Linking

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Hello World

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

int main(void) {
  printf("Hello world!\n");
  return EXIT_SUCCESS;
}
```

Compilation

- Compile

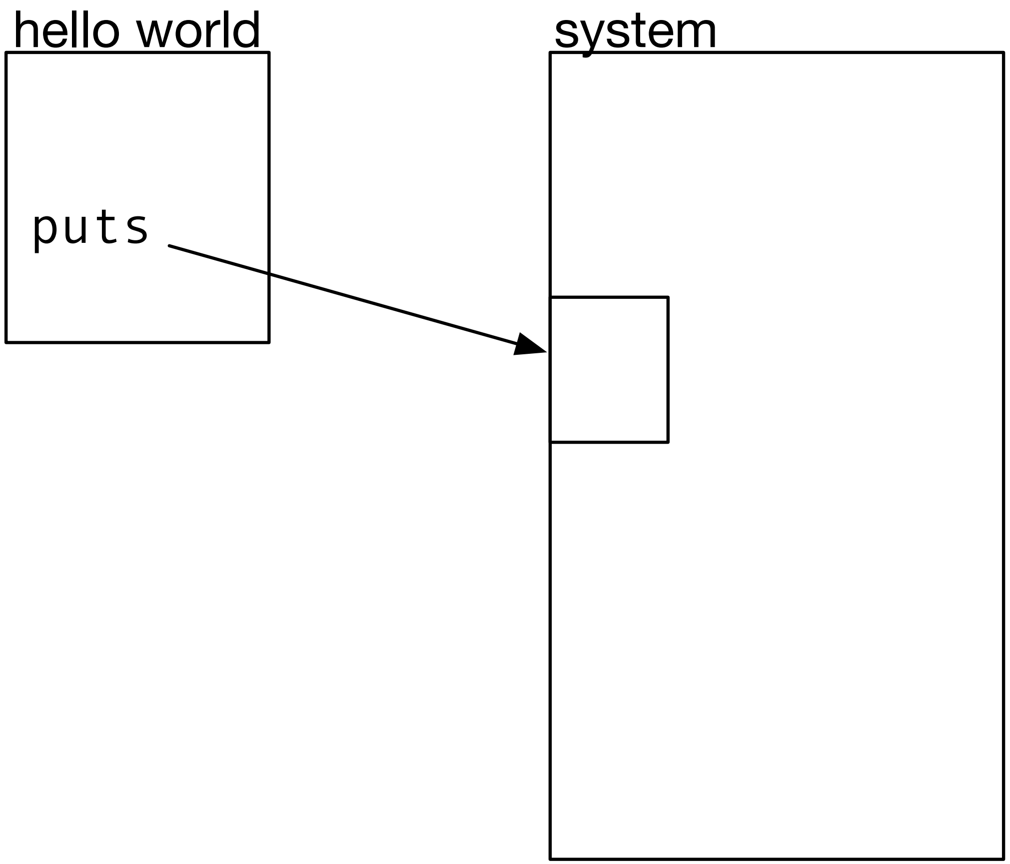
```
linux> gcc -Og hello-world.c
```

- Resulting program

```
linux> ls -l a.out
-rwxr-xr-x.  1 phi users 8512 Nov 16 03:57 a.out
```

- That's pretty small!

Dynamic Linking



Static Linking

- Compile with --static
- Results in very large file
- Includes the entire library!

Benefits of Dynamic Linking

- Makes code smaller
  - needs less disk space
  - needs less RAM

- Library is not part of the compiled program

  $\Rightarrow$ when it gets updated, no need to recompile

Example: Code in 2 Files

main.c

```
int sum(int *a, int n);

int array[2] = {1, 2};

int main() {
  int val = sum(array, 2);
  return val;
}
```

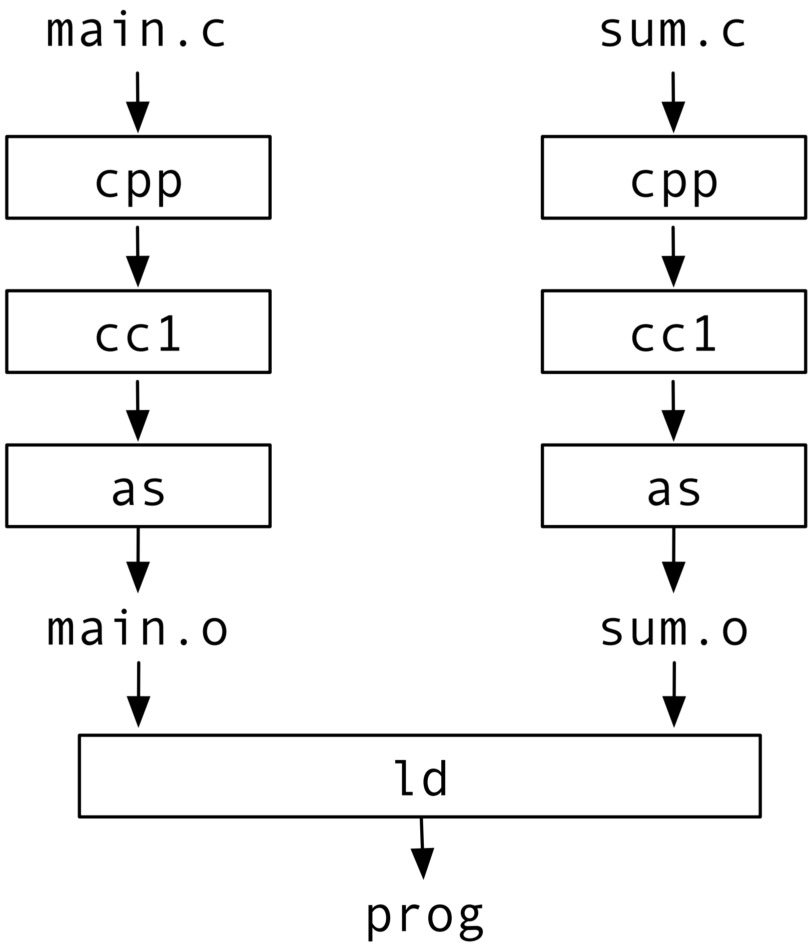
sum.c

```
int sum(int *a, int n) {
  int i, s = 0;
  for(i = 0; i<n; i++) {
    s += a[i];
  }
  return s;
}
```

Compile and Run

```
linux> gcc -Og -o prog main.c sum.c
linux> ./prog
linux> echo $?
3
```

Static Linking



Static Linking

- Symbol resolution
  - object files define and reference symbols (functions, global variables, static variables)
  - need to connect symbol to exactly one definition
- Relocation
  - assemblers generate object files that starts at address 0
  - when combining multiple object files, code must be shifted
  - all reference to memory addresses must be adjusted
  - assembler stores meta information in object file
  - linker is guided by relocation entries

Object Files

- Relocatable object file
  - binary code
  - meta information that allows symbol resolution and relocation

- Executable object file
  - binary code
  - can be copied into memory and executed

- Shared object file
  - binary code
  - can be loaded into memory
  - can be linked dynamically

Relocatable Object Files

- Executable and Linkable Format (ELF)
  - header
  - sections with different type of data
  - section header table

ELF header
.text
.rodata
.data
.bss
.symtab
.rel.text
.re.data
.debug
.line
.strtab
Section header table

Sections

.text machine code of compiled program

.rodata read-only data (e.g., strings in printf statements)

.data initialized global and static C variables

.bss uninitialized global and static C variables

.symtab symbol table

.rel.text list of locations in .text section (machine code)
to be modified when object is relocated

.rel.data same for .data

.debug debugging symbol table
(only compiled with -g)

.line mapping between line number and machine code
(only compiled with -g)

.strtab string table for .symtab and .debug

Symbols

- Global symbols that can be used by other objects
- Global symbols of other objects (not defined here)
- Local symbols only used in object defined with "static" attribute
- Note: non-static local variable are not exposed

ELF Symbol Table Entry

Name	Pointer to string of symbol name
Type	Function or data type
Binding	Indicates local or global
Section	Index of which section it belongs to
Value	Section offset
Size	Size in bytes

Example

```
linux> readelf -a main.o
Section Headers:
  [ 1] .text
  [ 3] .data

   Num:    Value          Size Type    Bind   Vis      Ndx Name
     8: 0000000000000000    24 FUNC    GLOBAL DEFAULT    1 main
     9: 0000000000000000     8 OBJECT  GLOBAL DEFAULT    3 array
    10: 0000000000000000     0 NOTYPE  GLOBAL DEFAULT  UND sum
```

- main is a function (FUNC) in section .text (1)
- array is an object (OBJECT) in section .data (3)
- sum is undefined (UND)

Symbol Resolution

- Linker must resolve all symbols to connect references to addresses
- Local symbols are contained to their object, each has a unique name
- Symbols in an object file may be undefined
  (listed as UND in symbol table)
  ⇒ these must be defined in other objects
- If not found, linker complains:

```
linux> gcc -Og main.c
/tmp/ccZzl3Pp.o: In function ‘main’:
main.c:(.text+0xf): undefined reference to ‘sum’
collect2: error: ld returned 1 exit status
```

Static Libraries

- Goal: link various standard functions statically

  → binary without dependency

- Plan A

  - put everything into big libc.o
  - link it to the application object file
  - ... but that adds too big of a file

- Plan B

  - have separate object files printf.o, scanf.o, ...
  - link only the ones that are needed
  - ... but that requires a lot of tedious bookkeeping by programmer

Static Libraries

- Solution: archives

- Combine object files printf.o, scanf.o, ... into archive libc.a

- Let linker pick out the ones that are needed

```
linux> gcc main.c /usr/lib/libc.a
```

- You can build your own libraries

```
linux> ar rcs libmy.a my1.o my2.o my3.o
```

Relocation

- Multiple object files
- Merge all sections, e.g., all .data sections together
- Assign run time memory addresses for each symbol
- Modify each symbol reference

- This is aided by relocation entries

Relocation Entry

Offset	Offset of reference within object
Type	Relocation type
Symbol	Symbol table index
Added	Constant part of relocation expression

Type may be
absolute 32 bit address or
address relative to program counter

Relocating Symbol Addresses

- main.o

```
 0: 48 83 ec 08             sub    $0x8,%rsp
 4: be 02 00 00 00          mov    $0x2,%esi
 9: bf 00 00 00 00          mov    $0x0,%edi
 e: e8 00 00 00 00          callq  13 <main+0x13>
13: 48 83 c4 08             add    $0x8,%rsp
17: c3                      retq
```

- Relocation entries
  - a: R_X86_64_32 array
  - f: R_X86_64_PC32 sum-0x4
- At line 9: reference to array
- At line e: reference to sum function (undefined in object)

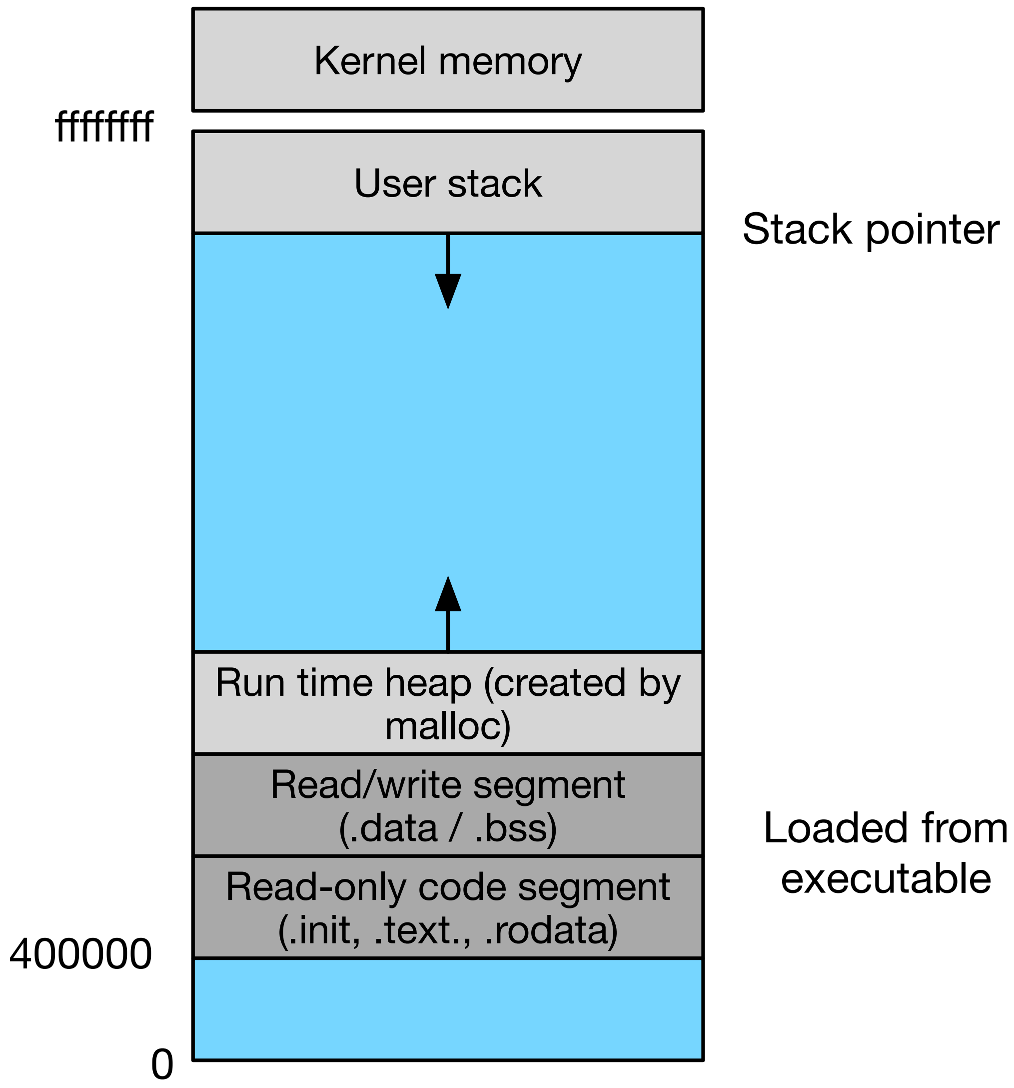
sum.o


```
0000000000000000 <sum>:
   0: b8 00 00 00 00        mov    $0x0,%eax
   5: ba 00 00 00 00        mov    $0x0,%edx
   a: eb 09                 jmp    15 <sum+0x15>
   c: 48 63 ca              movslq %edx,%rcx
   f: 03 04 8f              add    (%rdi,%rcx,4),%eax
  12: 83 c2 01              add    $0x1,%edx
  15: 39 f2                 cmp    %esi,%edx
  17: 7c f3                 jl     c <sum+0xc>
  19: f3 c3                 repz retq
```

main.o + sum.o → prog


```
00000000004004f6 <main>:
  4004f6:       48 83 ec 08                     sub    $0x8,%rsp
  4004fa:       be 02 00 00 00                  mov    $0x2,%esi
  4004ff:       bf 30 10 60 00                  mov    $0x601030,%edi
  400504:       e8 05 00 00 00                  callq  40050e <sum>
  400509:       48 83 c4 08                     add    $0x8,%rsp
  40050d:       c3                              retq
000000000040050e <sum>:
  40050e:       b8 00 00 00 00                  mov    $0x0,%eax
  400513:       ba 00 00 00 00                  mov    $0x0,%edx
  400518:       eb 09                           jmp    400523 <sum+0x15>
  40051a:       48 63 ca                        movslq %edx,%rcx
  40051d:       03 04 8f                        add    (%rdi,%rcx,4),%eax
  400520:       83 c2 01                        add    $0x1,%edx
  400523:       39 f2                           cmp    %esi,%edx
  400525:       7c f3                           jl     40051a <sum+0xc>
  400527:       f3 c3                           repz retq
  400529:       0f 1f 80 00 00 00 00            nopl   0x0(%rax)
```

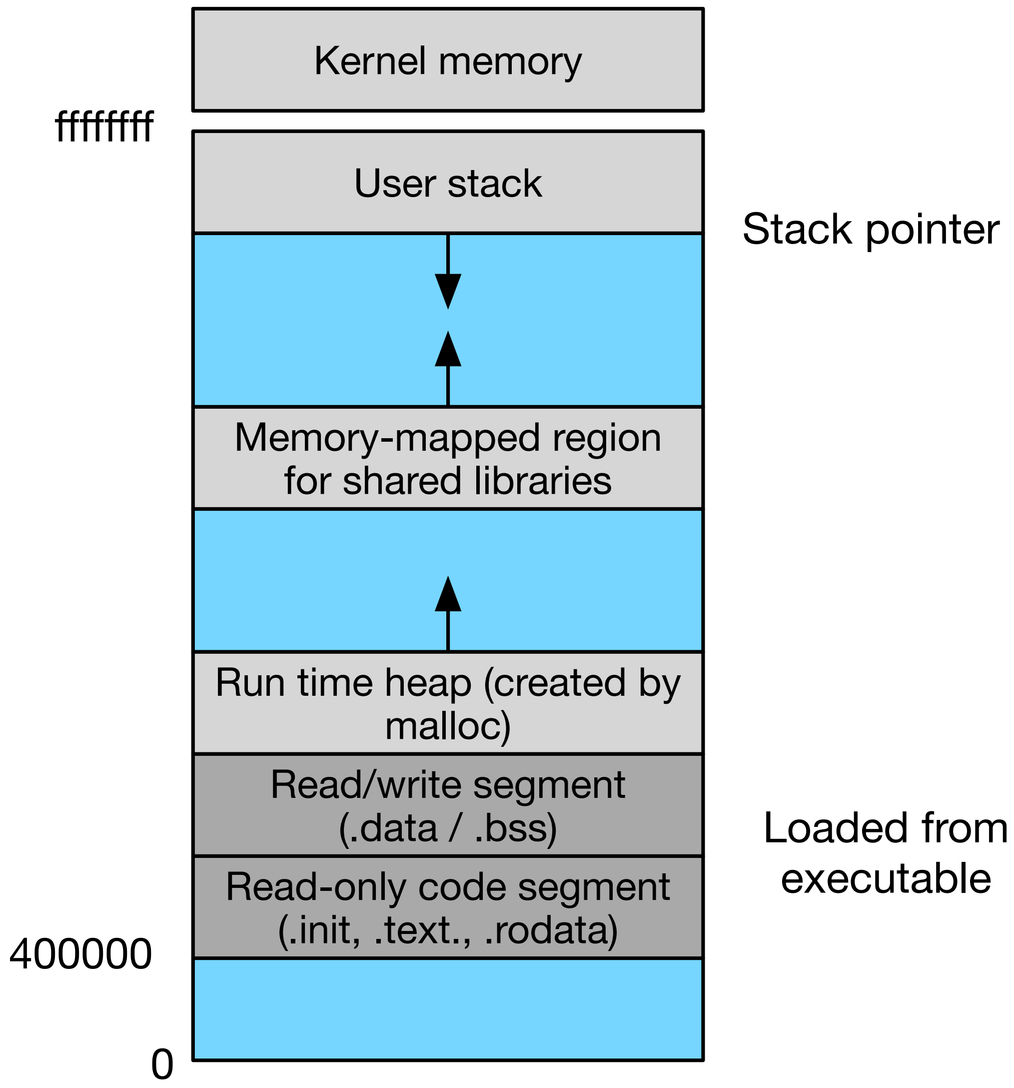
Loading Executable Object Files



Dynamic Linking Shared Libraries

- Once program is executed, loader calls dynamic linker
- Dynamic linker "loads" shared library
- Nothing is actually loaded
- Memory mapping: pretend its in memory
  (operation system deals with mapping of RAM address)

Dynamic Linking Shared Libraries



Addresses in Shared Libraries

- Multiple processes use same shared library
- Idea: put it into a dedicated place in memory
- But
  - there may be many libraries
  - we may run out of address space
    (or at least waste it)
- Instead: compile into position-independent code

Position-Independent Code

- No matter where the libraries is loaded into memory
  $\rightarrow$ distances between addresses are the same

- Global offset table
  - table in data segment (relative position is known)
  - contains absolute addresses of functions and variables
  - gets filled with correct values by dynamic linker

- Uses instruction point register (%rip)

Example

- Global offset table (in data segment)

0	address of symbol a
1	address of symbol b
2	...

- Code

```
mov  0x2008b9(%rip), %rax
addl $1, (%rax)
```

- Distance between code line and GOT entry 1 is 0x2008b9 bytes
- First line of code loads actual address of variable
- Second line increases it by 1

Tools for Manipulating Object Files

AR Creates static libraries, and inserts, deletes, and extracts members

STRINGS Lists all printable strings

STRIP Deletes symbol table information

NM Lists symbols defined in symbol table

READELF Displays complete structure

OBJDUMP Displays all information, useful to disassemble code