Assemblers, Linkers, and Loaders

Anne Bracy

CS 3410

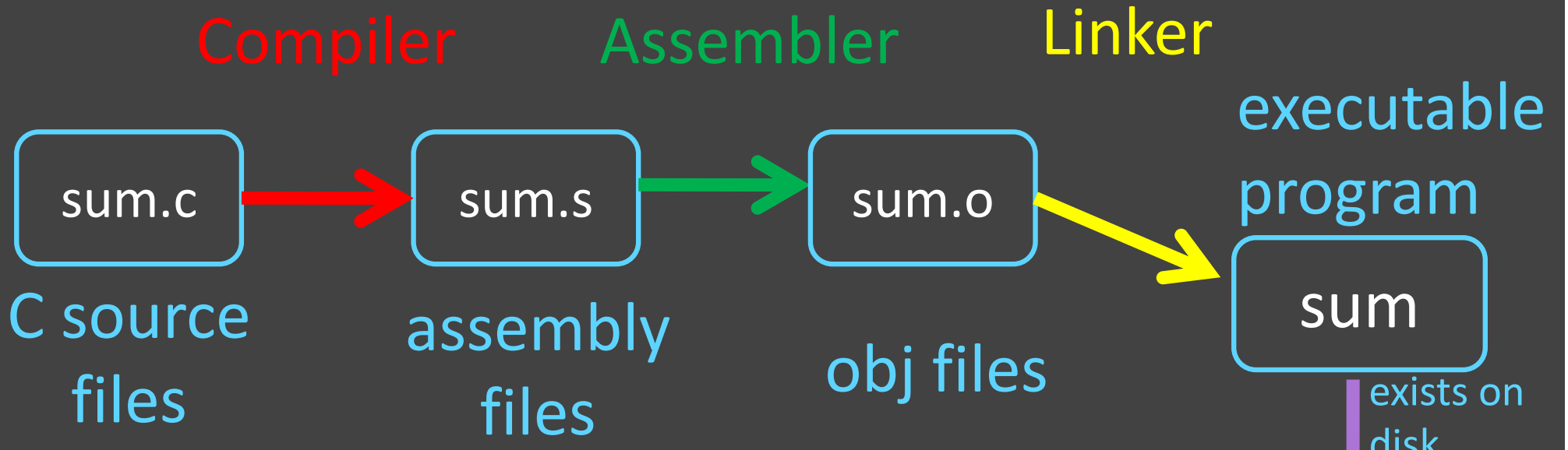
Computer Science

Cornell University

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

"It's alive!"

Executing in Memory process

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

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.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)

```
addi r5, r0, 10
muli r5, r5, 2
addi r5, r5, 15
```

```
00100000000001010000000000001010
00000000000001010010100001000000
00100000101001010000000000001111
```

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 int usrid;
extern int printf(char *str, …);


int square(int x) { … }
static int is_prime(int x) { … }
int pick_prime() { … }
int pick_random() {
        return usrid;
}
```

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
    sll $0, $0, 0
L:  addiu $2, $3, 0x2
```

Looking for L

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 usr = 41;

int pick_random() {   return usr;  }
```

Objdump symbols

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

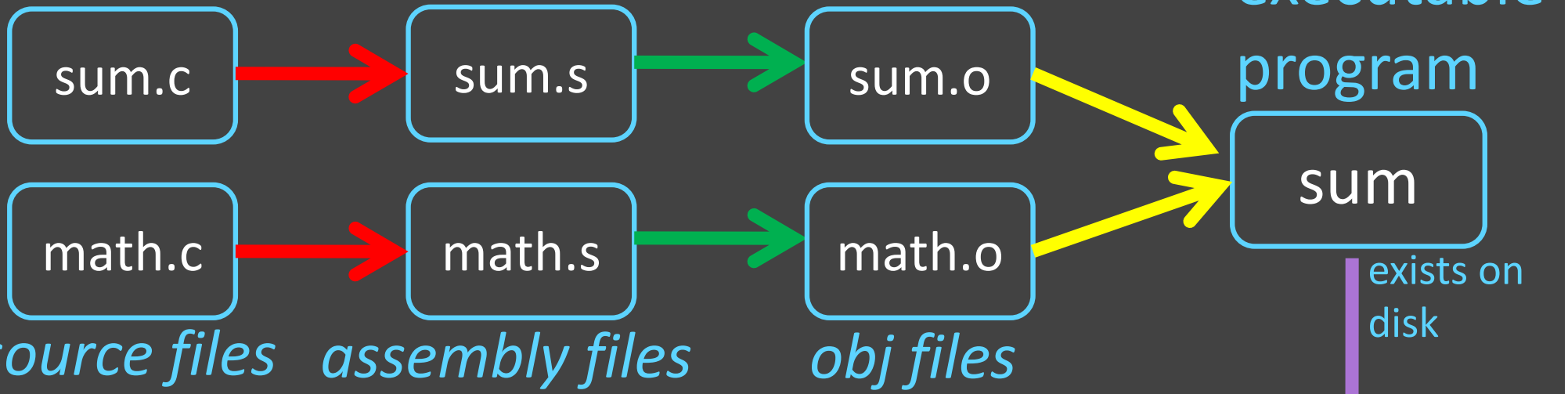
```
csug01 ~$ mipsel-linux-objdump --syms math.o
math.o:     file format elf32-tradlittlemips

SYMBOL TABLE:          segment          size
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 usr
00000000      *UND*                 00000000 printf
```

static local function @ address 0x60
Size = x28 bytes

external references (undefined)

Separate Compilation & Assembly

Compiler Assembler Linker



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)

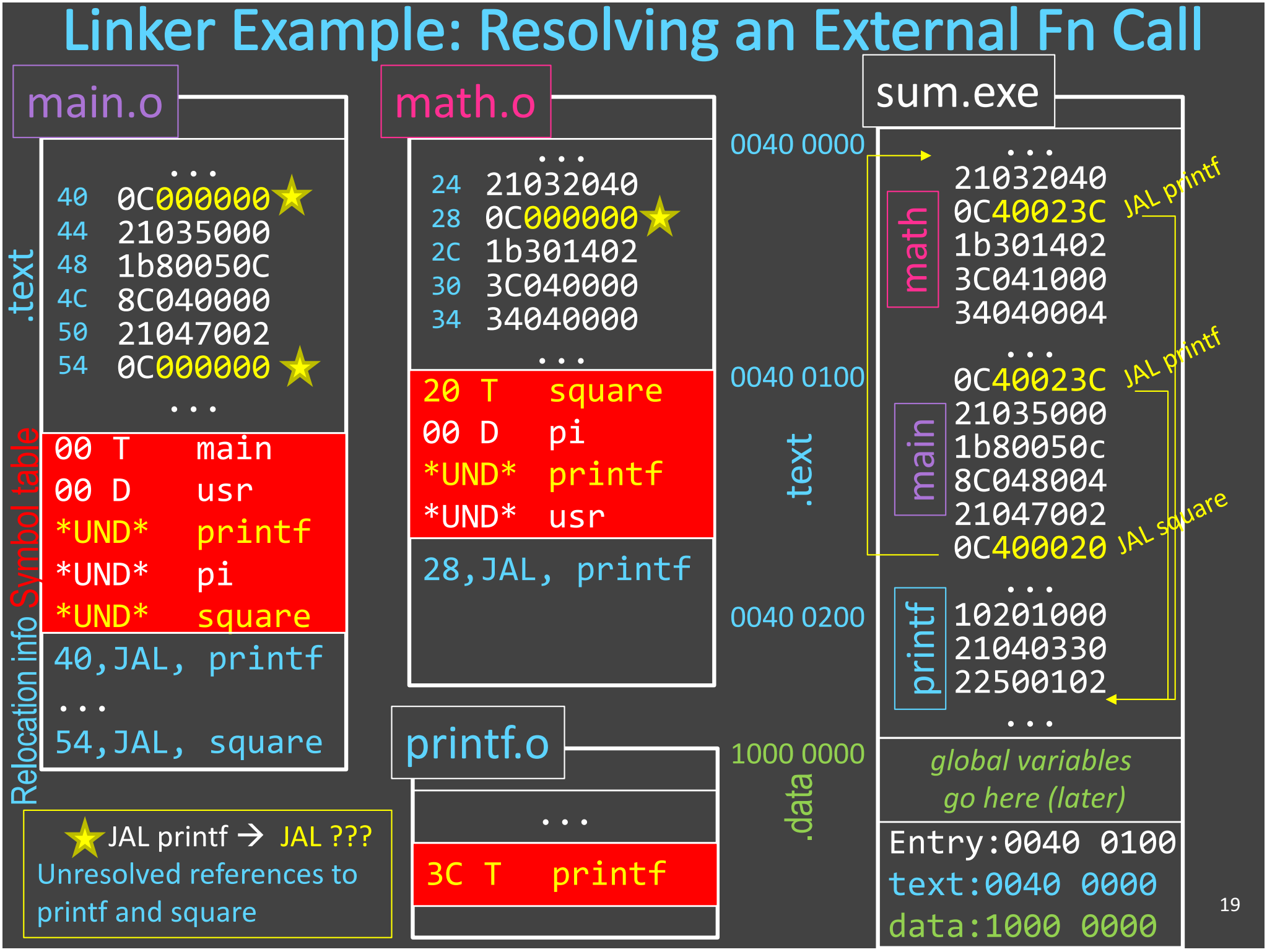
Q: Every program contains the entire library?!?

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

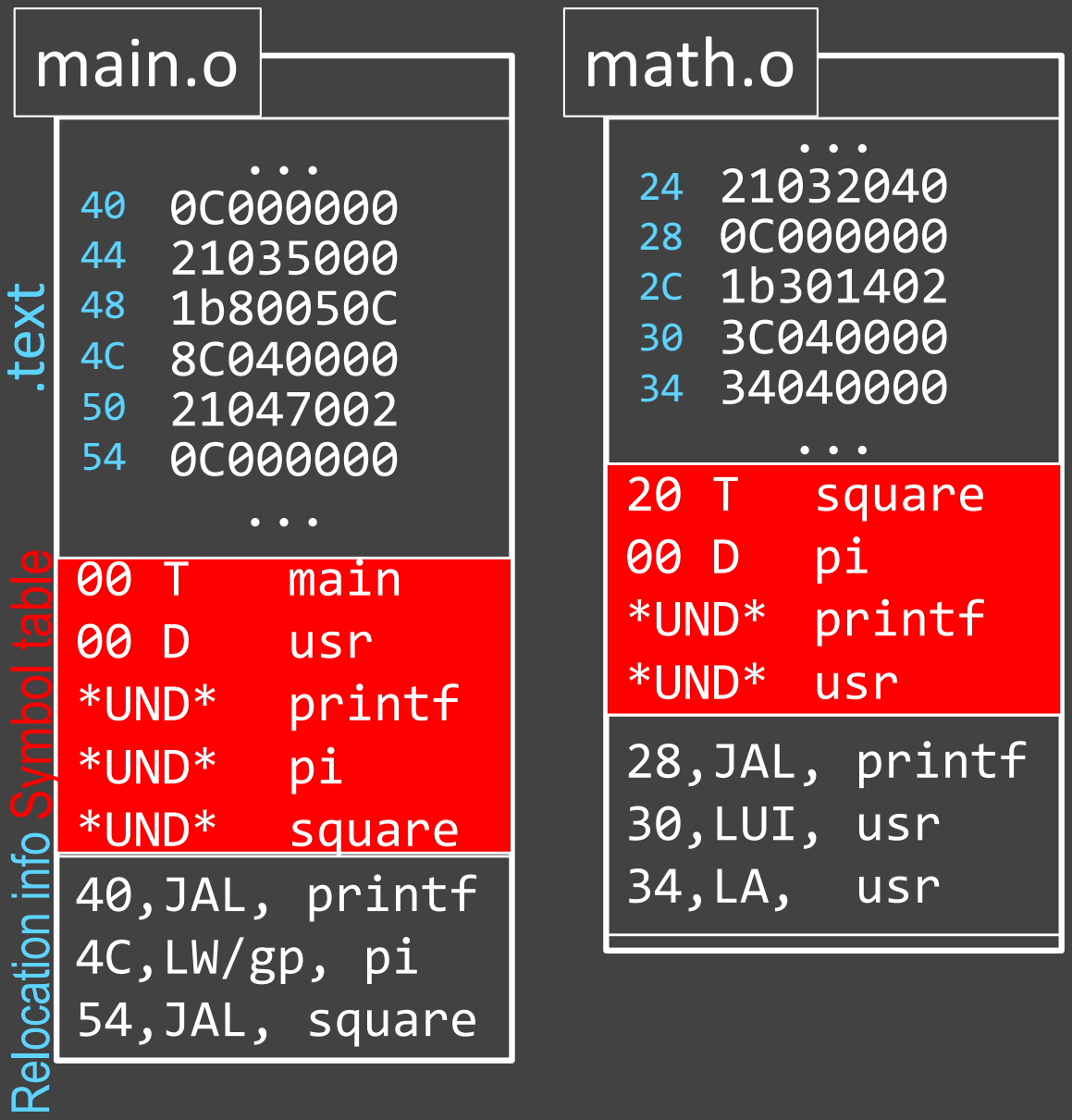
e.g. libc.a contains many objects:

- 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



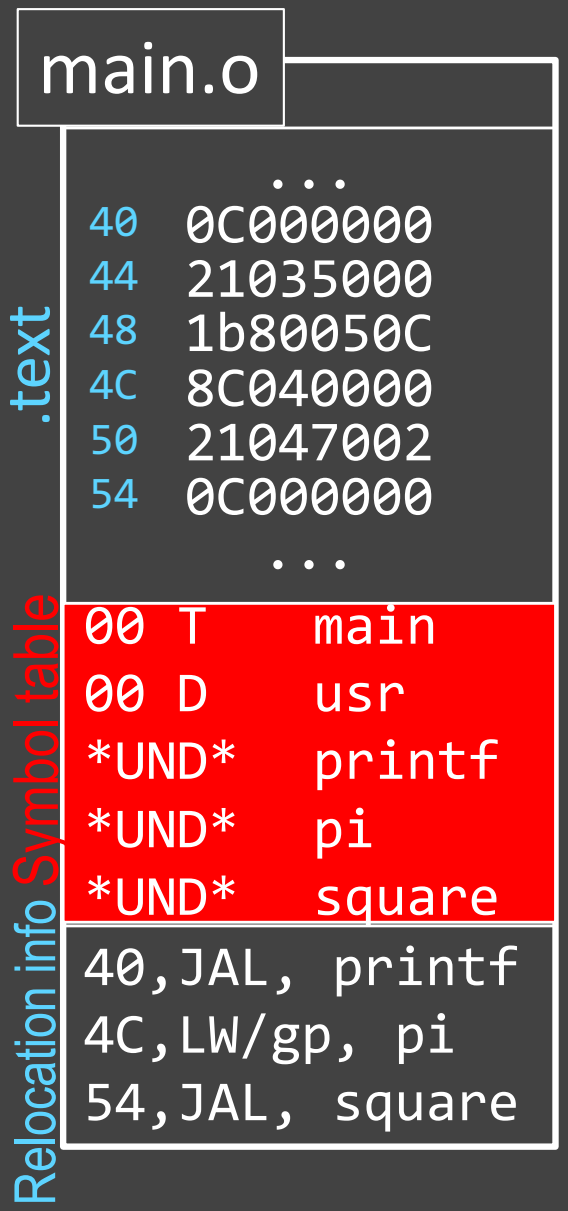
iClicker Question 1

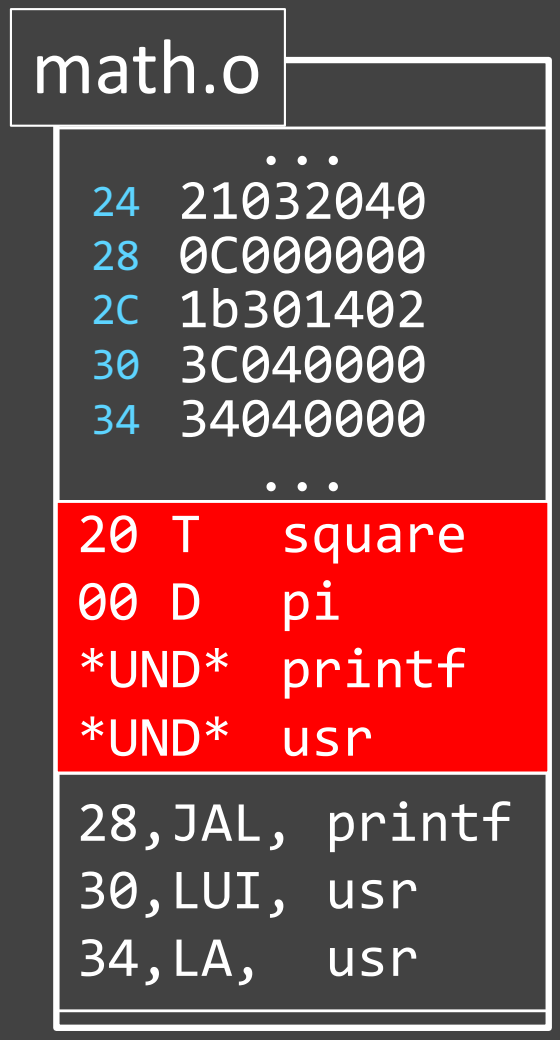


Which symbols are undefined according to both main.o and math.o's symbol table?

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

iClicker Question 2

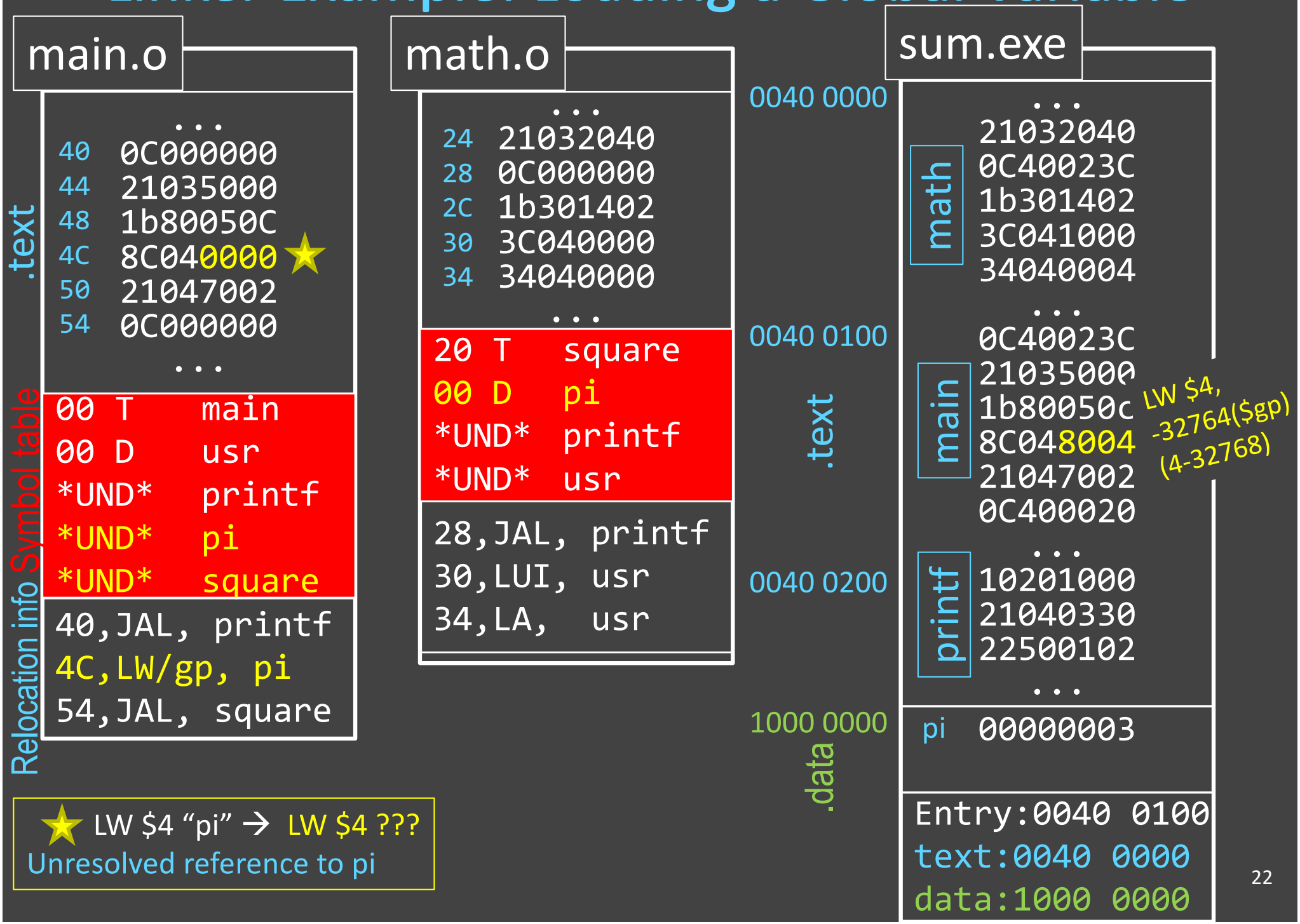




Which which 2 symbols are currently assigned the same location?

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

Linker Example: Loading a Global Variable



Linker Ex: Resolving Addr of Global Variable

main.o

.text

```
        ...
40  0C000000
44  21035000
48  1b80050C
4C  8C040000
50  21047002
54  0C000000
        ...
```

Symbol table

```
00 T    main
00 D    usr
*UND*   printf
*UND*   pi
*UND*   square
```

Relocation info

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

math.o

```
        ...
24  21032040
28  0C000000
2C  1b301402
30  3C040000   ★
34  34040000   ★
        ...
```

0040 0100

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

.text

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

0040 0200

1000 0000

.data

sum.exe

0040 0000

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

LA num:
LUI 1000
ORI 0004

```
pi   00000003
usr  0077616B
```

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

★ LA = LUI/ORI "usr" → ???
Unresolved reference to usr

Notice: usr gets relocated due to collision with pi

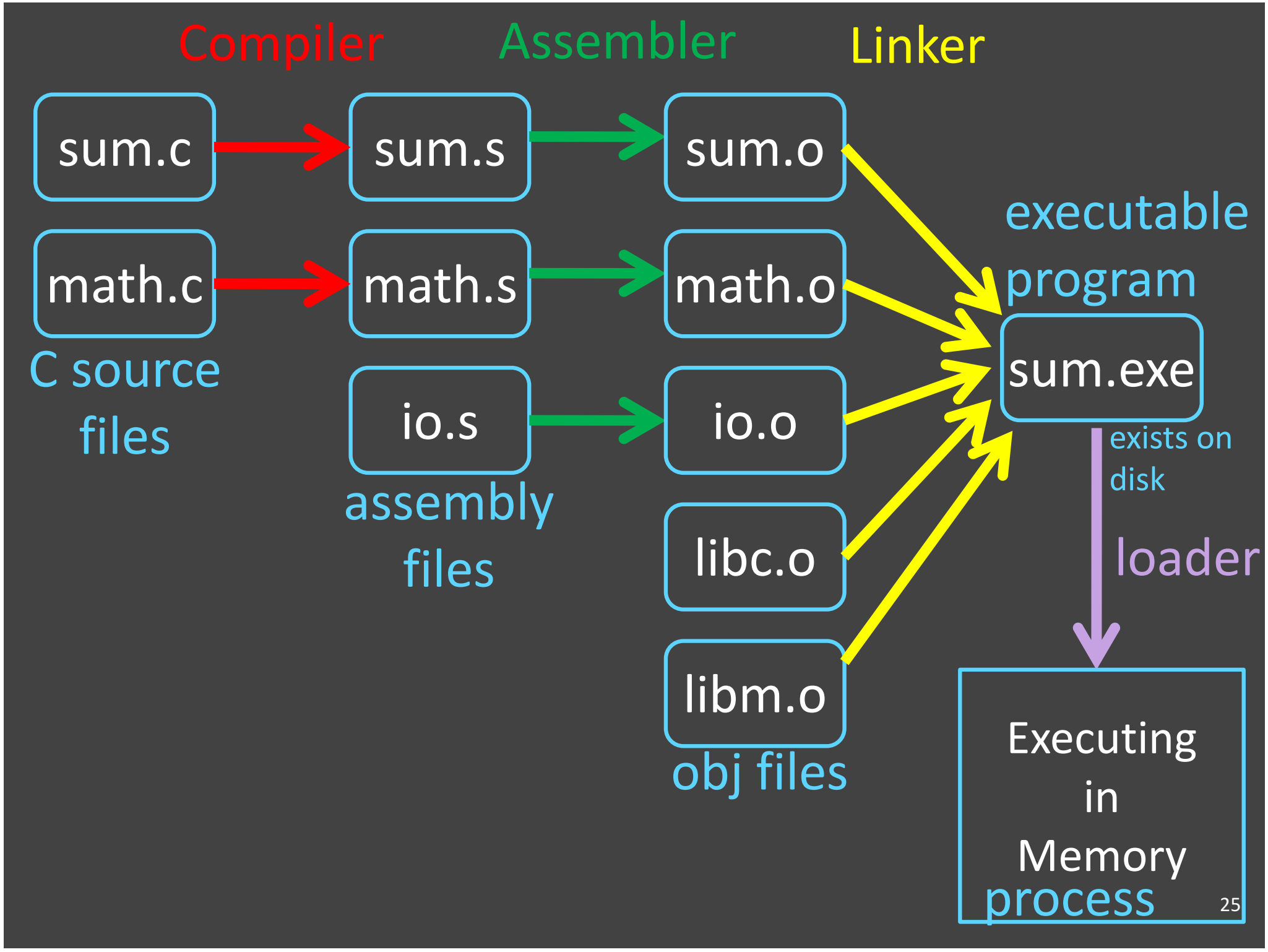
iClicker Question

Where does the assembler place the following symbols in the object file that it creates?

A. Text Segment
B. Data Segment
C. Exported reference in symbol table
D. Imported reference in symbol table
E. None of the above

```
#include <stdio.h>
#include heaplib.h

#define HEAP SIZE 16
static int ARR SIZE = 4;

int main() {
    char heap[HEAP SIZE];
    hl init(heap, HEAP SIZE * sizeof(char));
    char* ptr = (char *) hl alloc(heap, ARR SIZE * sizeof(char));
    ptr[0] = 'h';
    ptr[1] = 'i';
    ptr[2] = '\0';
    printf(%s\n, ptr); return 0;
}
```

Q1: HEAP_SIZE
Q2: ARR_SIZE
Q3: hl_init


Compiler
Assembler
Linker
sum.c
math.c
C source files
sum.s
math.s
io.s
assembly files
sum.o
math.o
io.o
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)