CS429: Computer Organization and Architecture

Linking II

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Relocating Symbols and Resolving External References

- *Symbols* are lexical entities that name functions and variables.
- Each symbol has a *value* (typically a memory address).
- Code consists of symbol *definitions* and *references*.
- References can be either *local* or *external*.

m.c

```c
int e = 7;              // def of local e

int main() {
    int r = a();        // ref to external symbol a
    exit(0);            // ref to external symbol exit
                        //   (defined in libc.so)
}
```

Relocating Symbols and Resolving External References (2)

a.c

```
extern int e;

int *ep = &e;          // def of local ep, ref to
                       //   external symbol e
int x = 15;            // def of local x
int y;                 // def of local y

int a() {              // def of local a
   return *ep+x+y;     // refs of locals ep, x, y
}
```

m.o Relocation Info

m.c

```
int e = 7;

int main() {
   int r = a();
   exit(0);
}
```

Source: objdump

Disassembly of section .text

```
00000000 <main>:
   0:   55                     pushl %ebp
   1:   89 e5                  movl  %esp, %ebp
   3:   e8 fc ff ff ff         call  4<main+0x4>
                          4: R_386_PC32   a
   8:   6a 00                  pushl $0x0
   a:   e8 fc ff ff ff         call  b<main+0xb>
                          b: R_386_PC32   exit
   f    90                     nop
```

Disassembly of section .data

```
00000000 <e>:
   0:   07 00 00 00
```

a.o Relocation Info (.text)

a.c

```c
extern int e;

int *ep = &e;
int x = 15;
int y;

int a() {
   return
      *ep + x + y;
}
```

Disassembly of section .text

```
00000000 <a>:
   0:   55                      pushl  %ebp
   1:   8b 15 00 00 00          movl   0x0, %edx
   6:   00
                        3: R_386_32    ep
   7:   a1 00 00 00 00          movl   0x0, %eax
                        8: R_386_32    x
   c:   89 e5                   movl   %esp, %ebp
   e:   03 02                   addl   (%edx),%eax
  10:   89 ec                   movl   %ebp, %esp
  12:   03 05 00 00 00          addl   0x0, %eax
  17:   00
                       14: R_386_32    y
  18:   5d                      popl   %ebp
  19:   3c                      ret
```

a.o Relocation Info (.data)

a.c

```
extern int e;

int *ep = &e;
int x = 15;
int y;

int a() {
   return *ep + x + y;
}
```

Disassembly of section .data

```
00000000 <ep>:
   0:    00 00 00 00
                     0:   R_386_32   e
00000004 <x>:
   4:    0f 00 00 00
```

Executable After Relocation

After Relocation and External Reference Resolution (.text)

```
08048530 <main>:
 8048530:   55                    pushl  %ebp
 8048531:   89 e5                 movl   %esp, %ebp
 8048533:   e8 08 00 00 00        call   8048540 <a>
 8048538:   6a 00                 pushl  $0x0
 804853a:   e8 35 ff ff ff        call   8048474 <_init+0x94>
 804853f:   90                    nop

08048540 <a>:
 8048540:   55                    pushl  %ebp
 8048541:   8b 15 1c a0 04        movl   0x804a01c, %edx
 8048546:   08
 8048547:   a1 20 a0 04 08        movl   0x804a020, %eax
 804854c:   89 e5                 movl   %esp, %ebp
 804854e:   03 02                 addl   (%edx), %eax
 8048550:   89 ec                 movl   %ebp, %esp
 8048552:   03 05 d0 a3 04        addl   0x804a3d0, %eax
 8048557:   08
 8048558:   5d                    popl   %ebp
 8048559:   c3                    ret
```

Executable After Relocation

After Relocation and External Reference Resolution (.data)

m.c

```c
int e = 7;

int main() {
    int r = a();
    exit(0);
}
```

a.c

```c
extern int e;

int *ep = &e;
int x = 15;
int y;

int a() {
    return *ep + x + ;y;
}
```

Disassembly of section .data

```
0804a018 <e>:
 804a018:        07 00 00 00

0804a01c <ep>:
 804a01c:        18 a0 04 08

0804a020 <x>:
 804a020:        0f 00 00 00
```

Strong and Weak Symbols

Program symbols are either *strong* or *weak*.

strong: procedures and initialized globals

weak: uninitialized globals

This doesn't apply to local variables.

p1.c

```
int foo = 5; // foo: strong

p1() {       // p1: strong
   ...
}
```

p2.c

```
int foo;      // foo: weak here

p2() {        // p2: strong
   ...
}
```

Linker Symbol Rules

Rule 1: A strong symbol can only appear once.

Rule 2: A weak symbol can be overridden by a strong symbol of the same name.

- References to the weak symbol resolve to the strong symbol.

Rule 3: If there are multiple weak symbols, the linker can pick one arbitrarily.

Linker Puzzles

What happens in each case?

File 1	File 2	Result

int x;
p1() {}
	p1() {}	

int x;
p1() {}
	int x;
	p2() {}	

int x;
int y;
p1() {}
	double x;
	p2() {}	

int x=7;
int y=5;
p1() {}
	double x;
	p2() {}	

int x=7;
p1() {}
	int x;
	p2() {}	

Linker Puzzles

Think carefully about each of these.

File 1	File 2	Result

`int x;`
`p1() {}`
	`p1() {}`	Link time error: two strong symbols (p1)

`int x;`
`p1() {}`
	`int x;`
	`p2() {}`
		References to x will refer to the same unitialized int. What you wanted?

`int x;`
int y;
`p1() {}`
	`double x;`
	`p2() {}`
		Writes to x in p2 might overwrite y! That's just evil!

`int x=7;`
`int y=5;`
`p1() {}`
	`double x;`
	`p2() {}`
		Writes to x in p2 might overwrite y! Very nasty!

`int x=7;`
`p1() {}`
	`int x;`
	`p2() {}`
		References to x will refer to the same initialized variable.

Nightmare scenario: two identical weak structs, compiled by different compilers with different alignment rules.

Packaging Commonly Used Functions

How to package functions commonly used by programmers?
(Math, I/O, memory management, string manipulation, etc.)

Awkward, given the linker framework so far:

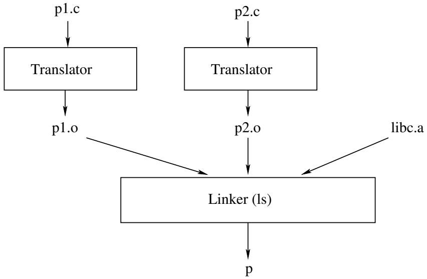
- Option 1: Put all functions into a single source file.
  - Programmers link big object file into their programs.
  - Space and time inefficient.
- Option 2: Put each function in a separate source file.
  - Programmers explicitly link appropriate binaries into their programs.
  - More efficient, but burdensome on the programmer.

Packaging Commonly Used Functions

Solution: *static libraries* (.a archive files)

- Concatenate related relocatable object files into a single repository with an index (called an archive).
- Enhance the linker so that it tries to resolve unresolved external reference by looking for symbols in one or more archives.
- If an archive member resolves the reference, link into the executable.

Static Libraries (archives)



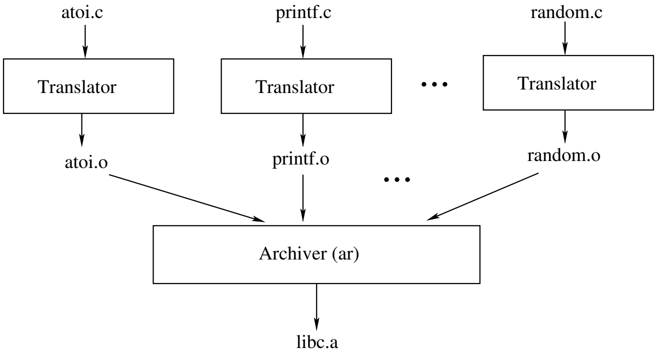
`libc.a` is a static library (archive) of relocatable object files concatenated into one file.

The output `p` is an executable object file that only contains code and data for libc functions called from p1.c and p2.c.

This further improves modularity and efficiency by packaging commonly used functions, e.g., C standard library (libc) or math library (libm).

The linker includes only the .o files in the archive that are actually needed by the program.

Creating Static Libraries



Command: `ar rs libc.a atoi.o printf.o ...  random.o`

Archiver allows incremental updates: Recompile a function that changes and replace the .o file in the archive.

Commonly Used Libraries

libc.a (the C standard library)

- 8MB archive of 900 object files
- I/O, memory allocation, signal handling, string handling, data and time, random numbers, integer math

libm.a (the C math library)

- 1MB archive of 226 object files
- floating point math (sin, cos, tan, log, exp, sqrt, ...)

```
% ar -t /usr/lib/libc.a |
    sort
...
fork.o
...
fprintf.o
fpu_control.o
fputc.o
freopen.o
fscanf.o
...
```

```
% ar -t /usr/lib/libm.a |
    sort
...
e_acos.o
e_acosf.o
e_acosh.o
e_acoshf.o
e_acoshl.o
e_acosl.o
...
```

Using Static Libraries

Linker's algorithm for resolving external references:

- Scan .o files and .a files in the command line order.
- During the scan, keep a list of the current unresolved references.
- As each new .o or .a file obj is encountered, try to resolve each unresolved reference in the list against the symbols in obj.
- If there are any entries in the unresolved list at the end of the scan, then error.

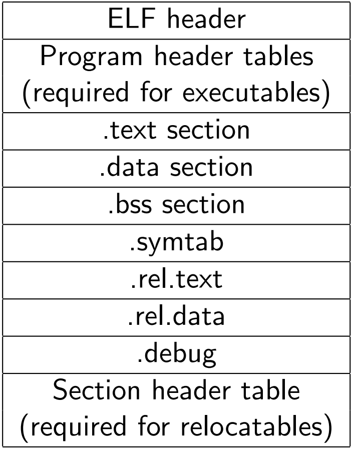
Problem:

- Command line order matters.
- Moral: put libraries at the end of the command line.

```
> gcc -L. libtest.o -lmine
> gcc -L. -lmine libtest.o
libtest.o:  In function ‘main’:
libtest.o(.text+0x4): undefined reference to ‘libfun’
```

Loading Executable Binaries

Executable object file for example program p:



ELF header

Program header tables (required for executables)

.text section

.data section

.bss section

.symtab

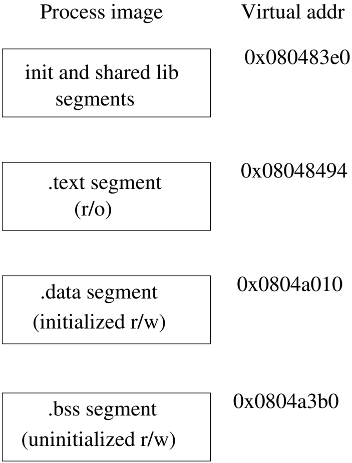
.rel.text

.rel.data

.debug

Section header table (required for relocatables)

Loaded segments:



Process image	Virtual addr
init and shared lib segments	0x080483e0
.text segment (r/o)	0x08048494
.data segment (initialized r/w)	0x0804a010
.bss segment (uninitialized r/w)	0x0804a3b0

Shared Libraries

Static libraries have some disadvantages:

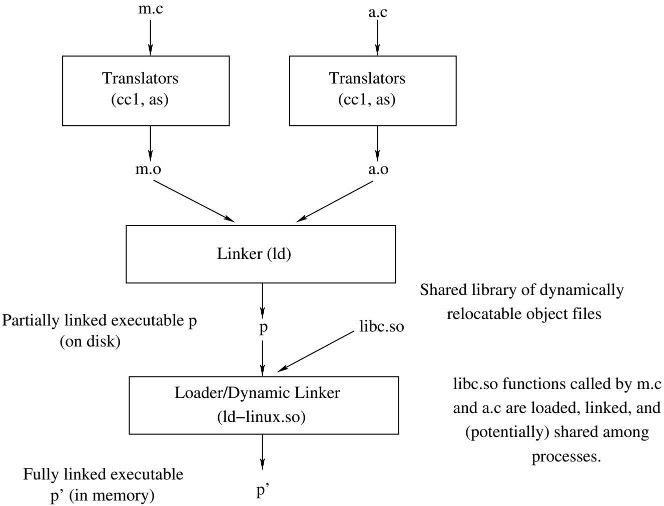
- Potential for duplicating lots of common code in the executable files on a file system. (e.g., every program needs the standard C library).
- Potential for duplicating lots of code in the virtual memory space of many processes.
- Minor bug fixes of system libraries require each application to explicitly relink.

Shared Libraries

Solution:

- *Shared libraries* (dynamic link libraries DLLs) whose members are dynamically loaded into memory and linked into an application at run-time.
- Dynamic linking can occur when an executable is first loaded and run. (The common case for Linux, handled automatically by `ld-linux.so`.)
- Dynamic linking can also occur after the program has begun.
  - In Linux, this is done explicitly by user with `dlopen()`.
  - Basis for High-Performance Web Servers.
- Shared library routines can be shared by multiple processes.

Dynamically Linked Shared Libraries



m.c

a.c

Translators (cc1, as)

Translators (cc1, as)

m.o

a.o

Linker (ld)

Partially linked executable p (on disk)

p

libc.so

Shared library of dynamically relocatable object files

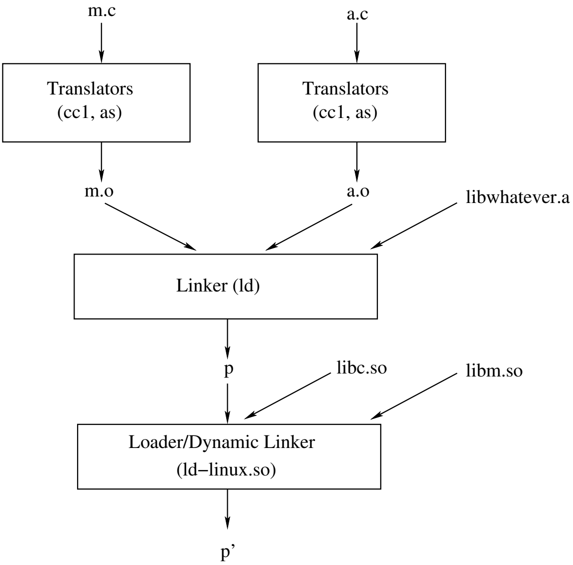
Loader/Dynamic Linker (ld–linux.so)

libc.so functions called by m.c and a.c are loaded, linked, and (potentially) shared among processes.

Fully linked executable p’ (in memory)

p’

The Complete Picture


m.c
a.c
Translators
(cc1, as)
Translators
(cc1, as)
m.o
a.o
libwhatever.a
Linker (ld)
p
libc.so
libm.so
Loader/Dynamic Linker
(ld–linux.so)
p'