CS412/413

Introduction to Compilers
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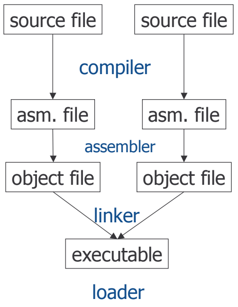
Lecture 35: Linking and Loading
25 Apr 03

Outline

- Static linking
  - Object files
  - Libraries
  - Shared libraries
  - Relocatable code
- Libraries
  - Shared libraries
  - Dynamically linked libraries
- Book: "Linkers and Loaders", by J. Levine

Big Picture

- Output of compiler is a set of assembly/object files
  - Not executable
  - May refer to external symbols (variables, functions, etc.)
  - Each object file has its own address space
- Linker joins together object files into one executable file
- Loader brings program in memory and executes it



Main Issues

- Symbol resolution
  - May have in one module references to external symbols from another module
  - Linker fixes such references when combining modules
- Relocation
  - Symbols may have different addresses in the final executable (they have been relocated)
  - Linker must fix references to relocated symbols
  - Loader may also need to relocate symbols
- Program loading
  - Bring the program from disk to memory
  - May require setting up virtual memory

Symbol Resolution

source code

```
extern int foo( int x );
extern int n;
…
foo(n);
```

assembly code

```
push _n
call _foo
add $4, %esp
```

object code

```
ff 35 00 00 00 00
e8 00 00 00 00
83 c4 04
```

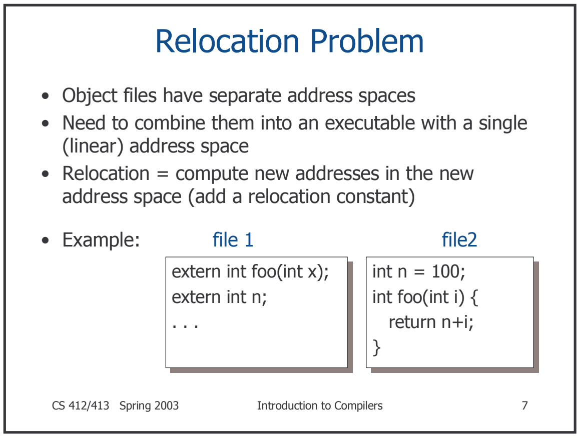
to be filled in by linker

Executable Code

```
00401044 <_bar>:
  401044:     55                        push   %ebp
  401045:     89 e5                     mov    %esp,%ebp
  401047:     ff 35 08 20 40 00         pushl  0x402008
  40104d:     e8 1e 00 00 00            call   401070 <_foo>
  401052:     83 c4 04                  add    $0x04,%esp
  401055:     89 ec                     mov    %ebp,%esp
  401057:     5d                        pop    %ebp
  401058:     c3                        ret

00401070 <_foo>:
  401070:     55                        push   %ebp
  401071:     89 e5                     mov    %esp,%ebp
  . . .

00402008 <_n>:
  402008:     64 00 00 00
```



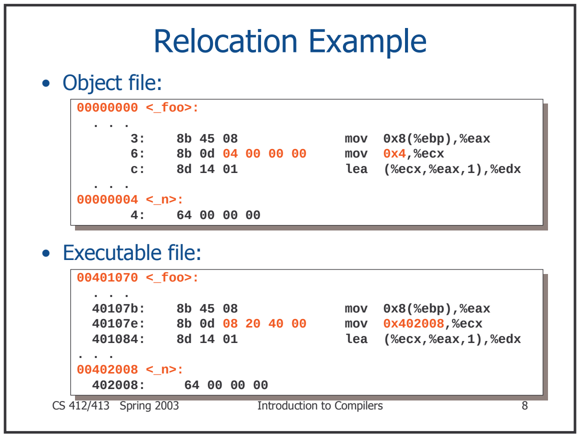
Relocation Problem

- Object files have separate address spaces
- Need to combine them into an executable with a single (linear) address space
- Relocation = compute new addresses in the new address space (add a relocation constant)

- Example:

file 1	file2

extern int foo(int x);
extern int n;
. . .
	int n = 100;
	int foo(int i) {
	return n+i;
	}



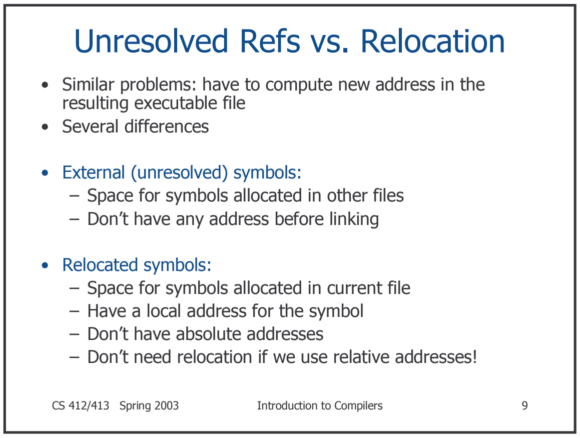
Relocation Example

- Object file:

```
00000000 <_foo>:
  . . .
      3:    8b 45 08                mov  0x8(%ebp),%eax
      6:    8b 0d 04 00 00 00       mov  0x4,%ecx
      c:    8d 14 01                lea  (%ecx,%eax,1),%edx
  . . .
00000004 <_n>:
      4:    64 00 00 00
```

- Executable file:

```
00401070 <_foo>:
  . . .
  40107b:   8b 45 08                mov  0x8(%ebp),%eax
  40107e:   8b 0d 08 20 40 00       mov  0x402008,%ecx
  401084:   8d 14 01                lea  (%ecx,%eax,1),%edx
. . .
00402008 <_n>:
  402008:    64 00 00 00
```

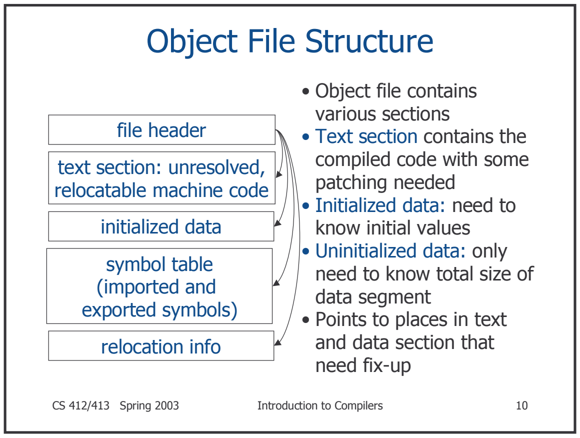


Unresolved Refs vs. Relocation

- Similar problems: have to compute new address in the resulting executable file
- Several differences

- External (unresolved) symbols:
  - Space for symbols allocated in other files
  - Don't have any address before linking

- Relocated symbols:
  - Space for symbols allocated in current file
  - Have a local address for the symbol
  - Don't have absolute addresses
  - Don't need relocation if we use relative addresses!



Object File Structure

file header

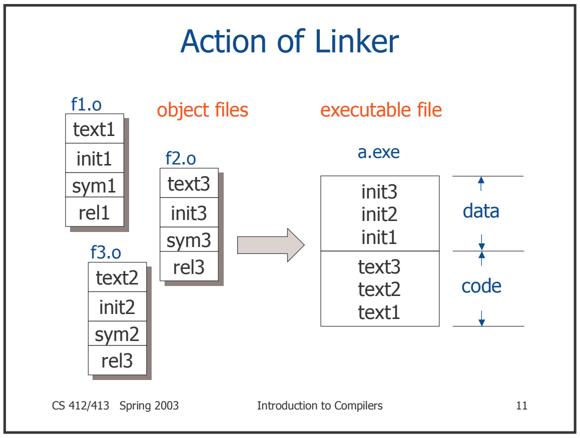
text section: unresolved, relocatable machine code

initialized data

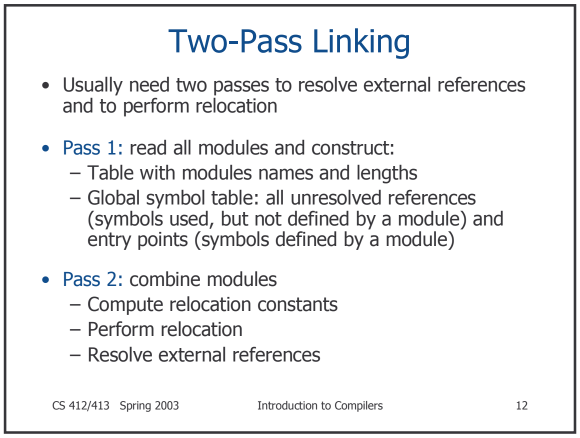
symbol table (imported and exported symbols)

relocation info

- Object file contains various sections
- Text section contains the compiled code with some patching needed
- Initialized data: need to know initial values
- Uninitialized data: only need to know total size of data segment
- Points to places in text and data section that need fix-up



Action of Linker



Two-Pass Linking

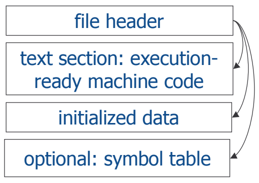
- Usually need two passes to resolve external references and to perform relocation

- Pass 1: read all modules and construct:
  - Table with modules names and lengths
  - Global symbol table: all unresolved references (symbols used, but not defined by a module) and entry points (symbols defined by a module)

- Pass 2: combine modules
  - Compute relocation constants
  - Perform relocation
  - Resolve external references

Executable File Structure

- Same as object file, but code is ready to be executed as-is
- Pages of code and data brought in lazily from text and data section as needed: rapid start-up
- Symbols allow debugging
- Text section shared across processes



file header

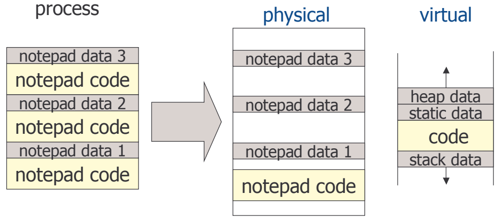
text section: execution-ready machine code

initialized data

optional: symbol table

Executing Programs

- Multiple copies of program share code (text), have own data
- Data appears at same virtual address in every process



physical

virtual

notepad data 3

notepad code

notepad data 2

notepad code

notepad data 1

notepad code

heap data

static data

code

stack data

File Formats

- Unix:
  - a.out format
  - COFF: Common Object File Format
  - ELF: Executable and Linking Format
  - All support both executable and object files
- Windows:
  - COM, EXE: executable formats
  - PE: Microsoft Portable Executable format
    - For Windows NT, adapted from COFF

Libraries

- Library = collection of object files
- Linker adds all object files necessary to resolve undefined references in explicitly named files
- Object files, libraries searched in user-specified order for external references

  Unix linker: ld

  ```
  ld main.o foo.o /usr/lib/X11.a /usr/lib/libc.a
  ```

  Microsoft linker:link

  ```
  link main.obj foo.obj kernel32.lib user32.lib …
  ```

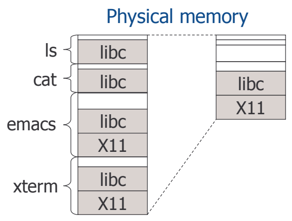
- Index over all object files in library for rapid searching

  Unix: ranlib

  ```
  ranlib mylib.a
  ```

Shared Libraries

- Problem: libraries take up a lot of memory when linked into many running applications
- Solution: shared libraries



Physical memory

ls

cat

emacs

xterm

libc

libc

libc

X11

libc

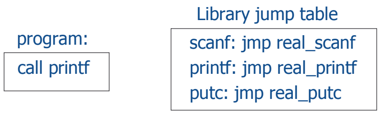
X11

libc

X11

Shared Libraries

- Executable file refers to, does not contain library code; library code brought in the address space when the program is loaded
- Library compiled at fixed address, far away from the application (e.g. Linux: hex 60000000, BSD a0000000)
- Link program against stub library (no code, data)
- Shared library uses a jump table: client code jumps to jump table and follows indirection (useful for library updates)



Library jump table

program:

```
call printf
```

```
scanf: jmp real_scanf
printf: jmp real_printf
putc: jmp real_putc
```

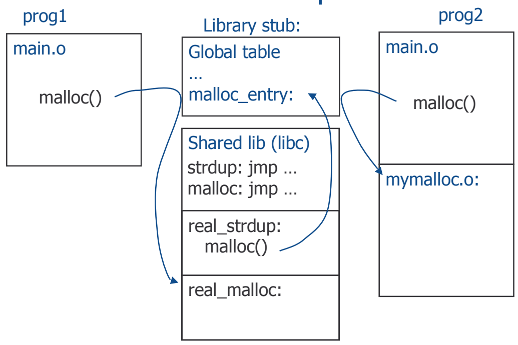
Intra-Library Calls

- Problem: shared libraries may depend on external symbols (even symbols within the shared library); different applications may have different linkage:

```
ld -o prog1 main.o /usr/lib/libc.a
ld -o prog2 main.o mymalloc.o /usr/lib/libc.a
```

- If routine in libc.a calls malloc(), for prog1 should get standard version; for prog2, version in mymalloc.o
- Calls to external symbols are made through global tables unique to each program

Malloc Example



Dynamic Linking

- Idea: link shared libraries when loading the program or at run-time
  - Easier to create
  - Easier to update
  - Programs can load and unload routines at run-time
- Drawback: loading-time or run-time overhead

Dynamic Shared Objects

- Unix systems: Code is typically compiled as a dynamic shared object (DSO), a relocatable shared library
- Shared libraries in UNIX use the ELF format, which supports Position-Independent Code (PIC)
  - Program can determine its current address
  - Add constant offset to access local data
  - If data located in a different library, use indirection through a Global Offset Table (GOT).
  - Address of GOT usually computed and stored in a register at the beginning of each procedure

Dynamic Shared Objects

- For calls to methods in shared libraries, uses procedure linkage tables (PLT) – same as GOT, but with entries for functions.
  - Entries represent pointers to functions from the shared library that may be invoked
  - The dynamic linker fills the PLT lazily: it fills in the entry for a function the first time that function is invoked
  - Subsequent calls just use the function pointer stored in the PLT

Cost of DSOs

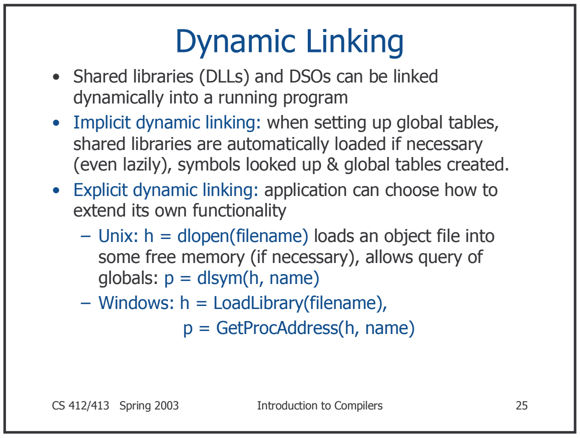
- Assume ebx contains PLT/GOT address
- Call to function f:

```
call *f_offset(%ebx)
```

- Global variable accesses:

```
mov v_offset(%ebx), %eax
mov (%eax), %eax
```

- Calling global functions ≈ calling methods
- Accessing global variables is more expensive than accessing local variables
- Most computer benchmarks run w/o DSOs!



Dynamic Linking

- Shared libraries (DLLs) and DSOs can be linked dynamically into a running program
- Implicit dynamic linking: when setting up global tables, shared libraries are automatically loaded if necessary (even lazily), symbols looked up & global tables created.
- Explicit dynamic linking: application can choose how to extend its own functionality
  - Unix: h = dlopen(filename) loads an object file into some free memory (if necessary), allows query of globals: p = dlsym(h, name)
  - Windows: h = LoadLibrary(filename),
    p = GetProcAddress(h, name)