**JDEP 284H**
**Foundations of Computer Systems**

# 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.

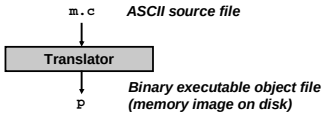


## Topics

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



## A Simplistic Program Translation Scheme

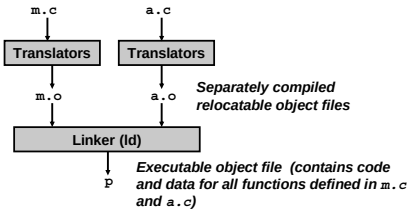



**Problems:**
- Efficiency: small change requires complete recompilation
- Modularity: hard to share common functions (e.g. `printf`)

**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 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 */`



## 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

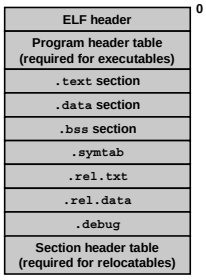
**Elf header**
- Magic number, type (.o, exec, .so), machine, byte ordering, etc.

**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





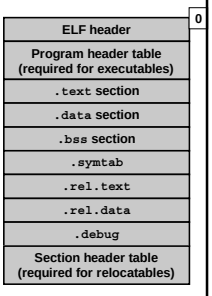

## ELF Object File Format (cont)

**`.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`)



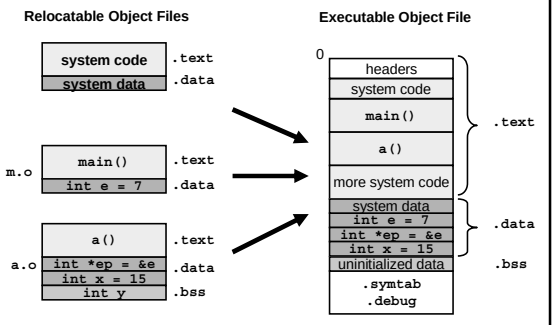



## Example C Program

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

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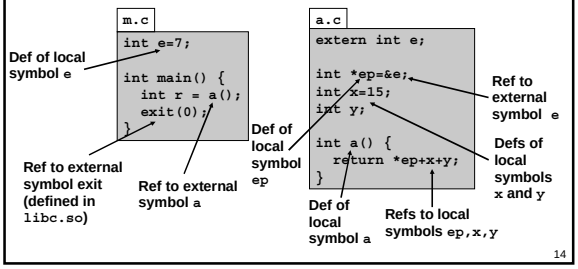
## Relocating Symbols and Resolving External References

- *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*.

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## 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

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## 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
```

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## 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
```

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## 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
```

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## 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
```

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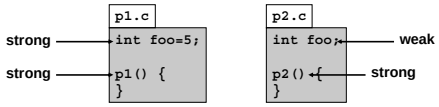
## Strong and Weak Symbols

**Program symbols are either strong or weak**

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

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## 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.**

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## 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.**

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## 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.**

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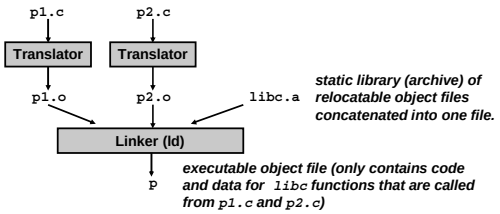
## Static Libraries (archives)




***static library (archive) of relocatable object files concatenated into one file.***

***executable object file (only contains code and data for `libc` functions that are called from `p1.c` and `p2.c`)***

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

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

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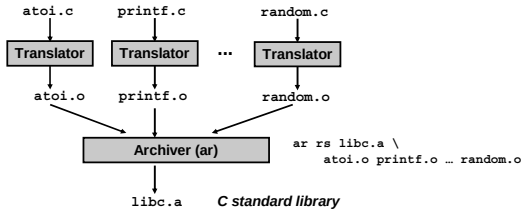
## Creating Static Libraries




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

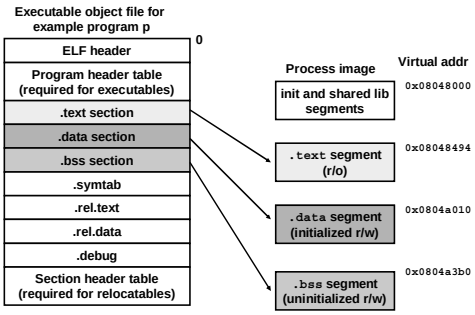
**Linker's algorithm for resolving external references:**
- Scan .o files and .a files in the command line order.
- During the scan, keep a list of the current unresolved references.
- As each new .o or .a file obj is encountered, try to resolve each unresolved reference in the list against the symbols 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





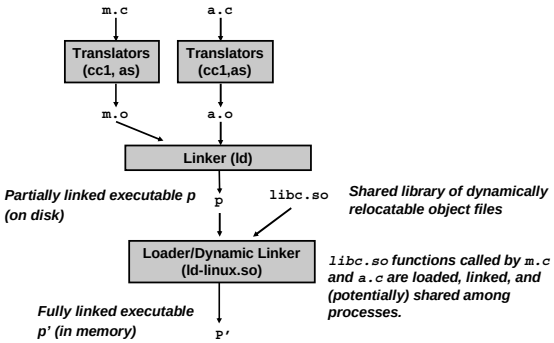

## Shared Libraries

**Static libraries have the following disadvantages:**
- Potential for duplicating a lot of common code in the executable files on a file system.
  - 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

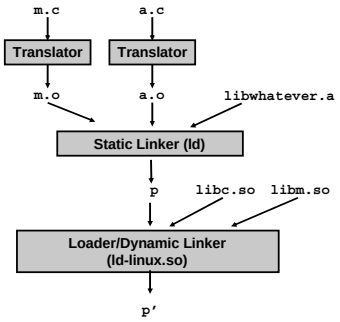
**Solution:**
- *Shared libraries* (dynamic link libraries, DLLs) whose members are dynamically loaded into memory and linked into an application at run-time.
  - Dynamic linking can occur when executable is first loaded and run.
    - » Common case for Linux, handled automatically by `ld-linux.so`.
  - 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



## The Complete Picture

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