CS 412/413

Introduction to
Compilers and Translators

Andrew Myers
Cornell University

Lecture 32: Linking and Loading

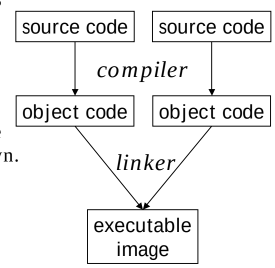
19 April 00

Outline

- Static linking
  - Object files
  - Libraries
  - Shared libraries
  - Relocatable code
- Dynamic linking
  - explicit vs. implicit linking
  - dynamically linked libraries/dynamic shared objects

Object files

- Output of compiler is an *object file*
  - not executable
  - may refer to external symbols (variables, functions, etc.) whose definition is not known.
- Linker joins together object files, resolves external references



Unresolved references

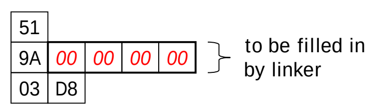
source code

```
extern int abs( int x );
…
y = y + abs(x);
```

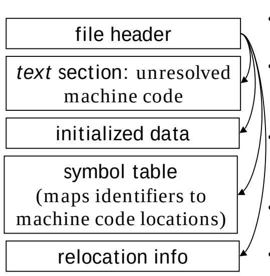
assembly code

```
PUSH ecx
CALL _abs
ADD ebx, eax
```

object code

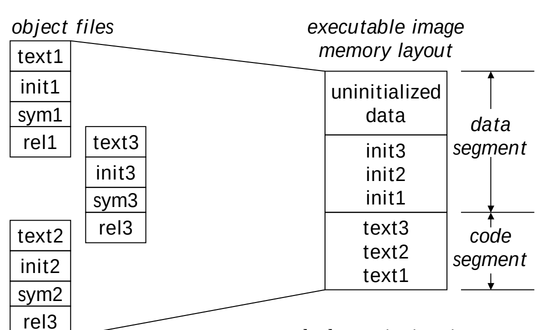


Object file structure



- Object file contains various ***sections***
- ***text*** section contains the compiled code with some patching needed
- For uninitialized data, only need to know total size of data segment
- Describes structure of text and data sections
- Points to places in text and data section that need fix-up

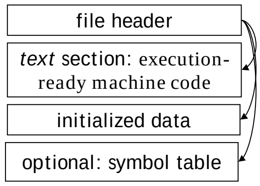
Action of Linker



+*peephole optimizations*

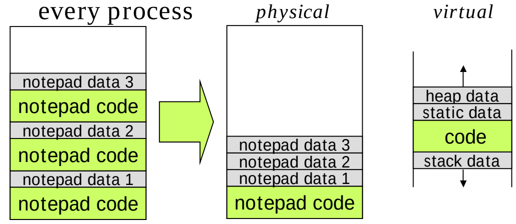
Executable file structure

- 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: allows rapid start-up
- Text section shared
- Symbols: debugging



Executing programs

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

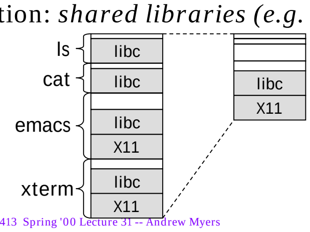


Libraries

- A *library* is a 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: ld main.o foo.o /usr/lib/X11.a /usr/lib/libc.a**
  - **NT: link main.obj foo.obj kernel32.lib user32.lib ...**
- Library provides index over all object files for rapid searching

Shared libraries

- Problem: libraries take up a lot of memory when linked into many running applications
- Solution: *shared libraries (e.g. DLLs)*



Step 1: Jump tables

- Executable file refers to, does not contain library code; library code loaded dynamically
- Library code found in separate shared library file (similar to DLL); linking done against *import library* that does not contain code
- Library compiled at fixed address, starts with *jump table* to allow new versions; client code jumps to jump table: indirection.

program: *library*:

```
                scanf: jmp real_scanf
call printf     printf: jmp real_printf
                putchar: jmp real_putchar
```


Global tables

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

Using global tables

- Global table contains entries for all external references

```
malloc(n) ⇒ push [ebp + n]
            mov eax, [malloc_entry]
            call eax            ; indirect jump!
```

- Same-module references can still be used directly
- Global table entries (malloc_entry) placed in non-shared memory locations so each program can have different linkage
- Initialized by dynamic loader when program begins: reads symbol tables, relocation info

Relocation

- Before widespread support for virtual memory, programs had to be brought into memory at different locations: code had to be *relocatable* (could not contain fixed memory addresses)
- With virtual memory, all programs could start at same address, *could* contain fixed addresses
- Problem with shared libraries (*e.g.*, DLLs): if allocated at fixed addresses, can collide in virtual memory and need to be copied and explicitly relocated to new address

Dynamic shared objects

- Unix systems: Code is typically compiled as a *dynamic shared object* (DSO): relocatable shared library
- Allows shared libraries to be mapped at any address in virtual memory—no copying needed!
- *Questions:* how can we make code completely relocatable? What performance impact does it have?

Relocation difficulties

- Can't use *absolute addresses* : directly named memory locations
- Can't use addresses in calls to external functions
- Can't use addresses for global variables—breaks the shared library scheme

```
push [ebp + n]
mov eax, [malloc_addr]    ; Oops!
call eax
```

- Not a problem: branch instructions, local calls. Instructions have *relative addressing*

Global tables

- Can't put the global table at a fixed address: not relocatable!
- Three approaches:
  - pass global table address as an extra argument (possibly in a register) : affects function ptr rep
  - use address arithmetic on current program counter (eip register) to find global table. Offset between eip and global table is a link-time constant
  - stick global table entries into the current object's dispatch vector : DV *is* the global table (only works for methods, but otherwise the best)

Cost of DSOs

- Assume esi contains global table pointer (can set up at beginning of function/method)
- Function calls:

  call [esi + constant]
- Global variable accesses:

  mov eax, [esi + constant]

  mov ebx, [eax]
- Calling global functions ≈ calling methods
- Accessing global variables is *more* expensive than accessing local variables
- Most computer benchmarks run w/o DSOs!

Module values return

- Let *M* be an external module, *f* a fcn in *M*
- When accessing *M.f*, must go through global table

  mov eax, [si + f_offset_constant]
- Looks just like the code to access a field of a record located at si...
- si refers to a module value!
- Dynamic loader creates module values as program starts (actually creates multiple copies for various using modules; si points to concatenated records for all modules used by the current code's module)

Link-time optimization

- When linking object files, linker provides flags to allow peephole optimization of inter-module references
- Unix: -non_shared link option causes application to get its own copy of library code, allowing calls and global variables to be performed directly (peephole opt.)

  call [esi + malloc_addr] ⇒ call malloc
- Allows performance/functionality trade-off

Dynamic linking

- Both shared libraries and DSOs can be linked dynamically into a running program
- Normal case: implicit linking. When setting up global tables, shared libraries are automatically loaded if necessary (*maybe lazily*), symbols looked up.
- 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)

Conclusions

- Shared libraries and DSOs allow efficient memory use on a machine running many different programs that share code
- Improves cache, TLB performance overall
- Hurts individual program performance by adding indirections through global tables, bloating code with extra instructions
- Important new functionality: dynamic extension of program
- Peephole linker optimization can restore performance, but with loss of functionality