

Linking

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Giving credit where credit is due

- Most of slides for this lecture are based on slides created by Drs. Bryant and O'Hallaron, Carnegie Mellon University.
- I have modified them and added new slides.

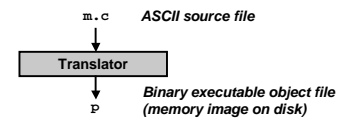
2

Topics

- Static linking
- Object files
- Static libraries
- Loading
- Dynamic linking of shared libraries

3

A Simplistic Program Translation Scheme



Problems:

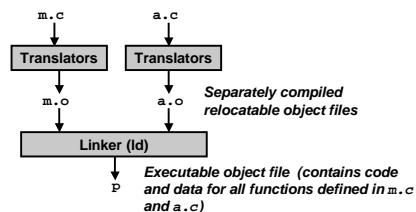
- Efficiency: small change requires complete recompilation
- Modularity: hard to share common functions (e.g. printf)

Solution:

- Static linker (or linker)

4

A Better Scheme Using a Linker



5

Translating the Example Program

Compiler driver coordinates all steps in the translation and linking process.

- Typically included with each compilation system (e.g., gcc)
- Invokes preprocessor (cpp), compiler (cc1), assembler (as), and linker (ld).
- Passes command line arguments to appropriate phases

Example: create executable p from m.c and a.c:

```
bass> gcc -O2 -v -o p m.c a.c
cpp [args] m.c /tmp/cca07630.i
cc1 /tmp/cca07630.i m.c -O2 [args] -o /tmp/cca07630.s
as [args] -o /tmp/cca076301.o /tmp/cca07630.s
<similar process for a.c>
ld -o p [system obj files] /tmp/cca076301.o /tmp/cca076302.o
bass>
```

6

What Does a Linker Do?

Merges object files

- Merges multiple relocatable (.o) object files into a single executable object file that can be loaded and executed by the loader.

Resolves external references

- As part of the merging process, resolves external references.
 - External reference: reference to a symbol defined in another object file.

Relocates symbols

- Relocates symbols from their relative locations in the .o files to new absolute positions in the executable.
- Updates all references to these symbols to reflect their new positions.
 - References can be in either code or data
 - » code: a(); /* reference to symbol a */
 - » data: int *xp=&x; /* reference to symbol x */

7

Why Linkers?

Modularity

- Program can be written as a collection of smaller source files, rather than one monolithic mass.
- Can build libraries of common functions (more on this later)
 - e.g., Math library, standard C library

Efficiency

- Time:
 - Change one source file, compile, and then relink.
 - No need to recompile other source files.
- Space:
 - Libraries of common functions can be aggregated into a single file...
 - Yet executable files and running memory images contain only code for the functions they actually use.

8

Executable and Linkable Format (ELF)

Standard binary format for object files

Derives from AT&T System V Unix

- Later adopted by BSD Unix variants and Linux

One unified format for

- Relocatable object files (.o),
- Executable object files
- Shared object files (.so)

Generic name: ELF binaries

Better support for shared libraries than old a.out formats.

9

ELF Object File Format

Elf header

- Magic number, type (.o, exec, .so), machine, byte ordering, etc.

Program header table

- Page size, virtual addresses memory segments (sections), segment sizes.

.text section

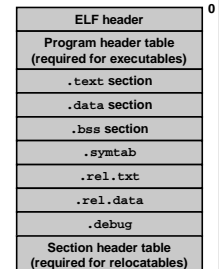
- Code

.data section

- Initialized (static) data

.bss section

- Uninitialized (static) data
- "Block Started by Symbol"
- "Better Save Space"
- Has section header but occupies no space



10

ELF Object File Format (cont)

.symtab section

- Symbol table
- Procedure and static variable names
- Section names and locations

.rel.text section

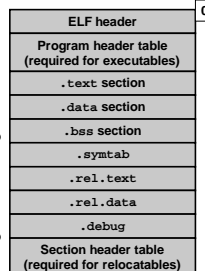
- Relocation info for .text section
- Addresses of instructions that will need to be modified in the executable
- Instructions for modifying.

.rel.data section

- Relocation info for .data section
- Addresses of pointer data that will need to be modified in the merged executable

.debug section

- Info for symbolic debugging (gcc -g)



11

Example C Program

```
m.c
int e=7;

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

```
a.c
extern int e;

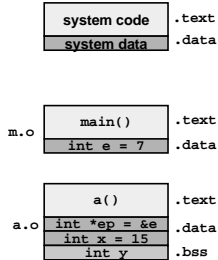
int *ep=&e;
int x=15;
int y;

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

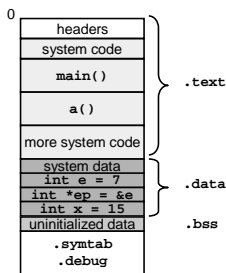
12

Merging Relocatable Object Files into an Executable Object File

Relocatable Object Files



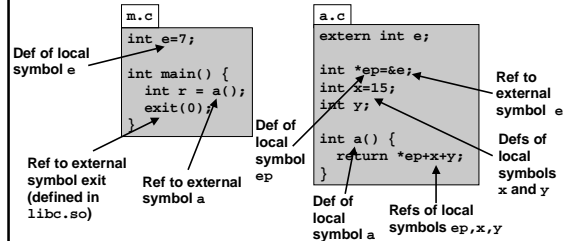
Executable Object File



13

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*.



14

m.o Relocation Info

m.c

```
int e=7;

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

Disassembly of section .text:

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

source: objdump

15

a.o Relocation Info (.text)

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 movl    0x0,%edx
6: 00
7: a1 00 00 00 movl    3: R_386_32 ep
               3: R_386_32 x
8: 8b 15 00 00 movl    8: R_386_32 x
c: 89 e5       movl    %esp,%ebp
e: 03 02       addl    (%edx),%eax
10: 89 ec       movl    %esp,%esp
12: 03 05 00 00 addl    0x0,%eax
17: 00
18: 5d          popl    %ebp
19: c3          ret
```

16

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
00000004 <x>:
4: 0f 00 00 00
```

17

Executable After Relocation and External Reference Resolution (.text)

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

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

18

Executable After Relocation and External Reference Resolution(.data)

```
m.c
int e=7;

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

a.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

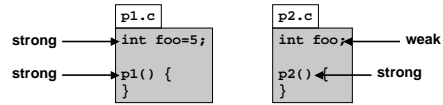
0804a020 <x>:
804a020: 0f 00 00 00
```

19

Strong and Weak Symbols

Program symbols are either strong or weak

- **strong**: procedures and initialized globals
- **weak**: uninitialized globals



20

Linker's Symbol Rules

Rule 1. A strong symbol can only appear once.

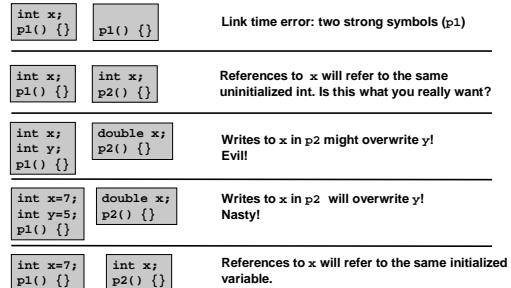
Rule 2. A weak symbol can be overridden by a strong symbol of the same name.

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

Rule 3. If there are multiple weak symbols, the linker can pick an arbitrary one.

21

Linker Puzzles



22

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:

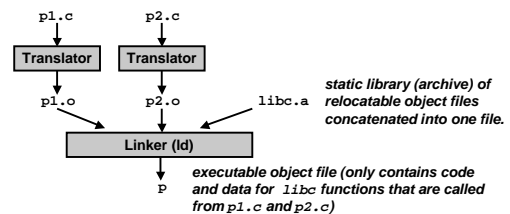
- Option 1: Put all functions in a single source file
 - Programmers link big object file into their programs
 - Space and time inefficient
- Option 2: Put each function in a separate source file
 - Programmers explicitly link appropriate binaries into their programs
 - More efficient, but burdensome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

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

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

23

Static Libraries (archives)

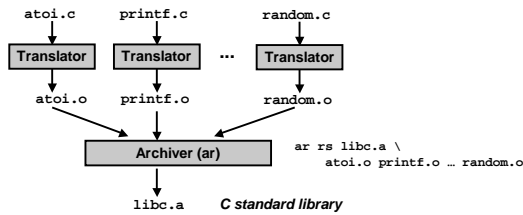


Further improves modularity and efficiency by packaging commonly used functions [e.g., C standard library (libc), math library (libm)]

Linker selectively only the .o files in the archive that are actually needed by the program.

24

Creating Static Libraries



Archiver allows incremental updates:

- Recompile function that changes and replace .o file in archive.

25

Commonly Used Libraries

libc.a (the C standard library)

- 8 MB 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)

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

```

% ar -t /usr/lib/libc.a | sort
...
e_acos.o
e_acosf.o
e_acosh.o
e_acoshf.o
e_acoshl.o
e_acosl.o
e_asin.o
e_asinf.o
e_asinl.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
e_asin.o
e_asinf.o
e_asinl.o
...
    
```

26

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 any entries in the unresolved list at end of scan, then error.

Problem:

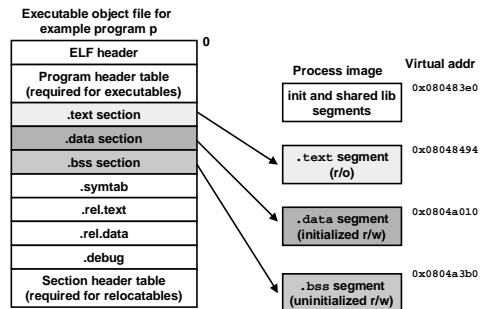
- Command line order matters!
- Moral: put libraries at the end of the command line.

```

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

27

Loading Executable Binaries



28

Shared Libraries

Static libraries have the following disadvantages:

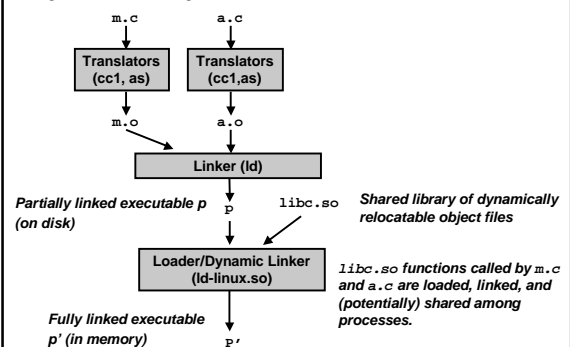
- Potential for duplicating lots of common code in the executable files on a filesystem.
 - e.g., every C program needs the standard C library
- Potential for duplicating lots of code in the virtual memory space of many processes.
- Minor bug fixes of system libraries require each application to explicitly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

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 executable is first loaded and run.
 - » Common case for Linux, handled automatically by ld-linux.so.
 - Dynamic linking can also occur after 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.

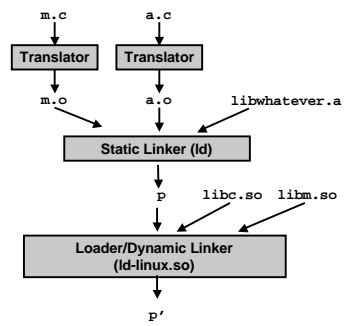
29

Dynamically Linked Shared Libraries



30

The Complete Picture



31