Assemblers, Linkers, and Loaders

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See: P&H Appendix B.3-4

```
#include <stdio.h>
int n = 100;
int main (int argc, char* argv[]) {
    int i, m = n, 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
```

Global variables in data segment

- Exist for all time, accessible to all functions

Dynamic variables in heap segment

- Exist between malloc() and free()

Function-Local variables in stack frame

- Exist solely for the duration of the stack frame

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

```
        .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
```

C Pointers can be trouble

Pointer to global variables are fine

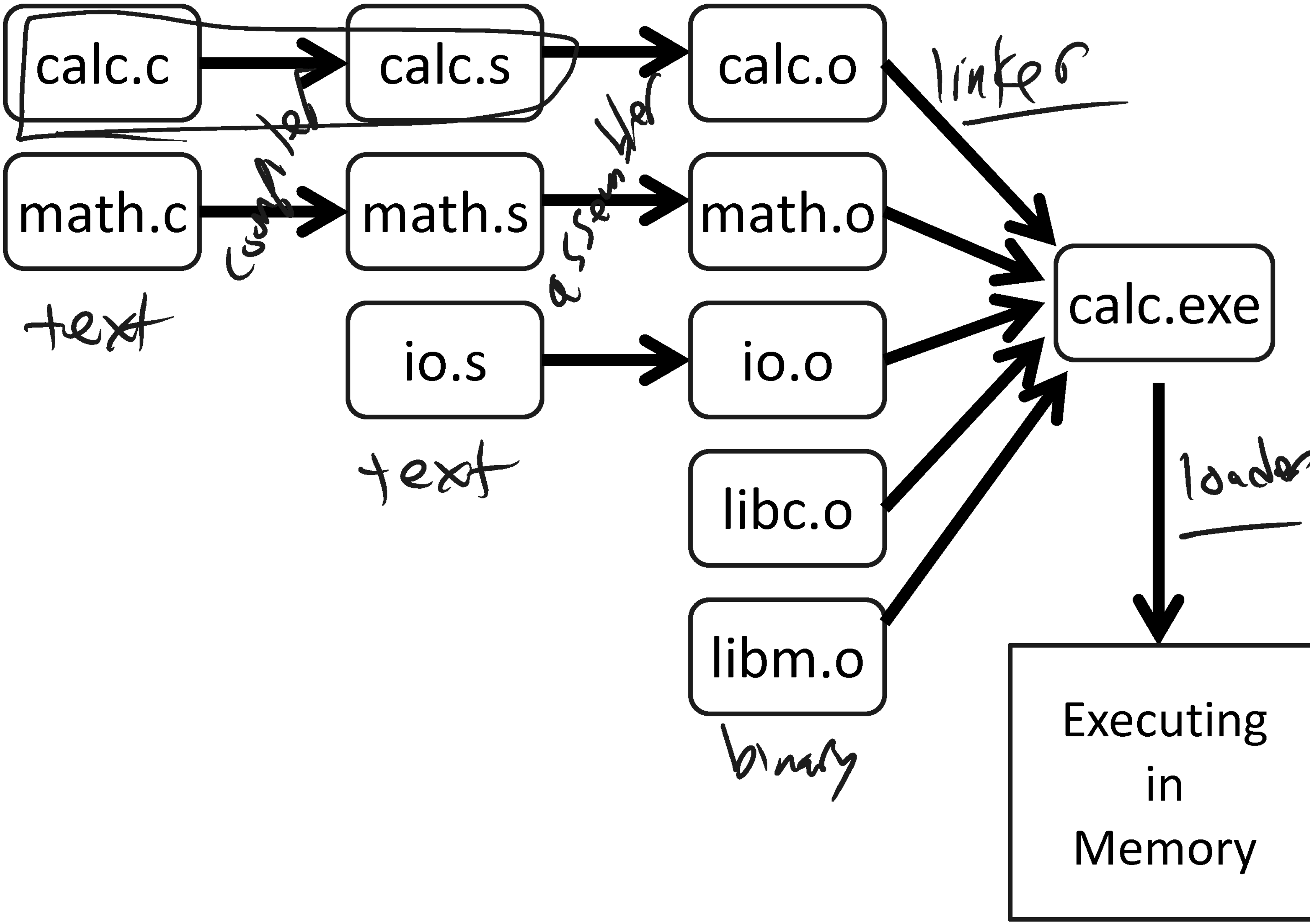
Pointer to dynamic variables in heap segment

```
int *bad()
{ s = malloc(20); … free(s); … return s; }
```

Pointer to function-local variables in stack frame

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

(Can't do this in Java, C#, ...)


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
compiler
assembler
linker
loader
text
text
binary

Assembler output is obj files

.o extension

.obj

- Not executable
- May refer to external symbols
- Each object file has illusion of its own address space

Linker joins object files into one executable

Loader brings it into memory and starts execution

Assemblers and Compilers

Object File

Header

- Size and position of pieces of file

Text Segment

- instructions

Data Segment

- static data (local/global vars, strings, constants)

Symbol Table

- External (exported) references main, n, ...
- Unresolved (imported) references printf,

Debugging Information

- line number → code address map, etc.

Global labels: External (exported) symbols

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

Local labels: Internal (non-exported) symbols

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

math.c

```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
```

```
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)
  ...
```

prolog

randomval 0x8000
0008

epilog

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

                                             size     names
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
```

Q: Why separate compile/assemble and linking steps?

A: Can recompile one object, then just relink.

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

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
```

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
...
```

```
00000003
0077616B
```

```
entry:400100
text:  400000
data:1000000
```

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
- COFF: Common Object File Format
- ELF: Executable and Linking Format
- …

.o

Windows

- PE: Portable Executable

.obj
.exe

All support both executable and object files

Loaders and Libraries

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
.lib

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, ….

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 address
  (makes linking trivial: few relocations needed)
- Jump table in each program
- 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

Direct call:

```
00400010 <main>:
  ...   lw t9 0
  jal   t9
  ...
  jal
  ...
  jal
  ...
00400330 <printf>:
  ...
00400620 <gets>:
  ...       pi
```

GOT: global offset table

00400010
00400330
00400620
~~3.4~~

Indirect call:

```
00400010 <main>:
  ...
  lw t9, -32708(gp)
  jalr t9
  ...
  lw t9, -32704(gp)
  jalr t9
  ...
00400330 <printf>:
  ...
00400620 <gets>:
  ...
```

```
# data segment
  ...
  ...
# global offset table
# at -32712(gp)
.got
-12 .word 00400010
-8  .word 00400330
-4  .word 00400620
-700
-696 ...
```

sp = fp = s8

Indirect call with on-demand dynamic linking:

```
00400010 <main>:
  ...
  lw t9, -32708(gp)
  jalr t9
  ...
.got
  .word 00400888
  .word 00400888
  .word 00400888
  .word 00400888
```

```
  ...
00400888 <dlresolve>:
```

t9 is entry
- xlate to name
- load (name)

fix got w/ new name.

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
```

Windows: dynamically loaded library (DLL)

- PE format .dll

Unix: dynamic shared object (DSO)

- ELF format .so

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

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