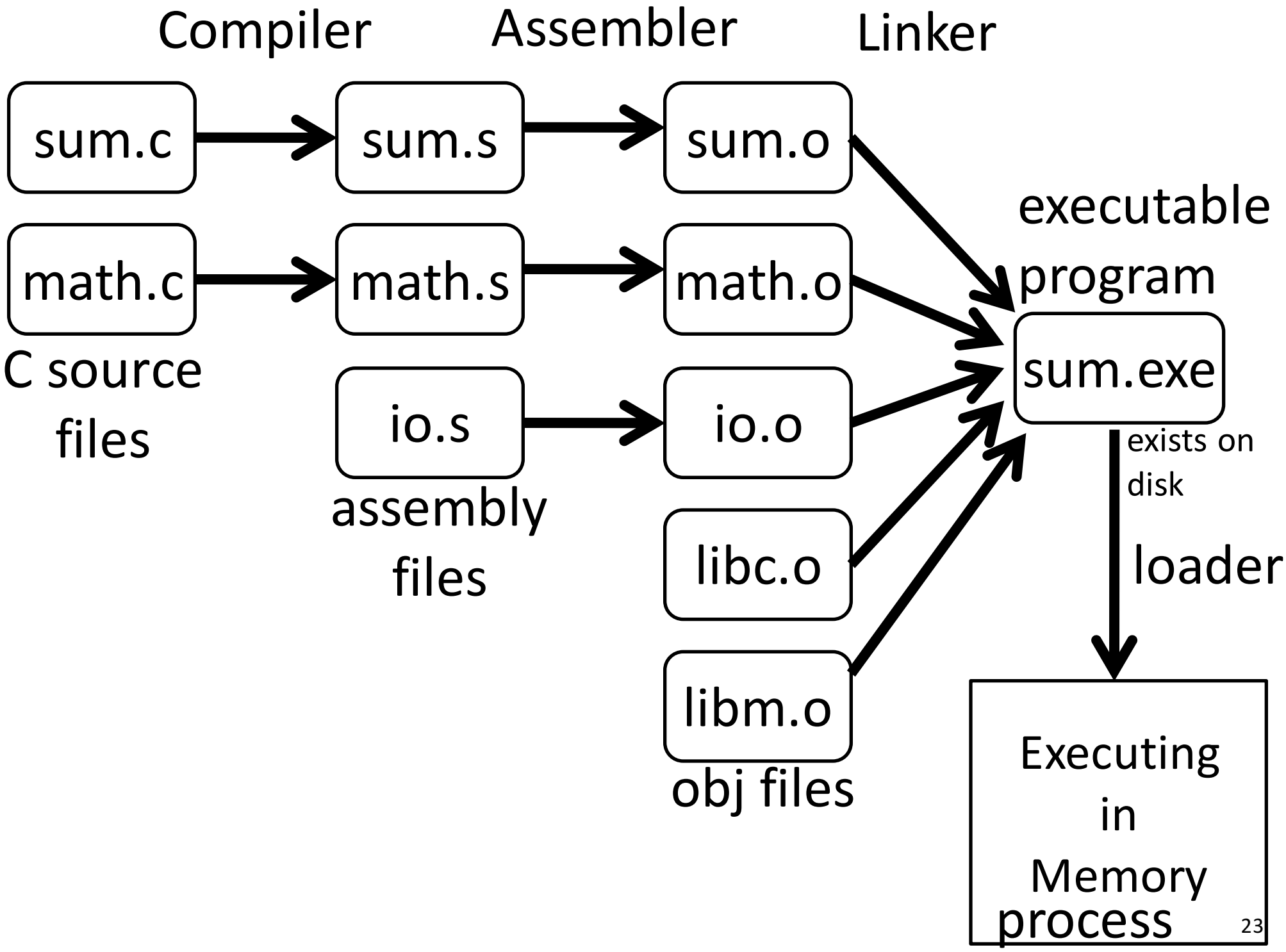
A) printf
B) pi
C) square
D) usr
E) printf & pi

Linker Example: Resolving Global Variables (1)



Linker Example: Resolving Global Variables (2)




Compiler
Assembler
Linker
sum.c
sum.s
sum.o
math.c
math.s
math.o
C source files
io.s
io.o
assembly files
libc.o
libm.o
obj files
executable program
sum.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)

Shared Libraries

Q: Every program contains parts of same library?!?

A: No, they can use shared libraries

- Executables 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

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

Takeaway

Compiler 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 joins object files into one executable file

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

Loader puts program into memory, jumps to 1st insn, and starts executing a *process*

- (machine code)