CS 4120
Introduction to Compilers

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Lecture 36: Linking and Loading

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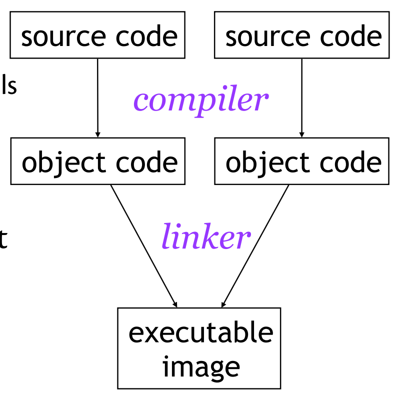
Outline

- 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

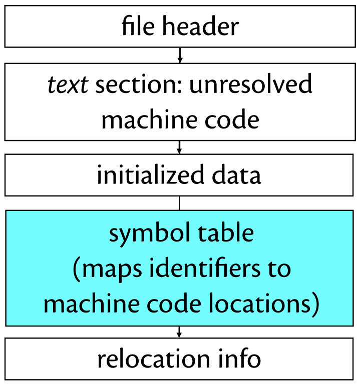
```
push %ecx
call _abs
add %eax, %edx
```

object code

51				
E8	00	00	00	00
01	C2			

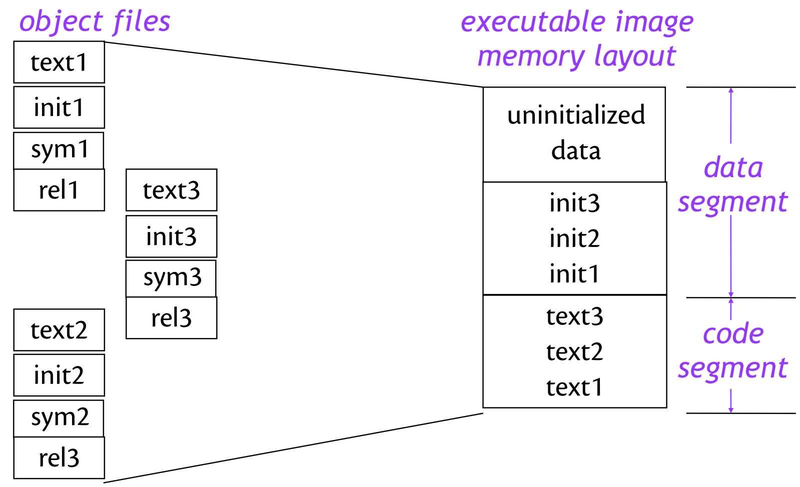
} to be filled in by linker

Object file structure



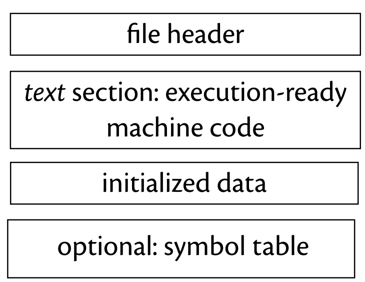
- Object file contains various **sections**
- **text** section contains the compiled code with some patching needed
- For uninitialized data, only need to know total size of data segment
- Describes structure of text and data sections
- Points to places in text and data section that need fix-up

Linker output



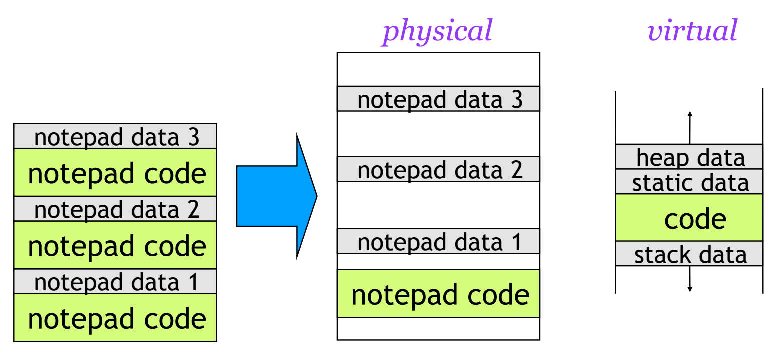
Executable file structure

- Same as object file, but 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 for debugging (global, stack frame layouts, line numbers, etc.)



Executing programs

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



Libraries

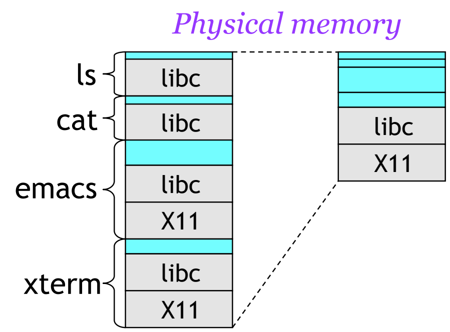
- *Library* : collection of object files
- Linker adds all object files necessary to resolve undefined references in explicitly named files
- Object files, libraries searched in user-specified order for external references

  Unix: ld main.o foo.o /usr/lib/X11.a /usr/lib/libc.a

  NT: link main.obj foo.obj kernel32.lib user32.lib ...
- Library contains 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 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; application code jumps to jump table (indirection).
  - library can evolve.

program:

```
call printf
```

library:

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

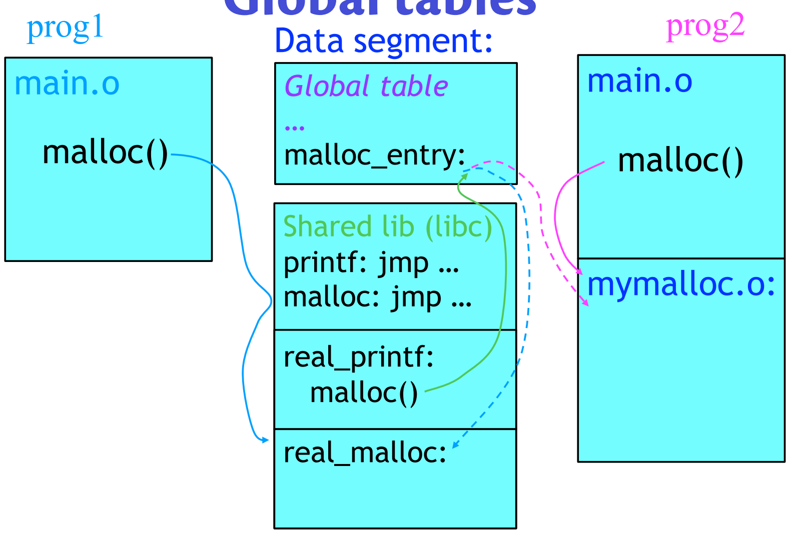

Global tables

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

  gcc -o prog1 main.o /usr/lib/libc.a

  gcc -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
- Solution: Calls to external symbols made through **global offset tables** unique to each program, generated at dynamic load time.

Global tables



Using global tables

- Global table contains entries for all external references

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

- 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.
- Code above may be dynamically generated as trampoline at load time

Relocation

- Before widespread support for virtual memory, code had to be **position-independent** (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 position-independent code!

Dynamic shared objects

- Unix systems: code typically compiled as a **dynamic shared object** (DSO): relocatable shared library
  - gcc: -shared option
- 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?

Relocation difficulties

- No **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**

Global offset tables

- Can put address of all globals into global table
- But...can't put the global table at a fixed address: not relocatable!

- 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. (extract eip w/ dummy call)
  3. Stick global table entries into the current object's dispatch table : DT *is* the global table (only works for OO code, but otherwise the best)

Cost of DSOs

- Assume esi contains global table pointer (setup 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 global functions ≈ calling methods
- Accessing global variables is *more* expensive than accessing local variables
- Most benchmarks run w/o DSOs!

Link-time optimization

- When linking object files, linker provides flags to allow peephole optimization of inter-module references
- Unix: -static 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.