CS 4120
Introduction to Compilers

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Lecture 35: Linking and Loading

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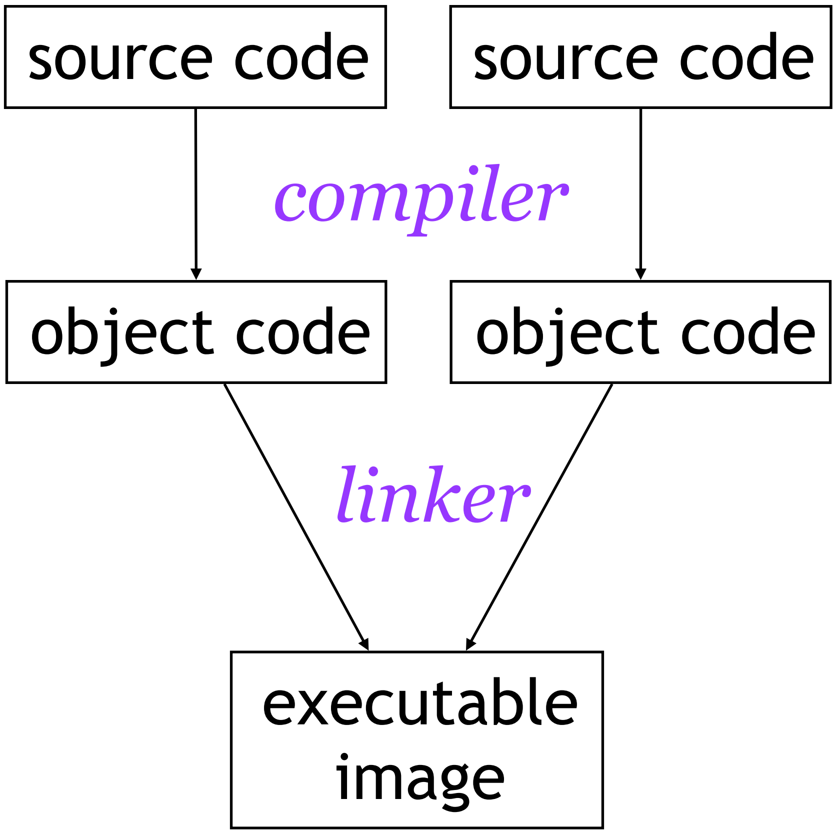
Outline

- 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

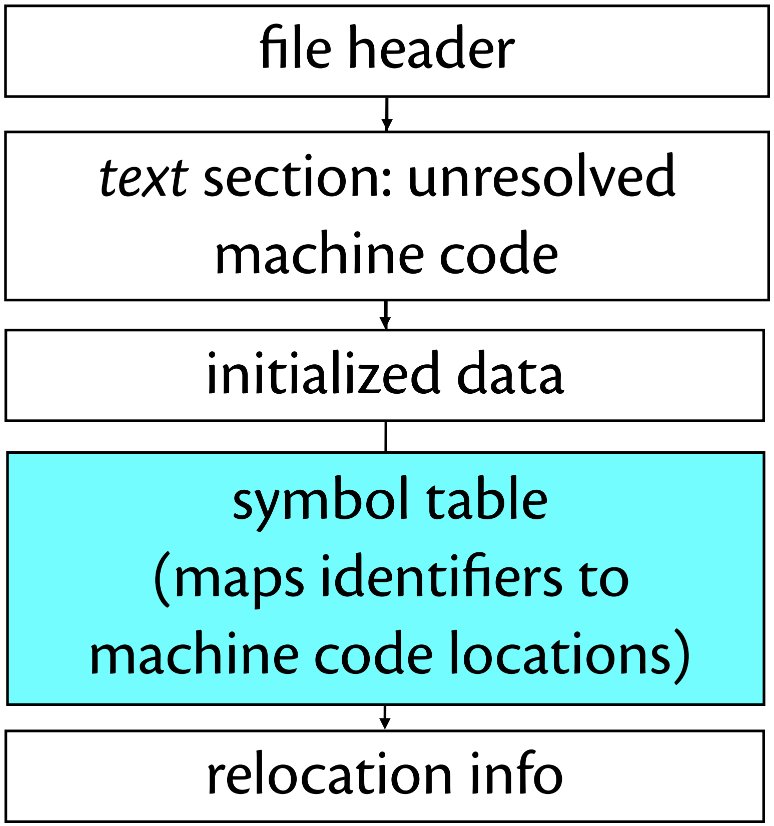
```
push %rcx
call _abs
add %eax, %edx
```

object code

51				
E8	*00*	*00*	*00*	*00*
01	C2			

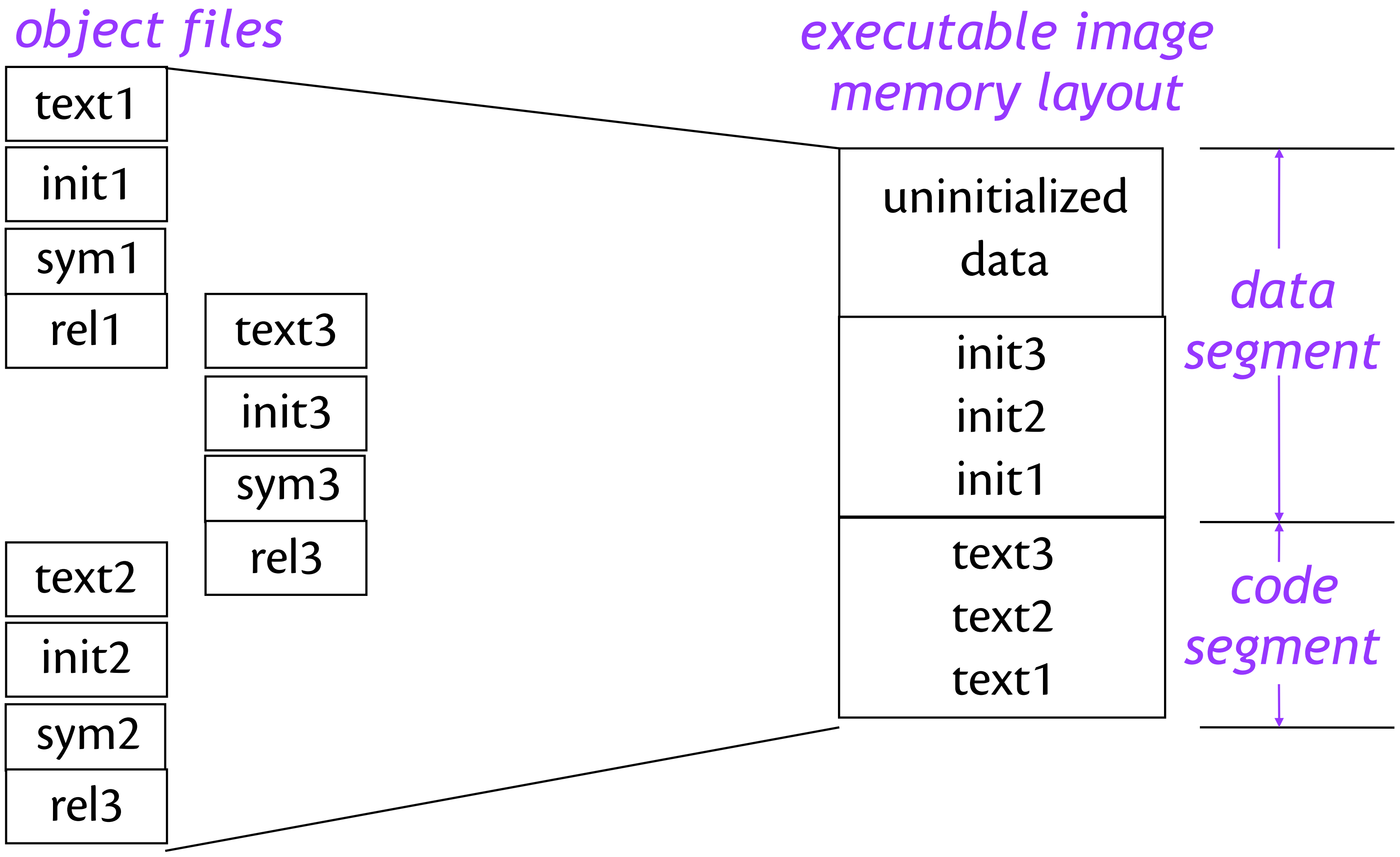
to be filled in by linker

Object file structure



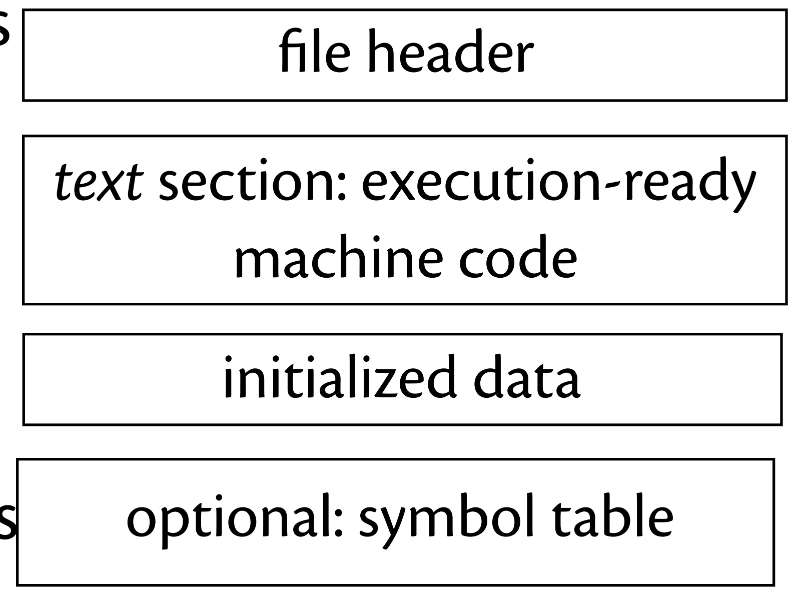
- Object file contains various **sections**
- **text** section contains the compiled code with some patching needed
- For uninitialized data, only need to know total size of data segment
- Describes structure of text and data sections
- Points to places in text and data section that need fix-up

Linker output



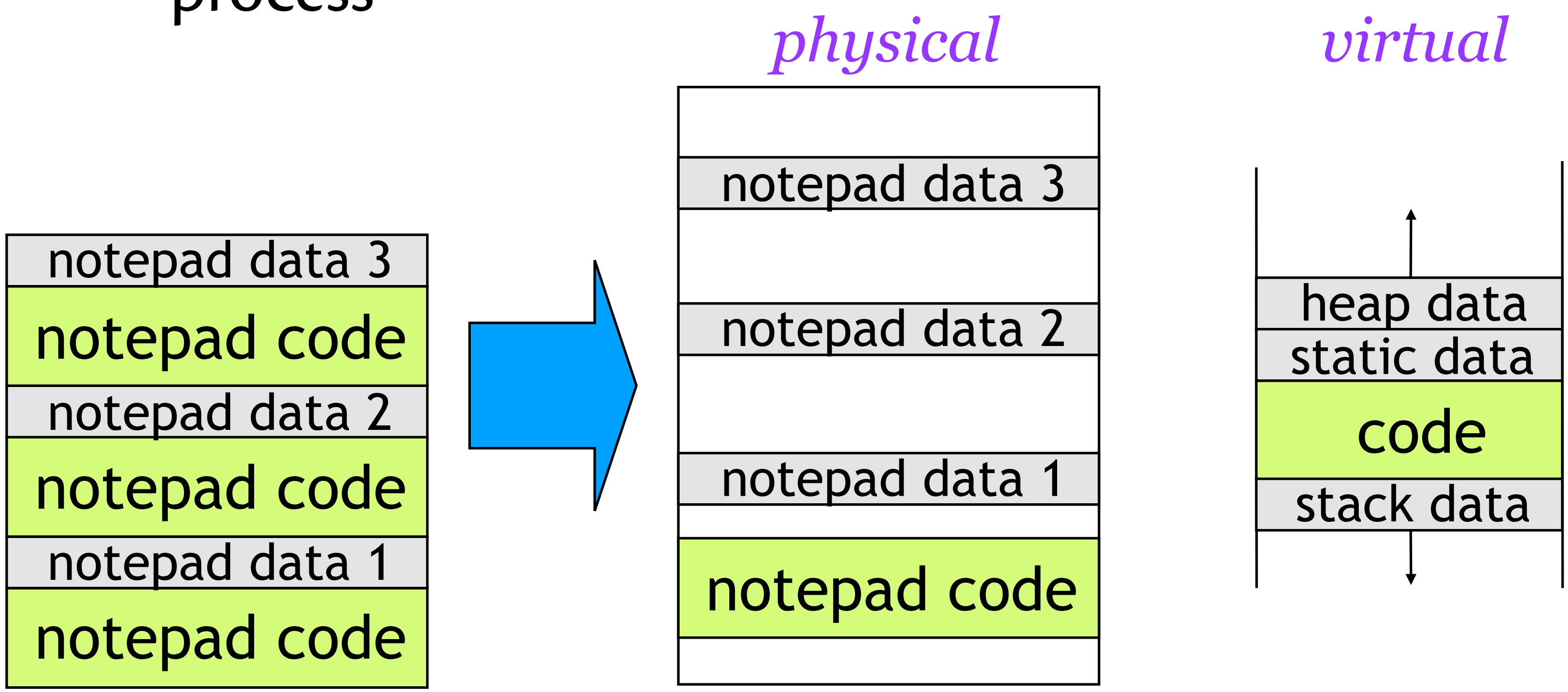
Executable file structure

- 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

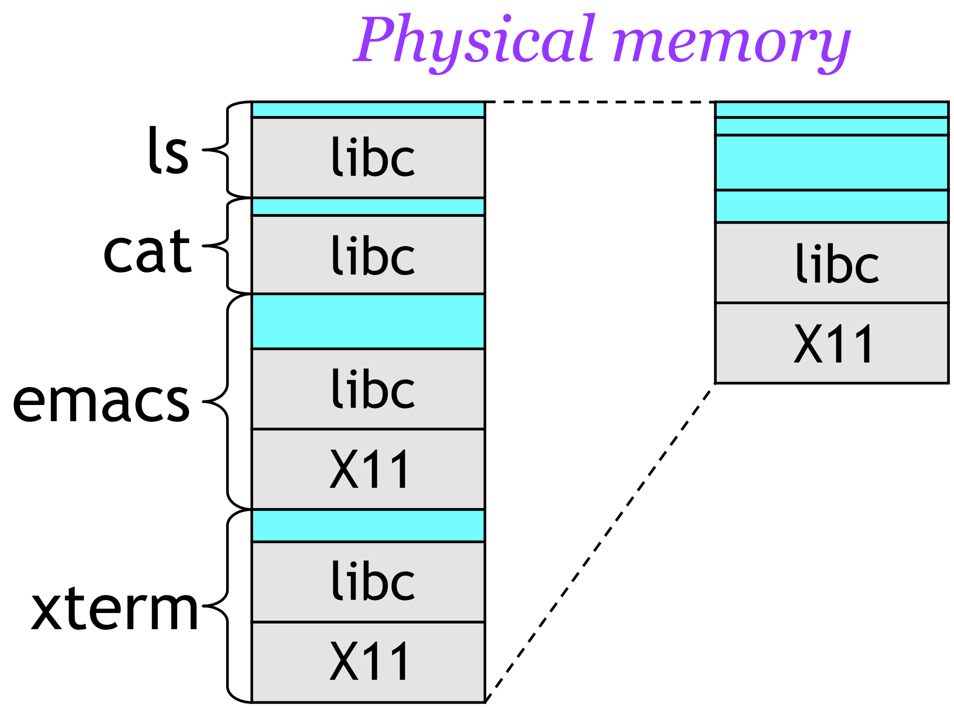
- *Library* : collection of object files
  - Linker adds all object files necessary to resolve undefined references in explicitly named files
  - Object files, libraries searched in user-specified order for external references

    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).
  - effect: library can evolve.

program:

```
call printf
```

library:

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

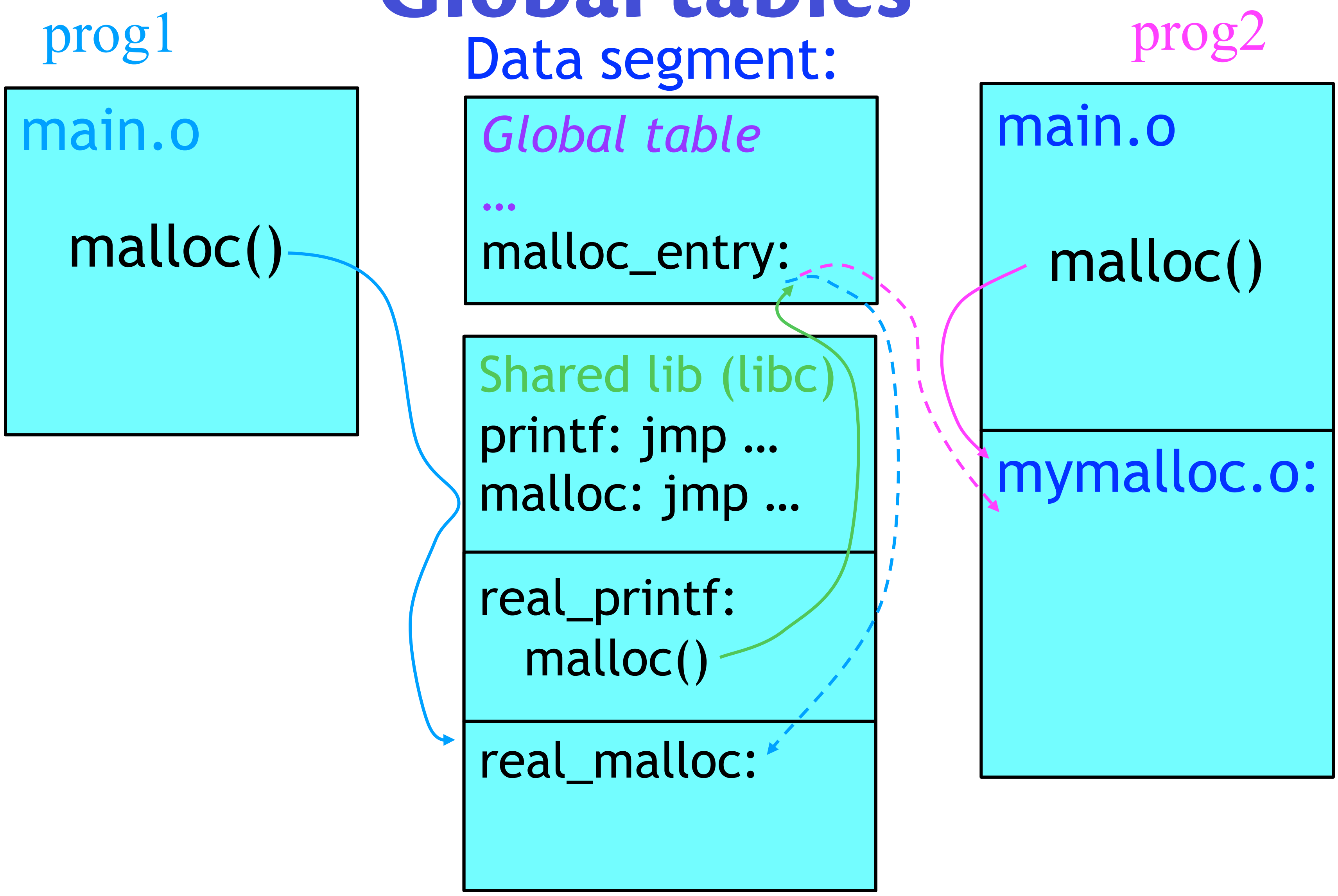
Global tables

- 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 n(%rbp)
              mov malloc_entry, %rax      ; load from GOT
              call *%rax                  ; 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, ...)
  - Prelinking/prebinding tries to position code ahead of time (Windows, Mac OS X)
  - 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/Linux: –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 n(%rbp)
mov malloc_entry, %rax      ;    Oops!
call %rax
```

- 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. Use link-time constant offset between pc (rip) and global table. Load indexed from current program counter (rip register) to find global table.
  2. Pass global table address as an extra argument (possibly in a register) : affects first-class functions (next global table address stored in current GT)
  3. Put 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

- Call to function f requires load from GOT.
- Global variable access requires extra load from GOT to find it.
- 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 malloc_offset(%rsi) ⇒ 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 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

- Linking has implications for code generation!
- 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: indirections through global table, code bloat with extra instructions.
- Important new functionality: dynamic extension of program.
- Peephole linker optimization can restore performance, but with loss of functionality.