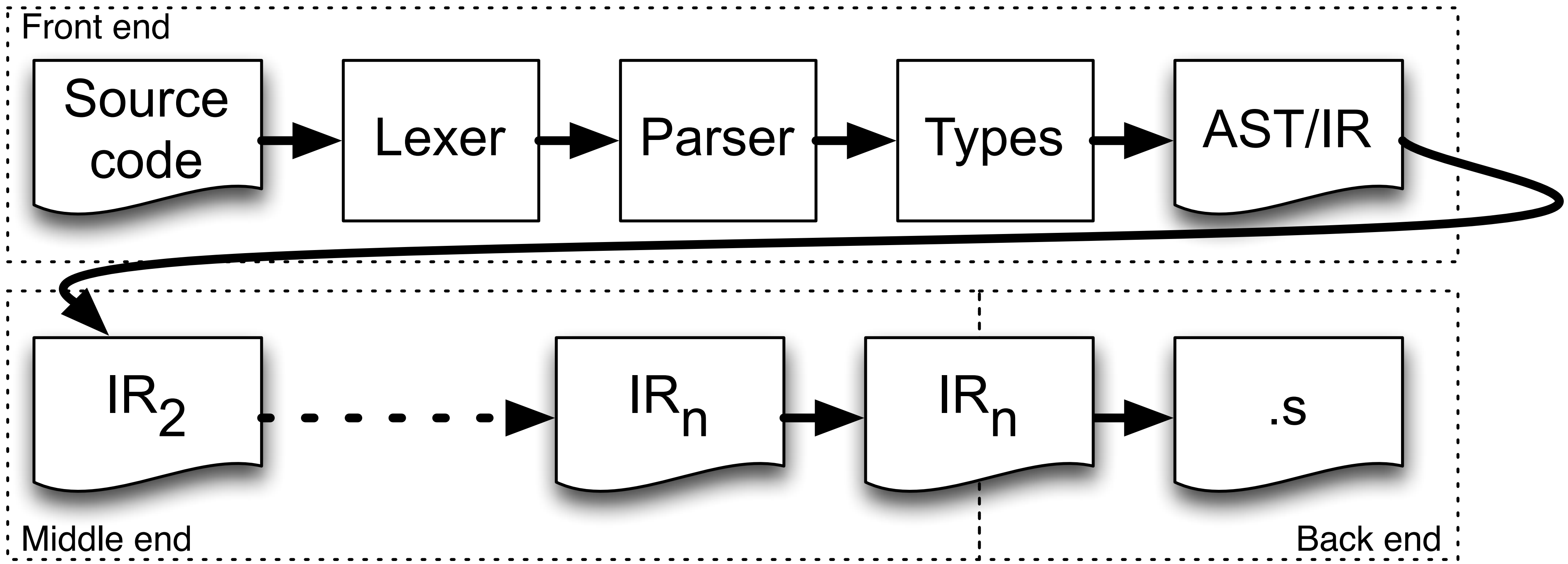
CMSC 430
Introduction to Compilers
Fall 2018

Code Generation

Code Representations



- Front end — syntax recognition, semantic analysis, produces first AST/IR
- Middle end — transforms IR into equivalent IRs that are more efficient and/or closer to final IR
- Back end — translates final IR into assembly or machine code

Three-address code

- Classic IR used in many compilers (or, at least, compiler textbooks)
- Core statements have one of the following forms
  - x = y *op* z — binary operation
  - x = op y — unary operation
  - x = y — copy statement

- Example:

```
z = x + 2 * y;
```

```
t = 2 * y
z = x + t
```

  - Need to introduce *temporarily variables* to hold intermediate computations
  - Notice: closer to machine code

Control Flow in Three-Address Code

- How to represent control flow in IRs?
  - l: statement — labeled statement
  - goto l — unconditional jump
  - if x rop y goto l — conditional jump (rop = relational op)

- Example

```
if (x + 2 > 5)
  y = 2;
else
  y = 3;
x++;
```

⇨

```
    t = x + 2
    if t > 5 goto l1
    y = 3
    goto l2
l1: y = 2
l2: x = x + 1
```

Looping in Three-Address Code

- Similar to conditionals

```
x = 10;
while (x != 0) {
  a = a * 2;
  x++;
}
y = 20;
```

```
    x = 10
l1: if (x == 0) goto l2
    a = a * 2
    x = x + 1
    goto l1
l2: y = 20
```

- The line labeled l1 is called the *loop header*, i.e., it's the target of the backward branch at the bottom of the loop
- Notice same code generated for

```
for (x = 10; x != 0; x++)
  a = a * 2;
y = 20;
```

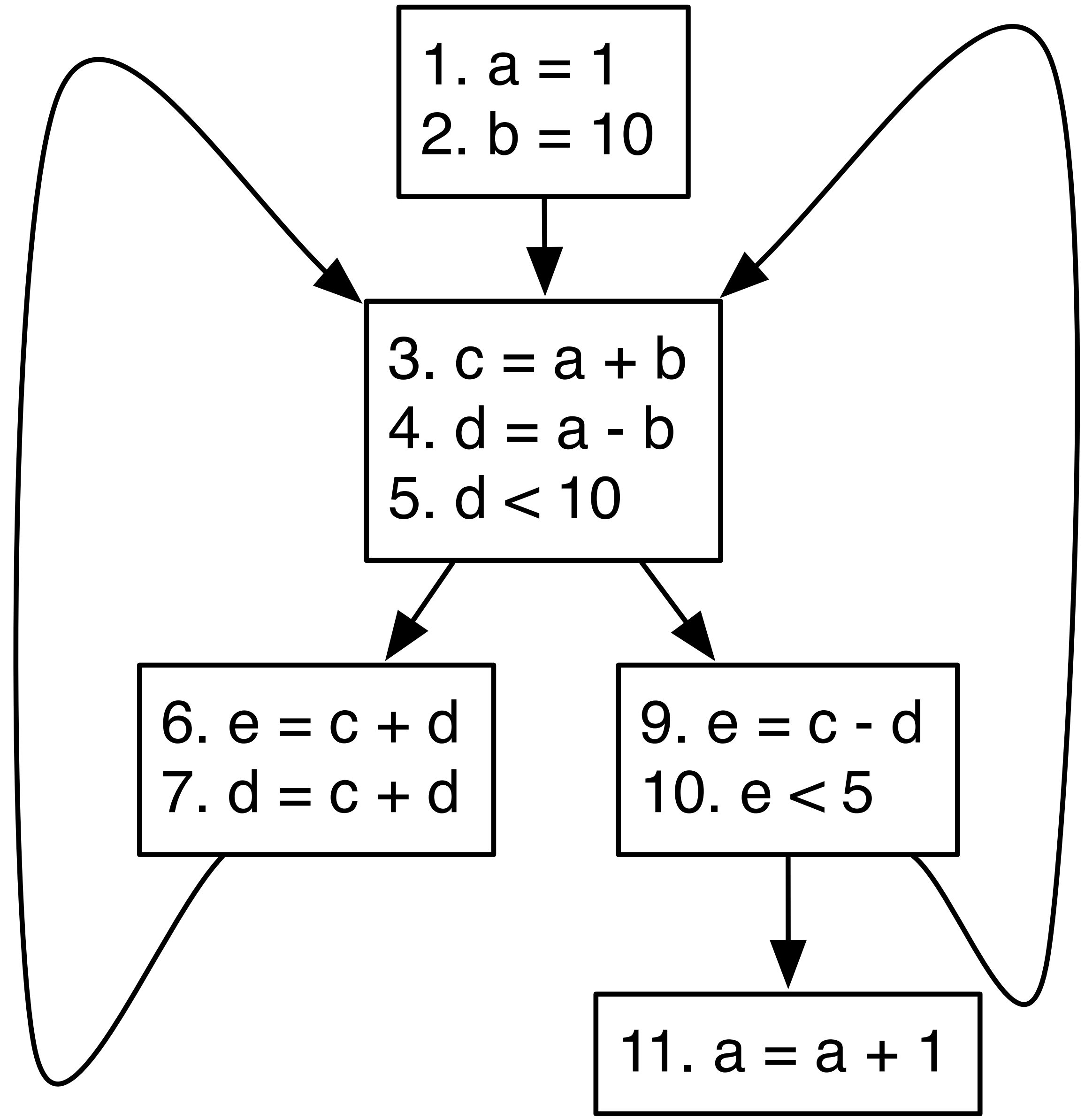
Basic Blocks

- A *basic block* is a sequence of three-addr code with
  - (a) no jumps from it except the last statement
  - (b) no jumps into the middle of the basic block

- A *control flow graph* (CFG) is a graphical representation of the basic blocks of a three-address program
  - Nodes are basic blocks
  - Edges represent jump from one basic block to another
    - Conditional branches identify true/false cases either by convention (e.g., all left branches true, all right branches false) or by labeling edges with true/false condition
  - Compiler may or may not create explicit CFG structure

Example

```
1. a = 1
2. b = 10
3. c = a + b
4. d = a - b
5. if (d < 10) goto 9
6. e = c + d
7. d = c + d
8. goto 3
9. e = c - d
10. if (e < 5) goto 3
11. a = a + 1
```



Levels of Abstraction

- Key design feature of IRs: what level of abstraction to represent
  - if x rop y goto l with explicit relation, OR
  - t = x rop y; if t goto l only booleans in guard
  - Which is preferable, under what circumstances?

- Representation of arrays
  - x = y[z] high-level, OR
  - t = y + 4*z; x = *t; low-level (ptr arith)
  - Which is preferable, under what circumstances?

Levels of Abstraction (cont’d)

- Function calls?
  - Should there be a function call instruction, or should the calling convention be made explicit?
    - Former is easier to work with, latter may enable some low-level optimizations, e.g.,passing parameters in registers
- Virtual method dispatch?
  - Same as above
- Object construction
  - Distinguished “new” call that invokes constructor, or separate object allocation and initialization?

Code Generation

- Code generation is the process of moving from “highest level” IR down to machine code
  - Usually takes place after data flow analysis
- Three major components
  - Instruction selection — Map IR into assembly code
  - Instruction scheduling — Reorder operations
    - Hide latencies in pipelined machines, ensure code obeys processor constraints
    - Modern processors do a lot of this already, and they have better information than the compiler...
  - Register allocation — Go from unbounded to finite reg set
    - Implies not all variables can always be in registers
- These problems are tightly coupled
  - But typically done separately in compilers

Code quality

- Compilers need to produce good “quality” code
  - This used to mean: code should match what an expert assembly programmer would write
  - With modern languages it’s much more unclear, but it mostly comes down to **performance**
    - ⇒ back-end needs to know ins and outs of target machine code
      - What kind of code can the machine run efficiently?
      - When does the machine need extra help from the compiler?
      - Rise of bytecode: fulfills a long-standing idea of splitting front- and back-end of compiler up, and reusing them in many combinations
    - ⇒ code generation cannot always be optimal
      - Benchmarking (e.g., SPEC) plays big role in code generator design
      - Compiler vendors play lots of games to do well on benchmarks
    - Rule of thumb: expose as much information as possible

Example: boolean operators

- How should these be represented?
  - Depends on the target machine and how they are used

- Example 1: If-then-else, x86, gcc

```
if (x < y)
  a = b + c;
else
  a = d + e;
```

```
    cmp rx, ry   // result in EFLAGS
    jge l1
    add ra, rb, rc
    jmp l2
l1: add ra, rd, re
l2: nop
```

Boolean operators (cont'd)

- Example 2: Standalone, x86, gcc

```
a = (x < y);
```

```
cmp rx, ry          // result in EFLAGS
setl %al            // 16-bit instruction
andb $1, %al        // only low bit set
movzbl %al, %eax    // extend to 32-bits
```

Boolean operations (cont'd)

- Example 3: If-then-else, Lua bytecode

```
local a,b,c,d,e,x,y;
if (x < y) then
  a = b + c;
else
  a = d + e;
end
```

```
    lt 0, R5, R6 // skip next instr if R5 < R6 true
    jmp l1       // pc += 2
    add R0, R1, R2
    jmp l2       // pc += 1
l1: add R0, R3, R4
l2: return
```

Boolean operations (cont'd)

- Example 4: Stand-alone, Lua

```
local a,x,y;
a = (x < y)
```

```
    lt 1, R1, R2 // skip next instr if R1 < R2 true
    jmp l1                // pc += 1
    loadbool R0, 0, l2 // R0 <- 0, jump to l2
l1: loadbool R0, 1, l2 // R0 <- 1, fall through to l2
l2: return
```

Example: case statements

- Consider compiling a case/switch statement with n guards
  - How expensive is it to decide which arm applies?
- Option 1: Cascaded if-then-else
  - O(n) — linear in the number of cases, and actual cost depends on where matching arm occurs
- Option 2: Binary search
  - O(log n) — but needs guards that are totally ordered
- Option 3: Jump table
  - O(1) — but best when guards are dense (e.g., ints 0..10)

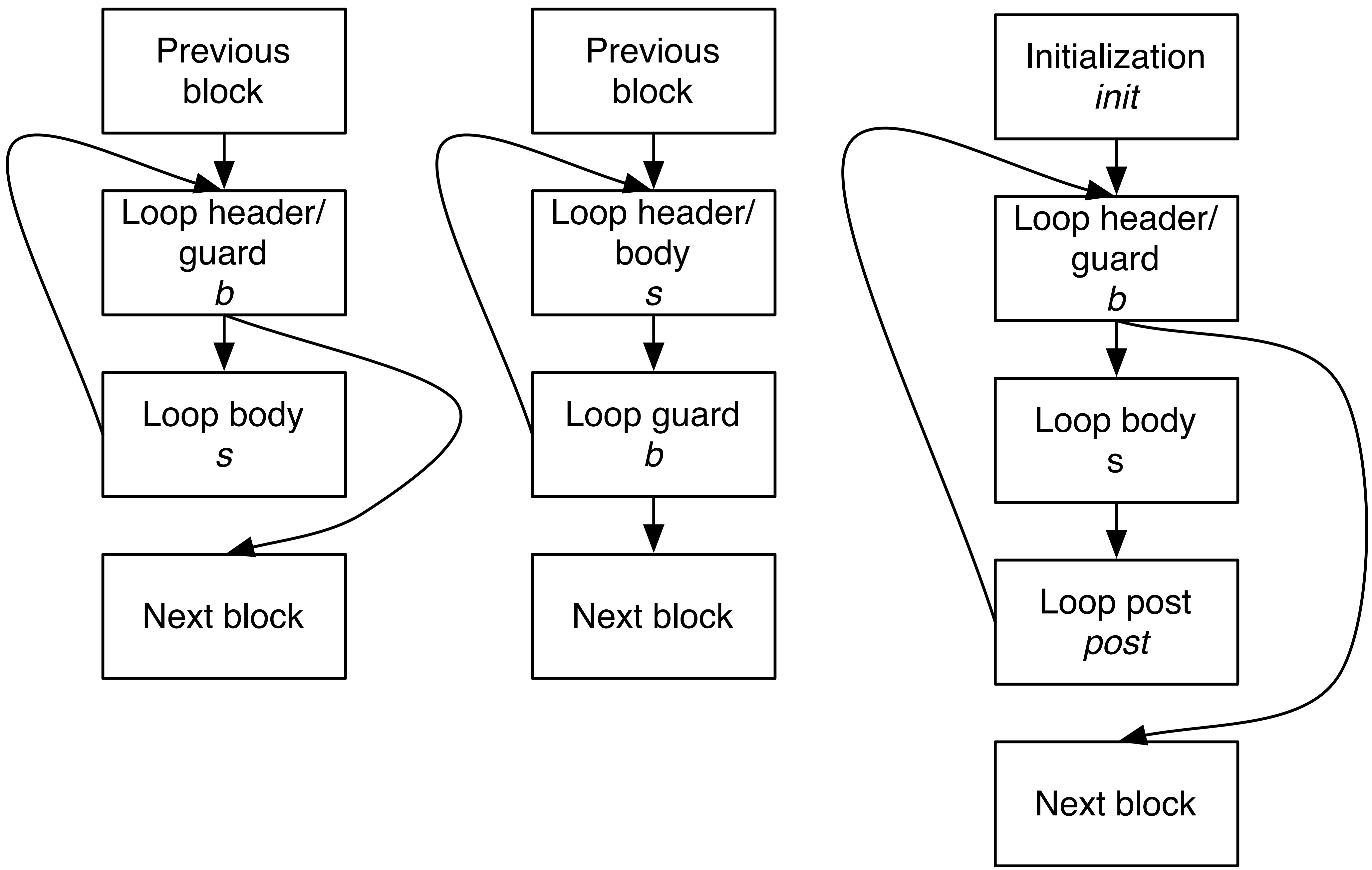
- No amount of “optimization” will covert one of these forms into another

Instruction selection

- Arithmetic exprs, global vars, if-then-else
  - See codegen*.ml files on web site

Instruction selection — loops

while (b) do s; *do s while (b);* *for (init; b; post) s;*



Multi-dimensional arrays

- Conceptually

A				
	1,1	1,2	1,3	1,4
	2,1	2,2	2,3	2,4

- Row-major order (most languages)

A								
	1,1	1,2	1,3	1,4	2,1	2,2	2,3	2,4

- Column-major order (Fortran)

A								
	1,1	2,1	1,2	2,2	1,3	2,3	1,4	2,4

- Indirection vectors (Java)

Computing an array address

- a[i]
  - a + i * sizeof(*a)
    - Here a is the base address of the array, and assume array 0-based
- a[i][j]
  - Row-major order
    - a + i * sizeof(*a) + j * sizeof(**a)
    - Here sizeof(*a) is the size of a row or column, as appropriate
    - Much more arithmetic needed if array not 0-based
  - Column-major order
    - a + j * sizeof(*a) + i * sizeof(**a)
  - Indirection vectors
    - *(a + i * sizeof(pointer)) + j * sizeof(**a)

Functions

- (Aka procedure, subroutine, routine, method, ...)
- Fundamental abstraction of computing
  - Reusable grouping of code
  - Usually also introduces a lexical scope/name space

- *Calling conventions* to interact with system, libraries, or separately compiled code
  - In these cases, don't have access to other code at compile time
    - Must have standard for passing parameters, return values, invariants maintained across function call, etc
  - Don't necessarily need to obey these "within" the language
    - But deviating from them reduces utility of system tools

Terminology

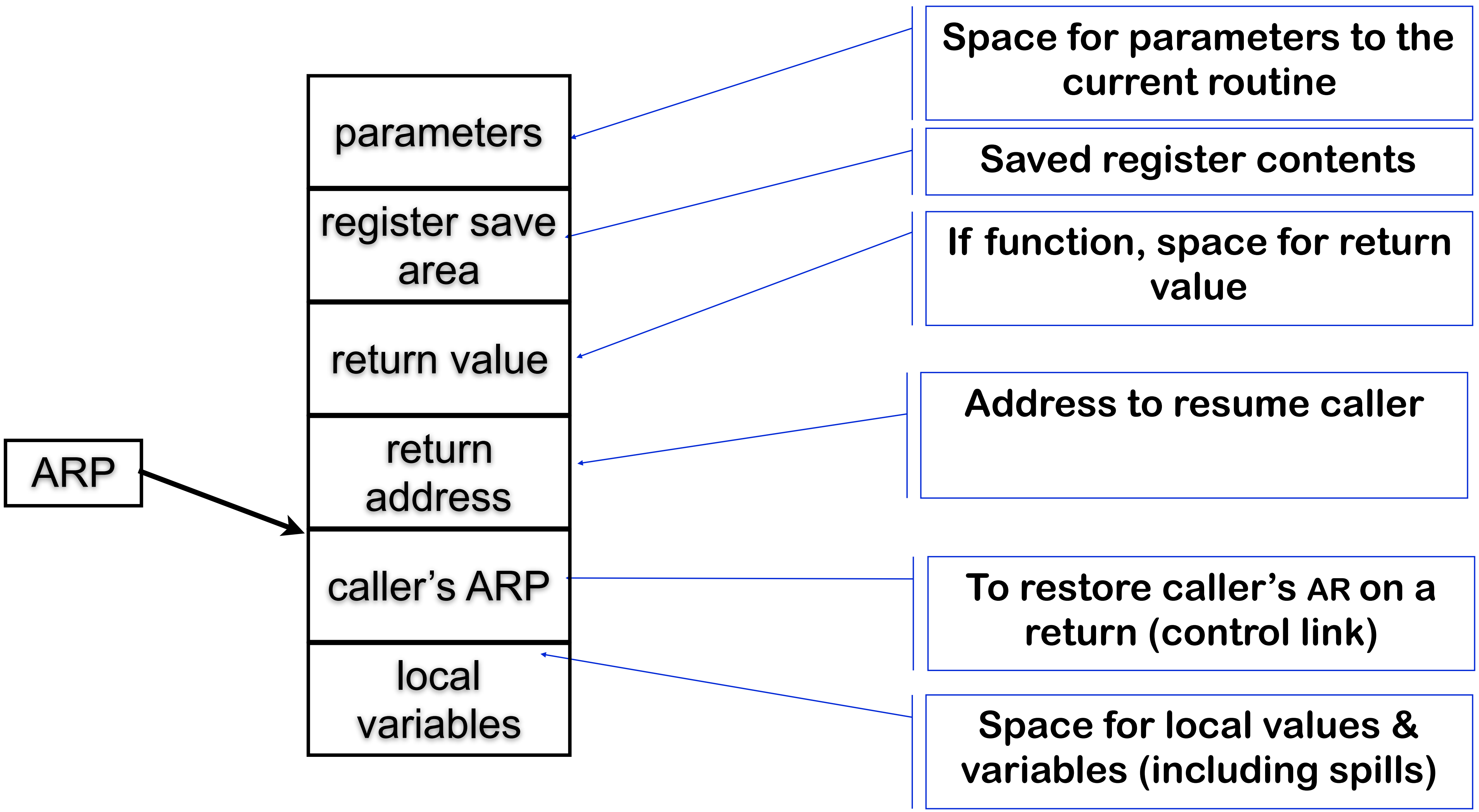
- Run time vs. compile time
  - The code that implements the calling convention is executed at *run time*
  - The code is generated at *compile time*

- Caller vs. callee
  - Caller — that function that made the call
  - Callee — the function that was called

(Algol, C) function call concerns

- Function invoked at call site
  - Control returns to call site when function returns
  - ⇒ need to save and restore a “return address”
- Function calls may be recursive
  - ⇒ need a stack of return addresses
- Need storage for parameters and local variables
- Must preserve caller’s state
  - ⇒ stack needs space for these
- Stack consists of *activation records*
  - We’ll see what these look like and how they are set up next

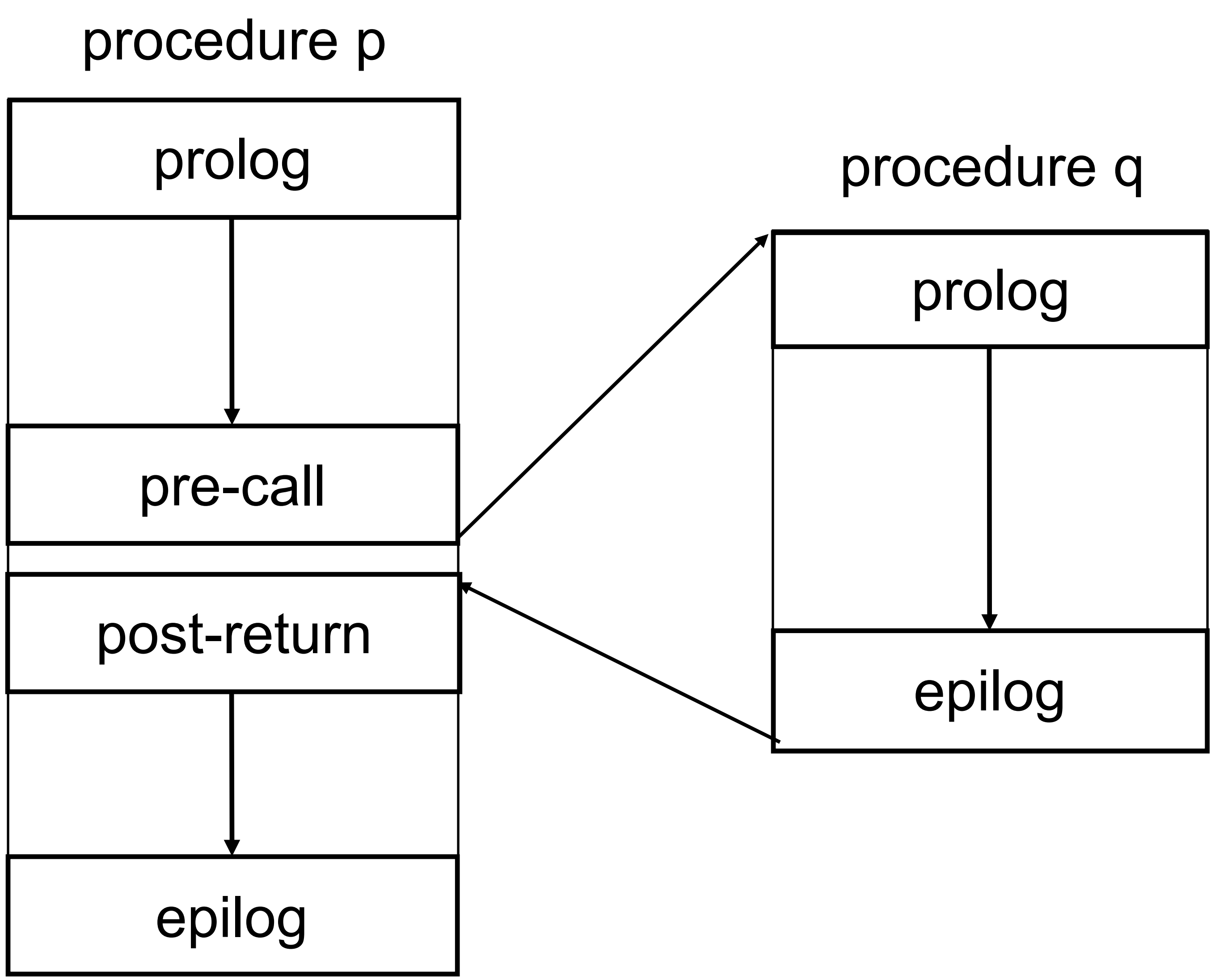
Activation Record Basics



One **AR** for each invocation of a procedure

Procedure Linkages

Standard procedure linkage



Procedure has
- standard prolog
- standard epilog

Each call involves a
- pre-call sequence
- post-return sequence

These are completely predictable from the call site ⇒ depend on the number & type of the actual parameters

Pre-call sequence

- Sets up callee's basic AR
- Helps preserve its own environment

- The Details
  - Allocate space for the callee's AR
    - except space for local variables
  - Evaluates each parameter & stores value or address
  - Saves return address, caller's ARP into callee's AR
  - Save any caller-save registers
    - Save into space in caller's AR
  - Jump to address of callee's prolog code

Post-return sequence

- Finish restoring caller’s environment
- Place any value back where it belongs

- The Details
  - Copy return value from callee’s AR, if necessary
  - Free the callee’s AR
  - Restore any caller-save registers
  - Copy back call-by-value/result parameters
  - Continue execution after the call

Prolog code

- Finish setting up callee’s environment
- Preserve parts of caller’s environment that will be disturbed

- The Details
  - Preserve any callee-save registers
  - Allocate space for local data
    - Easiest scenario is to extend the AR
  - Handle any local variable initializations

Epilog code

- Wind up the business of the callee
- Start restoring the caller's environment

- The Details
  - Store return value?
    - Some implementations do this on the return statement
    - Others have return assign it & epilog store it into caller's AR
    - Still others (x86) store it in a register
  - Restore callee-save registers
  - Free space for local data, if necessary
  - Load return address from AR
  - Restore caller's ARP
  - Jump to the return address

Concrete example: x86

- The CPU has a fixed number of *registers*
  - Think of these as memory that's really fast to access
  - For a 32-bit machine, each can hold a 32-bit word

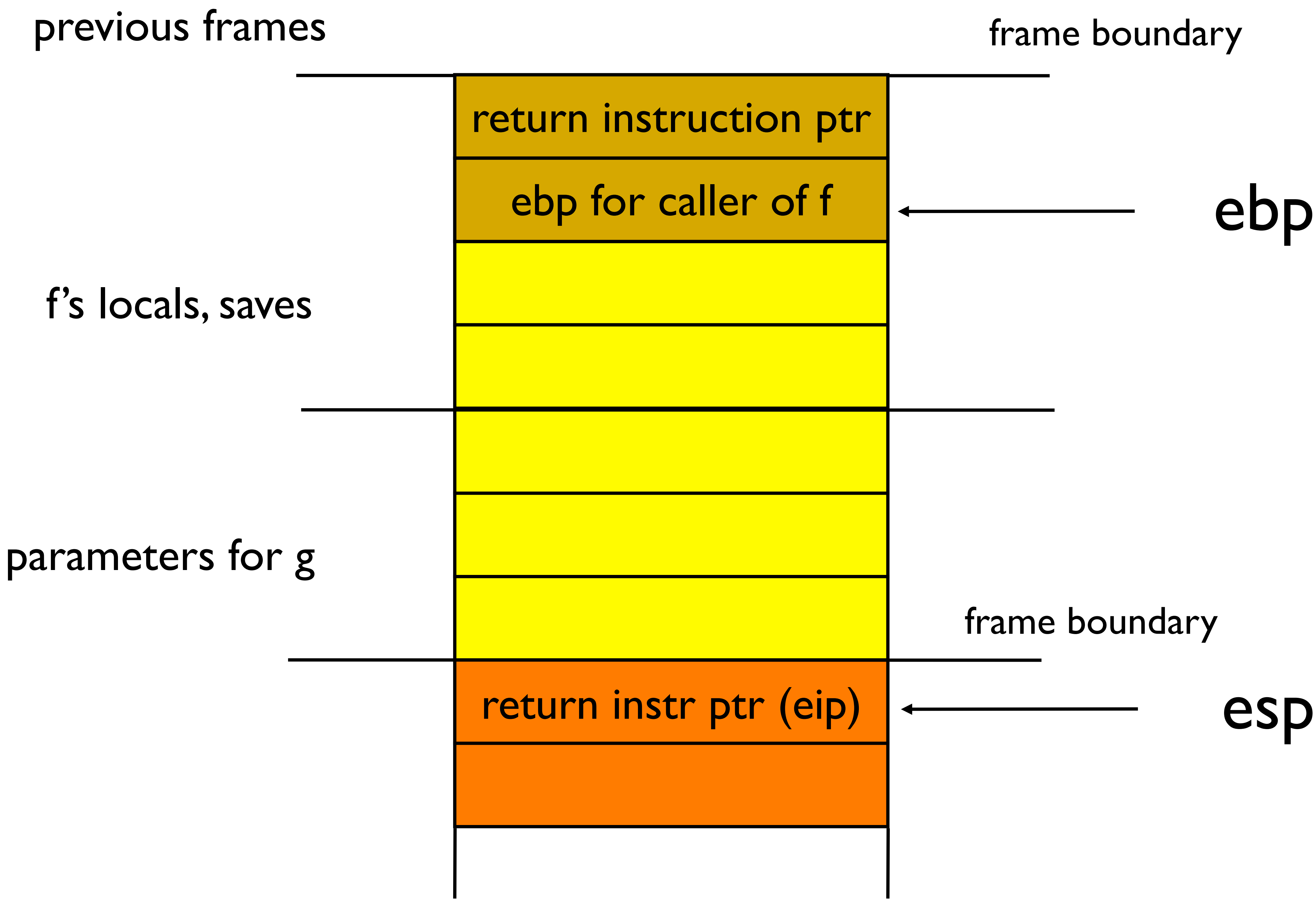
- Important x86 registers
  - eax generic register for computing values
  - esp pointer to the top of the stack
  - ebp pointer to start of current stack frame
  - eip the program counter (points to next instruction in text segment to execute)

x86 calling convention

- To call a function
  - Push parameters for function onto stack
  - Invoke CALL instruction to
    - Push current value of eip onto stack
      - I.e., save the program counter
    - Start executing code for called function
  - Callee pushes ebp onto stack to save it
- When a function returns
  - Put return value in eax
  - Invoke RET instruction to load return address into eip
    - I.e., start executing code where we left off at call

x86 activation record

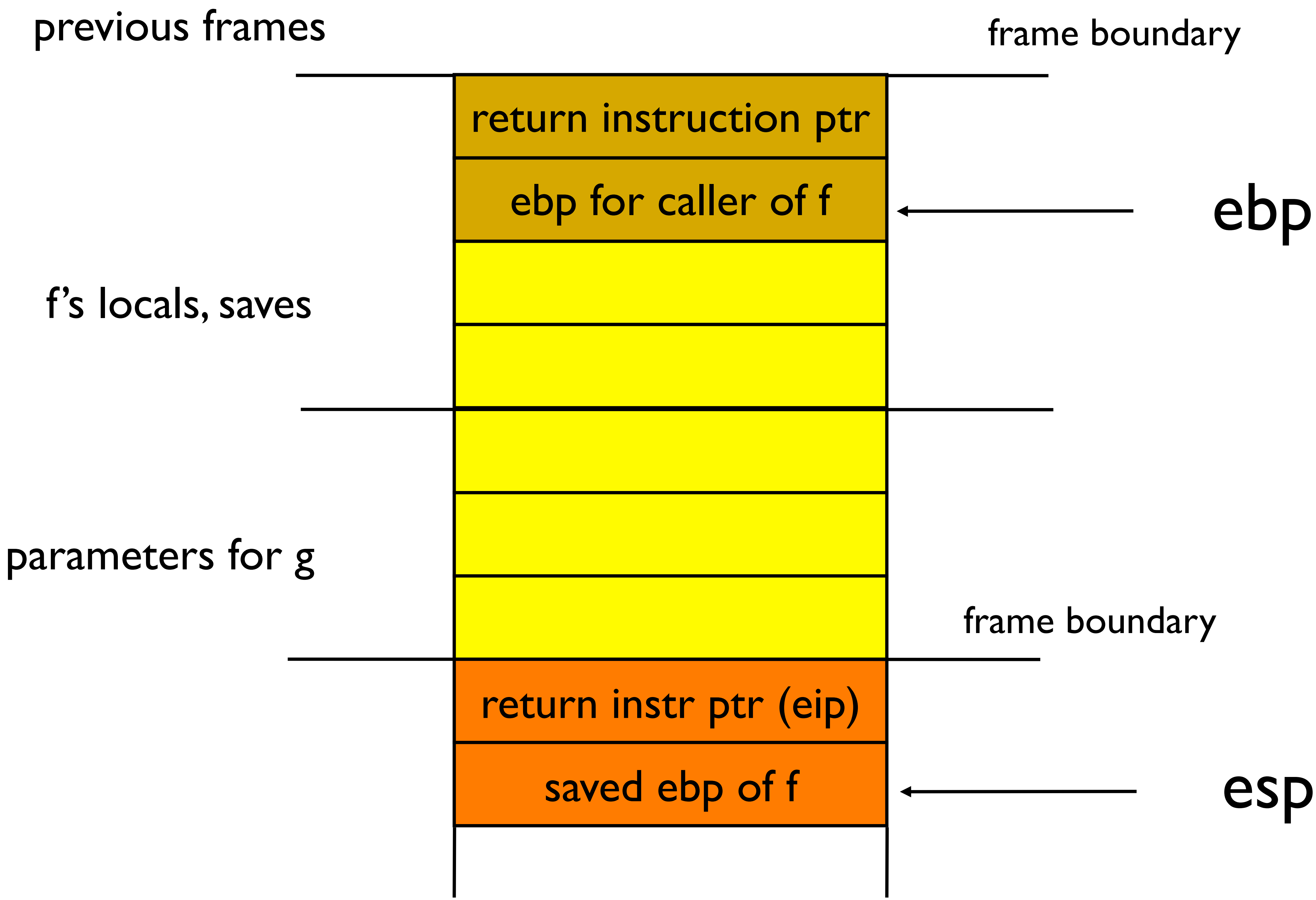
- The stack just after f calls g



Based on Fig 6-1 in Intel ia-32 manual

x86 activation record

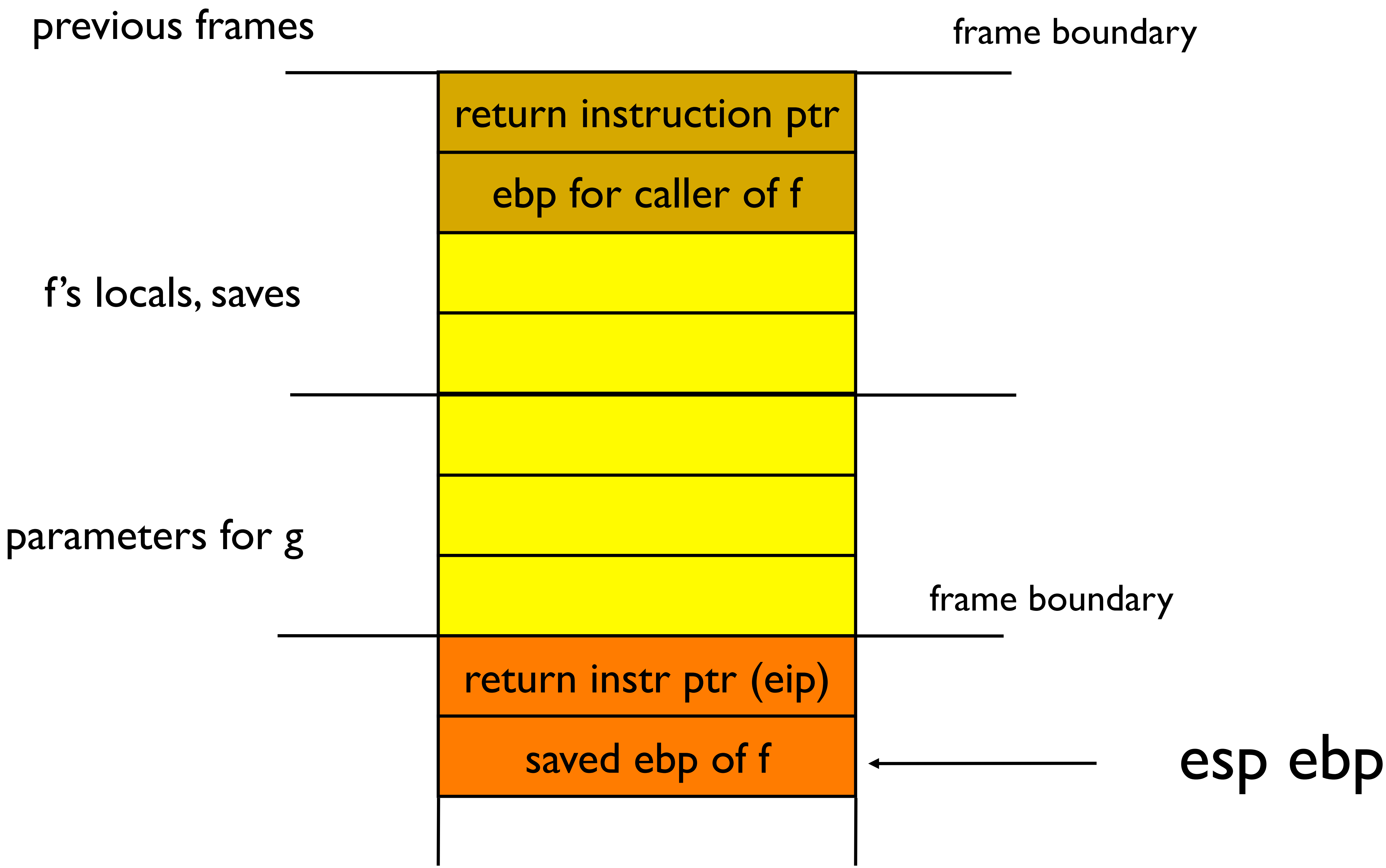
- The stack just after push ebp inside g



Based on Fig 6-1 in Intel ia-32 manual

x86 activation record

- The stack just after mov esp ebp inside g



Based on Fig 6-1 in Intel ia-32 manual

Example

```
int f(int a, int b) {
  return a + b;
}

int main(void) {
  int x;

  x = f(3, 4);
}
```

gcc -m32 -S a.c

```
f:
        pushl   %ebp
        movl    %esp, %ebp
        subl    $8, %esp
        movl    12(%ebp), %eax
        movl    8(%ebp), %ecx
        movl    %ecx, -4(%ebp)
        movl    %eax, -8(%ebp)
        movl    -4(%ebp), %eax
        addl    -8(%ebp), %eax
        addl    $8, %esp
        popl    %ebp
        retl
main:
        …
        movl    $3, %eax
        movl    $4, %ecx
        movl    $3, (%esp)
        movl    $4, 4(%esp)
        movl    %eax, -8(%ebp)
        movl    %ecx, -12(%ebp)
        calll   f
        movl    %eax, -4(%ebp)
        …
```

Example

```
int f(int a, int b) {
  return a + b;
}

int main(void) {
  int x;

  x = f(3, 4);
}
```

gcc -m32 -S a.c

```
f:
```

prolog

```
        pushl   %ebp
        movl    %esp, %ebp
        subl    $8, %esp
        movl    12(%ebp), %eax
        movl    8(%ebp), %ecx
        movl    %ecx, -4(%ebp)
        movl    %eax, -8(%ebp)
```

```
        movl    -4(%ebp), %eax
        addl    -8(%ebp), %eax
```

epilog

```
        addl    $8, %esp
        popl    %ebp
        retl
```

```
main:
        …
        movl    $3, %eax
        movl    $4, %ecx
```

pre-call

```
        movl    $3, (%esp)
        movl    $4, 4(%esp)
        movl    %eax, -8(%ebp)
        movl    %ecx, -12(%ebp)
```

```
        calll   f
        movl    %eax, -4(%ebp)
        …
```

Example

```c
int f(int a, int b) {
  return a + b;
}

int main(void) {
  int x;

  x = f(3, 4);
}
```

```
f:
        pushl   %ebp
        movl    %esp, %ebp
        movl    12(%ebp), %eax
        addl    8(%ebp), %eax
        popl    %ebp
        retl

main:
        pushl   %ebp
        movl    %esp, %ebp
        xorl    %eax, %eax
        popl    %ebp
        retl
```

gcc -m32 -S -O3 a.c

Lots more details

- There's a whole lot more to say about calling functions
  - Local variables are allocated on stack by the callee as needed
    - This is usually the first thing a called function does, by incrementing esp
  - Saving registers
    - If the callee is going to use eax itself, you'd better save it to the stack before you call
  - Passing parameters in registers
    - More efficient than pushing/popping from the stack
    - Can be done if caller and callee cooperate
    - (But watch out for extern functions that could be called from anywhere)
  - Etc...

Even more details

- Different languages/OS's can have different conventions
  - And conventions have changed over time

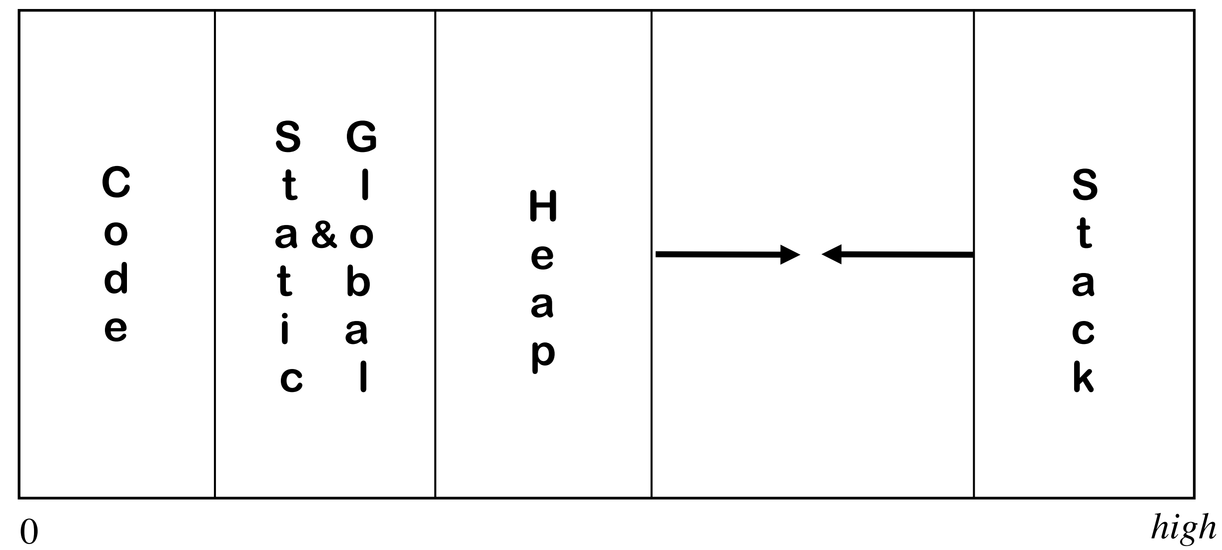
- System call interface is different application-level interface
  - Need to switch into kernel mode in some way
  - Details depend on OS
  - Typically, syscalls wrapped by standard library
    - E.g., calling open() in C calls into libc, which does some high-level stuff and then does a syscall
    - Syscall code often implemented as inline assembly

Higher-order languages

- If a called function can outlive its caller, need to keep activation record on the heap
  - `fun x -> (fun y -> x + y)`
  - I.e., we need *closures* for these

- These get allocated basically like we saw in 330
  - Try to avoid allocating these if curried functions called with all arguments at once

Memory layout

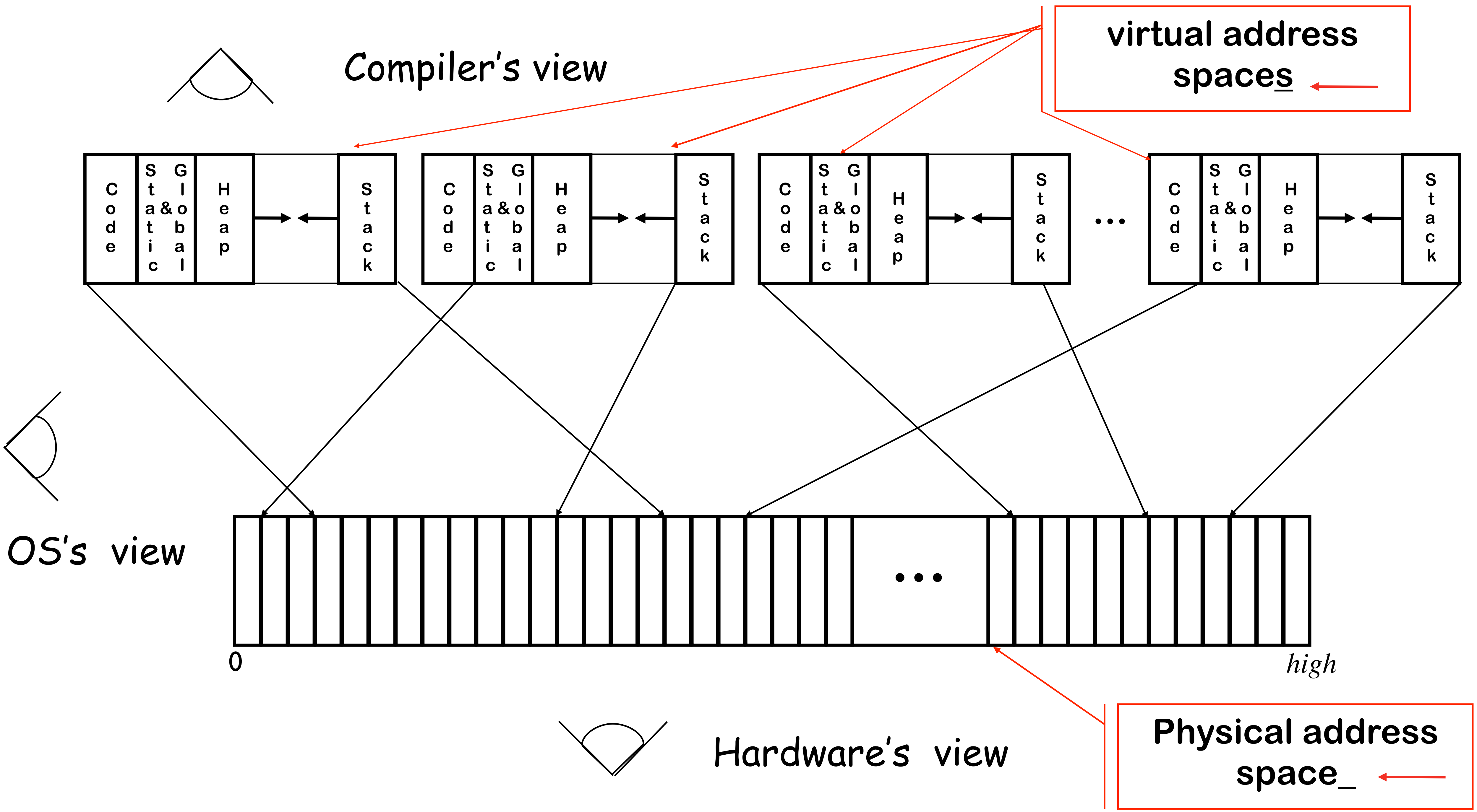


Single Logical Address Space

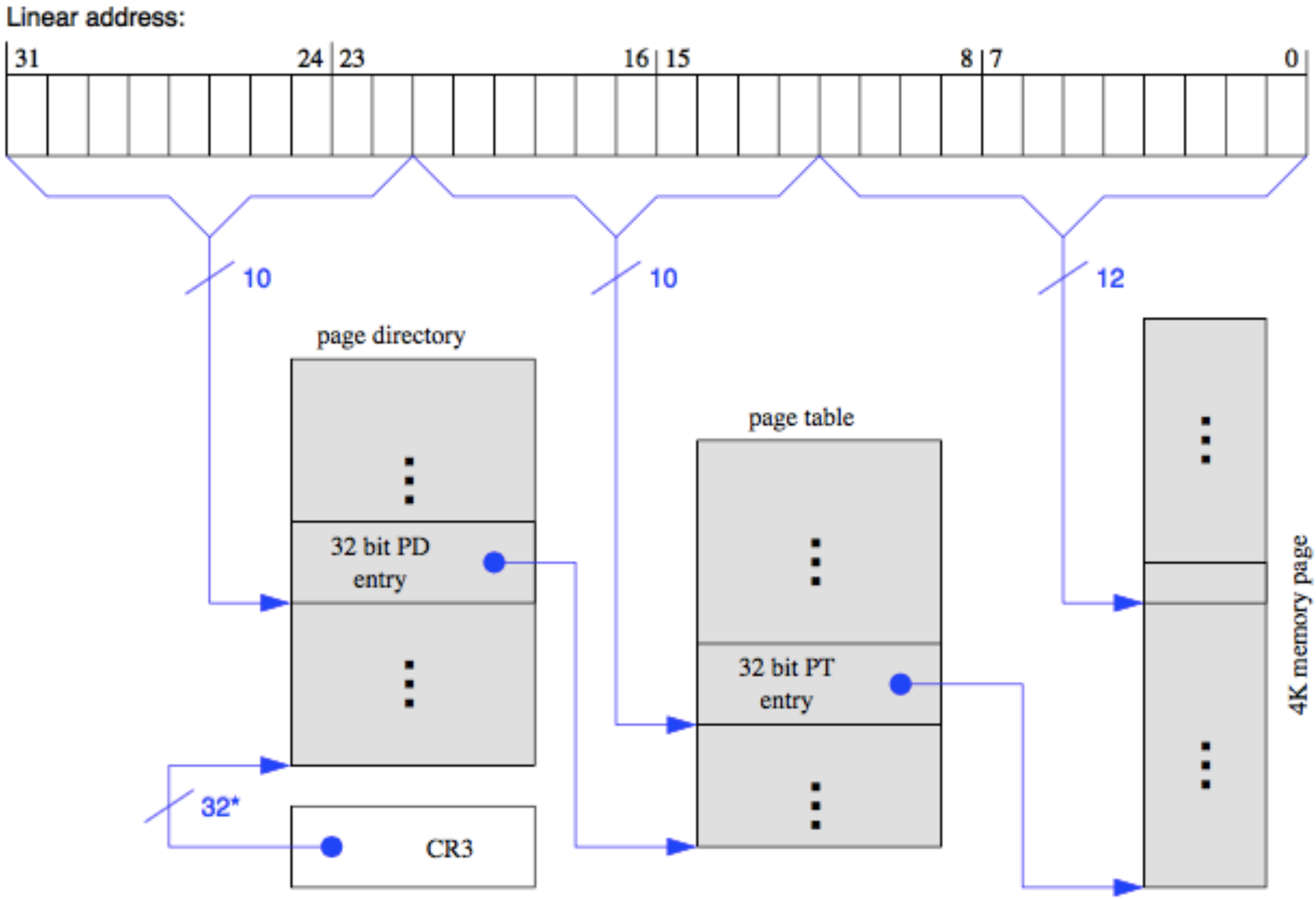
- Code, static, and global data have known size
  - Can refer to entities by predetermined offsets
    - (Note: ASLR used to prevent attackers from guessing these)
  - Heap and stack both grow and shrink over time
    - Better utilization if stack and heap grow toward each other (Knuth)

- Note this is a *virtual* address space

The really big picture



The really small picture



*) 32 bits aligned to a 4-KByte boundary

Source: https://en.wikipedia.org/wiki/Page_table

Linking

- Many languages support *separate compilation*
  - Individual modules or components are compiled by themselves, without needing to recompile the modules or components they depend on
  - Can dramatically reduce time to recompile program when program is changed
- *Linking* combines components together
  - In C and OCaml, linking is an explicit phase
  - In Java, linking is implicit as dependencies are loaded by the JVM
- Linkers often support *shared libraries*
  - Shared lib code appears only once on disk for all apps
  - Shared lib can be updated, apps automatically see new version
    - ⇒ linking against shared lib only checks existence (and maybe type) of symbol
  - Shard lib code must be *position independent*

Linking example

```
Makefile
all: main.o lib.o
        gcc main.o lib.o -o prog

lib.o: lib.c
  gcc -c lib.c

main.o: main.c
  gcc -c main.c
```

main.c

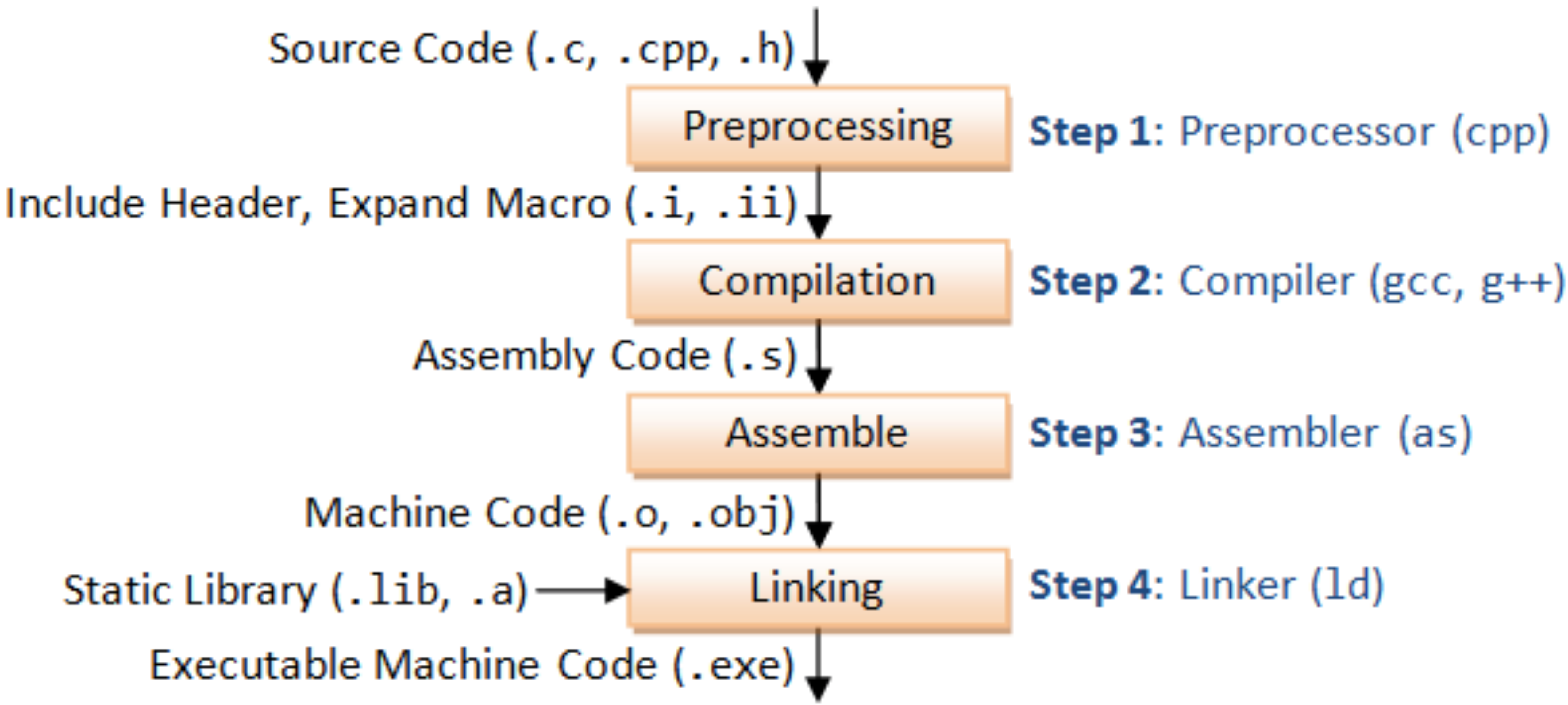
```c
extern int print_s(const char *);
int main() {
   print_s("Hello, world!”);
}
```

lib.c

```c
#include <stdio.h>
void print_s(const char *s) {
    printf("%s", s);
}
```

otool -tv main.o (OS X)
objdump -D main.o (linux)

gcc compilation process



Source: http://www3.ntu.edu.sg/home/ehchua/programming/cpp/gcc_make.html

Loading

- OS needs to know many things about a program
  - Where is the program code
  - Where are values for the data segment
  - How should the program be started
  - What shared libs does the program refer to

- Thus, compilers must create an executable that is in a standard format
  - E.g., ELF on Linux, PE32+ on Windows, Mach-O on OS X
- Details of all these can be found on the web, in man pages, and in developer documentation

ELF

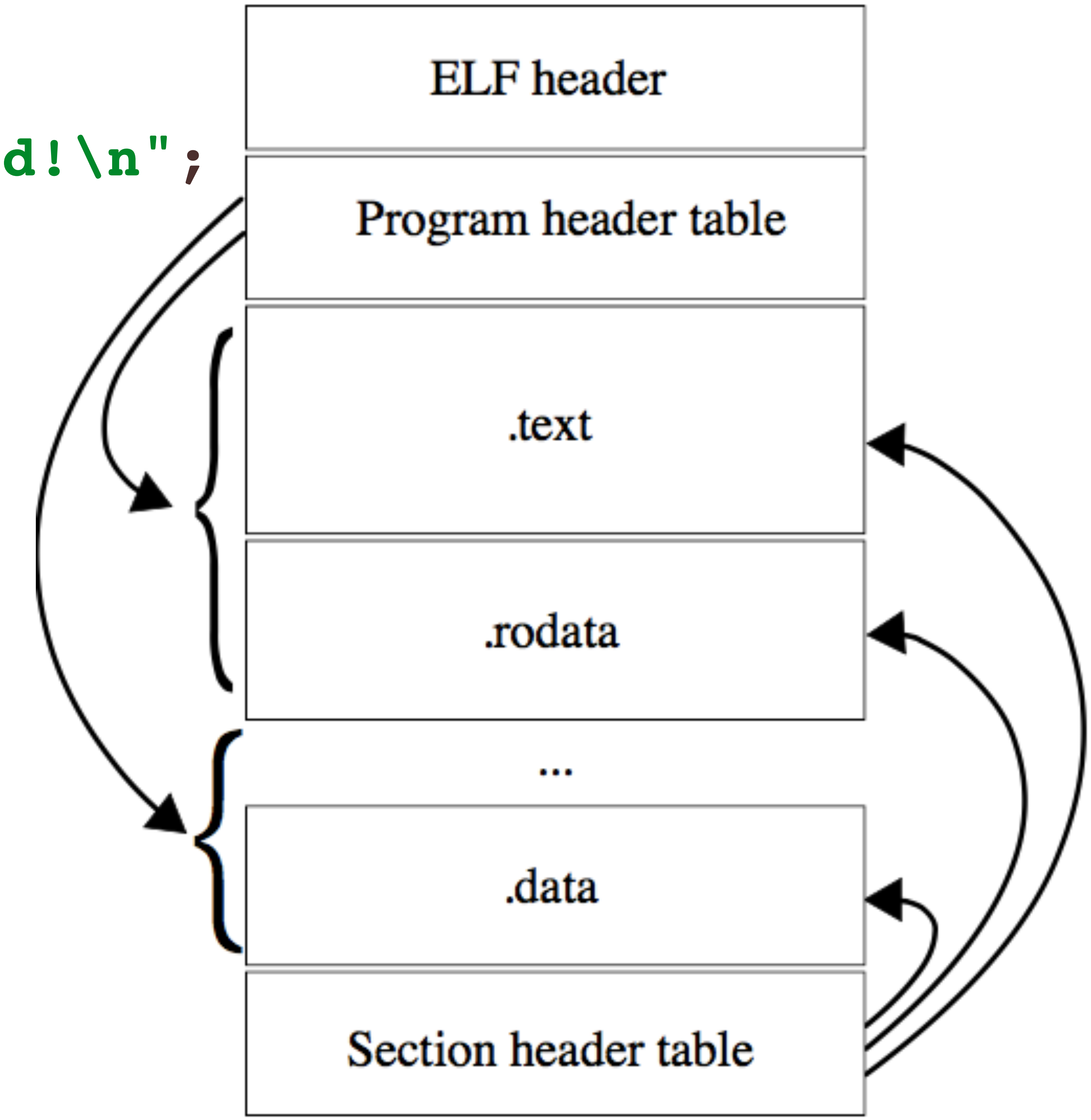
elf.c

```c
int x = 1010101;
char *s = "Hello, world!\n";

int main() {
    int x=1;
    return x;
}
```

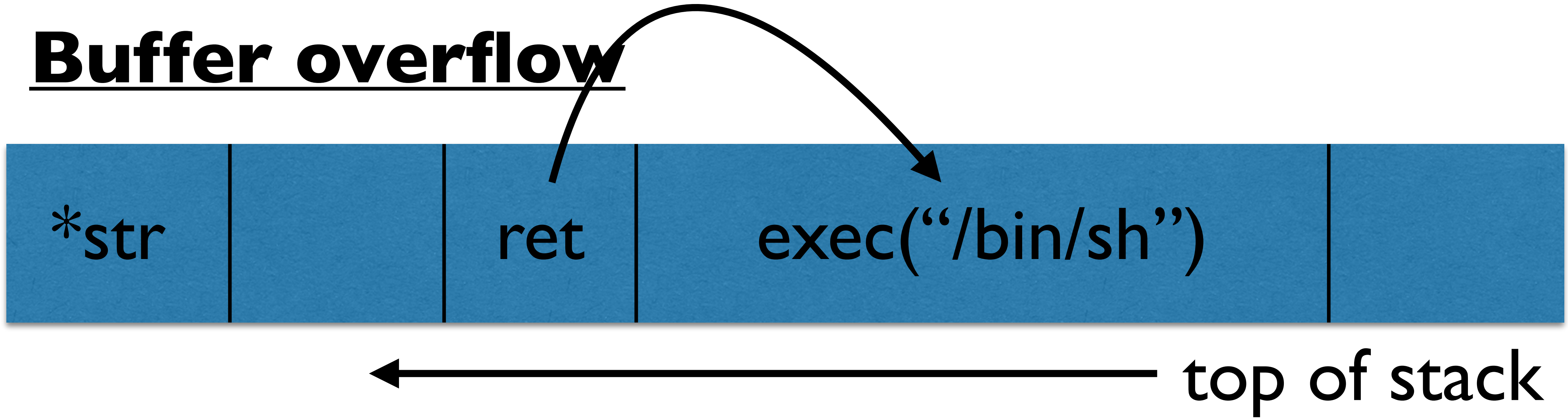
gcc -o elf.c

objdump -D elf.o



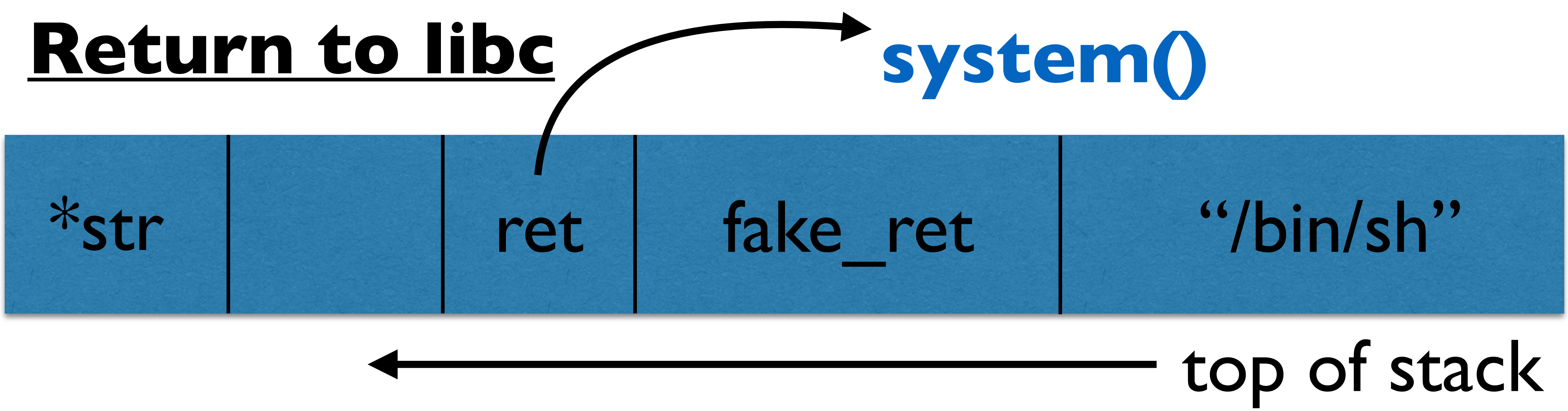
Stack SMASHING!

- **<u>Buffer overflow</u>**



- **strcpy()** - what if bounds aren't checked?

- **<u>Return to libc</u>**



Stack SMASHING! (defences)

- Canary values
  - inject random values in between stack frames
  - check those values during function call

- Address Space Layout Randomization
  - randomize the layout of key data areas (heap, stack, libraries)

```
int main () {
    register int *ebp asm("ebp");
    printf("%p\n", ebp);
}
```

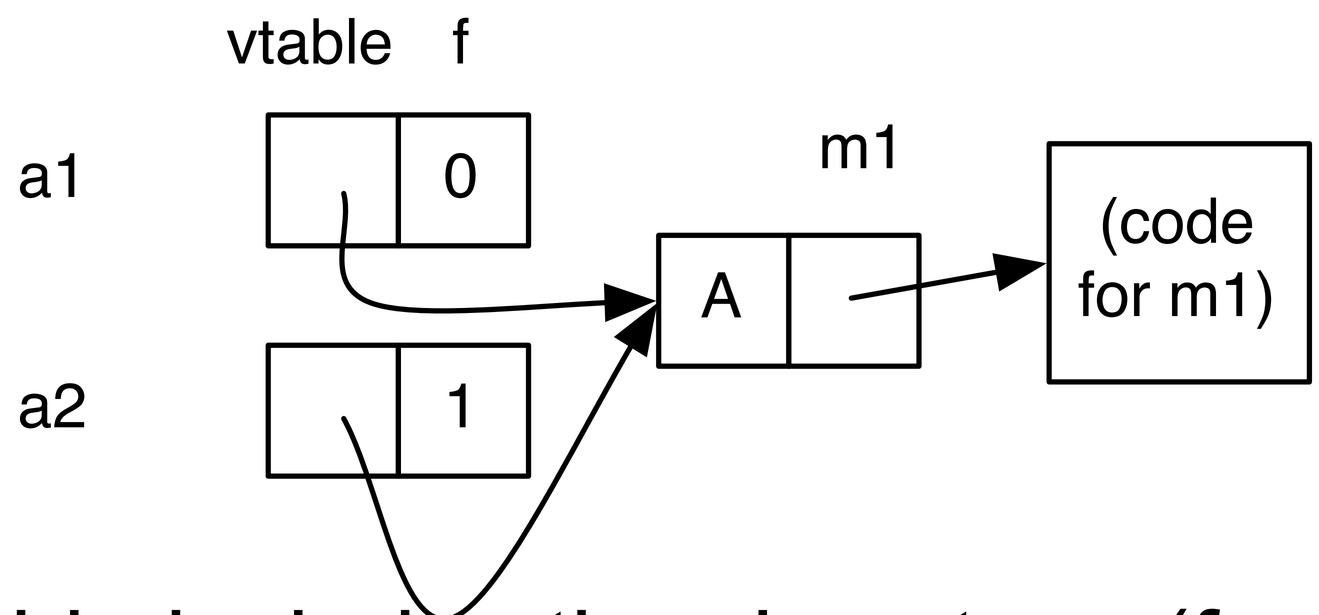
```
$: ./randomlayout
0x7fff67835036
$: ./randomlayout
0x7fff663e5036
```

Compiling objects and classes

- Object = record with data (fields) and code (meths)
  - In a classless OO language, in general case need to treat each object separately
- Class = set of objects with same meths
  - ⇒ All insts of a class can share memory used for meth code
  - (But, each inst has its own fields)
- *Virtual method table (vtable)* contains pointers to methods of class
  - Object record points to vtable, and then vtable used to resolve dynamic dispatch

Example

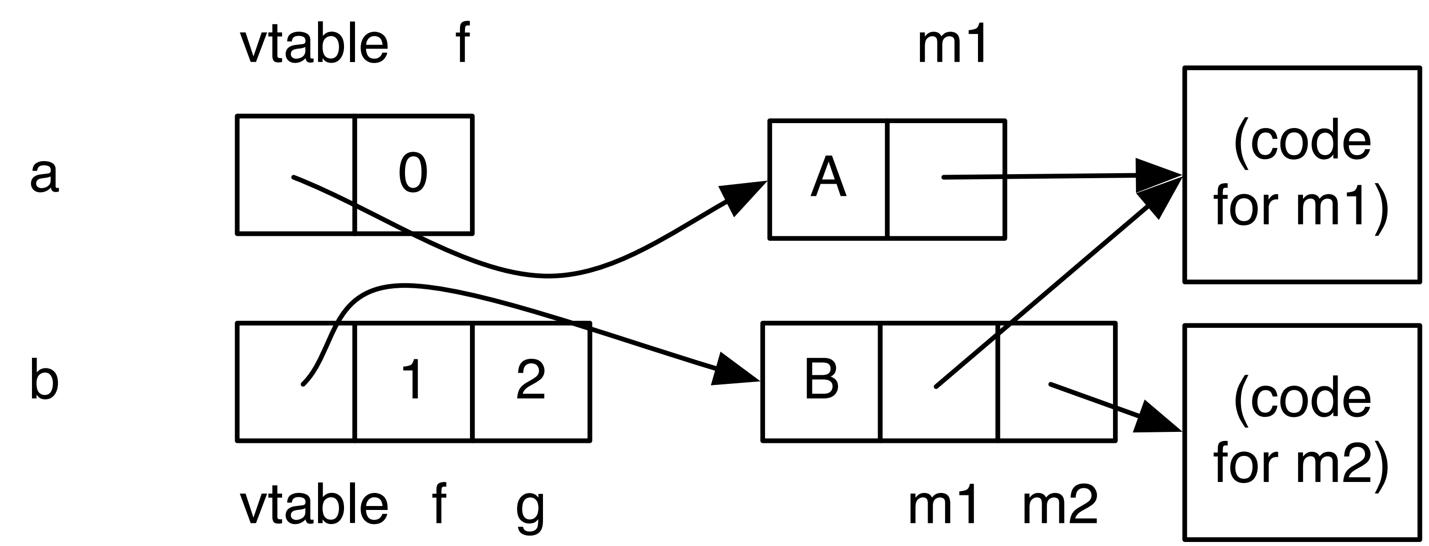
```
class A { int f; void m1(void) { ... } }
a1 = A.new();
a2 = A.new();
```



- The vtable includes the class type (for run-time type tests) and a function pointer for each method
  - At `x.m1()`, call `(x->vtable[0])()`
  - (Note we know the offset of m1 from the type of x)

Single Inheritance

```
class A { int f; void m1(void) { ... } }
class B extends A { int g; void m2(void) { ... } }
a = A.new();
b = B.new();
```



- Ensure superclass layouts are *prefixes* of subclass layouts
  - At `x.m1()`, still call `(x->vtable[0])()`
  - At `x.m2()`, call `(x->vtable[1])()`

Multiple inheritance

```
class A { int f; void m1(void) { ... } }
class B extends A { int g; void m2(void) { ... } }
class C extends A { int h; void m3(void) { ... } }
class D extends B { int i; void m1(void) { ... } }
class E extends C, D { int j; void m4(void) { ... } }
```

- (Notice that D overrides method m1)
- Much more complicated!
  - Separate compilation, so don’t know full inheritance hierarchy
  - Must support both up- and downcasts
  - Want method lookup to be efficient
- Solutions? Several—see web for details!