15-213

"The course that gives CMU its Zip!"

Linking
Oct. 15, 2002

Topics

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

Linker Puzzles

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

```
p1() {}
```

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

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

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

```
double x;
p2() {}
```

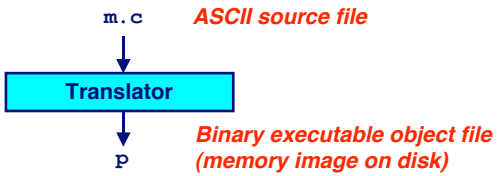
```
int x=7;
int y=5;
p1() {}
```

```
double x;
p2() {}
```

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

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

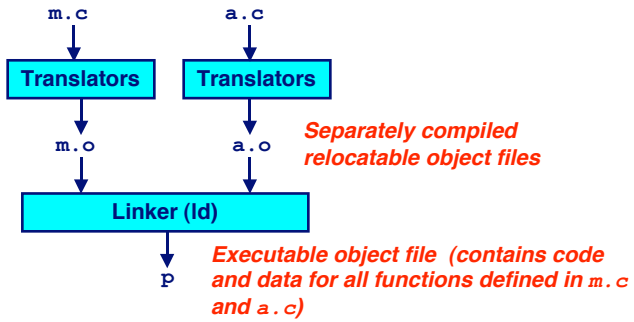

A Simplistic Program Translation Scheme



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

Solution:
- *Static linker (or linker)*

A Better Scheme Using a Linker



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>
```


What Does a Linker Do?

Merges object files

- Merges multiple relocatable (`.o`) object files into a single executable object file that can 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 */`

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.

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.

ELF Object File Format

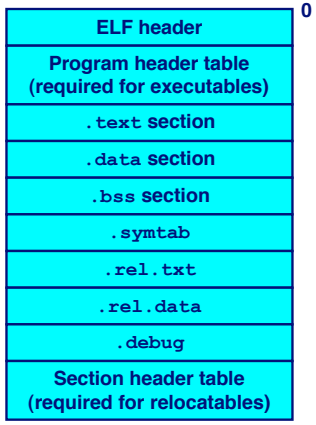
Elf header
- Magic number, type (.o, exec, .so), machine, byte ordering, etc.

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



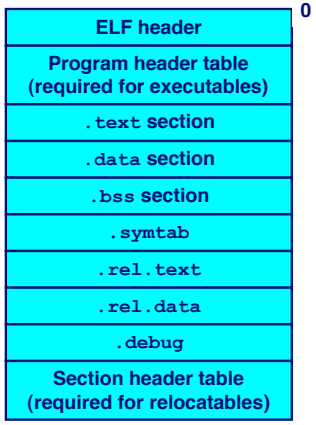
ELF Object File Format (cont)

`.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`)



Example C Program

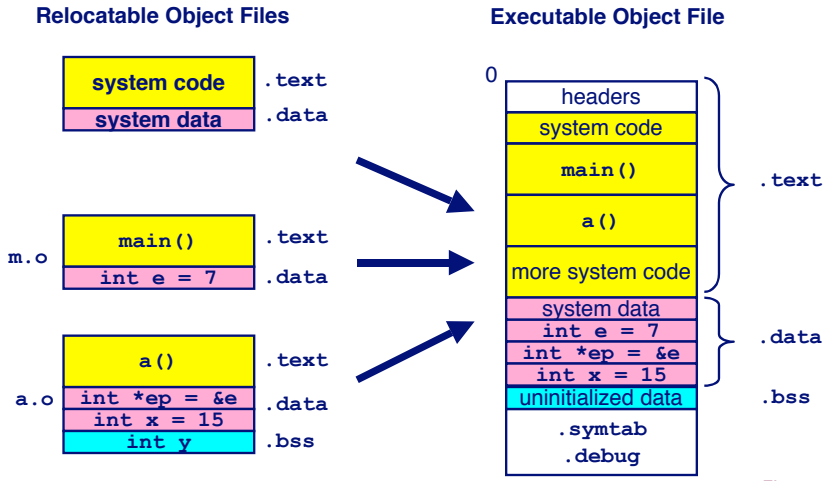
m.c

```
int e=7;

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

a.c

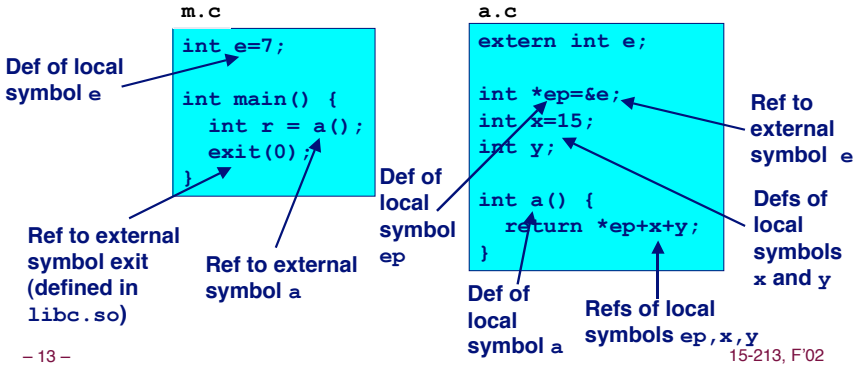
```
extern int e;

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

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


Merging Relocatable Object Files into an Executable Object File



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.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 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
```

source: objdump

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 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:   c3                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 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 and External Reference Resolution(.data)

m.c

```
int e=7;

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

a.c

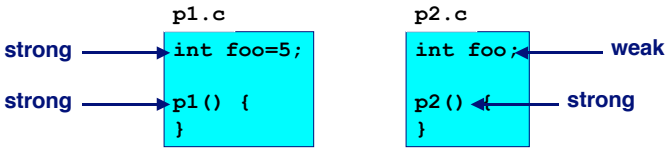
```
extern int e;

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
```


Strong and Weak Symbols

Program symbols are either strong or weak

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



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.

Linker Puzzles

`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 uninitialized int. Is this what you really want?
`int x; int y; p1() {}`	`double x; p2() {}`	Writes to `x` in `p2` might overwrite `y`! Evil!
`int x=7; int y=5; p1() {}`	`double x; p2() {}`	Writes to `x` in `p2` will overwrite `y`! 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.

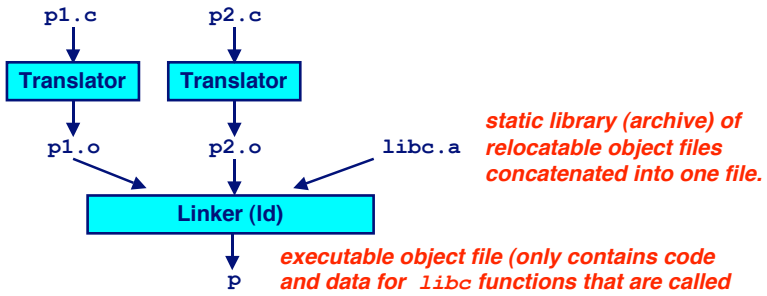
Awkward, given the linker framework so far:

- Option 1: Put all functions 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.

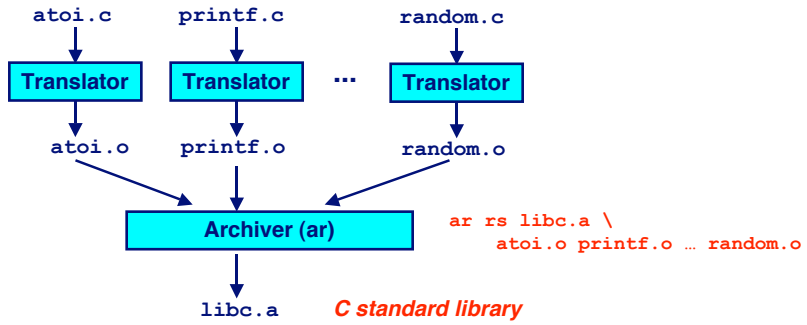
Static Libraries (archives)



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.

Creating Static Libraries



Archiver allows incremental updates:

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

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
…
fork.o
…
fprintf.o
fpu_control.o
fputc.o
freopen.o
fscanf.o
fseek.o
fstab.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
…
```


Using Static Libraries

Linker's algorithm for resolving external references:

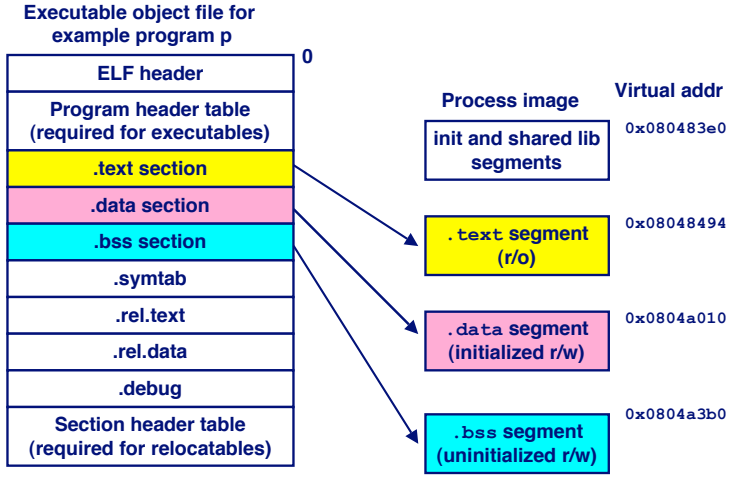
- Scan .o files and .a files in the command line order.
- During the scan, keep a list of the current unresolved references.
- As each new .o or .a file obj is encountered, try to resolve each unresolved reference in the list against the symbols in obj.
- If any entries in the unresolved list at end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


Loading Executable Binaries



Shared Libraries

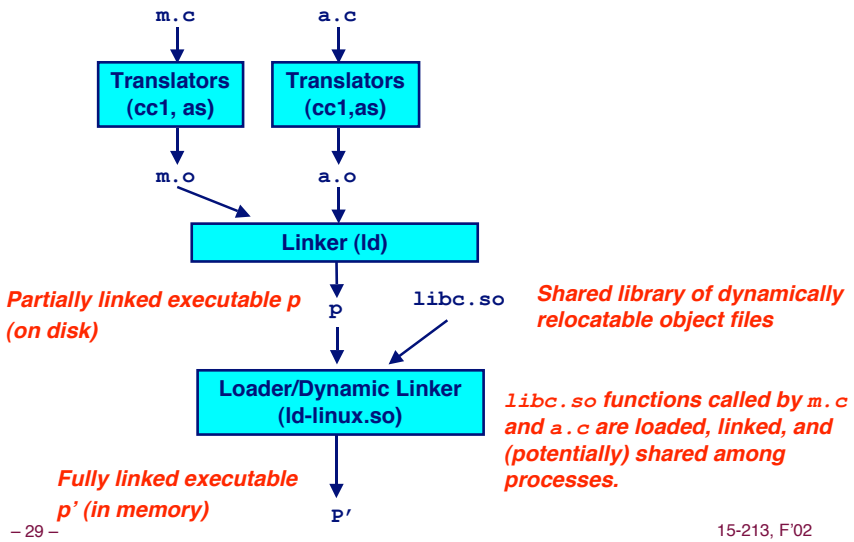
Static libraries have the following disadvantages:

- 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.

Dynamically Linked Shared Libraries



Partially linked executable p (on disk)

Shared library of dynamically relocatable object files

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

Fully linked executable p' (in memory)

The Complete Picture