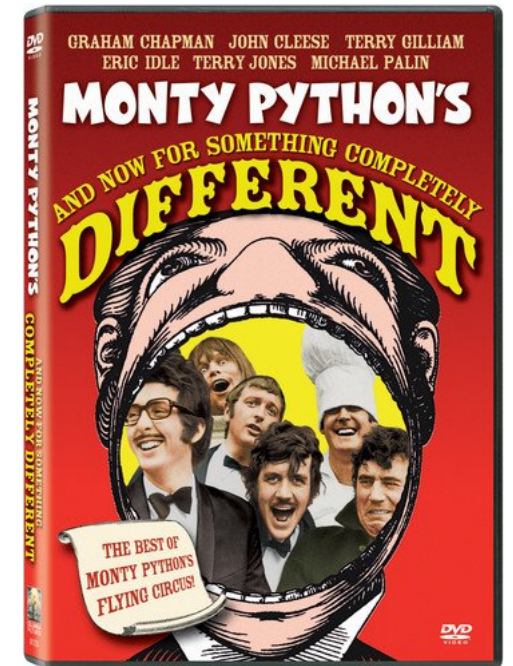


# COS 217: Introduction to Programming Systems

## Assembly Language

### Part 1

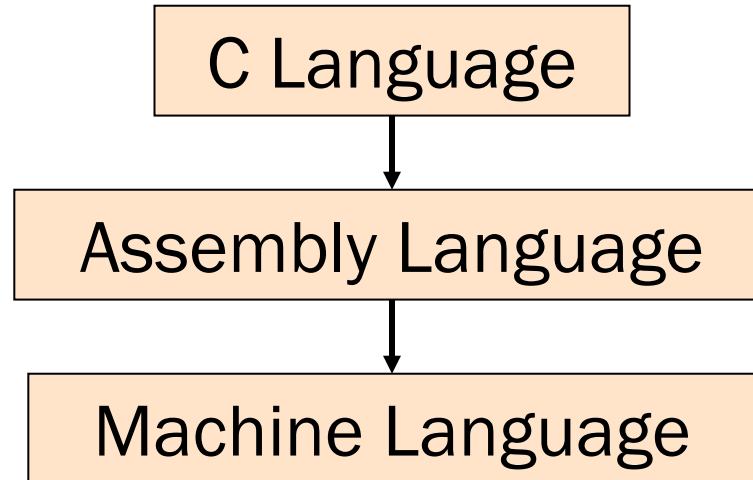


PRINCETON UNIVERSITY



# Context of this Lecture

“Under the hood”





# Lectures vs. Precepts

Approach to studying assembly language:

Lectures	Precepts
Study partial programs	Study complete programs
Begin with simple constructs; proceed to complex ones	Begin with small programs; proceed to large ones
Emphasis on reading code	Emphasis on writing code

# Agenda



## Language Levels

Architecture

Assembly Language: Performing Arithmetic

Assembly Language: Load/Store and Defining Global Data



# High-Level Languages

## Characteristics

- Portable (to varying degrees)
- Complex
  - One statement can do a lot of work – good ratio of functionality to code size
- Human readable
  - Structured: if(), for(), while(), etc.
  - Variable names can hide details of where data is stored (stack, heap, etc.)
  - Type system allows compiler to check usage details without burdening reader

```
int collatz(int n)
{
    int count = 0;
    while (n > 1) {
        count++;
        if (n & 1)
            n = 3 * n + 1;
        else
            n /= 2;
    }
    return count;
}
```



# Machine Languages

## Characteristics

- Not portable (hardware-specific)
- Simple
  - Each instruction does a simple task – poor ratio of functionality to code size
- Not human readable
  - Not structured
  - Requires lots of effort!
  - Requires tool support

0000	0000	0000	0000	0000	0000	0000	0000
0000	0000	0000	0000	0000	0000	0000	0000
9222	9120	1121	A120	1121	A121	7211	0000
0000	0001	0002	0003	0004	0005	0006	0007
0008	0009	000A	000B	000C	000D	000E	000F
0000	0000	0000	FE10	FACE	CAFE	ACED	CEDE
1234	5678	9ABC	DEF0	0000	0000	F00D	0000
0000	0000	EEEE	1111	EEEE	1111	0000	0000
B1B2	F1F5	0000	0000	0000	0000	0000	0000



# Assembly Languages

## Characteristics

- Not portable
  - Each assembly language instruction maps to one machine instruction
- Simple
  - Each instruction does a simple task
- **Human readable**  
(In the same sense that Polish is human readable ... if you know Polish.)

```
        mov     w1, 0
loop:   cmp     w0, 1
        ble    endloop
        add    w1, w1, #1
        ands  wzr, w0, #1
        beq   else
        add    w2, w0, w0
        add    w0, w0, w2
        add    w0, w0, 1
        b     endif
else:   asr    w0, w0, 1
endif:
        b     loop
endloop:
```



# Why Learn Assembly Language?

## Knowing assembly language helps you:

- Write faster code
  - In assembly language
  - In a high-level language!
- Write safer code
  - Understanding mechanism of potential security problems helps you avoid them – even in high-level languages
- Understand what’s happening “under the hood”
  - Someone needs to develop future computer systems
  - Maybe that will be you!
- Become more comfortable with levels of abstraction
  - Become a better programmer at all language levels!





# Why Learn ARM Assembly Lang?

## Why learn **ARMv8** (a.k.a. AARCH64 or A64) assembly language?

### Pros

- ARM is the most widely used processor in the world (in your phone, in your Mac (Silicon), in your Chromebook, in Armlab, in internet-of-things devices)
- ARM has a modern and (relatively) elegant instruction set, compared to the expansive but ugly x86-64 instruction set

### Cons

- x86-64 still has a huge presence in desktop/laptop/cloud (for now?)

# Agenda



Language Levels

## **Architecture**

Assembly Language: Performing Arithmetic

Assembly Language: Load/Store and Defining Global Data



# John von Neumann (1903-1957)

## In computing

- Stored program computers
- Cellular automata, self-replication,
- Game theory
- mergesort

## Other interests

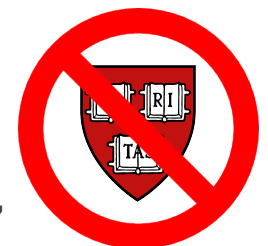
- Mathematics, statistics, game theory
- Nuclear physics

## Princeton connection

- Princeton University & IAS, 1930-1957
- <https://paw.princeton.edu/article/early-history-computing-princeton>

## Known for the “Von Neumann architecture”

- In which (machine-language) programs are just data in memory
- a.k.a. “Princeton architecture” – contrast to the now-mostly-obsolete “Harvard architecture”



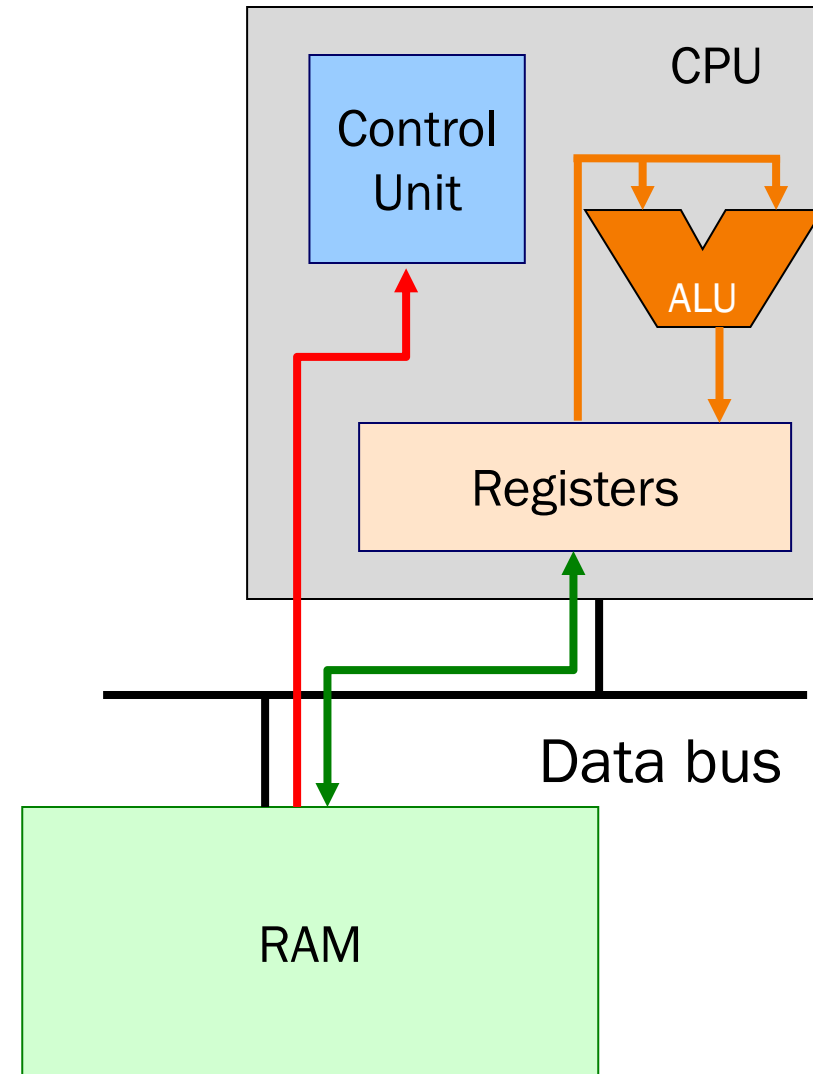


# Von Neumann Architecture

Instructions (encoded within words) are fetched from RAM

Control unit interprets instructions:

- to shuffle data between registers and RAM
- to move data from registers to ALU (arithmetic+logic unit) where operations are performed





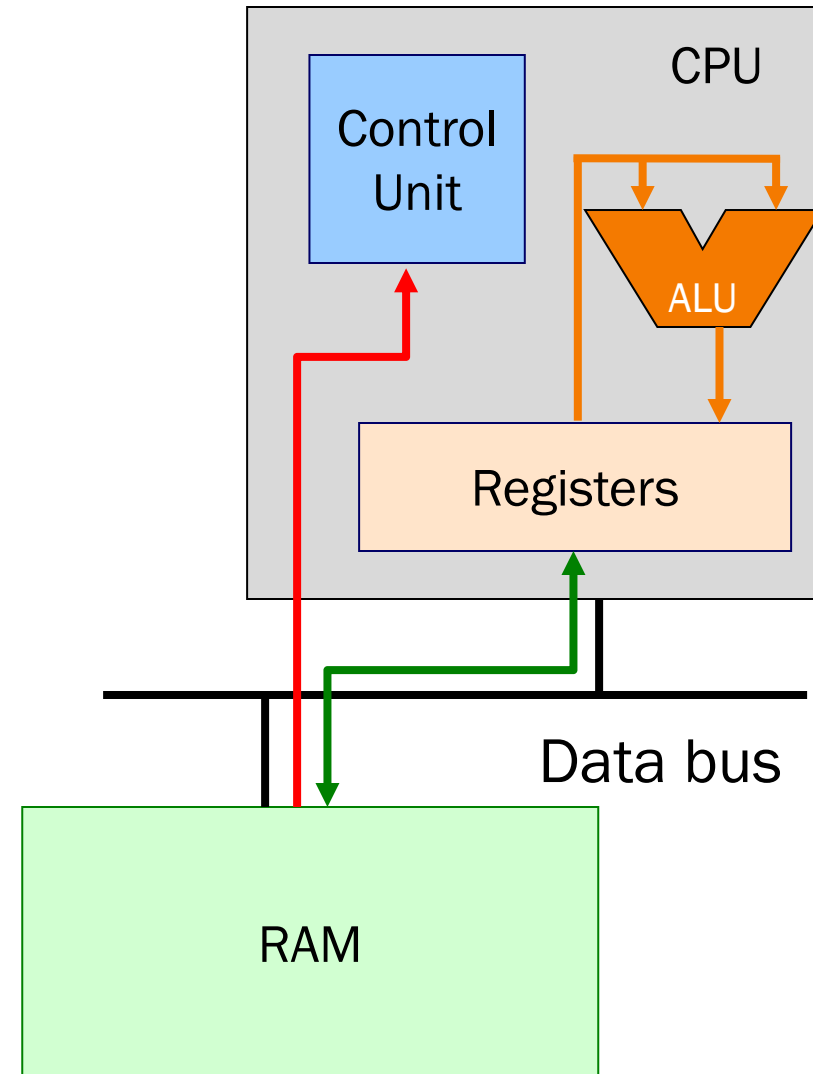
# Von Neumann Architecture

## Registers

Small amount of storage on the CPU

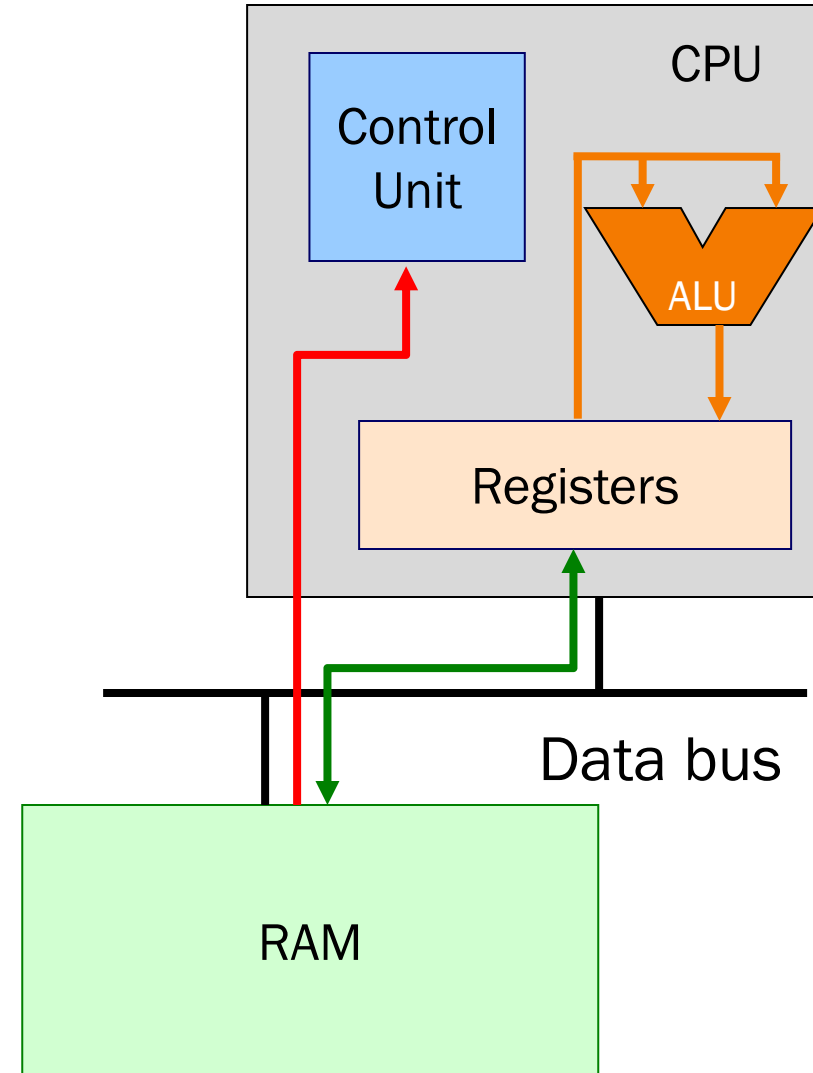
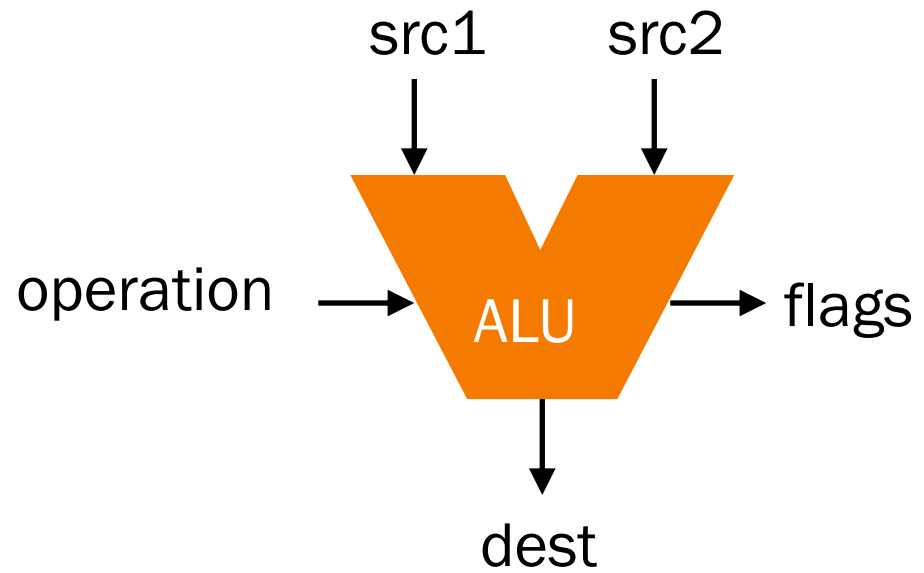
- Top of the “storage hierarchy”
- Very {small, expensive, fast}

ALU instructions operate on registers





# ALU Arithmetic Example





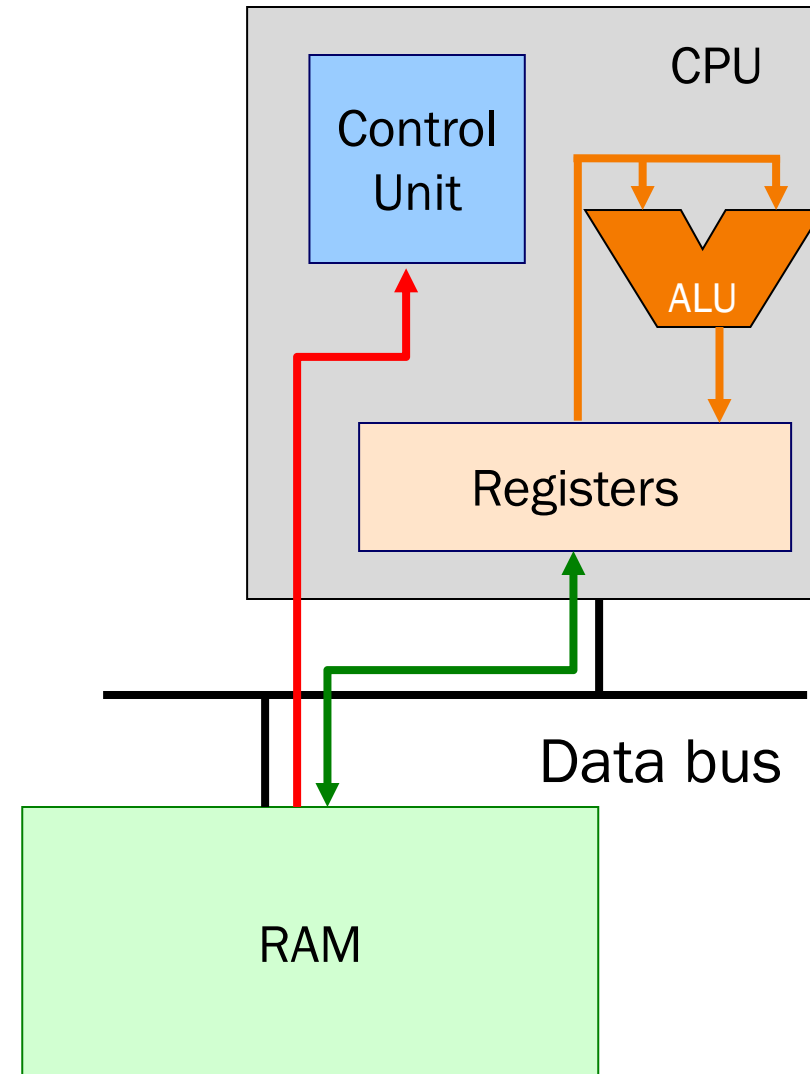
# Von Neumann Architecture

## RAM (Random Access Memory)

Conceptually: large array of bytes  
(gigabytes+ in modern machines)

- Contains data  
(program variables, structs, arrays)
- and the program!

Instructions are fetched from RAM





# Time to reminisce about old TOYs



Thinking back to COS 126,  
how did you feel about TOY?

- A. Loved it!
- B. Wasn't a fan.
- C. I placed out, so I have no idea what you're talking about.



Yuri Shirota





# Time to reminisce about old TOYs

## TOY REFERENCE CARD

### INSTRUCTION FORMATS

Format RR:	. . . .	. . . .	. . . .	. . . .	(0-6, A-B)
Format A:	opcode	d	s	t	(7-9, C-F)
	opcode	d	addr		

### ARITHMETIC and LOGICAL

- 1: add
- 2: subtract
- 3: and
- 4: xor
- 5: shift left
- 6: shift right

### TRANSFER between registers

- 7: load address
- 8: load
- 9: store
- A: load indirect
- B: store indirect

### CONTROL

- 0: halt
- C: branch zero
- D: branch positive
- E: jump register
- F: jump and link

Register 0 always reads 0.  
 Loads from M[FF] come from stdin.  
 Stores to M[FF] go to stdout.

16-bit registers (two's complement)  
 16-bit memory locations  
 8-bit program counter

**Word size.** The TOY machine has two types of storage: main memory and registers. Each entity stores one *word* of information. On the TOY machine, a word is a sequence of 16 bits. Typically, we interpret these 16 bits as a hexadecimal integer in the range 0000 through FFFF. Using *two's complement notation*, we can also interpret it as a decimal integer in the range -32,768 to +32,767. See Section 5.1 for a refresher on number representations and two's complement integers.

**Main memory.** The TOY machine has 256 words of *main memory*. Each memory location is labeled with a unique *memory address*. By convention, we use the 256 hexadecimal integers in the range 00 through FF. Think of a memory location as a mailbox, and a memory address as a postal address. Main memory is used to store instructions and data.

**Registers.** The TOY machine has 16 *registers*, indexed from 0 through F. Registers are much like main memory: each register stores one 16-bit word. However, registers provide a faster form of storage than main memory. Registers are used as scratch space during computation and play the role of variables in the TOY language. Register 0 is a special register whose output value is always 0.

**Program counter.** The *program counter* or *pc* is an extra register that keeps track of the next instruction to be executed. It stores 8 bits, corresponding to a hexadecimal integer in the range 00 through FF. This integer stores the memory address of the next instruction to execute.

<https://introcs.cs.princeton.edu/java/62toy/>



# Registers and RAM

Typical pattern:

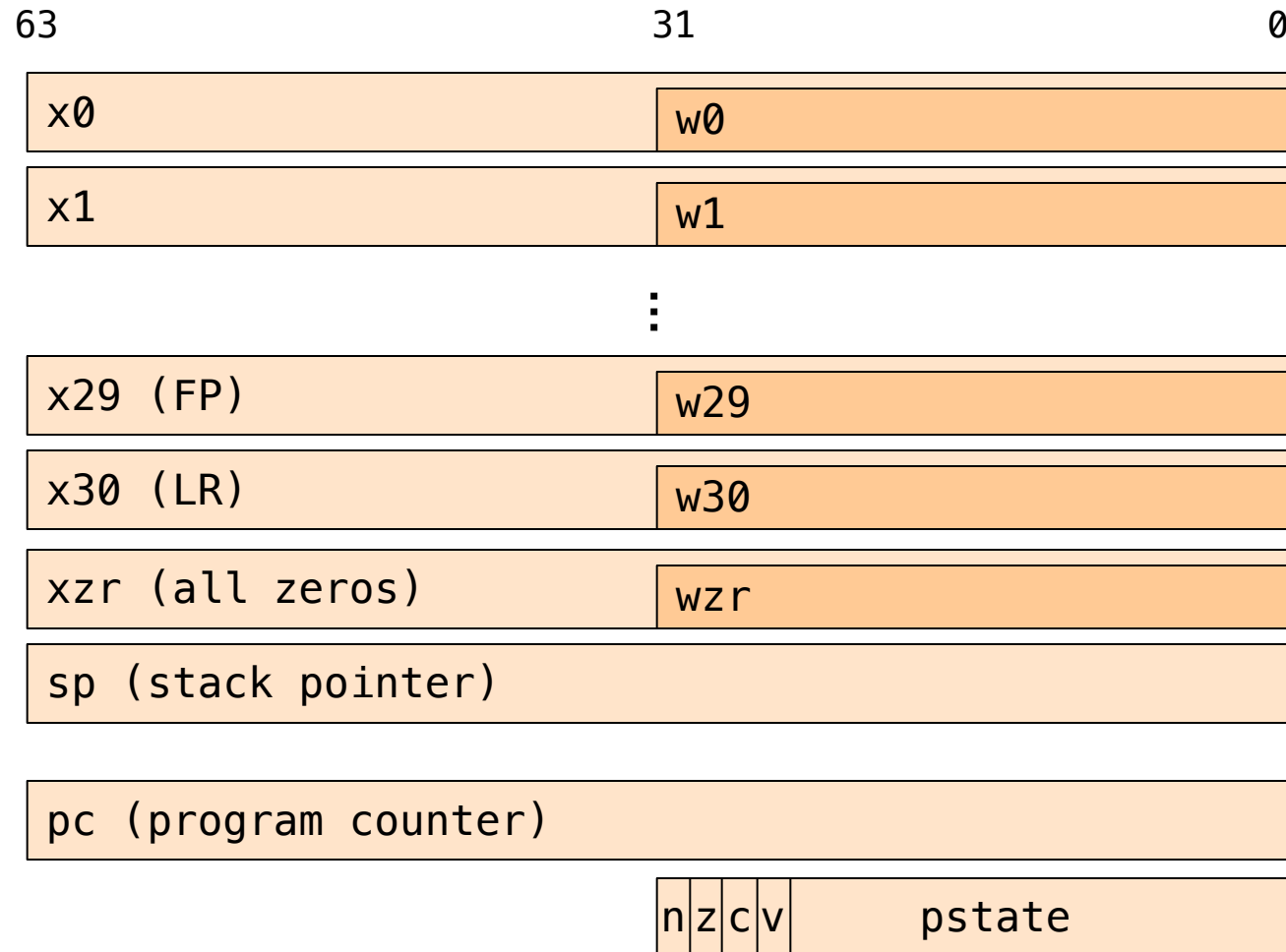
- **Load** data from RAM to registers
- **Manipulate** data in registers
- **Store** data from registers to RAM

On AARCH64, this pattern is enforced

- “Manipulation” instructions can *only* access registers
- This is known as a **load-store architecture**  
(as opposed to “register-memory” architectures)
- Characteristic of “RISC” (Reduced Instruction Set Computer) vs.  
“CISC” (Complex Instruction Set Computer) architectures, e.g. x86



# Registers (ARM-64 architecture)





# General-Purpose 64-bit Registers

## X0 ... X30

- Scratch space for instructions, parameter passing to/from functions, return address for function calls, etc.
- Some have special roles defined *in hardware* (e.g. X30) or defined *by software convention* (e.g. X29)
- Also available as 32-bit versions: W0 .. W30

## XZR

- On read: all zeros
- On write: data thrown away
- Also available as 32-bit version: WZR

# SP Register



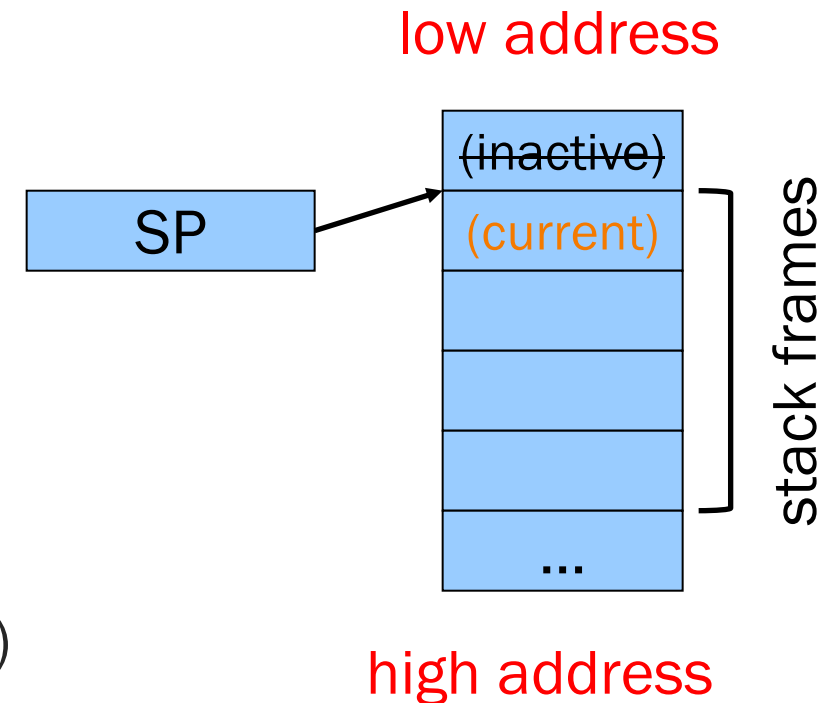
Special-purpose register...

- **SP (Stack Pointer):**

Contains address of top (low memory address) of current function's stack frame

Allows use of the STACK section of memory

(See **Assembly Language: Function Calls** lecture later)

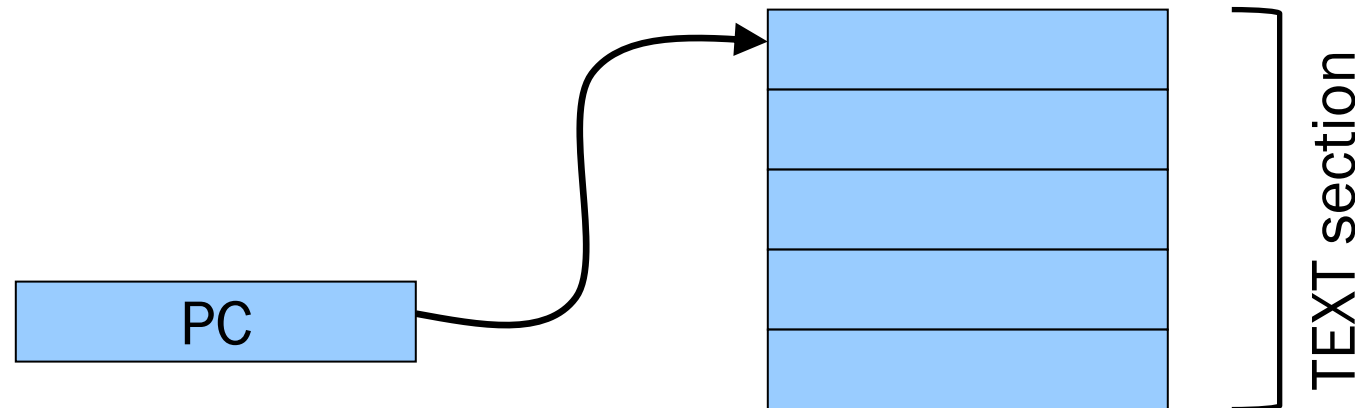




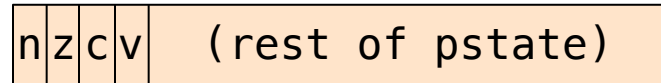
# PC Register

Special-purpose register...

- **PC (Program Counter)**
- Stores the location of the next instruction
  - Address (in TEXT section) of machine-language instruction to be executed next
- Value changed:
  - Automatically to implement sequential control flow (increment by 4 bytes)
  - By branch instructions to implement selection, repetition



# PSTATE Register



Special-purpose register...

- Contains **condition flags**:
  - **n** (**N**egative), **z** (**Z**ero), **c** (**C**arry), **v** (**o**Verflow)
- Affected by compare (cmp) instruction
  - And many others, if requested
- Used by conditional branch instructions
  - beq, bne, blo, bhi, ble, bge, ...
  - (See **Assembly Language: Part 2** lecture)

# Agenda



Language Levels

Architecture

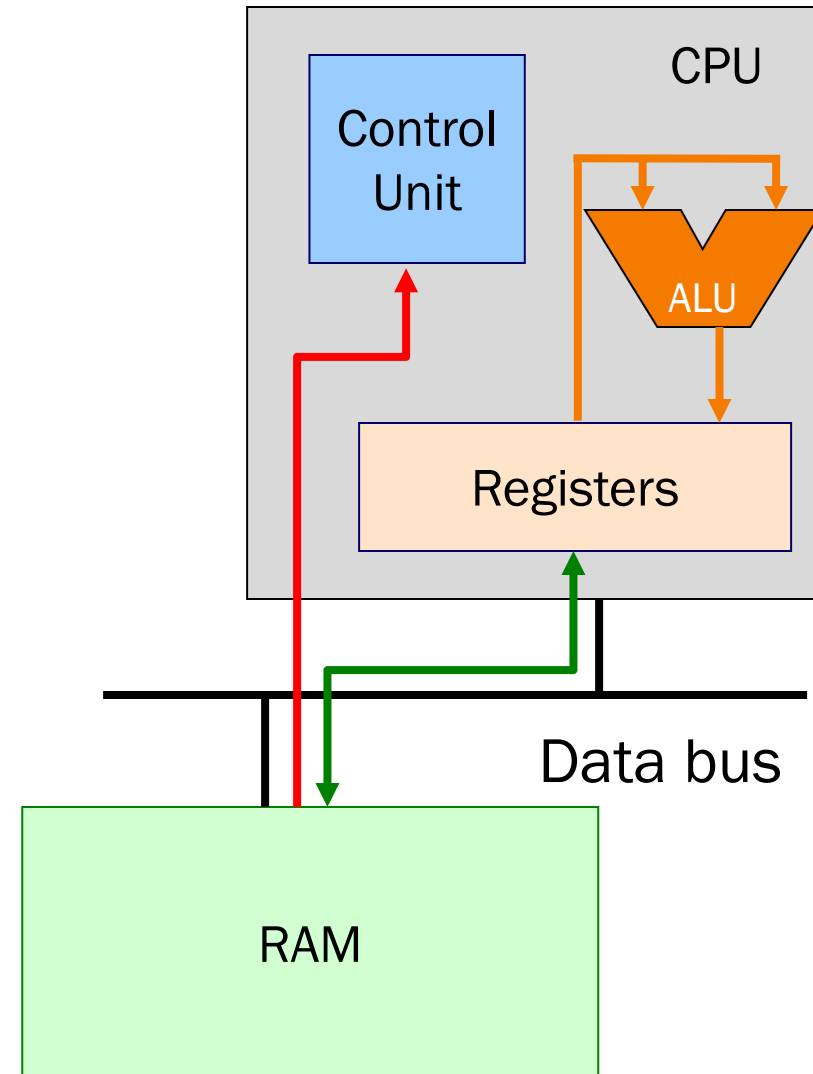
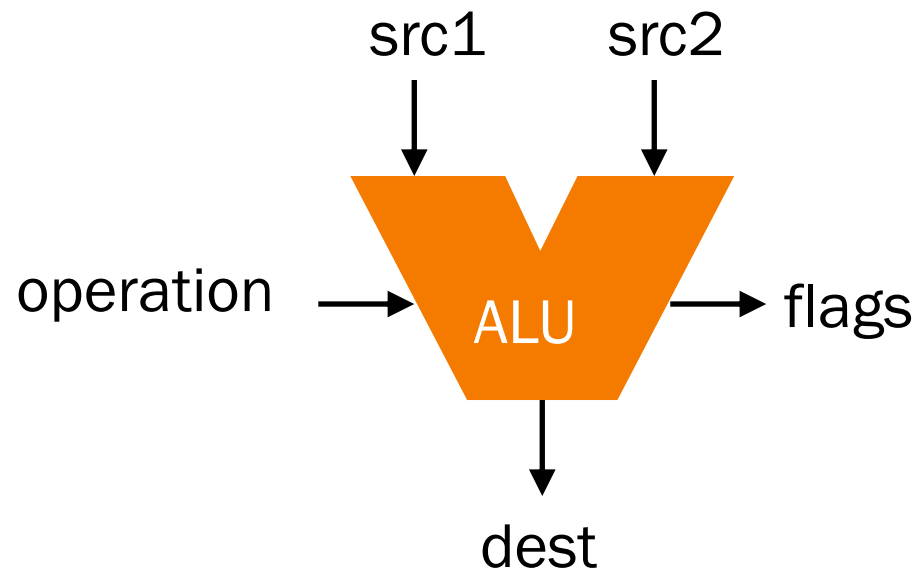
**Assembly Language: Performing Arithmetic**

Assembly Language: Load/Store and Defining Global Data





# ALU Arithmetic Example

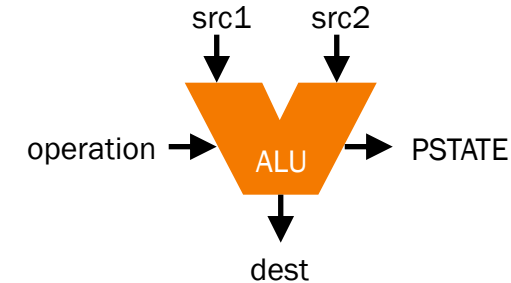




# Instruction Format

Many instructions have this format:

```
name{,s} dest, src1, src2  
name{,s} dest, src1, immed
```



- **name:** name of the instruction (add, sub, mul, and, etc.)
- **s:** if present, specifies that condition flags should be Set
- dest and src1,src2 are x registers: 64-bit operation
- dest and src1,src2 are w registers: 32-bit operation
  - No mixing and matching between x and w registers
- src2 may be a constant (“immediate” value) instead of a register



# 64-bit Arithmetic

C code:

```
static long length;  
static long width;  
static long perim;  
...  
perim =  
    (length + width) * 2;
```

Assume that...

- there's a good reason for having variables with file scope, process duration
- length held in x1
- width held in x2
- perim held in x3

We'll see later how to make this happen

Assembly code:

```
add x3, x1, x2  
lsl x3, x3, 1
```

Recall use of left shift by 1 bit to multiply by 2



# More Arithmetic

```
static long x;  
static long y;  
static long z;  
...  
z = x - y;  
z = x * y;  
z = x / y;  
z = x & y;  
z = x | y;  
z = x ^ y;  
z = x >> y;
```

Assume that...

- x held in x1
- y held in x2
- z held in x3

Assembly code:

```
sub x3, x1, x2  
mul x3, x1, x2  
sdiv x3, x1, x2  
and x3, x1, x2  
orr x3, x1, x2  
eor x3, x1, x2  
asr x3, x1, x2
```



Not **xor**!



# More Arithmetic: Shortcuts

```
static long x;  
static long y;  
static long z;  
...  
z = x;  
z = -x;
```

Assume that...

- x held in x1
- y held in x2
- z held in x3

Assembly code:

```
mov x3, x1  
neg x3, x1
```

```
orr x3, xzr, x1  
sub x3, xzr, x1
```

These are actually  
assembler shortcuts  
for instructions with  
XZR!



# Signed vs Unsigned?

```
static long x;  
static unsigned long y;  
...  
x++;  
y--;
```

Assume that...

- x held in x1
- y held in x2

Assembly code:

```
add x1, x1, 1  
sub x2, x2, 1
```

Mostly the same algorithms, same instructions!

- Can set different condition flags in PSTATE
- But some exceptions...



# Signed vs Unsigned: Exceptions

```
static long x;  
static unsigned long y;  
...  
x /= 17;  
y /= 42;  
x >>= 1;  
y >>= 2;
```

Assume that...

- x held in x1
- y held in x2

Assembly code:

```
sdiv x1, x1, 17  
udiv x2, x2, 42  
asr x1, x1, 1  
lsr x2, x2, 2
```

“Arithmetic” right shift  
(shift in sign bit on left)  
vs. “logical” right shift  
(shift in zeros on left)



# 32-bit Arithmetic using “w” registers

C code:

```
static int length;  
static int width;  
static int perim;  
...  
perim =  
    (length + width) * 2;
```

Assume that...

- length held in w1
- width held in w2
- perim held in w3

Assembly code:

```
add w3, w1, w2  
lsl w3, w3, 1
```





# 8- and 16-bit Arithmetic?

```
static char x;  
static short y;  
  
...  
x++;  
y--;
```

No specialized arithmetic instructions

- Use “w” registers
- Specialized “load” and “store” instructions for transfer of shorter data types from / to memory – we’ll see these later
- Corresponds to C language semantics: all arithmetic is implicitly done on (at least) ints

# Agenda



Language Levels

Architecture

Assembly Language: Performing Arithmetic

**Assembly Language: Load/Store and Defining Global Data**



# Loads and Stores

Most basic way to load (from RAM) and store (to RAM):

```
ldr dest, [src]  
str src, [dest]
```

- dest and src are (x-flavored) registers!
- Contents of registers in [brackets] must be memory addresses
  - Every memory access is through a “pointer”!



# Signed vs Unsigned, 8- and 16-bit

```
ldrb  dest, [src]
ldrh  dest, [src]
strb  src, [dest]
strh  src, [dest]

ldrsb dest, [src]
ldrsh dest, [src]
ldrsw dest, [src]
```

Special instructions for reading/writing **B**ytes (8 bit) and shorts (“**H**alf-words”: 16 bit)

- See appendix of these slides for information on ordering:  
little-endian vs. big-endian

Special instructions for signed reads

- “**S**ign-extend” byte, half-word, or word to 32 or 64 bits



# Loads and Stores

Most basic way to load (from RAM) and store (to RAM):

```
ldr dest, [src]  
str src, [dest]
```

- dest and src are registers!
- Registers in [brackets] contain memory addresses
  - Every memory access is through a “pointer”!
- How to get correct memory address into register?
  - Depends on whether data is on stack (local variables), heap (dynamically-allocated memory), or global / static
  - For today, we’ll look only at the global / static case



# Our First Full Program\*

```
static int length = 1;
static int width = 2;
static int perim = 0;

int main()
{
    perim =
        (length + width) * 2;
    return 0;
}
```

```
.section .data
length: .word 1
width: .word 2
perim: .word 0
.section .text
.global main
main:
adr    x0, length
ldr    w1, [x0]
adr    x0, width
ldr    w2, [x0]
add    w1, w1, w2
lsl    w1, w1, 1
adr    x0, perim
str    w1, [x0]
mov    w0, 0
ret
```

\* Sorry, I know by convention it should be “Hello, World!”. You’ll see that in precept.



# Memory sections

```
static int length = 1;
static int width = 2;
static int perim = 0;

int main()
{
    perim =
        (length + width) * 2;
    return 0;
}
```

**Sections** (Stack/heap are different!)

**.rodata**: read-only

**.data**: read-write

**.bss**: read-write (initialized to 0)

**.text**: read-only, program code

```
.section .data
length: .word 1
width: .word 2
perim: .word 0

.section .text
.global main
main:
adr    x0, length
ldr    w1, [x0]
adr    x0, width
ldr    w2, [x0]
add    w1, w1, w2
lsl    w1, w1, 1
adr    x0, perim
str    w1, [x0]
mov    w0, 0
ret
```



# Variable definitions

```
static int length = 1;
static int width = 2;
static int perim = 0;

int main()
{
    perim =
        (length + width) * 2;
    return 0;
}
```

## Declaring data

“Labels” for locations in memory  
**.word**: 32-bit int and initial value

```
.section .data
length: .word 1
width: .word 2
perim: .word 0

.section .text
.global main
main:
adr    x0, length
ldr    w1, [x0]
adr    x0, width
ldr    w2, [x0]
add    w1, w1, w2
lsl    w1, w1, 1
adr    x0, perim
str    w1, [x0]
mov    w0, 0
ret
```

See appendix for variables in other sections, with other types.





# main()

```
static int length = 1;
static int width = 2;
static int perim = 0;

int main()
{
    perim =
        (length + width) * 2;
    return 0;
}
```

## Global visibility

**.global**: Declare “main” to be a globally-visible label

```
.section .data
length: .word 1
width: .word 2
perim: .word 0
.section .text
.global main
main:
adr    x0, length
ldr    w1, [x0]
adr    x0, width
ldr    w2, [x0]
add    w1, w1, w2
lsl    w1, w1, 1
adr    x0, perim
str    w1, [x0]
mov    w0, 0
ret
```



# Make a “pointer”

```
static int length = 1;
static int width = 2;
static int perim = 0;

int main()
{
    perim =
        (length + width) * 2;
    return 0;
}
```

## Generating addresses

**adr**: put address of  
a label in a register

```
.section .data
length: .word 1
width: .word 2
perim: .word 0
.section .text
.global main
main:
adr    x0, length
ldr     w1, [x0]
adr    x0, width
ldr     w2, [x0]
add     w1, w1, w2
lsl     w1, w1, 1
adr    x0, perim
str     w1, [x0]
mov     w0, 0
ret
```



# Loads and Stores

```
static int length = 1;
static int width = 2;
static int perim = 0;

int main()
{
    perim =
        (length + width) * 2;
    return 0;
}
```

## Load and store

Use x0 as a “pointer” to load from and store to memory

```
.section .data
length: .word 1
width: .word 2
perim: .word 0

.section .text
.global main
main:
adr    x0, length
ldr    w1, [x0]
adr    x0, width
ldr    w2, [x0]
add    w1, w1, w2
lsl    w1, w1, 1
adr    x0, perim
str    w1, [x0]
mov    w0, 0
ret
```



# Return

```
static int length = 1;
static int width = 2;
static int perim = 0;

int main()
{
    perim =
        (length + width) * 2;
    return 0;
}
```

## Return a value

**ret**: return to the caller\*, with register 0 holding the return value

```
.section .data
length: .word 1
width: .word 2
perim: .word 0
.section .text
.global main
main:
adr    x0, length
ldr    w1, [x0]
adr    x0, width
ldr    w2, [x0]
add    w1, w1, w2
lsl    w1, w1, 1
adr    x0, perim
str    w1, [x0]
mov   w0, 0
ret
```

\* or, in A6, not.



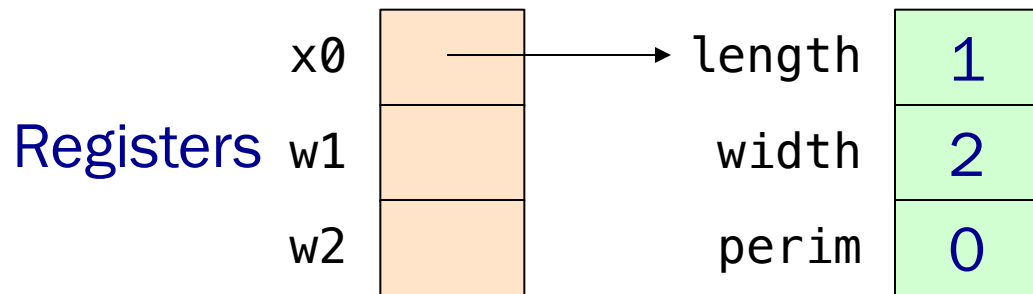
# Trace

```
static int length = 1;
static int width = 2;
static int perim = 0;

int main()
{
    perim =
        (length + width) * 2;
    return 0;
}
```

```
.section .data
length: .word 1
width: .word 2
perim: .word 0
.section .text
.global main
main:
adr    x0, length
ldr    w1, [x0]
adr    x0, width
ldr    w2, [x0]
add    w1, w1, w2
lsl    w1, w1, 1
adr    x0, perim
str    w1, [x0]
mov    w0, 0
ret
```

Memory





# Trace

```

static int length = 1;
static int width = 2;
static int perim = 0;

int main()
{
    perim =
        (length + width) * 2;
    return 0;
}

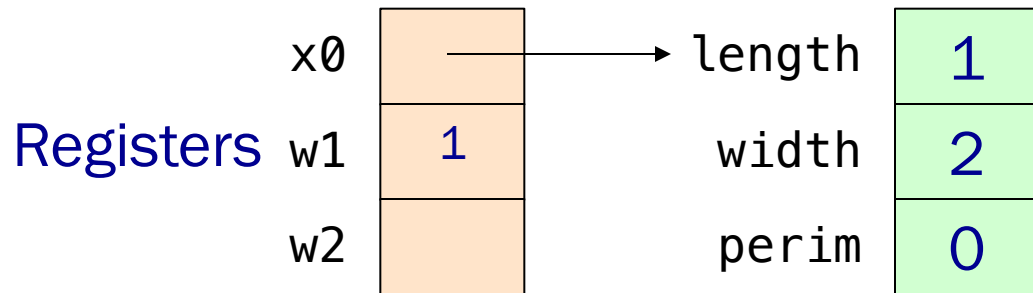
```

```

.section .data
length: .word 1
width: .word 2
perim: .word 0
.section .text
.global main
main:
adr    x0, length
ldr    w1, [x0]
adr    x0, width
ldr    w2, [x0]
add    w1, w1, w2
lsl    w1, w1, 1
adr    x0, perim
str    w1, [x0]
mov    w0, 0
ret

```

Memory





# Trace

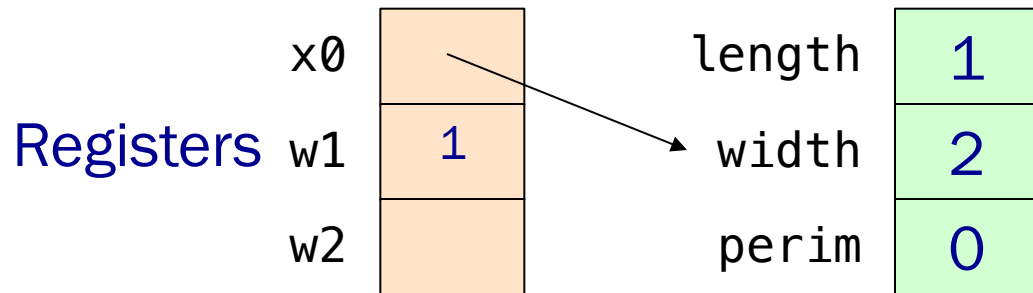
```
static int length = 1;
static int width = 2;
static int perim = 0;

int main()
{
    perim =
        (length + width) * 2;
    return 0;
}
```

```
.section .data
length: .word 1
width: .word 2
perim: .word 0

.section .text
.global main
main:
adr    x0, length
ldr    w1, [x0]
adr    x0, width
ldr    w2, [x0]
add    w1, w1, w2
lsl    w1, w1, 1
adr    x0, perim
str    w1, [x0]
mov    w0, 0
ret
```

Memory





# Trace

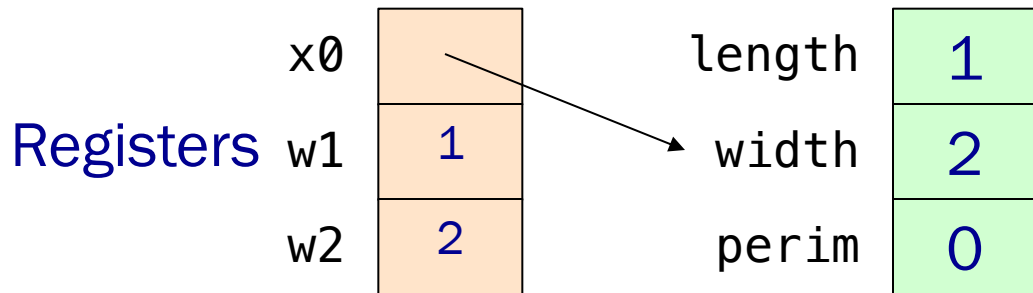
```
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static int perim = 0;

int main()
{
    perim =
        (length + width) * 2;
    return 0;
}
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.section .data
length: .word 1
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add    w1, w1, w2
lsl    w1, w1, 1
adr    x0, perim
str    w1, [x0]
mov    w0, 0
ret
```

Memory







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int main()
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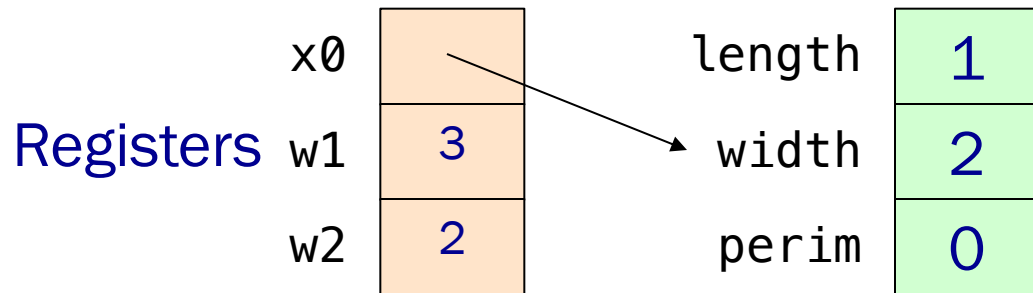
```

```

.section .data
length: .word 1
width: .word 2
perim: .word 0
.section .text
.global main
main:
adr    x0, length
ldr    w1, [x0]
adr    x0, width
ldr    w2, [x0]
add   w1, w1, w2
lsl    w1, w1, 1
adr    x0, perim
str    w1, [x0]
mov    w0, 0
ret

```

Memory





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static int width = 2;
static int perim = 0;

int main()
{
    perim =
        (length + width) * 2;
    return 0;
}

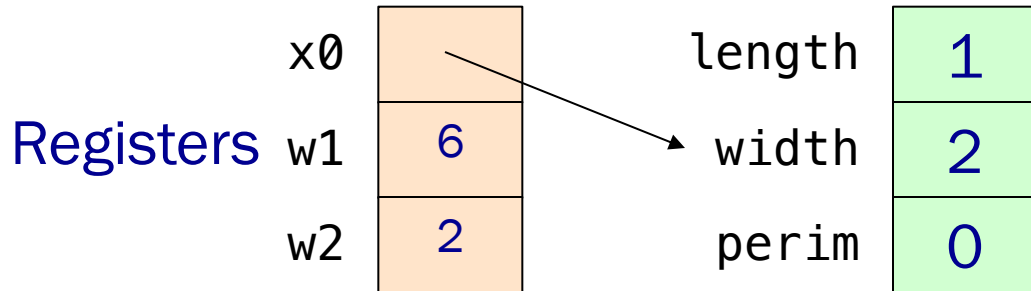
```

```

.section .data
length: .word 1
width: .word 2
perim: .word 0
.section .text
.global main
main:
adr    x0, length
ldr    w1, [x0]
adr    x0, width
ldr    w2, [x0]
add    w1, w1, w2
lsl    w1, w1, 1
adr    x0, perim
str    w1, [x0]
mov    w0, 0
ret

```

Memory





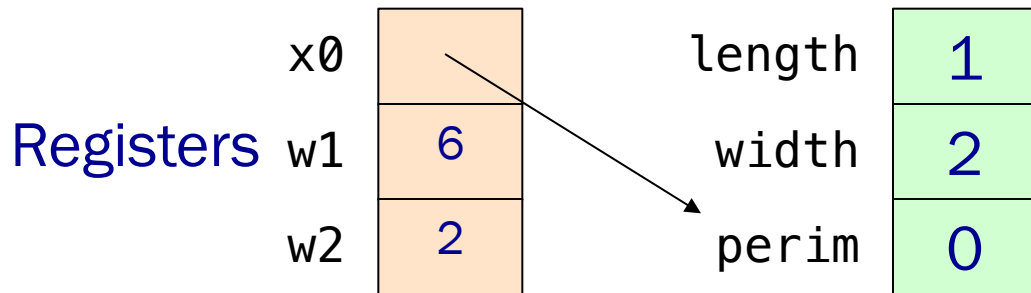
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static int perim = 0;

int main()
{
    perim =
        (length + width) * 2;
    return 0;
}
```

```
.section .data
length: .word 1
width: .word 2
perim: .word 0
.section .text
.global main
main:
adr    x0, length
ldr    w1, [x0]
adr    x0, width
ldr    w2, [x0]
add    w1, w1, w2
lsl    w1, w1, 1
adr    x0, perim
str    w1, [x0]
mov    w0, 0
ret
```

Memory





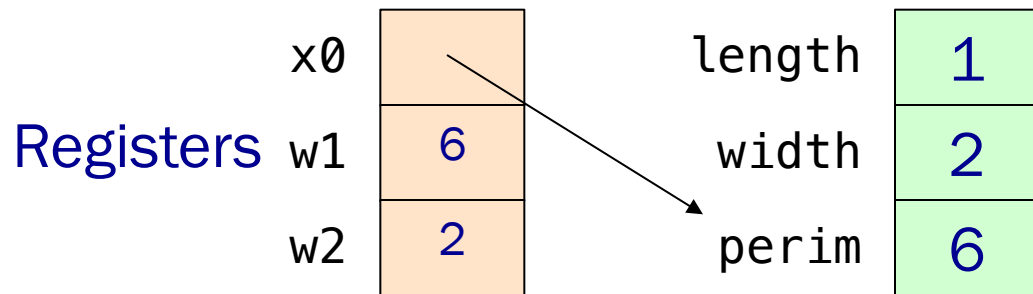
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static int width = 2;
static int perim = 0;

int main()
{
    perim =
        (length + width) * 2;
    return 0;
}
```

```
.section .data
length: .word 1
width: .word 2
perim: .word 0
.section .text
.global main
main:
adr    x0, length
ldr    w1, [x0]
adr    x0, width
ldr    w2, [x0]
add    w1, w1, w2
lsl    w1, w1, 1
adr    x0, perim
str    w1, [x0]
mov    w0, 0
ret
```

Memory





# Trace

```
static int length = 1;
static int width = 2;
static int perim = 0;

int main()
{
    perim =
        (length + width) * 2;
    return 0;
}
```

Return value

Passed back in register w0

```
.section .data
length: .word 1
width: .word 2
perim: .word 0
.section .text
.global main
main:
adr    x0, length
ldr    w1, [x0]
adr    x0, width
ldr    w2, [x0]
add    w1, w1, w2
lsl    w1, w1, 1
adr    x0, perim
str    w1, [x0]
mov    w0, 0
ret
```



# Trace

```
static int length = 1;
static int width = 2;
static int perim = 0;

int main()
{
    perim =
        (length + width) * 2;
    return 0;
}
```

Return to caller  
ret instruction

```
.section .data
length: .word 1
width: .word 2
perim: .word 0
.section .text
.global main
main:
adr    x0, length
ldr    w1, [x0]
adr    x0, width
ldr    w2, [x0]
add    w1, w1, w2
lsl    w1, w1, 1
adr    x0, perim
str    w1, [x0]
mov    w0, 0
ret
```



# Summary

## Language levels

### The basics of computer architecture

- Enough to understand AARCH64 assembly language

### The basics of AARCH64 assembly language

- Instructions to perform arithmetic
- Instructions to define global data and perform data transfer

## To learn more

- Study more assembly language examples
  - Chapters 2-5 of Pyeatt and Ughetta book
- Study compiler-generated assembly language code (though it will be challenging!)
  - `gcc217 -S somefile.c`



Appendix 1

# DEFINING DATA: OTHER SECTIONS AND SIZES





# Defining Data: DATA Section 1

```
static char c = 'a';  
static short s = 12;  
static int i = 345;  
static long l = 6789;
```

```
.section ".data"  
c:  
    .byte 'a'  
s:  
    .short 12  
i:  
    .word 345  
l:  
    .quad 6789
```

## Notes:

`.section` directive  
(to announce DATA section)

label definition  
(marks a spot in RAM)

`.byte` directive (1 byte)  
`.short` directive (2 bytes)  
`.word` directive (4 bytes)  
`.quad` directive (8 bytes)



# Defining Data: DATA Section 2

```
char c = 'a';  
short s = 12;  
int i = 345;  
long l = 6789;
```

```
.section ".data"  
    .global c  
c: .byte 'a'  
    .global s  
s: .short 12  
    .global i  
i: .word 345  
    .global l  
l: .quad 6789
```

## Notes:

Can place label on same line  
as next instruction

`.global` directive can also apply  
to variables, not just functions



# Defining Data: BSS Section

```
static char c;  
static short s;  
static int i;  
static long l;
```

```
.section ".bss"  
c:  
    .skip 1  
s:  
    .skip 2  
i:  
    .skip 4  
l:  
    .skip 8
```

## Notes:

- `.section` directive  
(to announce BSS section)
- `.skip` directive  
(to specify number of bytes)



# Defining Data: RODATA Section

```
...  
..."hello\n"...;  
...
```

```
    .section ".rodata"  
helloLabel:  
    .string "hello\n"
```

## Notes:

- `.section` directive (to announce RODATA section)
- `.string` directive



Appendix 2

# BYTE ORDER: BIG-ENDIAN VS LITTLE-ENDIAN



# Byte Order

AARCH64 is a **little endian** architecture

- Least significant byte of multi-byte entity is stored at lowest memory address
- “Little end goes first”

The int 5 at address 1000:

1000	00000101
1001	00000000
1002	00000000
1003	00000000

Some other systems use **big endian**

- Most significant byte of multi-byte entity is stored at lowest memory address
- “Big end goes first”

The int 5 at address 1000:

1000	00000000
1001	00000000
1002	00000000
1003	00000101



# Byte Order Example 1

```
#include <stdio.h>
int main(void)
{
    unsigned int i = 0x003377ff;
    unsigned char *p;
    int j;
    p = (unsigned char *)&i;
    for (j = 0; j < 4; j++)
        printf("Byte %d: %2x\n", j, p[j]);
}
```

Output on a  
little-endian  
machine

Byte 0: ff  
Byte 1: 77  
Byte 2: 33  
Byte 3: 00

Output on a  
big-endian  
machine

Byte 0: 00  
Byte 1: 33  
Byte 2: 77  
Byte 3: ff



# Byte Order Example 2

Note:

Flawed code; uses “b” instructions to load from a four-byte memory area

```
.section ".data"
foo: .word 7
    .section ".text"
    .global "main"
main:
adr    x0, foo
ldrb  w0, [x0]
ret
```

AARCH64 is little endian, so what will be the value returned from w0?

What would be the value returned from w0 if AARCH64 were big endian?