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

```
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.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?

Case 1	**Case 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.

Case 1	Case 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:

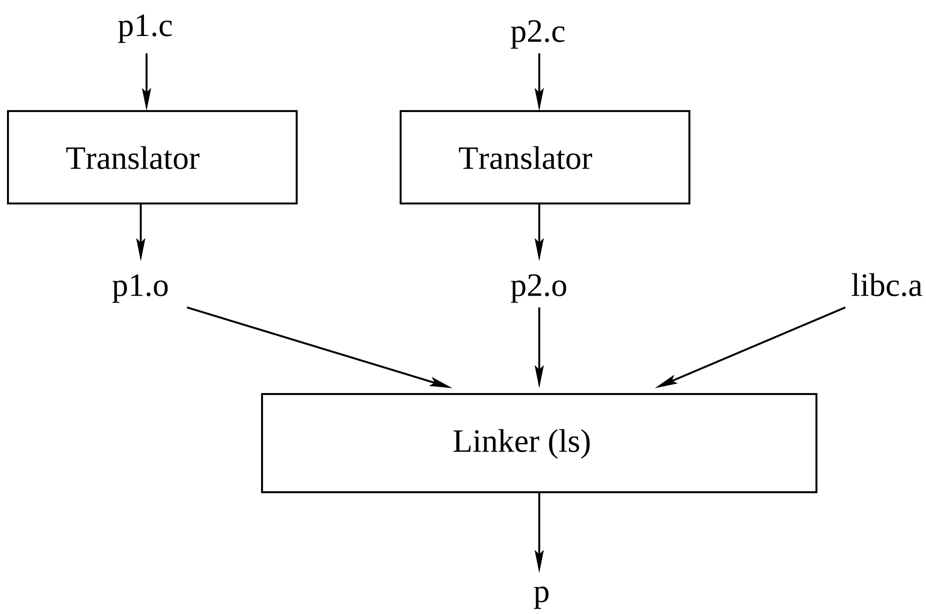
- Option 1: Put all functions into a single source file.
  - Programmers link big object file into their programs.
  - Space and time inefficient.
- Option 2: Put each function in a separate source file.
  - Programmers explicitly link appropriate binaries into their programs.
  - More efficient, but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

Packaging Commonly Used Functions

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

- Concatenate related relocatable object files into a single file 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)



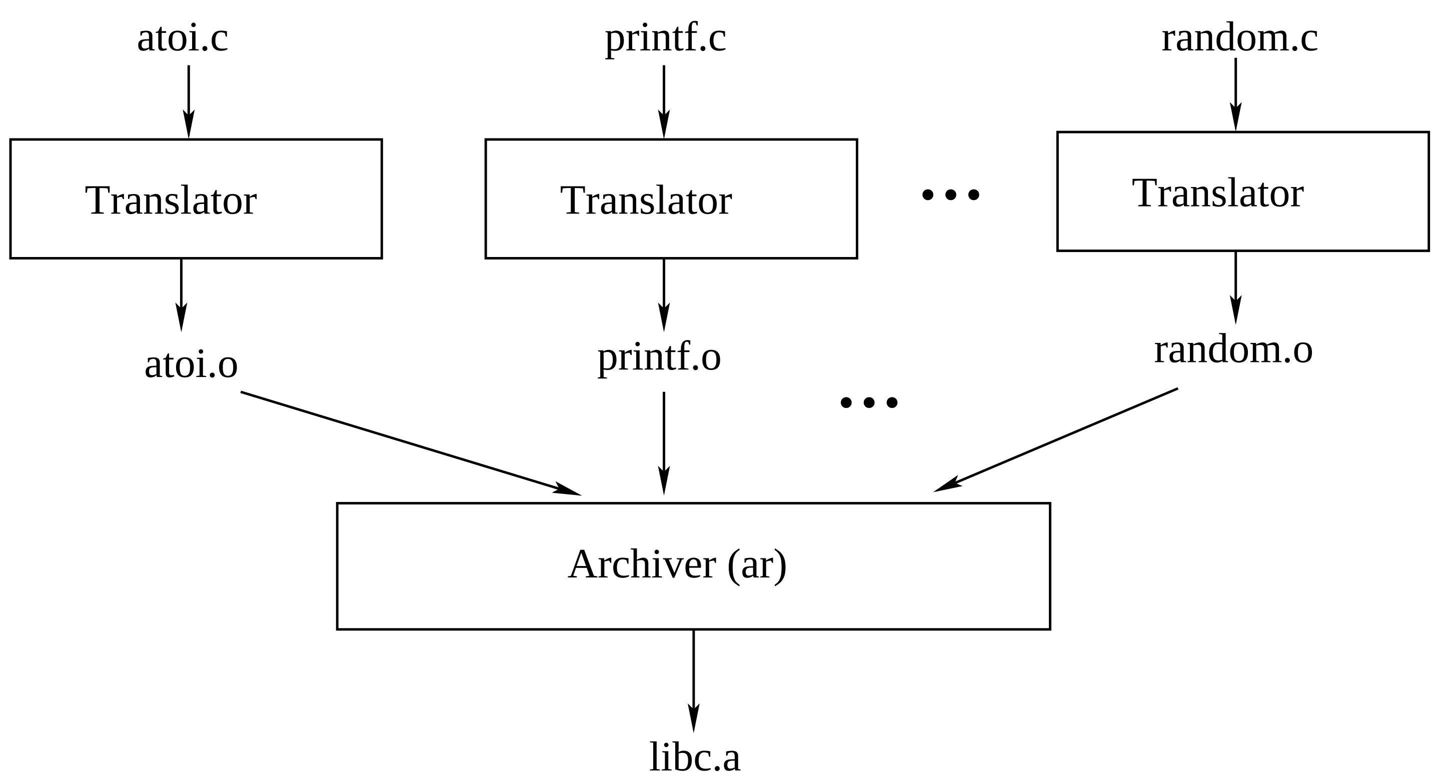
`libc.a` is a static library (archive) of relocatable object files concatenated into one file.

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.tex
.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:

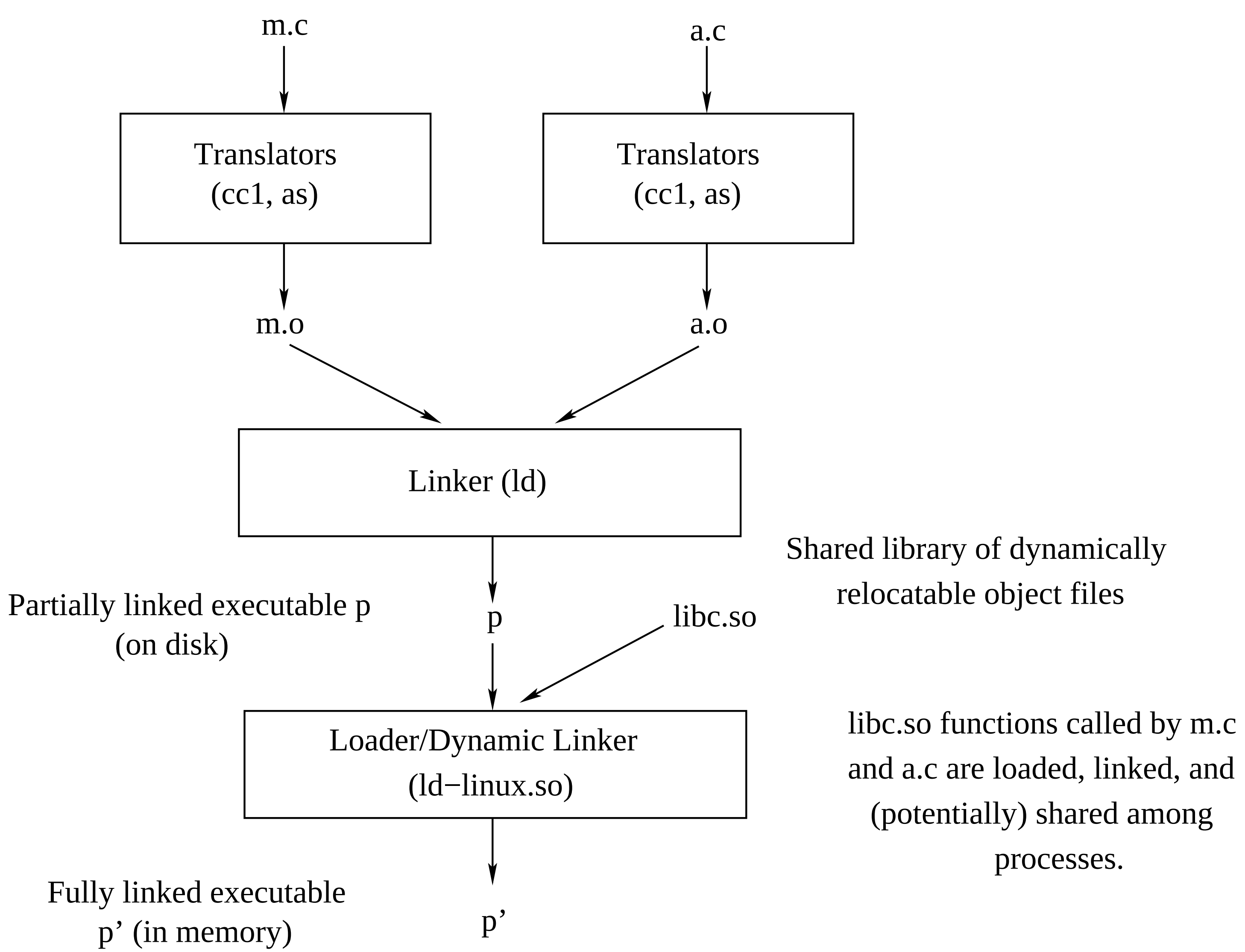
- Potential for duplicating lots of common code in the executable files on a file system. (e.g., every program needs the standard C library).
- Potential for duplicating lots of code in the virtual memory space of many processes.
- Minor bug fixes of system libraries require each application to explicitly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



The Complete Picture