CS 4120
Introduction to Compilers

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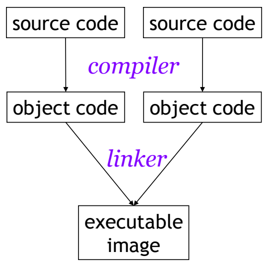
Lecture 37: Linking and Loading

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

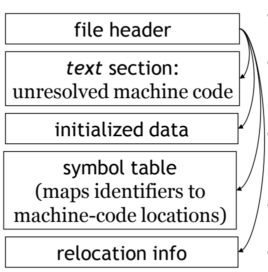
```
PUSH ecx
CALL _abs
ADD ebx, eax
```

object code

```
51
9A 00 00 00 00
03 D8
```

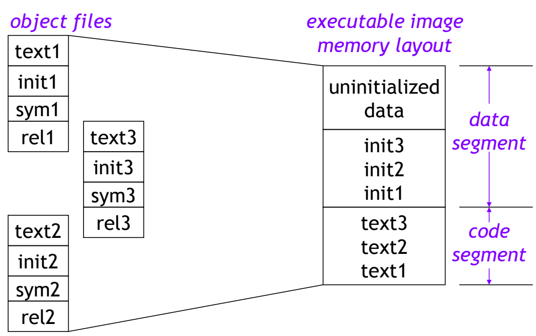
} to be filled in by linker

Object file structure



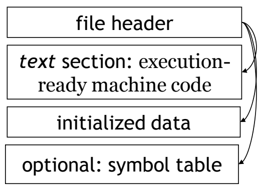
- Object file contains various ***sections***
- ***text*** section contains the compiled code with some patching needed
- For uninitialized data, only need to know total size of data segment
- Describes structure of text and data sections
- Points to places in text and data section that need fix-up

Action of Linker



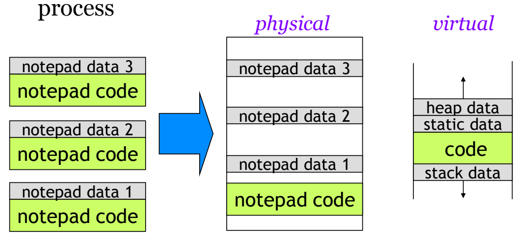
Executable file structure

- 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
- Text section shared across processes
- Symbols allow debugging



Executing programs

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

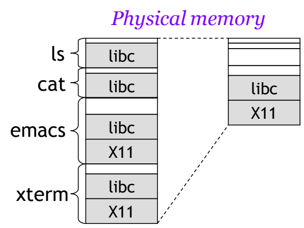


Libraries

- *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:** ld main.o foo.o /usr/lib/X11.a /usr/lib/libc.a
  - **NT:** link main.obj foo.obj kernel32.lib user32.lib …
- Index over all object files in library 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).

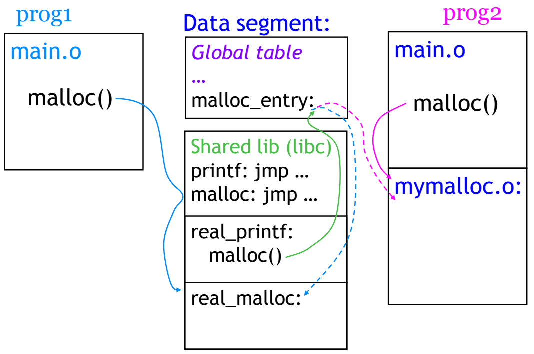
program: *library:*

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


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 /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

Global tables



13

Using global tables

- Global table contains entries for all external references

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

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

14

Relocation

- Before widespread support for virtual memory, 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 (code, data, global tables, ...)
  - Collision ⇒ code copied and explicitly relocated
- Back to relocatable code!

15

Dynamic shared objects

- Unix systems: Code is typically compiled as a *dynamic shared object* (DSO): location-independent shared library
- Shared libraries can be mapped to any address in virtual memory—no copying!
- *Questions:*
  - how to make code completely relocatable?
  - what is the performance impact?

16

Location Independence

- Can't use *absolute addresses* (directly named memory locations) anywhere:
  - Not in calls to external functions
  - Not for global variables in data segment
  - Not even for global table entries

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

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

17

Global tables

- Can put address of all globals into global table
- But...can't put the global table at a fixed address: not location independent!
- Three solutions:
  1. Pass global-table address as an extra argument (possibly in a register) : affects first-class functions (next global-table address stored in current GT)
  2. Use address arithmetic on current program counter (eip register) to find global table. Use link-time constant offset between eip and global table.
  3. Stick global-table entries into the current object's vtable : V-Table *is* the global table (only works for methods, but otherwise the best)

18

Cost of DSOs

- Assume esi contains global table pointer (set-up code at beginning of function)
- Call to function f:

```
call [esi + f_offset]
```

- Global variable accesses:

```
mov eax, [esi + v_offset]
mov ebx, [eax]
```

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

Link-time optimization

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

```
call [esi + malloc_addr] ⇒ call malloc
```

- Allows performance/functionality trade-off

Dynamic linking

- Shared libraries (DLLs) 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 (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)

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