Linking

Operating System Design – MOSIG 1

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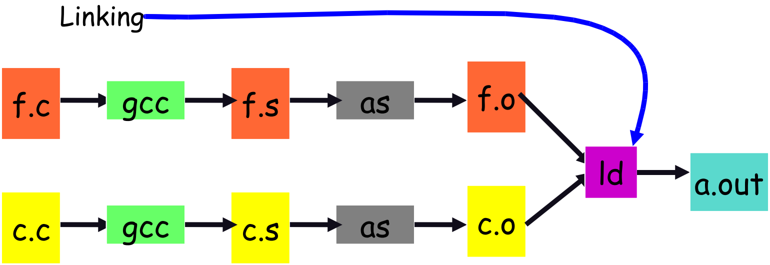
Today's Big Adventure



- How to name and refer to things that don't exist yet
- How to merge separate name spaces into a cohesive whole

- **Readings**
  - a.out & elf man pages, ELF standard
  - Run "`nm`" or "`objdump`" on a few .o and a.out files.

Linking as our first naming system

- **Naming is a very deep theme that comes up everywhere**
- **Naming system: maps names to values**
- **Examples:**
  - Linking: Where is `printf`? How to refer to it? How to deal with synonyms? What if it doesn't exist?
  - Virtual memory address (name) resolved to physical address (value) using page table
  - File systems: translating file and directory names to disk locations, organizing names so you can navigate, ...
  - `www.stanford.edu` resolved 171.67.216.17 using DNS
  - IP addresses resolved to Ethernet addresses with ARP
  - Street names: translating (elk, pine, ...) vs (1st, 2nd, ...) to actual location

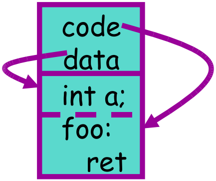
Perspectives on memory contents

- **Programming language view:** `x += 1;  add $1, %eax`
  - Instructions: Specify operations to perform
  - Variables: Operands that can change over time
  - Constants: Operands that never change
- **Hardware view:**
  - executable: code, usually read-only
  - read only: constants (maybe one copy for all processes)
  - read/write: variables (each process needs own copy)
- **Need addresses to use data:**
  - Addresses locate things. Must update them when you move
  - Examples: linkers, garbage collectors, changing apartment
- **Binding time: When is a value determined/computed?**
  - Early to late: Compile time, Link time, Load time, Runtime

Outline

How is a process specified?

- **Executable file: the linker/OS interface.**
  - What is code? What is data?
  - Where should they live?



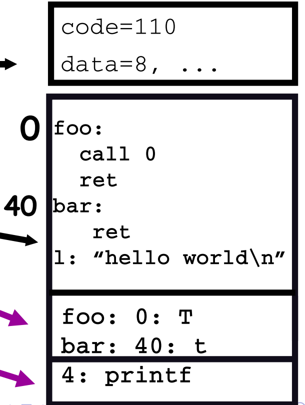
“foo.o”

- **Linker builds executables from object files:**

Header: code/data size, symtab offset

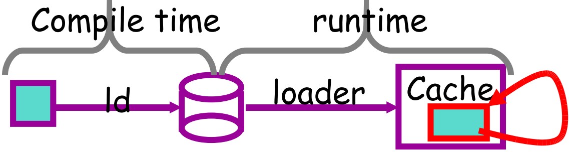
Object code: instructions and data gen'd by compiler

Symbol table:
external defs (exported objects in file)
external refs (global syms used in file)



How is a program executed?

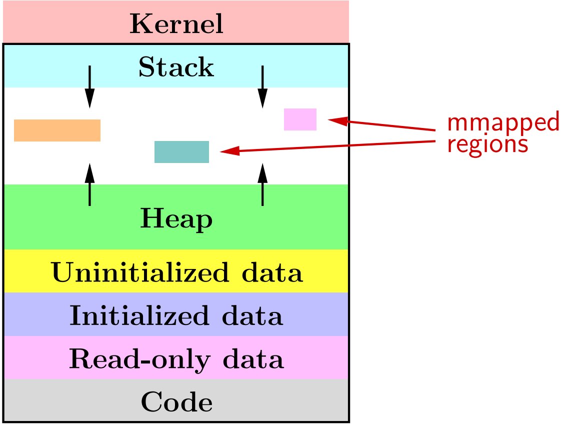
- **On Unix systems, read by "loader"**



  - Reads all code/data segs into buffer cache;
    Maps code (read only) and initialized data (r/w) into addr space
  - Or. . . fakes process state to look like paged out
- **Lots of optimizations happen in practice:**
  - Zero-initialized data does not need to be read in.
  - Demand load: wait until code used before get from disk
  - Copies of same program running? Share code
  - Multiple programs use same routines: share code (harder)

What does a process look like? (Unix)

- **Process address space divided into "segments"**
  - text (code), data, heap (dynamic data), and stack



  - Why? (1) different allocation patterns; (2) separate code/data

Who builds what?

- **Heap: allocated and laid out at runtime by malloc**
  - Compiler, linker not involved other than saying where it can start
  - Namespace constructed dynamically and managed by programmer (names stored in pointers, and organized using data structures)
- **Stack: alloc at runtime (proc call), layout by compiler**
  - Names are relative off of stack (or frame) pointer
  - Managed by compiler (alloc on proc entry, free on exit)
  - Linker not involved because name space entirely local: Compiler has enough information to build it.
- **Global data/code: alloc by compiler, layout by linker**
  - Compiler emits them and names with symbolic references
  - Linker lays them out and translates references

Outline

Example

- **Simple program has "`printf ("hello world\n");`"**
- **Compile with:** `cc -m32 -fno-builtin -S hello.c`
  - `-S` says don't run assembler (`-m32` is 32-bit x86 code)
- **Output in `hello.s` has symbolic reference to `printf`**

```
        .section        .rodata
.LC0:   .string "hello world\n"
        .text
.globl main
main:   ...
        subl    $4, %esp
        movl    $.LC0, (%esp)
        call    printf
```

- **Disassemble `a.out` or `hello.o` with `objdump -d`:**

```
8048415:    e8 26 ff ff ff        call    8048340 <printf@plt>
```

- **Jumps to PC - d5 = address of address within instruction.** This is used to get *Position Independant Code*.

Linkers (Linkage editors)

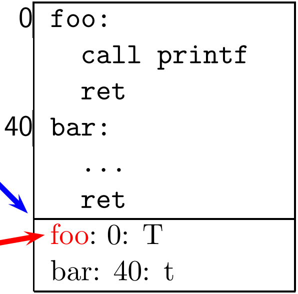
- **Unix: ld**
  - Usually hidden behind compiler
  - Run `gcc -v hello.c` to see ld or invoked
- **Three functions:**
  - Collect together all pieces of a program
  - Coalesce like segments
  - Fix addresses of code and data so the program can run
- **Result: runnable program stored in new object file**
- **Why can't compiler do this?**
  - Limited world view: sees one file, rather than all files
- **Usually linkers don't rearrange segments, but can**
  - E.g., re-order instructions for fewer cache misses; remove routines that are never called from a.out

Simple linker: two passes needed

- **Pass 1:**
  - Coalesce like segments; arrange in non-overlapping mem.
  - Read file's symbol table, construct global symbol table with entry for every symbol used or defined
  - Compute virtual address of each segment (at start+offset)
- **Pass 2:**
  - Patch references using file and global symbol table
  - Emit result
- **Symbol table: information about program kept while linker running**
  - Segments: name, size, old location, new location
  - Symbols: name, input segment, offset within segment

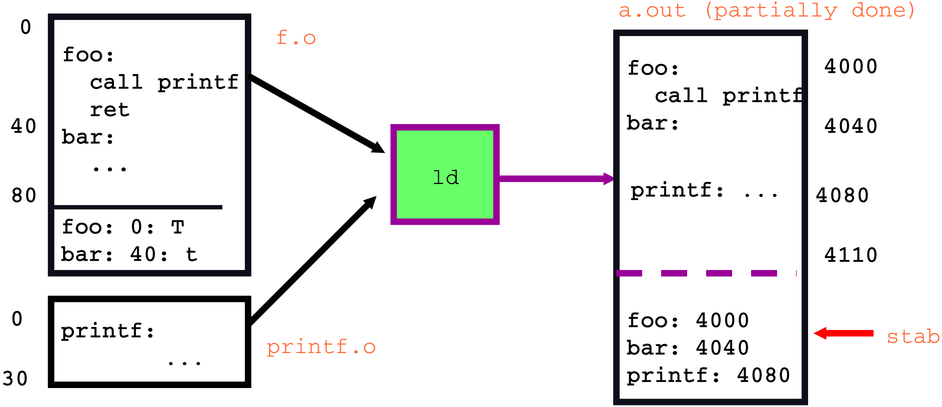
Where to put emitted objects?

- **Assembler:**
  - Doesn't know where data/code should be placed in the process's address space
  - Assumes everything starts at zero
  - Emits symbol table that holds the name and offset of each created object
  - Routines/variables exported by file are recorded as global definitions
- **Simpler perspective:**
  - Code is in a big char array
  - Data is in another big char array
  - Assembler creates (object name, index) tuple for each interesting thing
  - Linker then merges all of these arrays



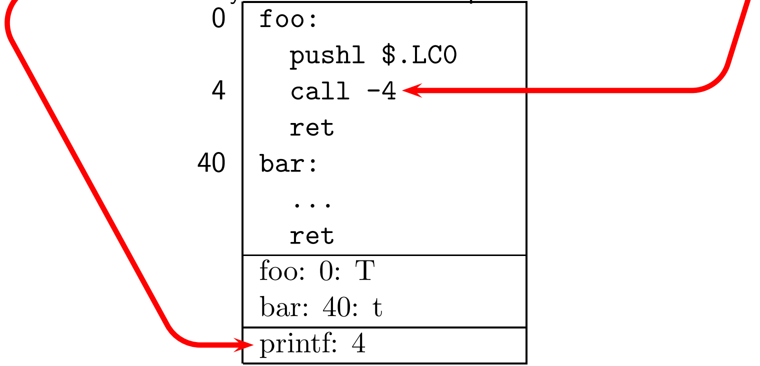
Where to put emitted objects

- **At link time, linker**
  - Determines the size of each segment and the resulting address to place each object at
  - Stores all global definitions in a global symbol table that maps the definition to its final virtual address



Where is everything?

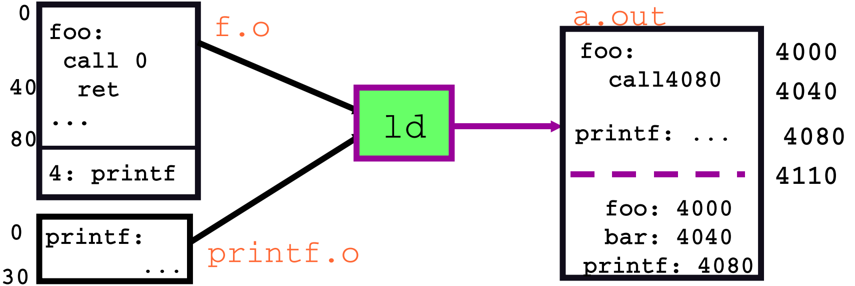
- **How to call procedures or reference variables?**
  - E.g., call to `printf` needs a target addr
  - Assembler uses 0 or PC for address
  - Emits an external reference telling the linker the instruction's offset and the symbol it needs to be patched with



- **At link time the linker patches every reference**

Linker: Where is everything

- **At link time the linker**
  - Records all references in the global symbol table
  - After reading all files, each symbol should have exactly one definition and 0 or more uses
  - The linker then enumerates all references and fixes them by inserting their symbol's virtual address into the reference's specified instruction or data location



Outline

Example: 2 modules and C lib

```
main.c:
  extern float sin();
  extern int printf(), scanf();
  float val = 0.0;
  main() {
    static float x = 0.0;
    printf("enter number");
    scanf("%f", &x);
    val = sin(x);
    printf("Sine is %f", val);
  }
```

```
C library:
  int scanf(char *fmt, ...) { ... }
  int printf(char *fmt, ...) { ... }
```

```
math.c:
  float sin(float x) {
      float tmp1, tmp2;
      static float res = 0.0;
      static float lastx = 0.0;
      if(x != lastx) {
        lastx = x;
        ... compute sin(x)...
      }
      return res;
  }
```

Initial object files

Main.o:

```
     def: val @ 0:D      symbols
     def: main @ 0:T
     def: x @ 4:d

                      relocation
     ref: printf @ 0:T,12:T
     ref: scanf @ 4:T
     ref: x @ 4:T, 8:T
     ref: sin @ ?:T
     ref: val @ ?:T, ?:T

0    x:
4    val:        data

0    call printf
4    call scanf(&x)
8    val = call sin(x)    text
12   call printf(val)
```

Math.o:

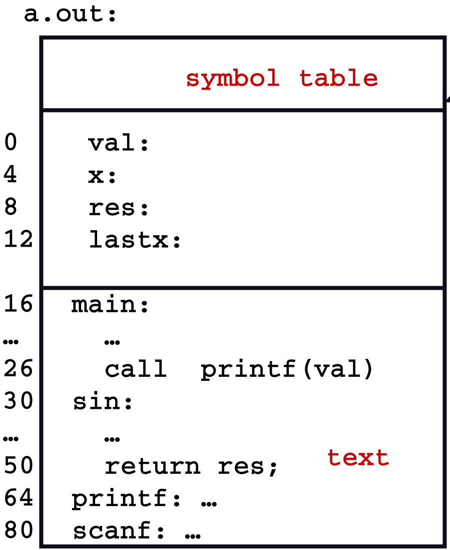
```
                       symbols
     def: sin @0:T
     def: res @ 0:d
     def: lastx @4:d

                        relocation
     ref: lastx@0:T,4:T
     ref res @24:T

0    res:              data
4    lastx:

0    if(x != lastx)
4       lastx = x;    text
…       … compute sin(x)…
24   return res;
```

Pass 1: Linker reorganization



Starting virtual addr: 4000

Symbol table:

```
data starts @ 0
text starts @ 16
def: val @ 0
def: x @ 4
def: res @ 8
def: main @ 16
…
ref: printf @ 26
ref: res @ 50
…
```

(what are some other refs?)

Pass 2: Relocation

"final" a.out:

Starting virtual addr: 4000

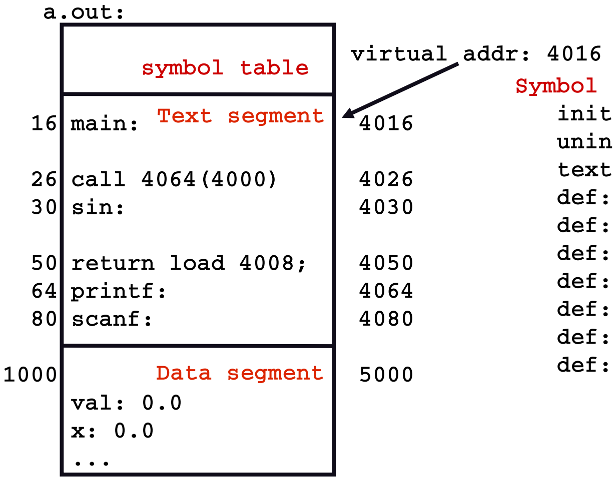
```
        +------------------------------------+
        |            symbol table            |
        +------------------------------------+
0       |  val:                              |  4000
4       |  x:                                |  4004
8       |  res:                              |  4008
12      |  lastx:      data                  |  4012
        |                                    |
        +------------------------------------+
16      | main:                              |  4016
        |                                    |  …
26      |   call ??(??)//printf(val)         |  4026
30      | sin:                 text          |  4030
        |                                    |  …
50      |   return load ??;// res            |  4050
64      | printf: …                          |  4064
80      | scanf: …                           |  4080
        +------------------------------------+
```

Symbol table:

```
data starts 4000
text starts 4016
def: val @ 0
def: x @ 4
def: res @ 8
def: main @ 14
def: sin @ 30
def: printf @ 64
def: scanf @80
…
```

(usually don't keep refs, since won't relink. Defs are for debugger: can be stripped out)

What gets written out




```
Symbol table:
    initialized data = 4000
    uninitialized data = 4000
    text = 4016
    def: val @ 1000
    def: x @ 1004
    def: res @ 1008
    def: main @ 14
    def: sin @ 30
    def: printf @ 64
    def: scanf @ 80
```

Examining programs with nm

```
int uninitialized;
int initialized = 1;
const int constant = 2;
int main ()
{
  return 0;
}
```

VA — symbol type

```
% nm a.out
...
0400400 T _start
04005bc R constant
0601008 W data_start
0601020 D initialized
04004b8 T main
0601028 B uninitialized
```

- `const` **variables of type R won't be written**
  - Note constant VA on same page as `main`
  - Share pages of read-only data just like text
- **Uninitialized data in "BSS" segment, B**
  - No actual contents in executable file
  - Goes in pages that the OS allocates zero-filled, on-demand

Examining programs with objdump

Note Load mem addr. and File off have same page alignment for easy mmapping

```
% objdump -h a.out
a.out: file format elf64-x86-64
Sections:
Idx Name Size VMA LMA File off Algn
...
12 .text 000001a8 00400400 00400400 00000400 2**4
CONTENTS, ALLOC, LOAD, READONLY, CODE
...
14 .rodata 00000008 004005b8 004005b8 000005b8 2**2
CONTENTS, ALLOC, LOAD, READONLY, DATA
...
17 .ctors 00000010 00600e18 00600e18 00000e18 2**3
CONTENTS, ALLOC, LOAD, DATA
...
23 .data 0000001c 00601008 00601008 00001008 2**3
CONTENTS, ALLOC, LOAD, DATA
...
24 .bss 0000000c 00601024 00601024 00001024 2**2
ALLOC
...
```

No contents in file

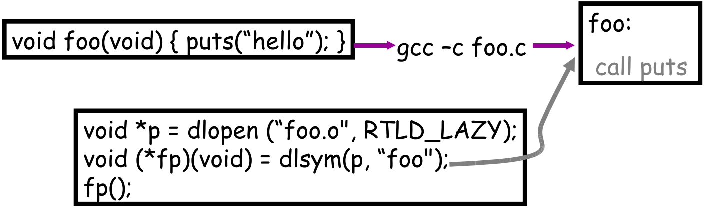
Types of relocation

- **Place final address of symbol here**
  - Example: `int y, *x = &y;`
    `y` gets address in BSS, `x` in data segment, contains VA of `y`
  - Code example: `call printf` becomes
    `8048248:  e8 e3 09 00 00  call 8048c30 <printf>`
  - Binary encoding reflects computed VMA of `printf`
    (Note encoding of `call` argument is actually PC-relative)
- **Add address of symbol to contents of this location**
  - Used for record/struct offsets
  - Example: `q.head = 1` → `move $1, q+4` → `movl $1, 0x804a01c`
- **Add diff between final and original seg to this location**
  - Segment was moved, "static" variables need to be reloc'ed

Outline

Variation 0: Dynamic linking

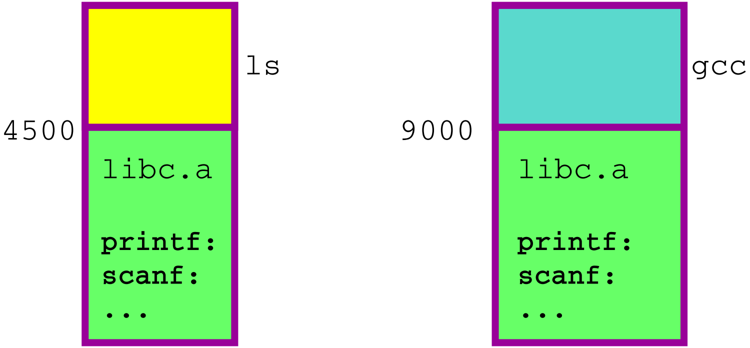
- **Link time isn't special, can link at runtime too**
  - Get code not available when program compiled
  - Defer loading code until needed



  - Issues: what happens if can't resolve? How can behavior differ compared to static linking? Where to get unresolved syms (e.g., "puts") from?

Variation 1: Static shared libraries

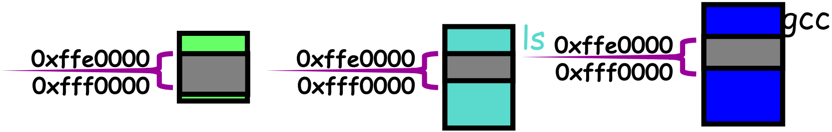
- **Observation: everyone links in standard libraries (libc.a.), these libs consume space in every executable.**



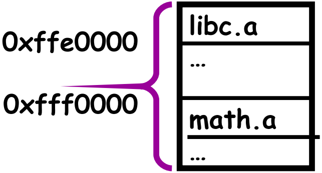
- **Insight: we can have a single copy on disk if we don't actually include lib code in executable**

Static shared libraries

- **Define a "shared library segment" at same address in every program's address space**



- Every shared lib is allocated a unique range in this seg, and computes where its external defs reside
- Linker links program against lib (why?) but does not bring in actual code



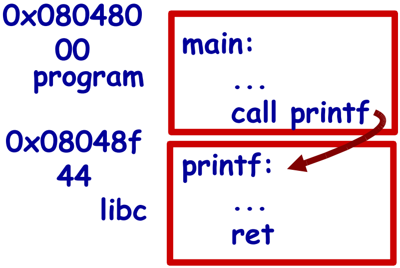
- Loader marks shared lib region as unreadable
- When process calls lib code, seg faults: embedded linker brings in lib code from known place & maps it in.
- Now different running programs can now share code!

Variation 2: Dynamic shared libs

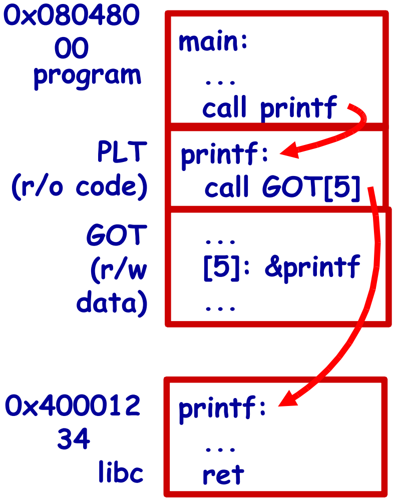
- **Static shared libraries require system-wide pre-allocation of address space**
  - Clumsy, inconvenient
  - What if a library gets too big for its space?
  - Can space ever be reused?
- **Solution: Dynamic shared libraries**
  - Let any library be loaded at any VA
  - New problem: Linker won't know what names are valid
  - Solution: stub library
  - New problem: How to call functions if their position may vary?
  - Solution: next page...

Position-independent code

- **Code must be able to run anywhere in virtual mem**
- **Runtime linking would prevent code sharing, so...**
- **Add a level of indirection!**
  - Procedure Linkage Table
  - Global Offset Table

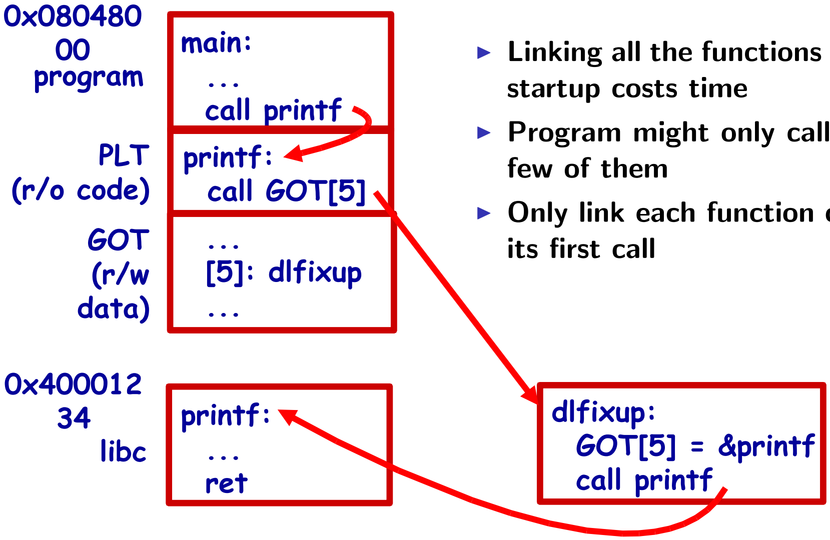


Static Libraries



Dynamic Shared Libraries

Lazy dynamic linking



- **Linking all the functions at startup costs time**
- **Program might only call a few of them**
- **Only link each function on its first call**

Outline

Code = data, data = code

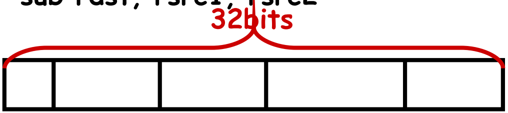
- **No inherent difference between code and data**
  - Code is just something that can be run through a CPU without causing an "illegal instruction fault"
  - Can be written/read at runtime just like data "dynamically generated code"
- **Why? Speed (usually)**
  - Big use: eliminate interpretation overhead. Gives 10-100x performance improvement
  - Example: Just-in-time compilers for java, or qemu vs. bochs.
  - In general: optimizations thrive on information. More information at runtime.
- **The big tradeoff:**
  - Total runtime = code gen cost + cost of running code

How?

- Determine binary encoding of desired instructions

  SPARC: sub instruction

  symbolic = "sub rdst, rsrc1, rsrc2"



  binary = 10 rd 100 rs1 rs2

  bit pos: 31 30 25 19 14 0

- Write these integer values into a memory buffer

```
unsigned code[1024], *cp = &code[0];
/* sub %g5, %g4, %g3 */
*cp++ = (2<<30) | (5<<25) | (4<<19) |(4<<14) | 3;
...
```

- Jump to the address of the buffer:

```
((int (*)())code)();
```

Linking and security

```
void fn ()
{
  char buf[80];
  gets (buf);
  /* ... */
}
```

1. **Attacker puts code in buf**
   - Overwrites return address to jump to code
2. **Attacker puts shell command above buf**
   - Overwrites return address so function "returns" to `system` function in libc

- **People try to address problem with linker**
- **W^X: No memory both writable and executable**
  - Prevents 1 but not 2, breaks jits
- **Address space randomization**
  - Makes attack #2 a little harder, not impossible

Linking Summary

- **Compiler/Assembler: 1 object file for each source file**
  - Problem: incomplete world view
  - Where to put variables and code? How to refer to them?
  - Names definitions symbolically ("`printf`"), refers to routines/variable by symbolic name
- **Linker: combines all object files into 1 executable file**
  - Big lever: global view of everything. Decides where everything lives, finds all references and updates them
  - Important interface with OS: what is code, what is data, where is start point?
- **OS loader reads object files into memory:**
  - Allows optimizations across trust boundaries (share code)
  - Provides interface for process to allocate memory (`sbrk`)