We made it! ☺

C:

```
car *c = malloc(sizeof(car));
c->miles = 100;
c->gals = 17;
float mpg = get_mpg(c);
free(c);
```

Java:

```
Car c = new Car();
c.setMiles(100);
c.setGals(17);
float mpg =
    c.getMPG();
```

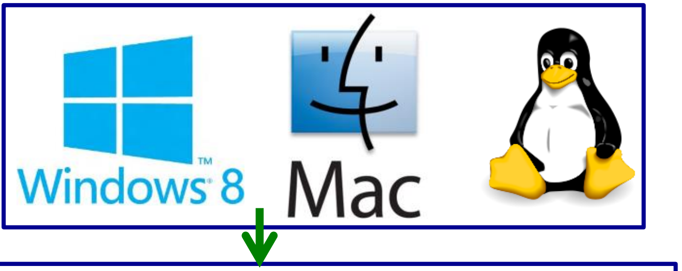
Assembly language:

```
get_mpg:
    pushq   %rbp
    movq    %rsp, %rbp
    ...
    popq    %rbp
    ret
```

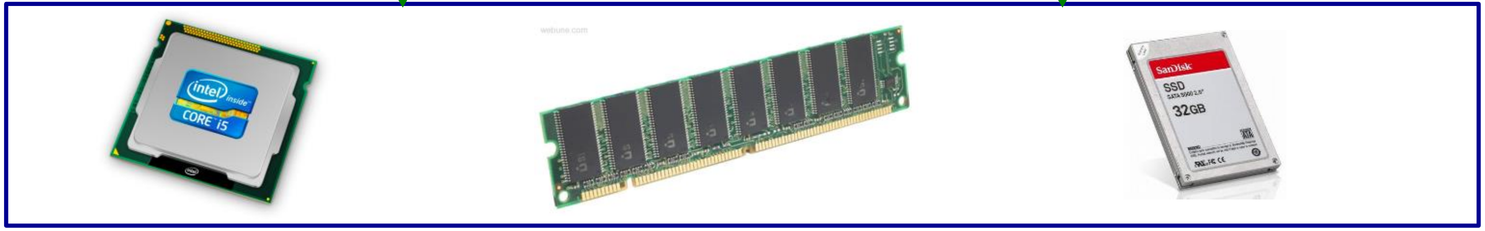
Machine code:

```
0111010000011000
100011010000010000000010
1000100111000010
110000011111101000011111
```

OS:



Computer system:



Memory & data
Integers & floats
Machine code & C
x86 assembly
Procedures & stacks
Arrays & structs
Memory & caches
Processes
Virtual memory
Memory allocation
Java vs. C

Today

- **Imploring you to do your course evaluations, please!**
- **I’m Just a Program**
  - End-to-end review
- **Victory lap and high-level concepts (*major 🔑 points*)**
  - More useful for “5 years from now” than “next week’s final”
- **Question time**

Final Exam

- **Wednesday, June 8, 2:30pm-4:20pm**
  - Right here in Miller 301.

- **We’ve covered a lot this quarter!**
  - I know it’s a lot to review
  - But probably less time pressure than midterm

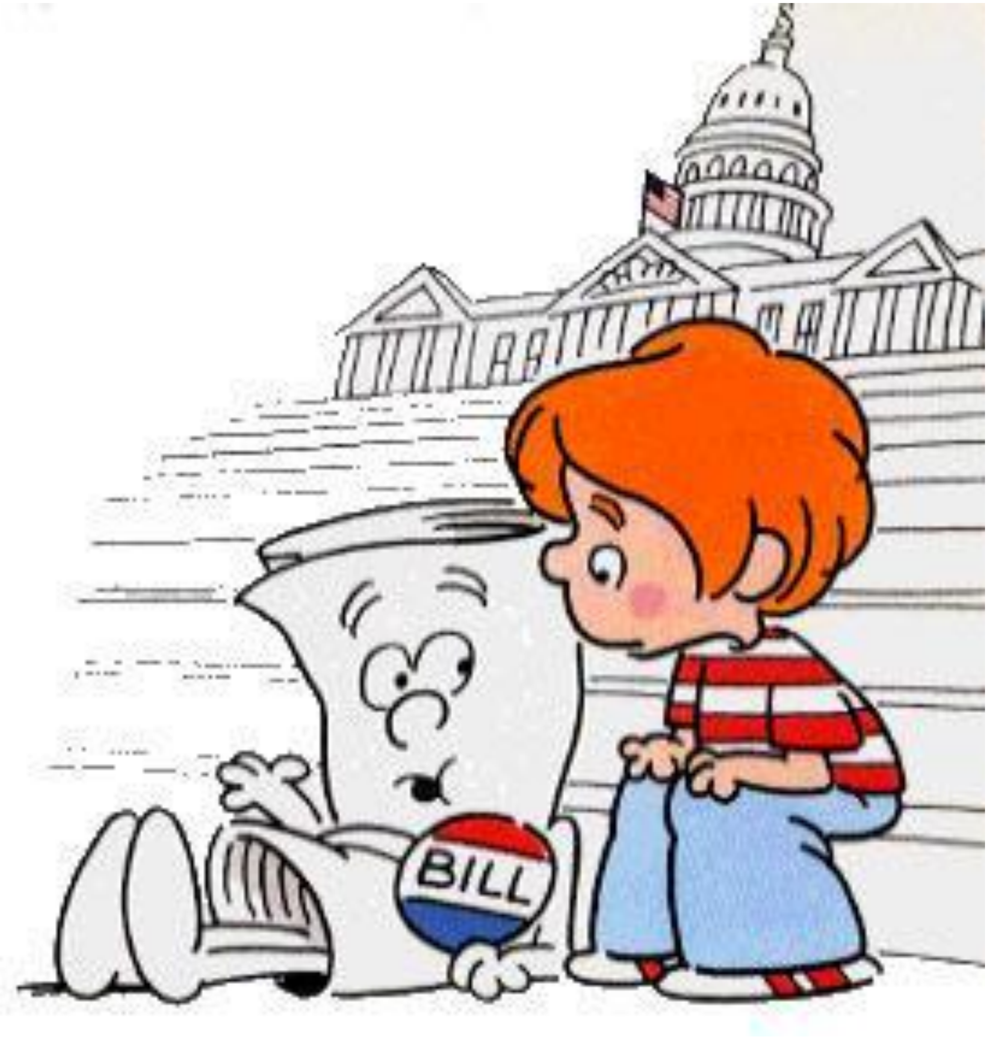
- **Will cover material from the entire course**
  - Focuses primarily on the material from the second half
  - But we’ve been building on the earlier stuff, so expect to still see concepts and material from the first half
  - Best way to get a feel for it is to look at past exams (that’s what I’m doing!)

Course Evaluations

- **Really matters, and 90-100% response rate makes them much more useful than 60%**
  - Have to guess what sampling bias is for “missing 40%”
- **We really do take them seriously and use them to improve!**
  - This is my first time teaching, so I *especially* need your feedback!
  - I’ve been sticking to mostly what has been done before, but we need you all to help us figure out how to make it better and more useful!
- **Evaluations close this Sunday, June 5th at 11:59pm**
  - I don’t know why it’s so early, but please please please do it!
  - I still can’t see them until after I submit grades. ☺
    - But you can’t see the final until after… ;)

I’m Just a Bill (I mean, *Program*)

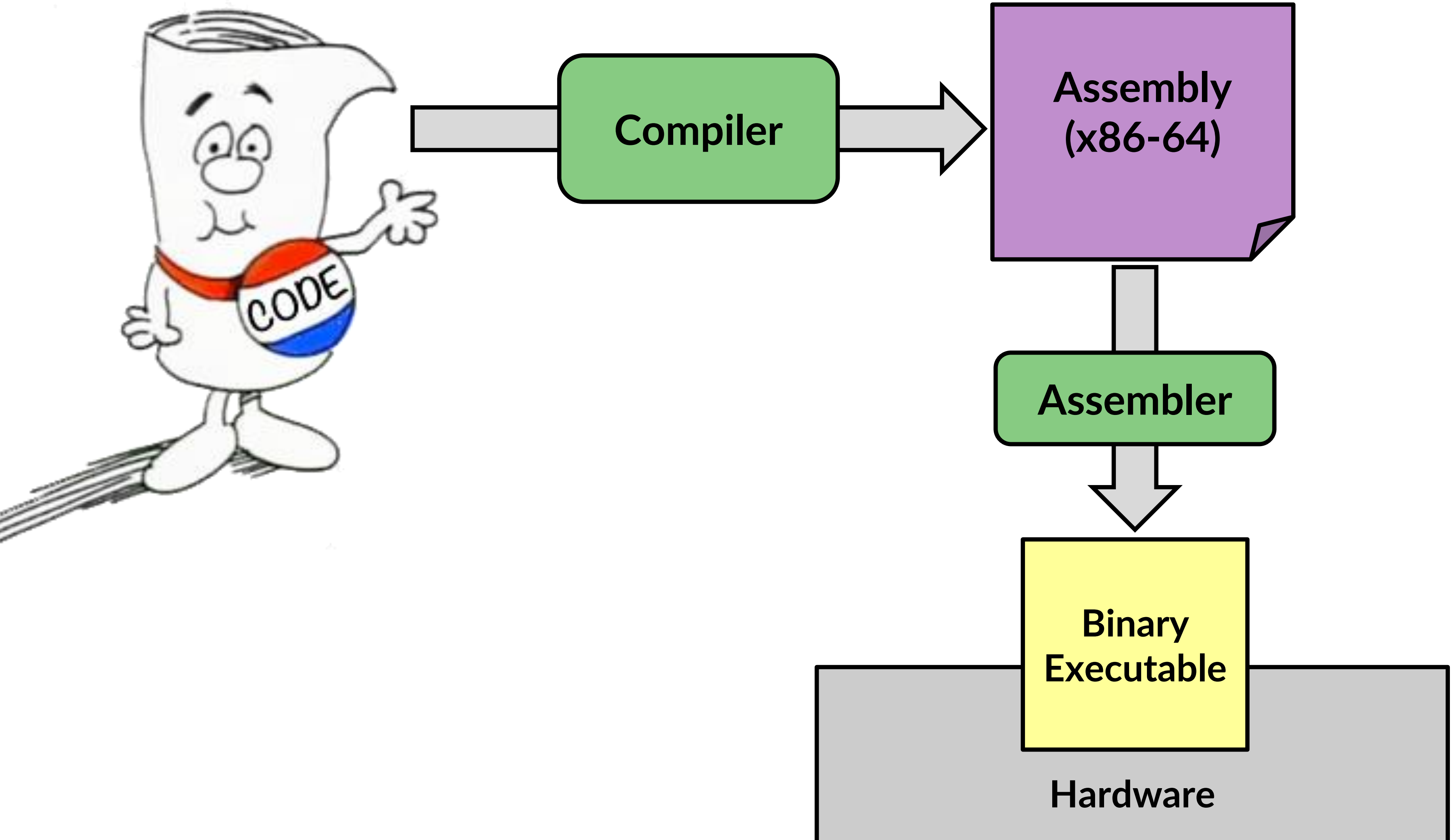
How Code Becomes A Program.



Schoolhouse Rock!, 1976, “I’m Just a Bill”, written by Dave Frishberg

How Code Becomes A Program.

Source code
in high-level language



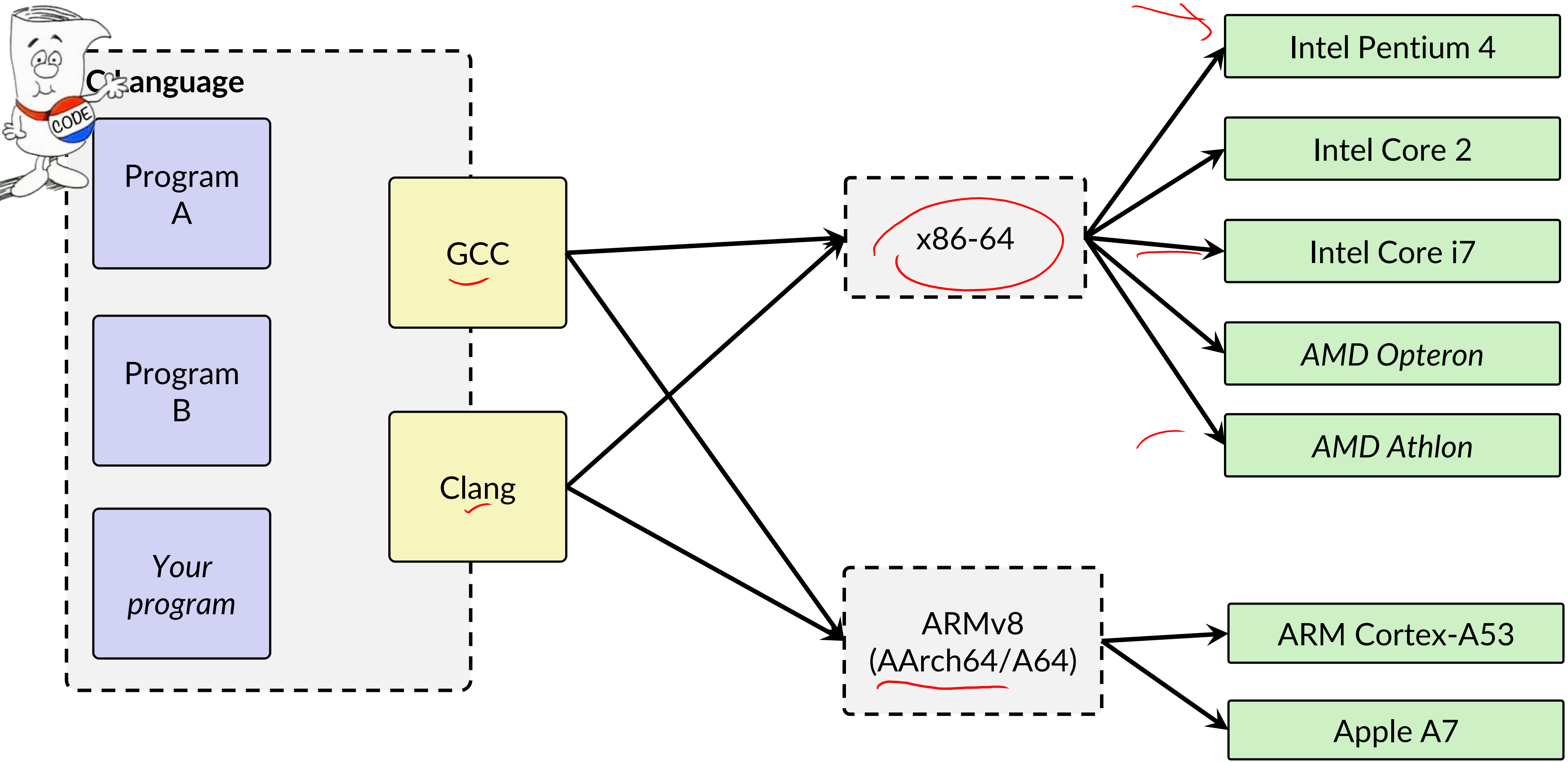
Instruction Set Architecture

Source code
Different applications or algorithms

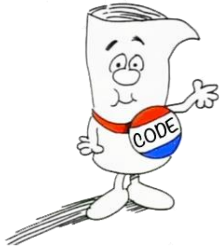
Compiler
Perform optimizations, generate instructions

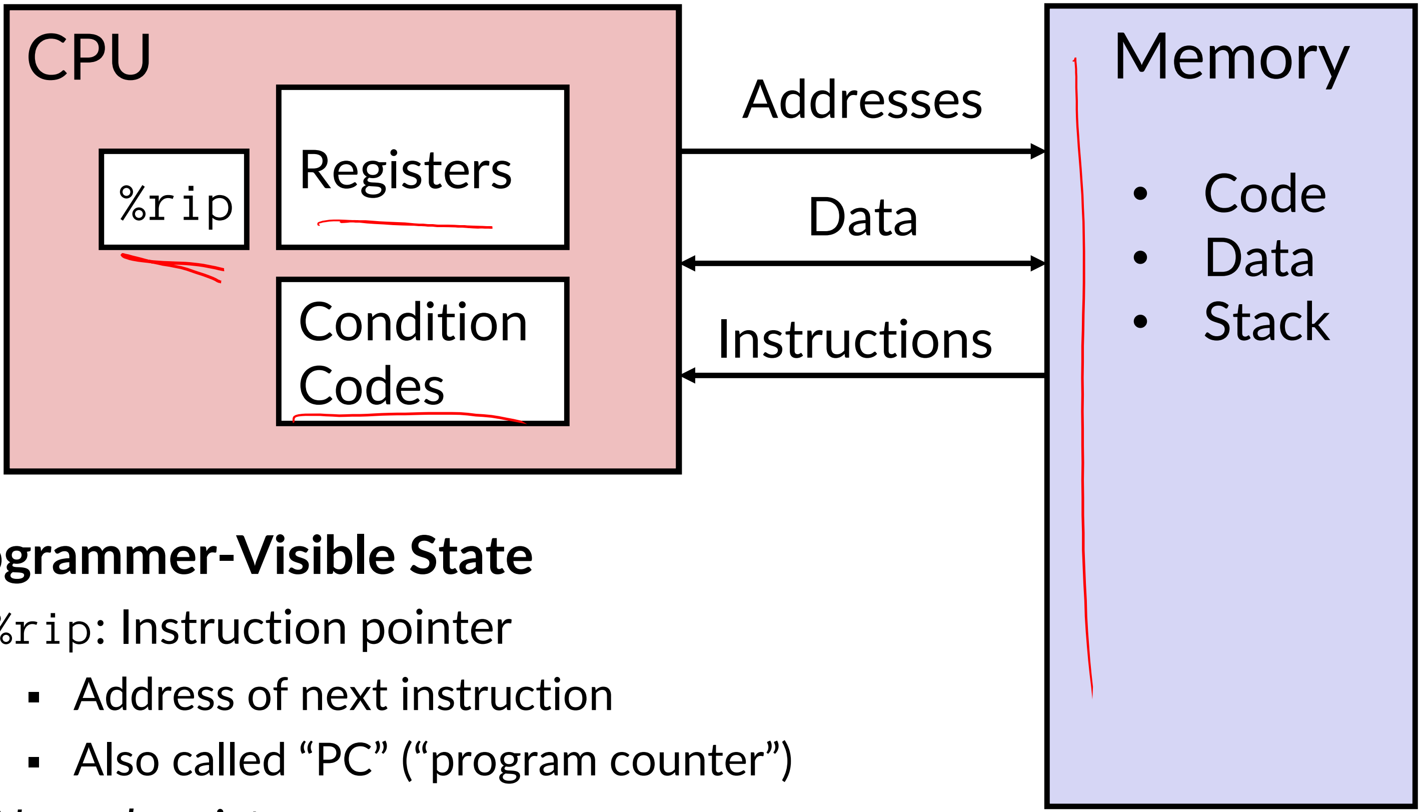
Architecture
Instruction set

Hardware
Different implementations



Assembly Programmer’s View

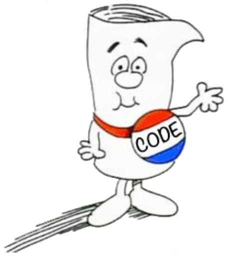


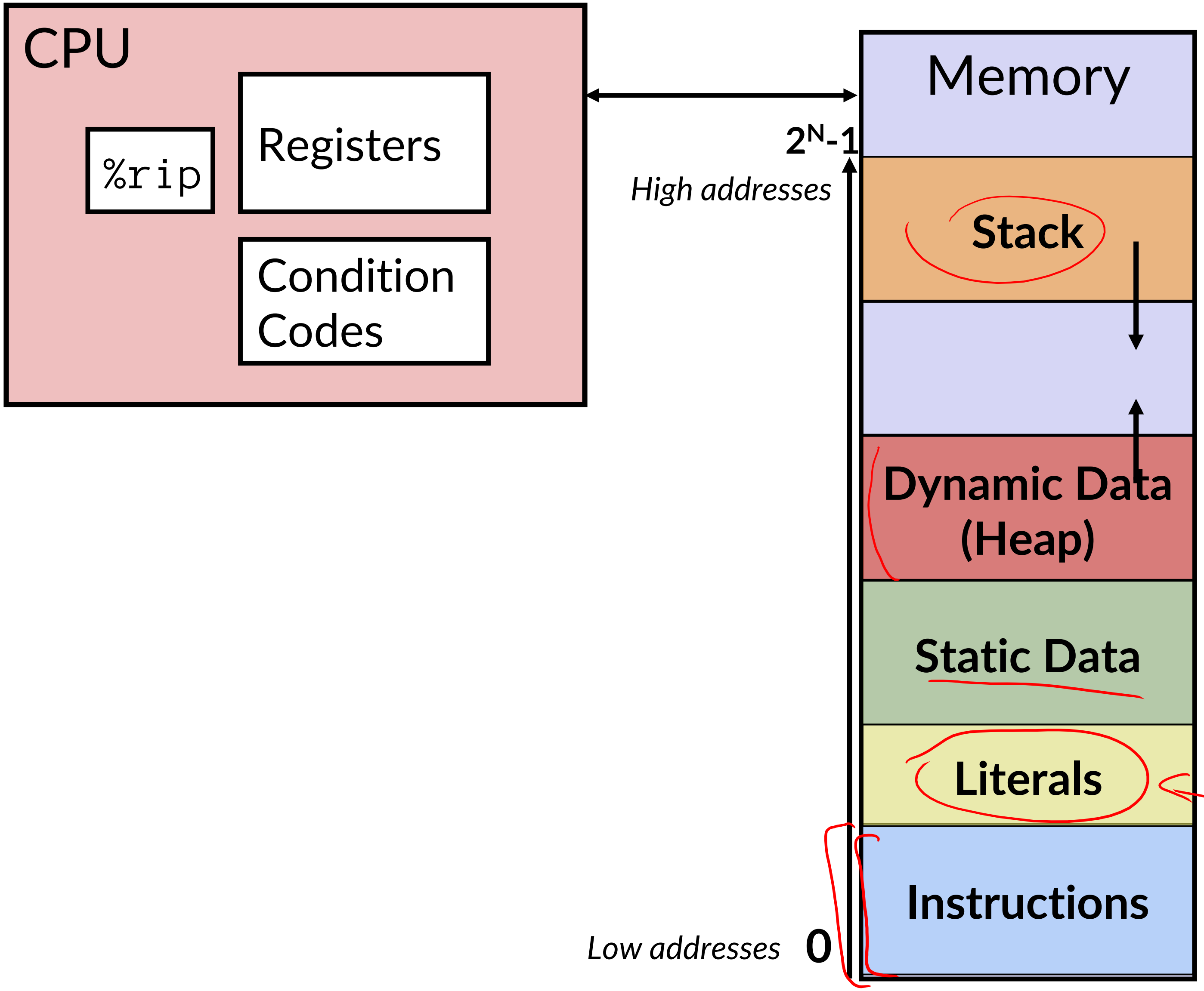


- **Programmer-Visible State**
  - `%rip`: Instruction pointer
    - Address of next instruction
    - Also called “PC” (“program counter”)
  - *Named* registers
    - Heavily used program data
    - Together, called “register file”
  - Condition codes
    - Used for conditional branching

- Memory
  - Byte addressable array
  - 2^{64} *virtual* addresses (18 exabytes)
  - *Private, all to you yourself…*

Program’s View





CPU

%rip

Registers

Condition Codes

Memory

2^N-1

High addresses

Stack

Dynamic Data (Heap)

Static Data

Literals

Instructions

Low addresses 0

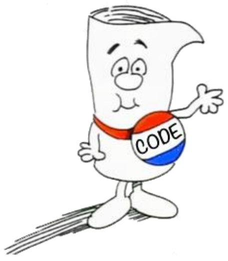
local variables; procedure context

variables allocated with *new* or *malloc*

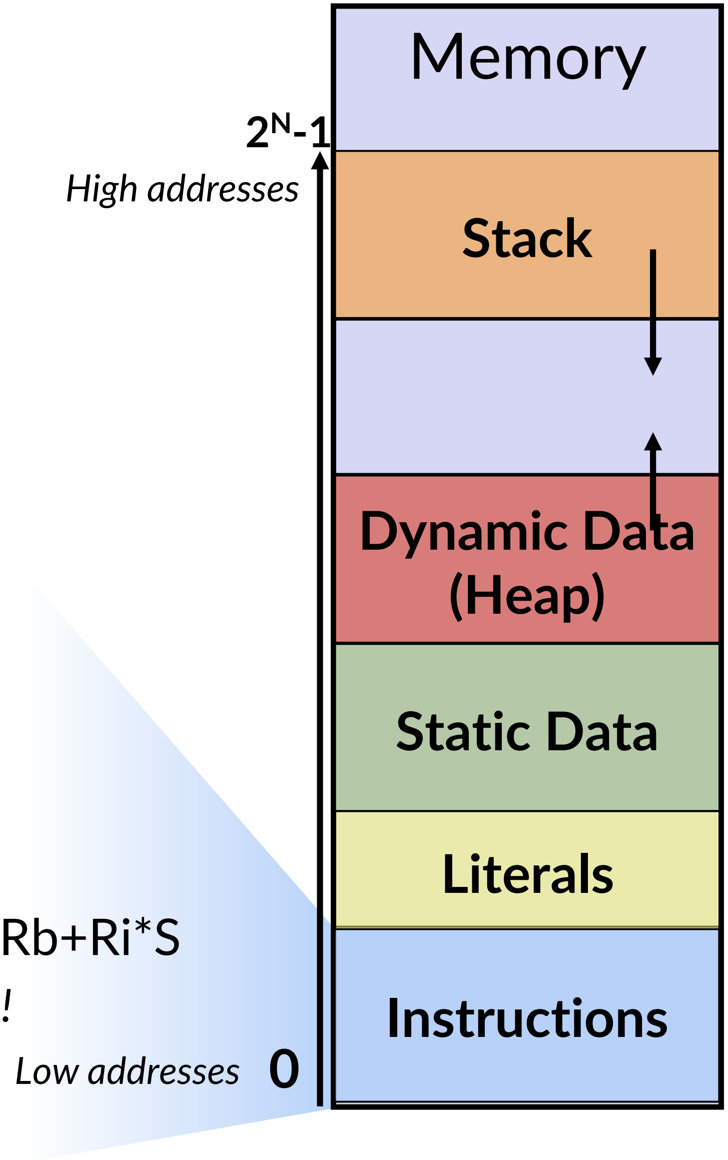
static variables (global variables in C)

Large constants (e.g., “example”)

Program's View



- **Instructions**
  - Data movement
    - mov, movz, movz
    - push, pop
  - Arithmetic
    - add, sub, imul
  - Control flow
    - cmp, test
    - jmp, je, jgt, ...
    - call, ret
- **Operand types**
  - Literal: $8
  - Register: %rdi, %al
  - Memory: D(Rb,Ri,S) = D+Rb+Ri*S
    - lea: *not a memory access!*



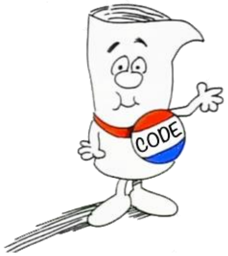
local variables; procedure context

variables allocated with *new* or *malloc*

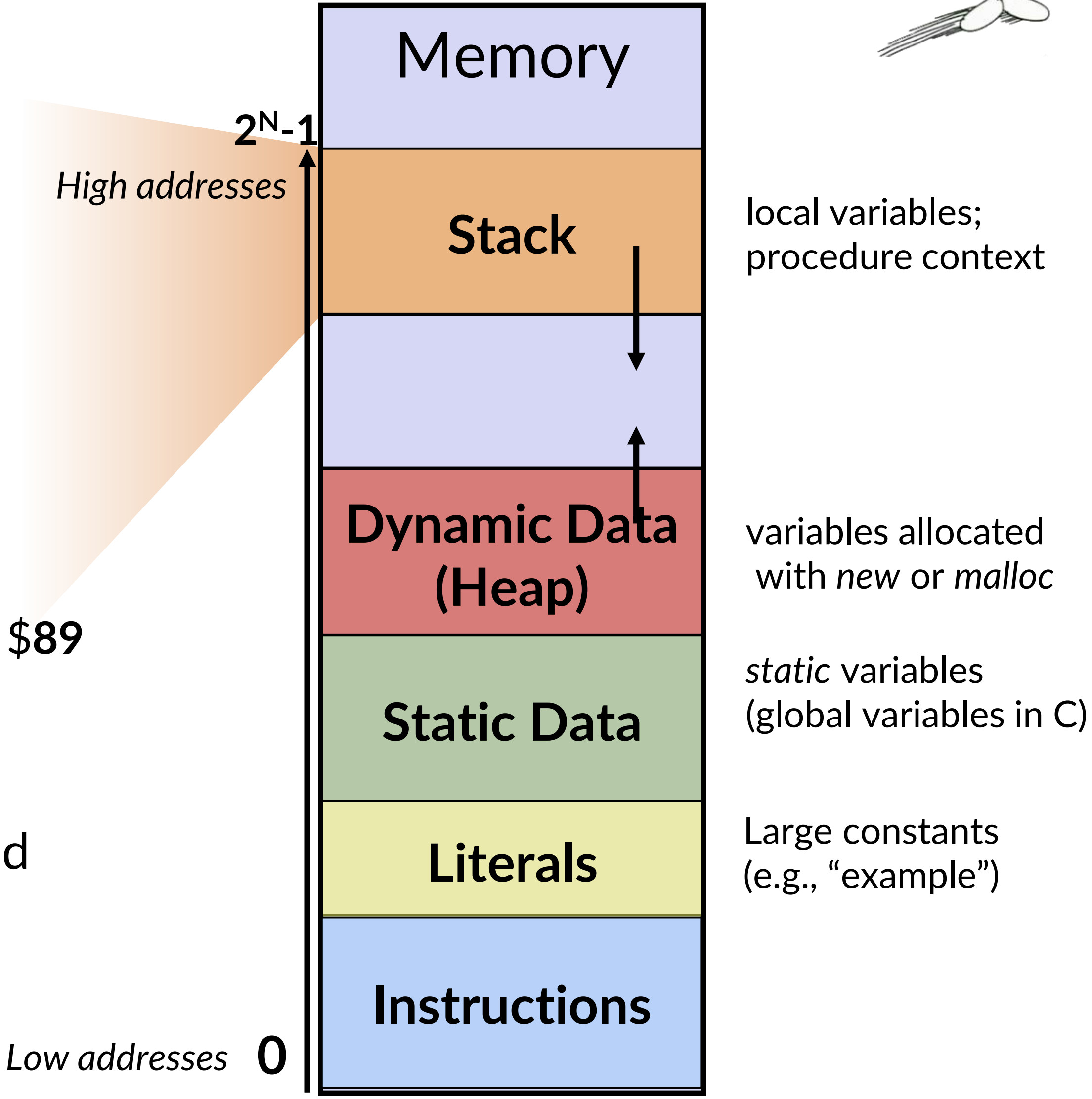
static variables (global variables in C)

Large constants (e.g., "example")

Program's View



- **Procedures**
  - Essential abstraction
  - Recursion…
- **Stack discipline**
  - Stack frame per call
  - Local variables
- **Calling convention**
  - How to pass arguments
    - **Diane's Silk Dress Costs $89**
  - How to return data
  - Return address
  - Caller-saved / callee-saved registers



local variables; procedure context

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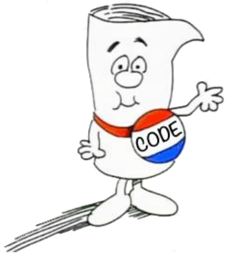
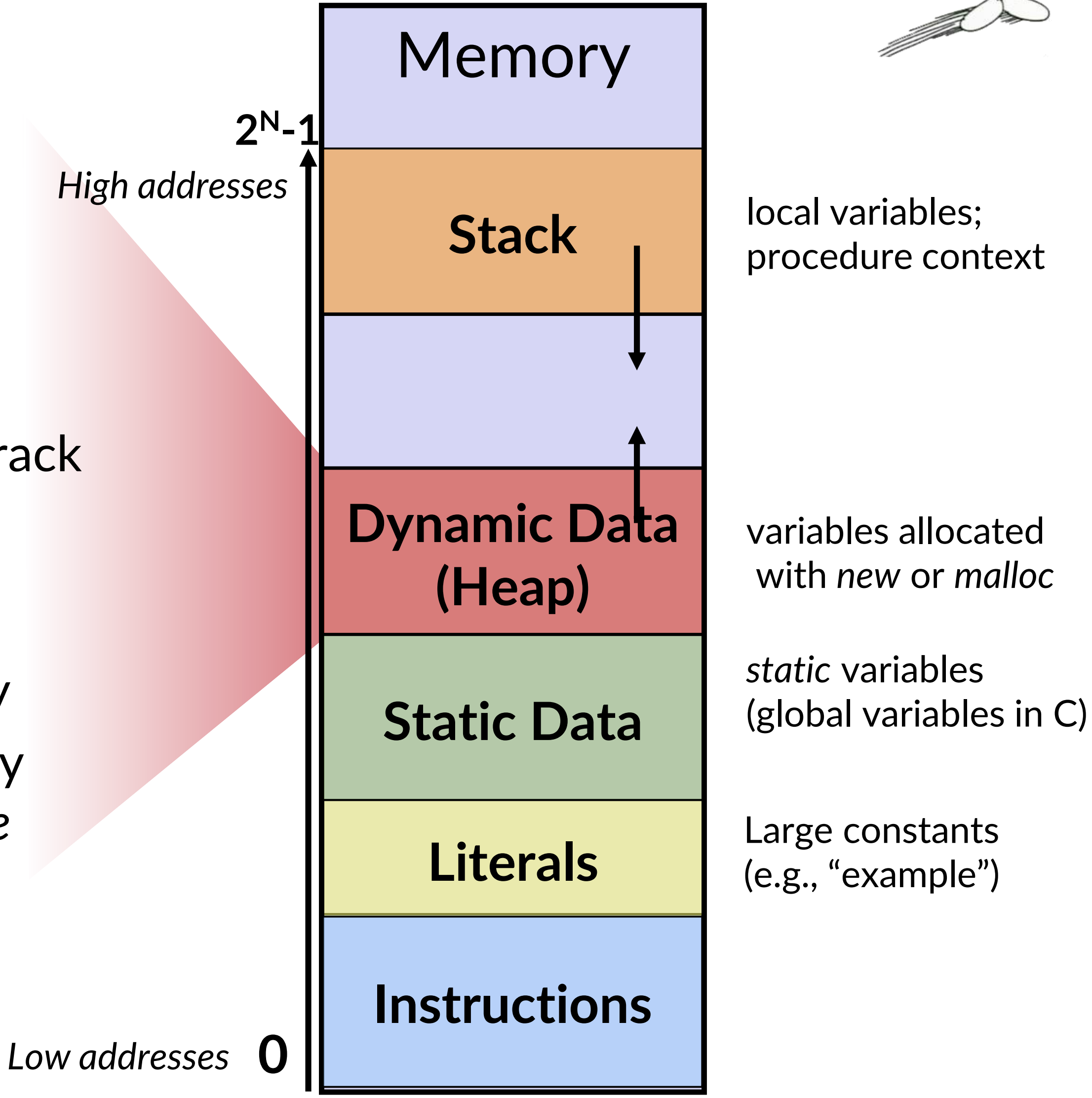
Large constants (e.g., "example")

Program's View



- **Heap data**
  - Variable size
  - Variable lifetime
- **Allocator**
  - Balance *throughput* and *memory utilization*
  - Data structures to keep track of free blocks.
- **Garbage collection**
  - Must always free memory
  - Garbage collectors help by finding anything *reachable*
  - Failing to free results in *memory leaks.*



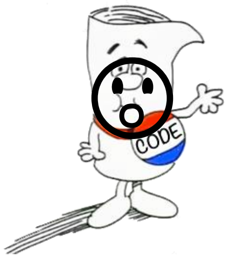
local variables; procedure context

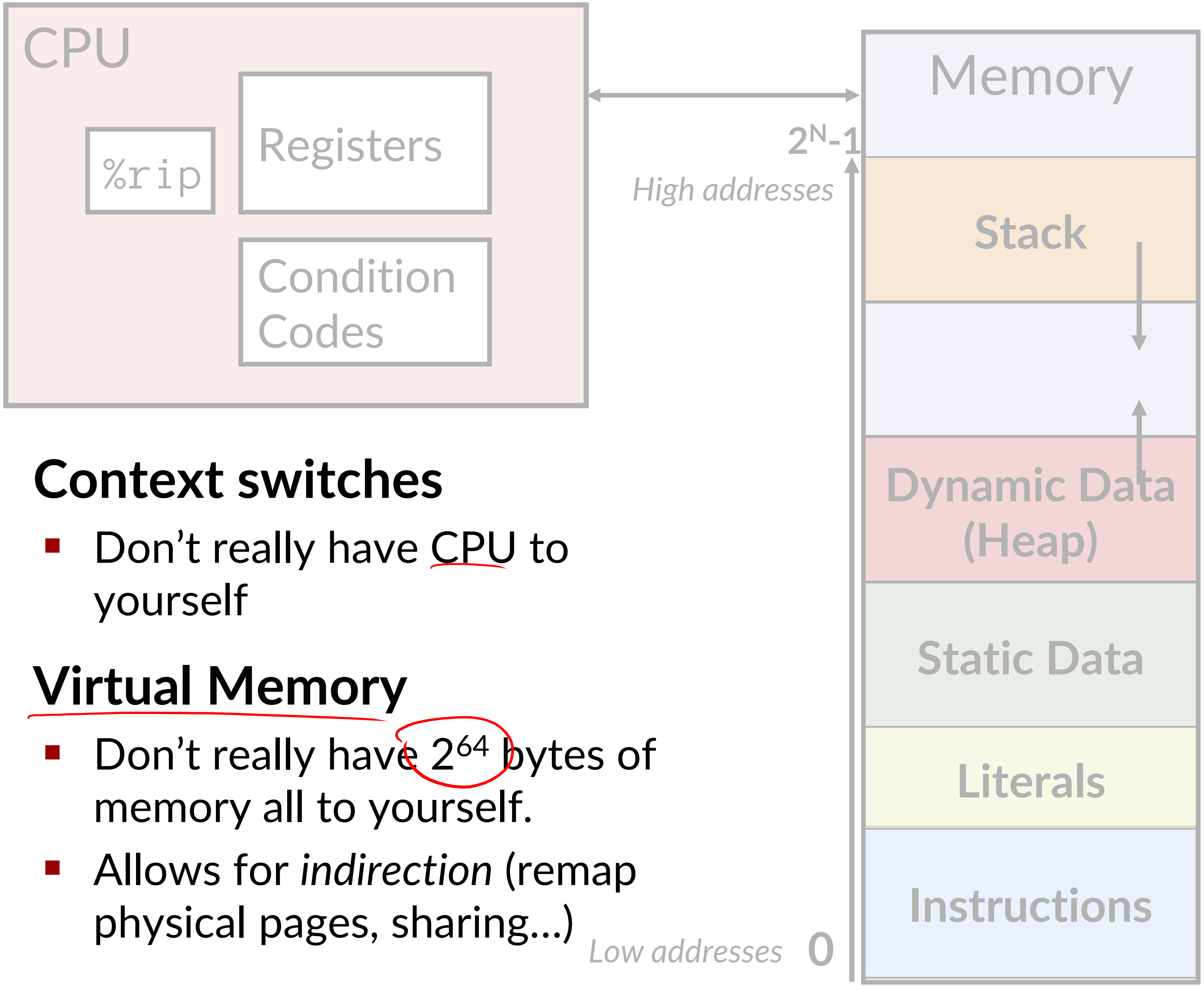
variables allocated with *new* or *malloc*

static variables (global variables in C)

Large constants (e.g., "example")

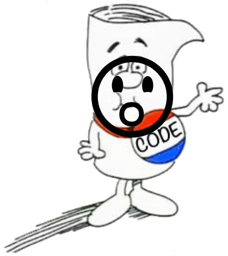
But remember… it's all an *illusion!*

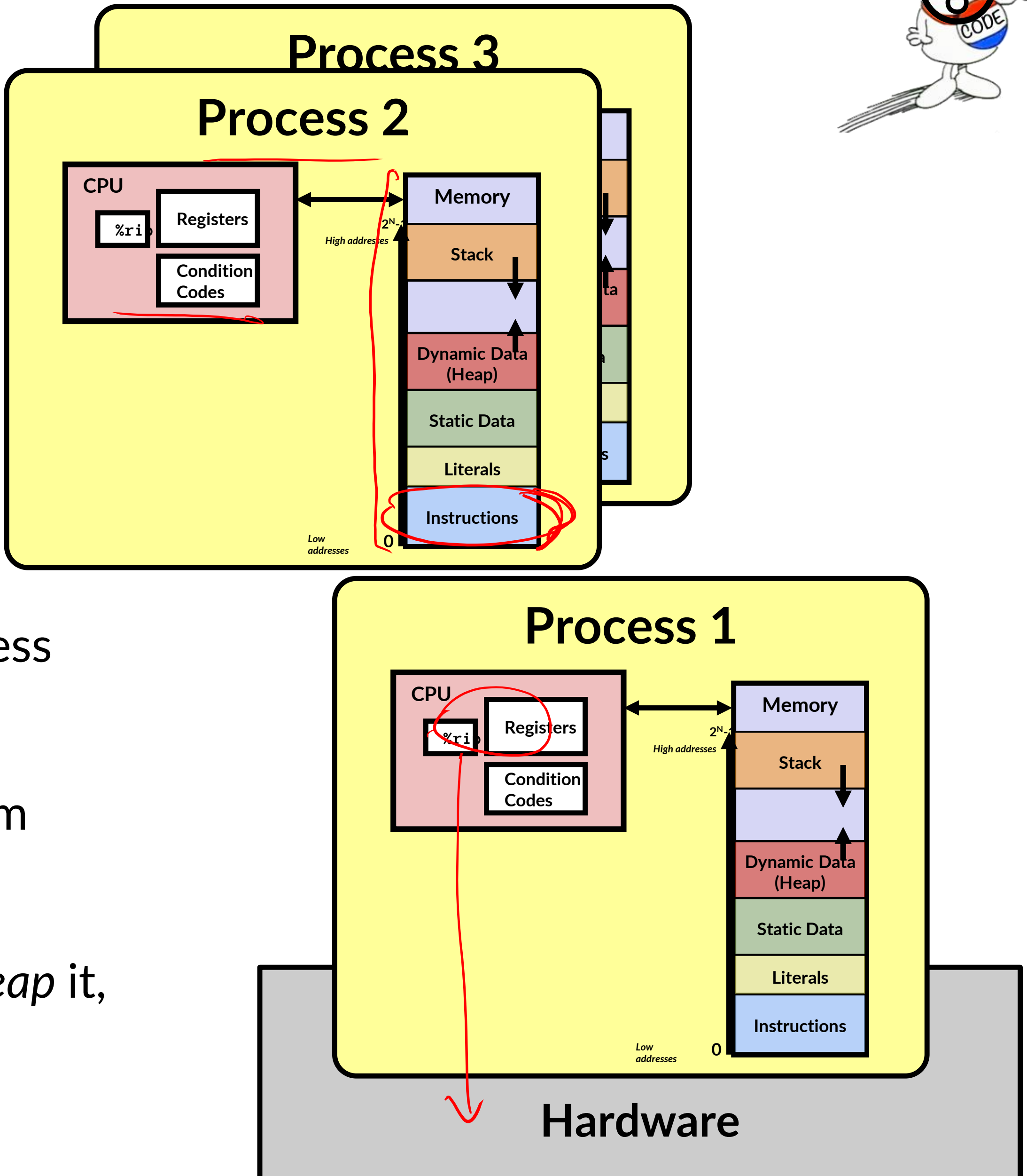



CPU
%rip
Registers
Condition Codes
Memory
2^N-1
High addresses
Stack
Dynamic Data (Heap)
Static Data
Literals
Instructions
Low addresses
0
local variables; procedure context
variables allocated with *new* or *malloc*
static variables (global variables in C)
Large constants (e.g., "example")

- **Context switches**
  - Don't really have CPU to yourself
- **Virtual Memory**
  - Don't really have 2^{64} bytes of memory all to yourself.
  - Allows for *indirection* (remap physical pages, sharing…)

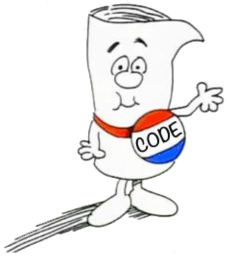
But remember… it's all an *illusion!*

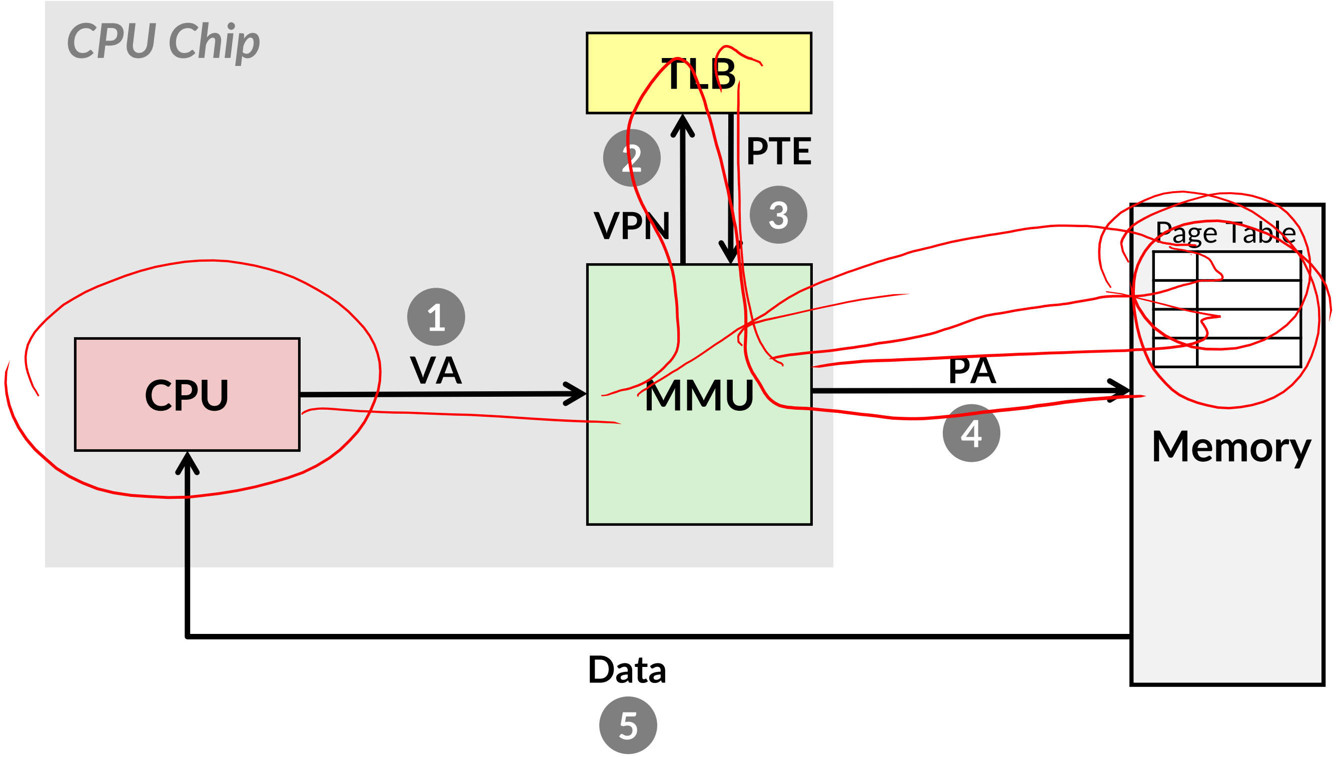




- **Fork**
  - Creates copy of the process
- **Exec**
  - Replace with new program
- **Wait**
  - Wait for child to die (to *reap* it, and prevent *zombies*)

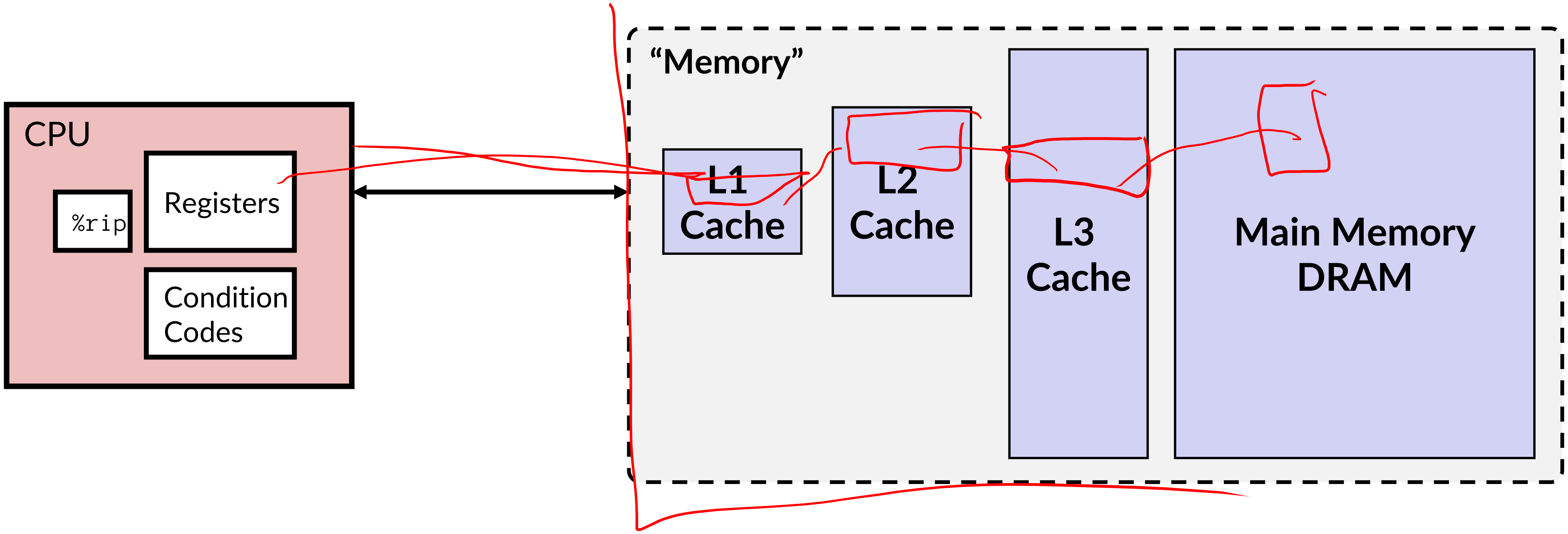
Virtual Memory



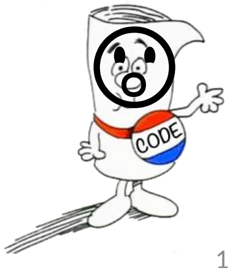


- **Address Translation**
  - Every memory access must first be converted from virtual to physical!!
  - *Indirection:* just change the address mapping when switching processes!
  - Luckily, TLB (and page size) makes it pretty fast.

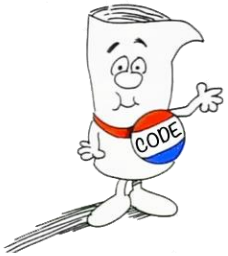
But memory is also a lie!



- ***Illusion* of one flat array of bytes**
  - But *caches* invisibly make accesses (*to physical addresses*) faster!
  - Locality: temporal vs spatial
- **Caches**
  - Need to be fast, so **direct-mapped/indexed** (*sets*)
  - Need to be flexible, so **associative** (*ways*)



C: The Low Level-High Level Language



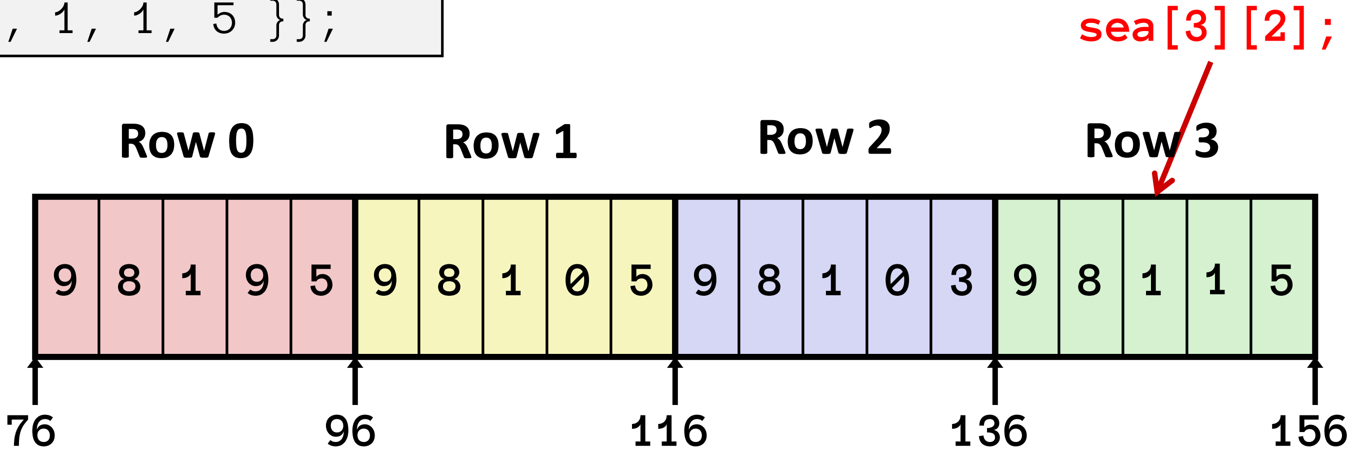
- **Along the way, we learned about C data types…**
- **Primitive types: fixed sizes & alignments**
  - Endianness: **only applies to memory;** is the first byte the least significant (little endian) or most (big)?
- **Pointers: addresses with a type**
  - Always point at the beginning of the int*
- **Arrays**
  - Contiguous chunks of memory
  - 2D arrays = still one continuous chunk
  - Nested arrays: array of pointers to other arrays
  - **Buffer Overflow:** No array bounds checks in C!!!
    - How do we protect against them?
- **Structs**

Nested Array Example

```
typedef int zip_dig[5];
```

```
zip_dig sea[4] =
  {{ 9, 8, 1, 9, 5 },
   { 9, 8, 1, 0, 5 },
   { 9, 8, 1, 0, 3 },
   { 9, 8, 1, 1, 5 }};
```

Remember, `T A[N]` is an array with elements of type `T`, with length `N`



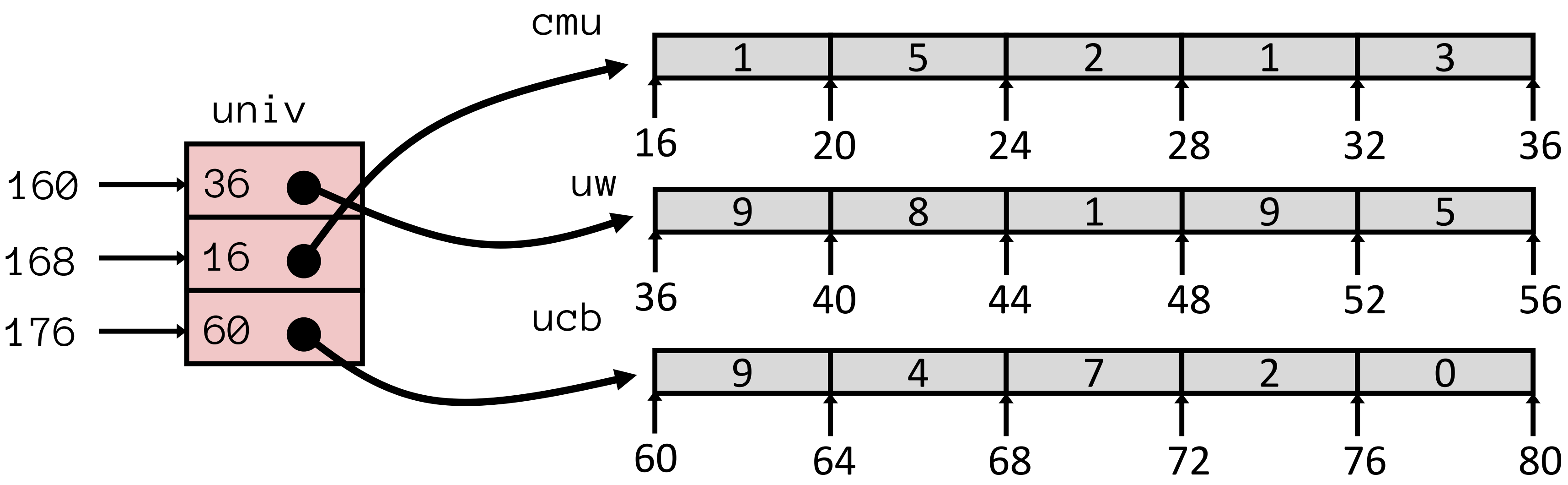
- "Row-major" ordering of all elements
- Elements in the same row are contiguous
- Guaranteed (in C)

Multi-Level Array Example

```
int cmu[5] = { 1, 5, 2, 1, 3 };
int  uw[5] = { 9, 8, 1, 9, 5 };
int ucb[5] = { 9, 4, 7, 2, 0 };
```

```
int* univ[3] = {uw, cmu, ucb};
```

- Variable `univ` denotes array of 3 elements
- Each element is a pointer
  - 8 bytes each
- Each pointer points to array of `int`s

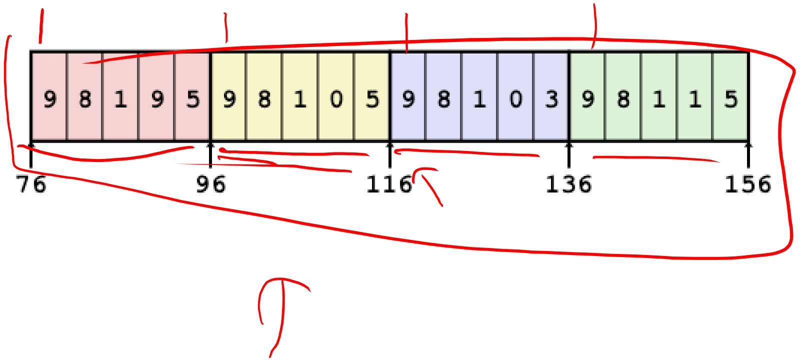


Note: this is how Java represents multi-dimensional arrays.

Array Element Accesses

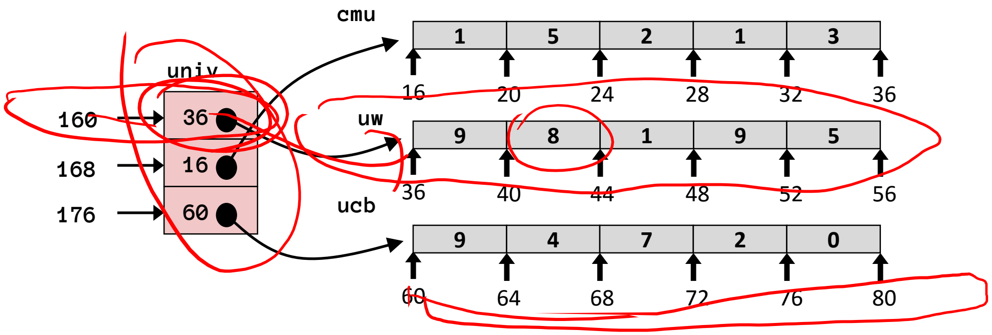
Nested array

```
int get_sea_digit
  (int index, int digit)
{
  return sea[index][digit];
}
```



Multi-level array

```
int get_univ_digit
  (int index, int digit)
{
  return univ[index][digit];
}
```

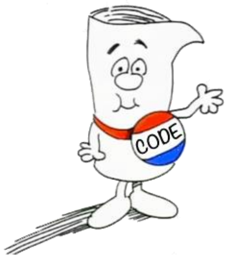


Access *looks* the same, but it isn't:

Mem[sea+20*index+4*digit]

Mem[Mem[univ+8*index]+4*digit]

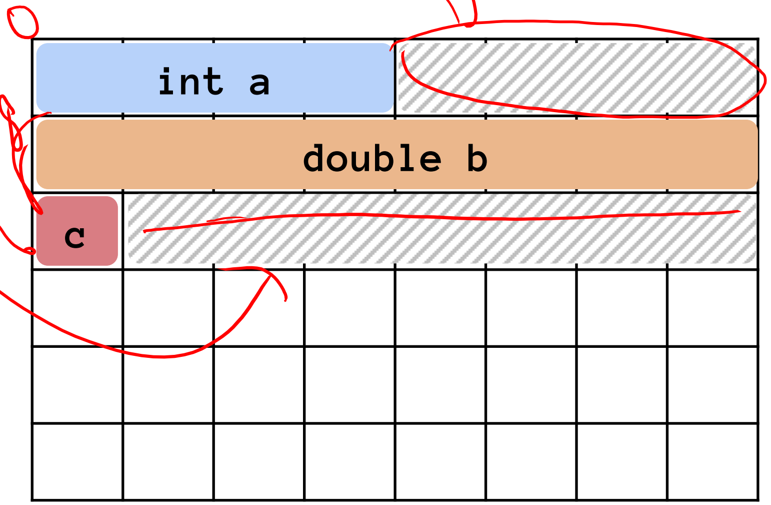
C: The Low Level-High Level Language



- **Structs**
  - Each *primitive element* must be aligned
  - **Overall struct must be aligned to alignment of largest primitive member, size must be multiple of that as well.**
  - Fragmentation
    - **Internal fragmentation:** space between members
    - **External fragmentation:** space after last member, *inside the struct*

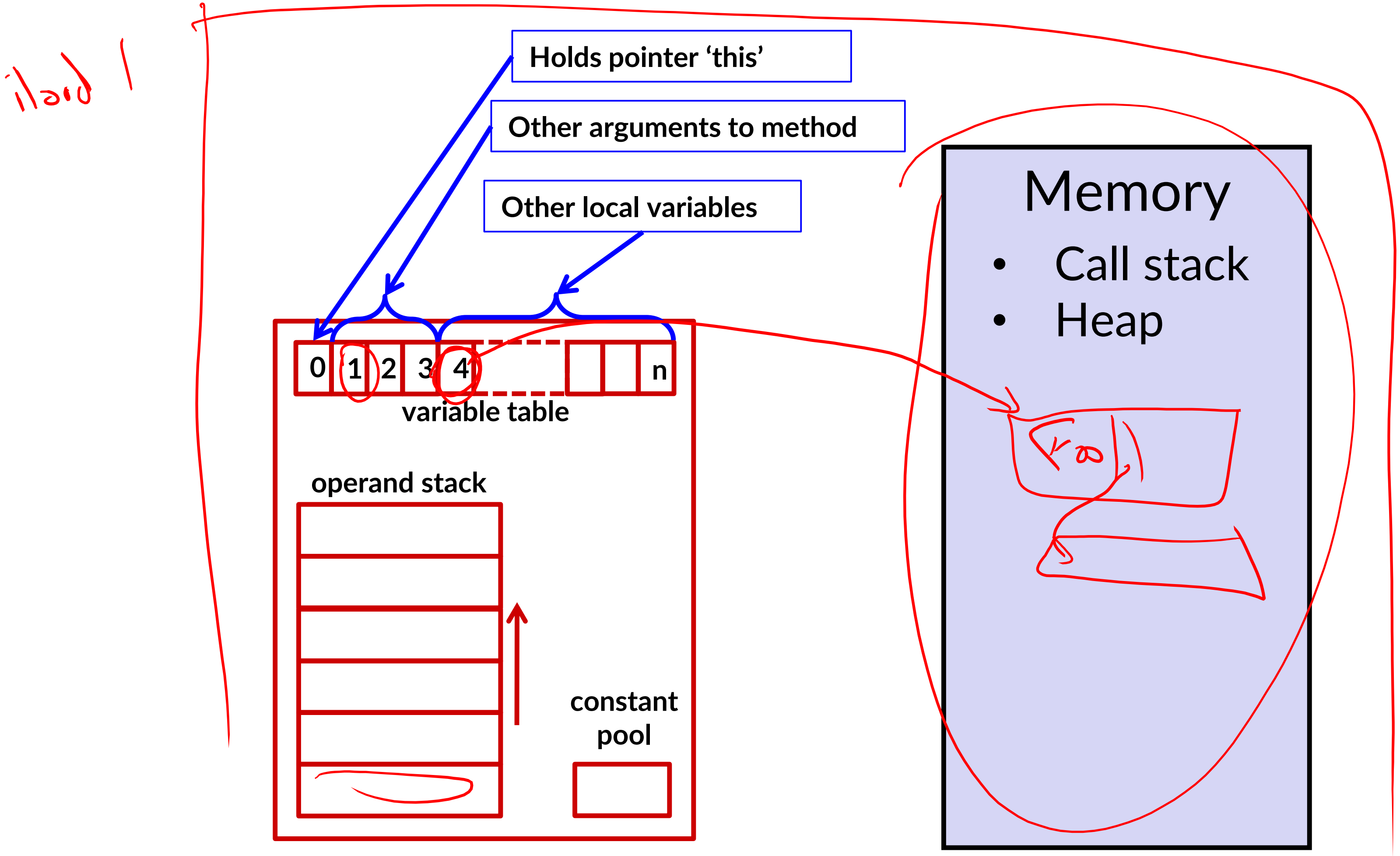
```
struct Foo {
  int a;
  double b;
  char c;
};

sizeof(Foo) == 24
```



Java: A High Level Language

- **Java Virtual Machine is an *interpreter***
  - Just need to port the JVM to your machine, then it can run your program
  - It has its own "Assembly Program's View"



Victory Lap

A victory lap is an extra trip around the track

- By the exhausted victors (that's us) ☺

Review course goals

- Slides from Lecture 1
- What makes CSE351 special

Next 7 slides copied without change from Lecture 1

They should make much more sense now!

Welcome!

10 weeks to see the key abstractions "under the hood" to describe "what really happens" when a program runs

- How is it that "everything is 1s and 0s"?
- Where does all the data get stored and how do you find it?
- How can more than one program run at once?
- What happens to a Java or C program before the hardware can execute it?
- What is *The* Stack and *The* Heap?
- And much, much, much more…

An *introduction* that will:

- Profoundly change/augment your view of computers and programs
- Connect your source code down to the hardware
- Leave you impressed that computers ever work.

C/Java, assembly, and machine code

```
if (x != 0) y = (y+z)/x;
```

```
    cmpl   $0, -4(%ebp)
    je     .L2
    movl   -12(%ebp), %eax
    movl   -8(%ebp), %edx
    leal   (%edx, %eax), %eax
    movl   %eax, %edx
    sarl   $31, %edx
    idivl  -4(%ebp)
    movl   %eax, -8(%ebp)
.L2:
```

```
1000001101111110000100100000011100000000000
0111010000011000
100010110100010000100100000010100
10001011010001100010010100010100
1000110100000010000000010
1000100111000010
1100000111111010000011111
11110111011111000010010000011100
10001001010001000010010000011000
```

- **The three program fragments are equivalent**
- **You'd rather write C! (more human-friendly)**
- **Hardware likes bit strings!**
  - Everything is voltages
  - The machine instructions are actually much shorter than the number of bits we would need to represent the characters in the assembly language

The Big Theme: Abstractions and Interfaces

- **Computing is about abstractions**
  - (but we can't forget reality)
- **What are the abstractions that we use?**
- **What do you need to know about them?**
  - When do they break down and you have to peek under the hood?
  - What bugs can they cause and how do you find them?
- **How does the hardware (0s and 1s, processor executing instructions) relate to the software (C/Java programs)?**
  - Become a better programmer and begin to understand the important concepts that have evolved in building ever more complex computer systems

Little Theme 1: Representation

- **All digital systems represent everything as 0s and 1s**
  - The 0 and 1 are really two different voltage ranges in the wires
  - Or magnetic positions on a disc, or hole depths on a DVD, or even *DNA*…
- **“Everything” includes:**
  - Numbers – integers and floating point
  - Characters – the building blocks of strings
  - Instructions – the directives to the CPU that make up a program
  - Pointers – addresses of data objects stored away in memory
- **These encodings are stored throughout a computer system**
  - In registers, caches, memories, disks, etc.
- **They all need addresses**
  - A way to find them
  - Find a new place to put a new item
  - Reclaim the place in memory when data no longer needed

Little Theme 2: Translation

- There is a **big gap** between how we think about programs and data and the 0s and 1s of computers
- Need **languages** to describe what we mean
- These languages need to be **translated** one level at a time
- We know **Java** as a programming language
  - Have to work our way down to the 0s and 1s of computers
  - Try not to lose anything in translation!
  - We'll encounter Java byte-codes, C language, assembly language, and machine code (for the X86 family of CPU architectures)
    - Not in that order, but will all connect by the last lecture!!!

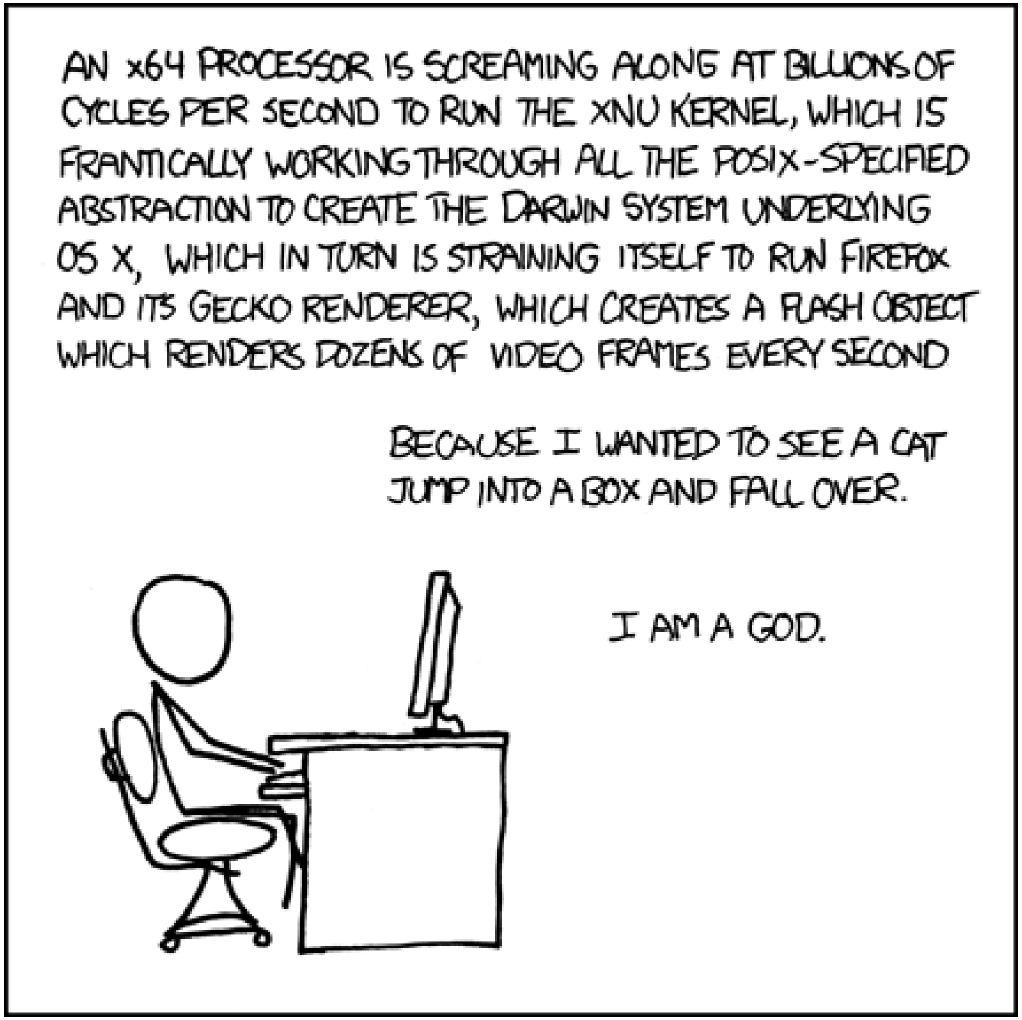
Little Theme 3: Control Flow

- **How do computers orchestrate everything they are doing?**
- **Within one program:**
  - How do we implement if/else, loops, switches?
  - What do we have to keep track of when we call a procedure, and then another, and then another, and so on?
  - How do we know what to do upon "return"?
- **Across programs and operating systems:**
  - Multiple user programs
  - Operating system has to orchestrate them all
    - Each gets a share of computing cycles
    - They may need to share system resources (memory, I/O, disks)
  - Yielding and taking control of the processor
    - Voluntary or "by force"?

Course Perspective

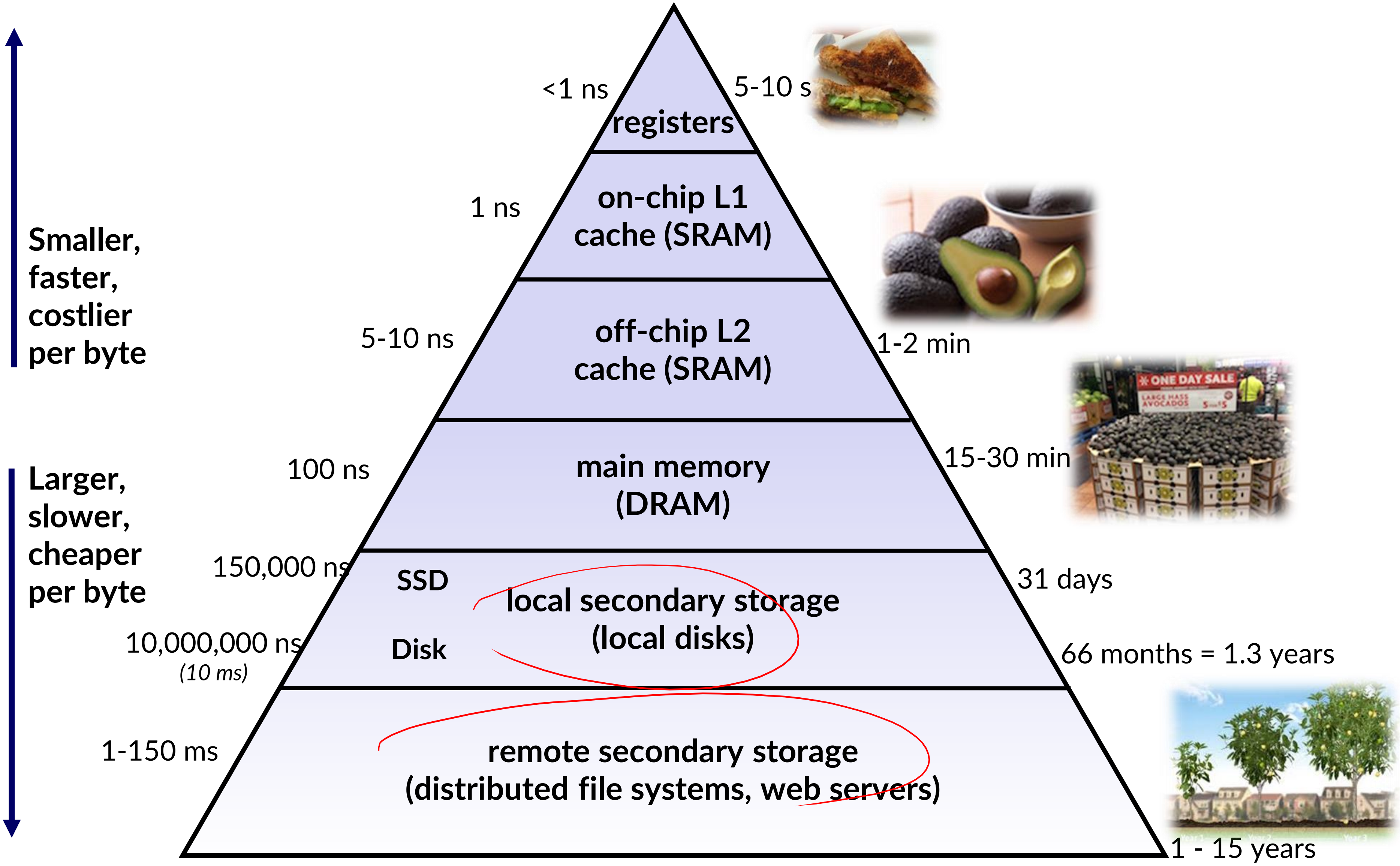
- **CSE351 will make you a better programmer**
  - Purpose is to show how software really works
  - Understanding the underlying system makes you more effective
    - Better debugging
    - Better basis for evaluating performance
    - How multiple activities work in concert (e.g., OS and user programs)
  - Not just a course for hardware enthusiasts!
    - What **every** CSE major needs to know (plus many more details)
    - See many **patterns** that come up over and over in computing (like caching)
  - Like other 300-level courses,
    “stuff everybody learns and uses and forgets not knowing”
- **CSE351 presents a world-view that will empower you**
  - The intellectual tools and software tools to understand the trillions+ of 1s and 0s that are “flying around” when your program runs

HTTP://XKCD.COM/676/


AN x64 PROCESSOR IS SCREAMING ALONG AT BILLIONS OF CYCLES PER SECOND TO RUN THE XNU KERNEL, WHICH IS FRANTICALLY WORKING THROUGH ALL THE POSIX-SPECIFIED ABSTRACTION TO CREATE THE DARWIN SYSTEM UNDERLYING OS X, WHICH IN TURN IS STRAINING ITSELF TO RUN FIREFOX AND ITS GECKO RENDERER, WHICH CREATES A FLASH OBJECT WHICH RENDERS DOZENS OF VIDEO FRAMES EVERY SECOND
BECAUSE I WANTED TO SEE A CAT JUMP INTO A BOX AND FALL OVER.
I AM A GOD.

And of course don’t forget…

Memory Hierarchy



Smaller, faster, costlier per byte

Larger, slower, cheaper per byte

<1 ns — **registers** — 5-10 s

1 ns — **on-chip L1 cache (SRAM)**

5-10 ns — **off-chip L2 cache (SRAM)** — 1-2 min

100 ns — **main memory (DRAM)** — 15-30 min

150,000 ns — **SSD** — 31 days

10,000,000 ns *(10 ms)* — **Disk** — 66 months = 1.3 years

local secondary storage (local disks)

1-150 ms — **remote secondary storage (distributed file systems, web servers)** — 1 - 15 years

Thanks for a great quarter!

- **Thanks to your awesome TAs!**
  - Everything that went smoothly was probably because of them!
  - Anything that didn’t was because I didn’t ask them how to do it. ;)
- **Thanks for laughing occasionally at stupid jokes!**
- **Don’t be a stranger!**
  - *(although fingers crossed, I’ll graduate one of these days and you’ll have to find me somewhere else)*