Systems I

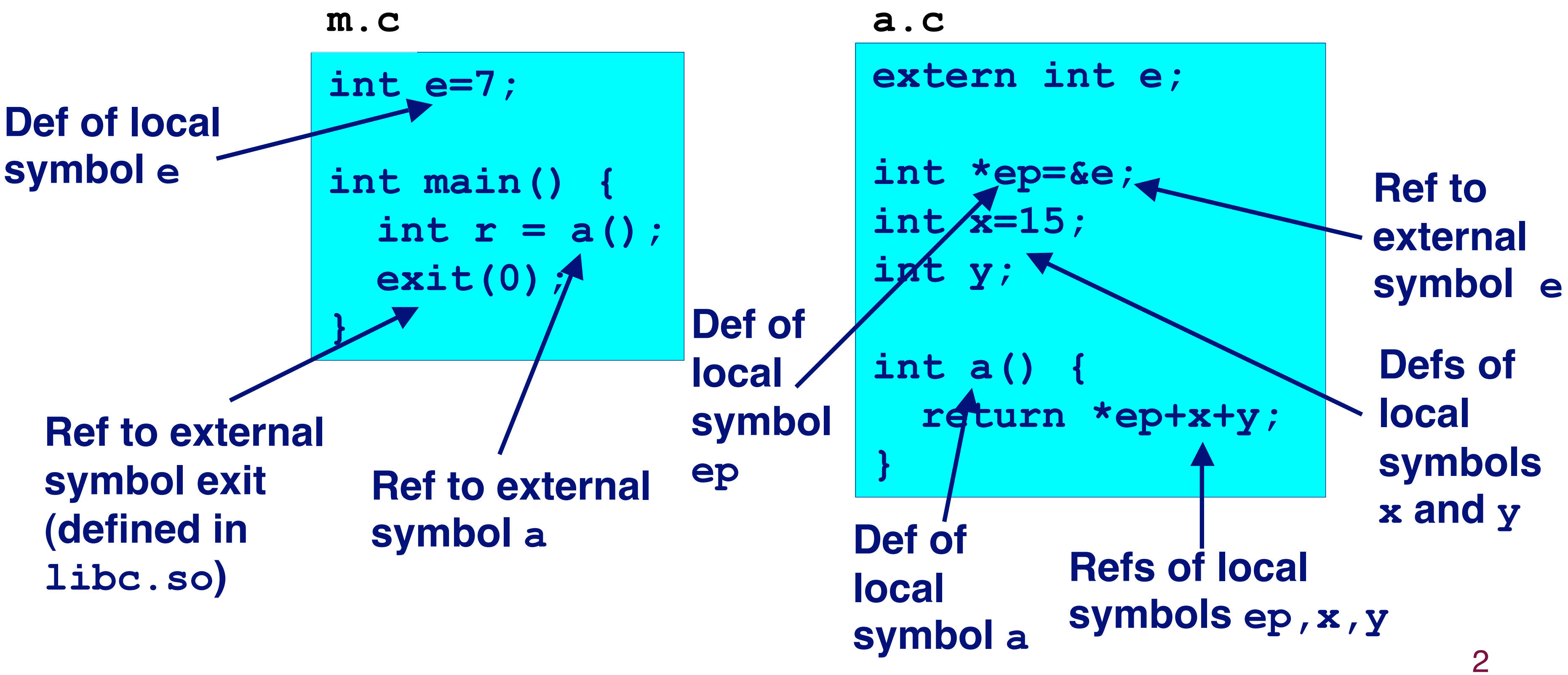
Linking II

Topics

- Relocation
- Static libraries
- Loading
- Dynamic linking of shared libraries

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;

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;
}
```

Def of local symbol e

Ref to external symbol exit (defined in libc.so)

Ref to external symbol a

Def of local symbol ep

Def of local symbol a

Refs of local symbols ep,x,y

Ref to external symbol e

Defs of local symbols x and y

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

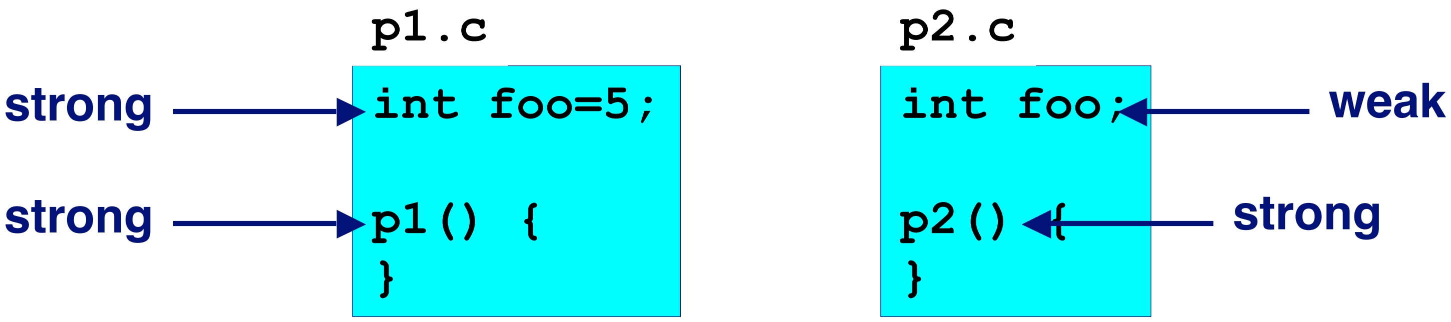
```
extern int e;

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



p1.c

```
int foo=5;

p1() {
}
```

p2.c

```
int foo;

p2() {
}
```

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() {}
```

```
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

```
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.

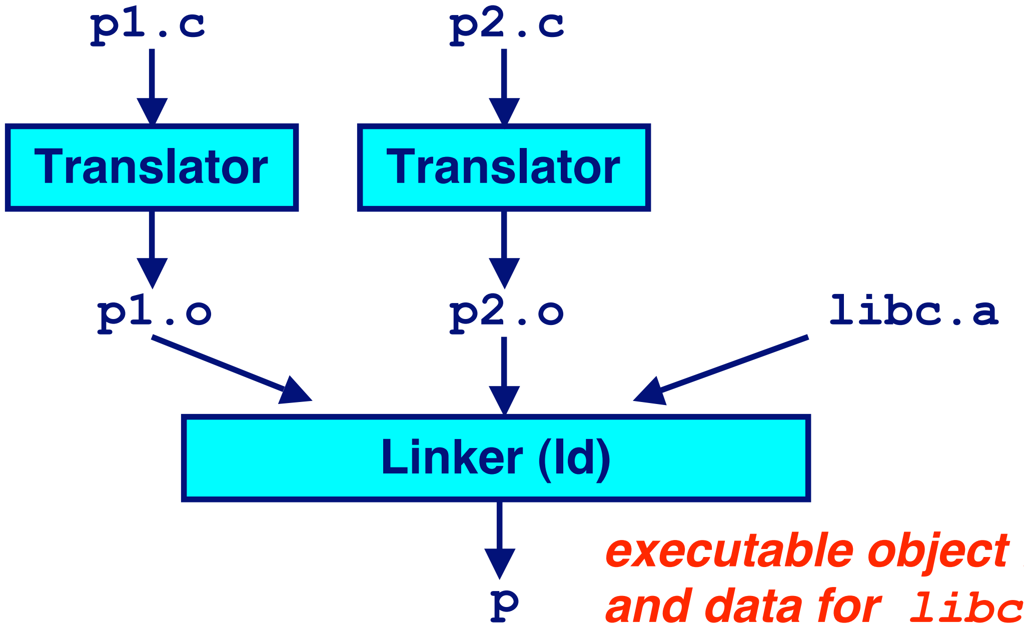
Awkward, given the linker framework so far:

- 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)



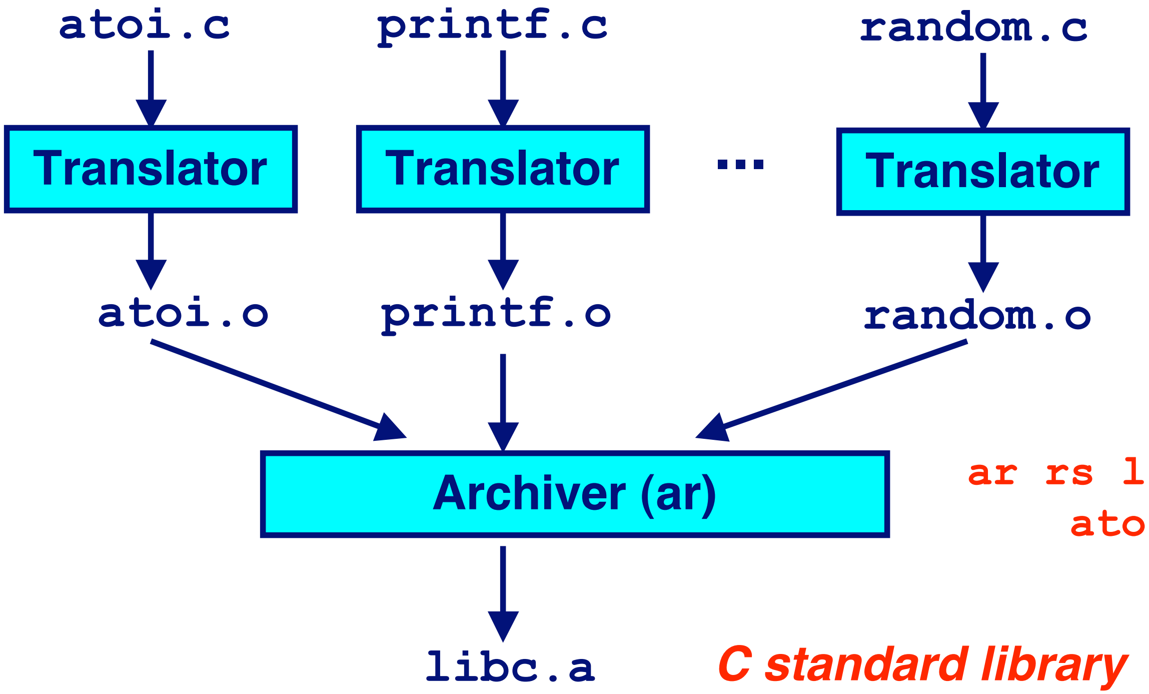
static library (archive) of relocatable object files concatenated into one file.

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 selects only the `.o` files in the archive that are actually needed by the program.

Creating Static Libraries



```
ar rs libc.a \
    atoi.o printf.o … random.o
```

C standard library

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:

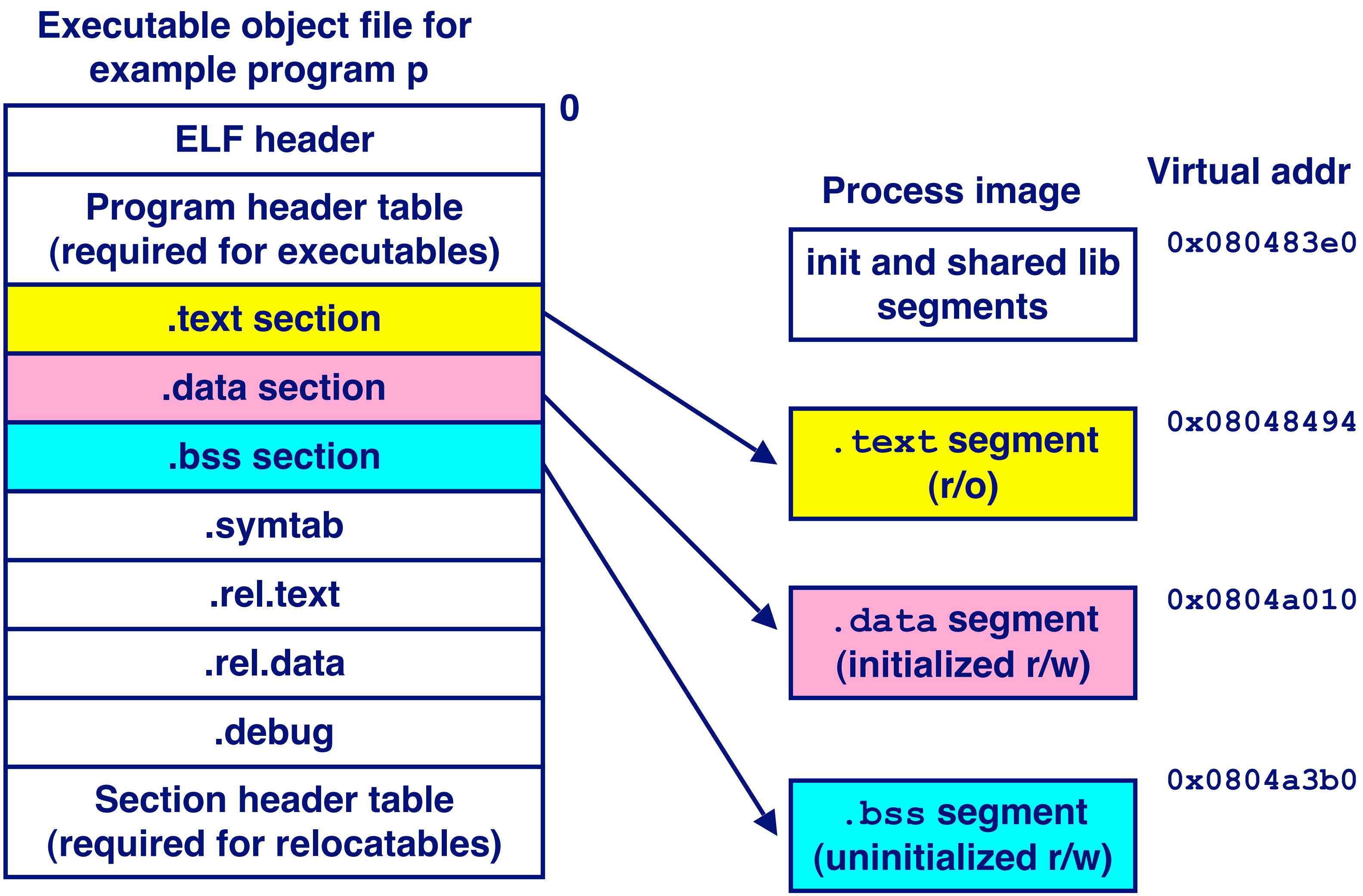
- Scan .o files and .a files in the command line order.
- During the scan, keep a list of the current unresolved references.
- As each new .o or .a file obj is encountered, try to resolve each unresolved reference in the list against the symbols in obj.
- If any entries in the unresolved list at end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


Executable object file for example program p
0
ELF header
Program header table (required for executables)
.text section
.data section
.bss section
.symtab
.rel.text
.rel.data
.debug
Section header table (required for relocatables)
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

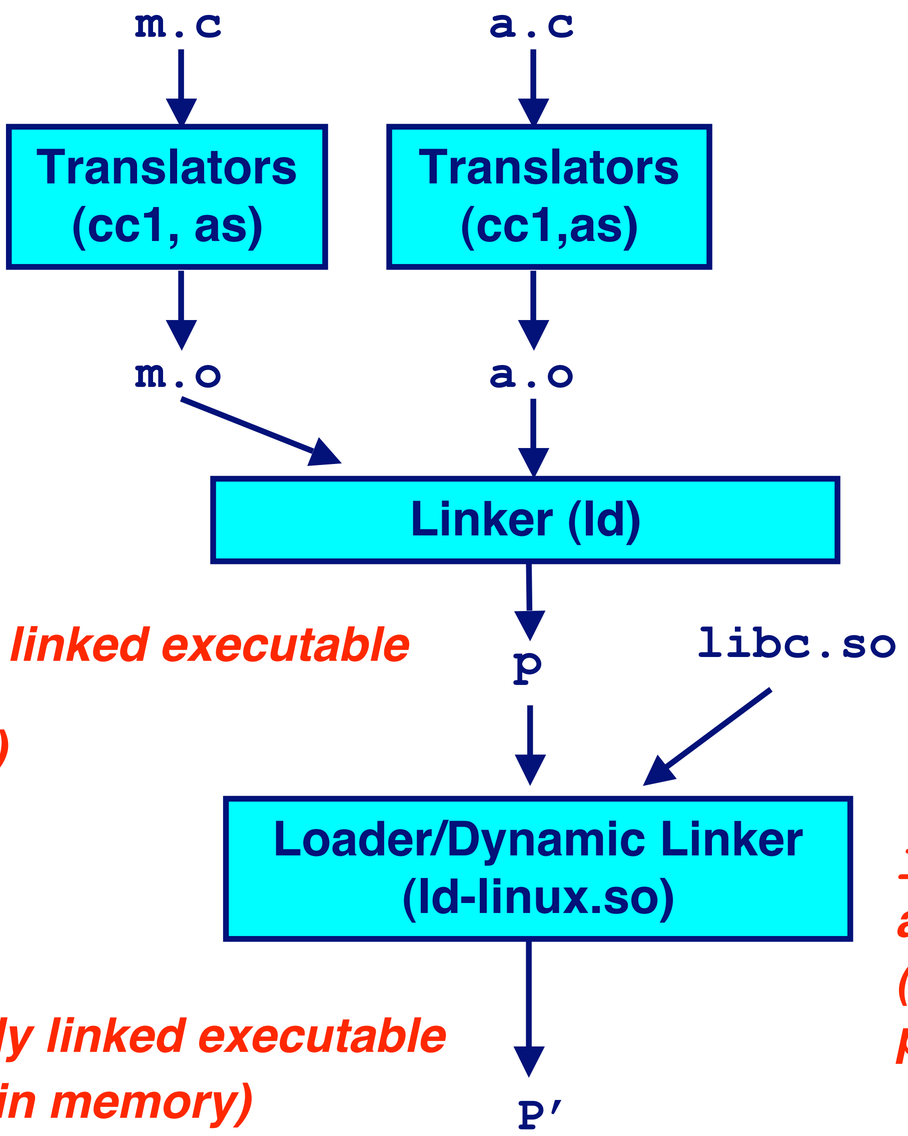
Static libraries have the following disadvantages:

- 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



m.c

a.c

Translators (cc1, as)

Translators (cc1,as)

m.o

a.o

Linker (ld)

p

libc.so

Loader/Dynamic Linker (ld-linux.so)

p′

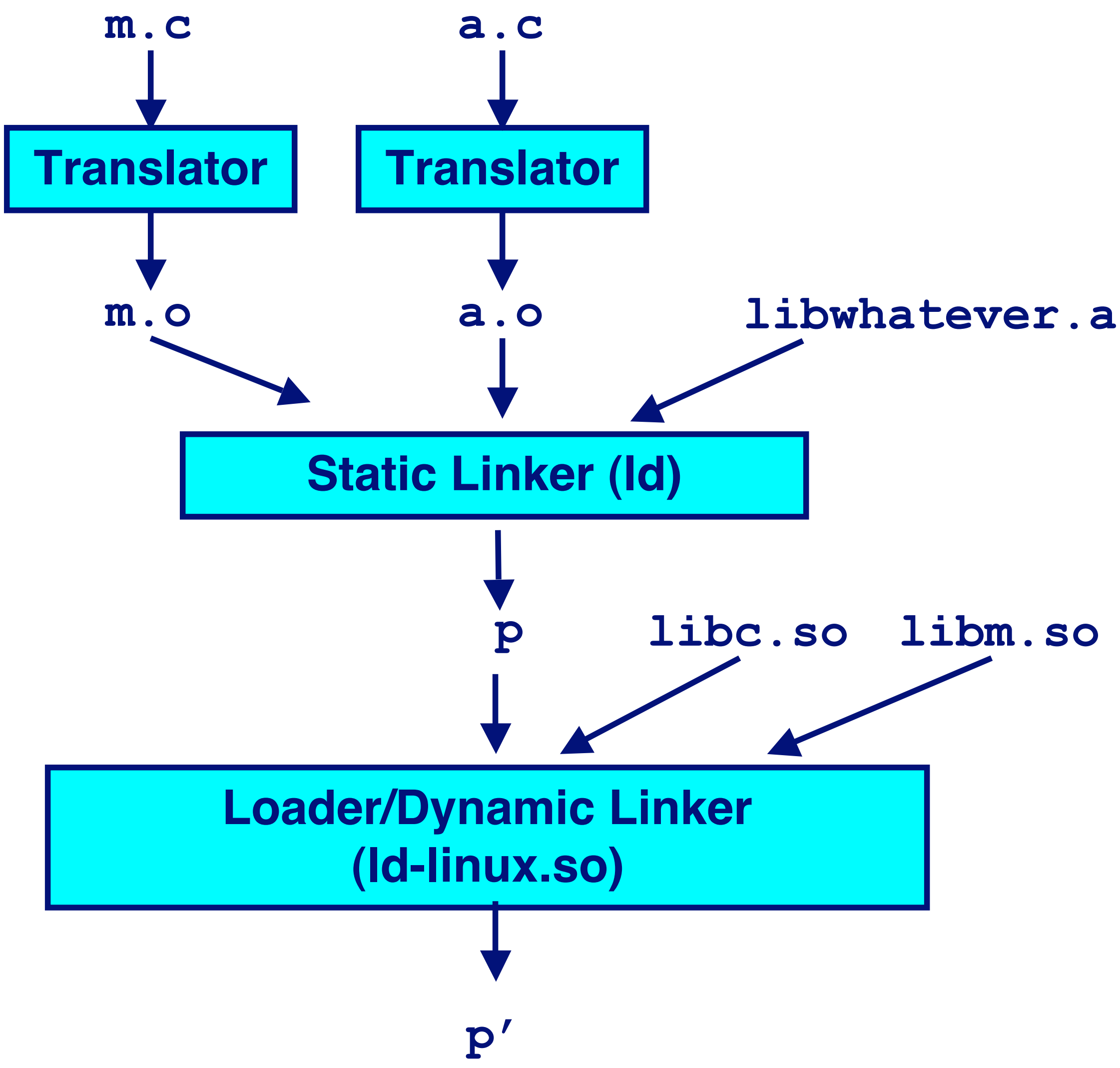
Partially linked executable p
(on disk)

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


m.c
a.c
Translator
Translator
m.o
a.o
libwhatever.a
Static Linker (ld)
p
libc.so
libm.so
Loader/Dynamic Linker
(ld-linux.so)
p′