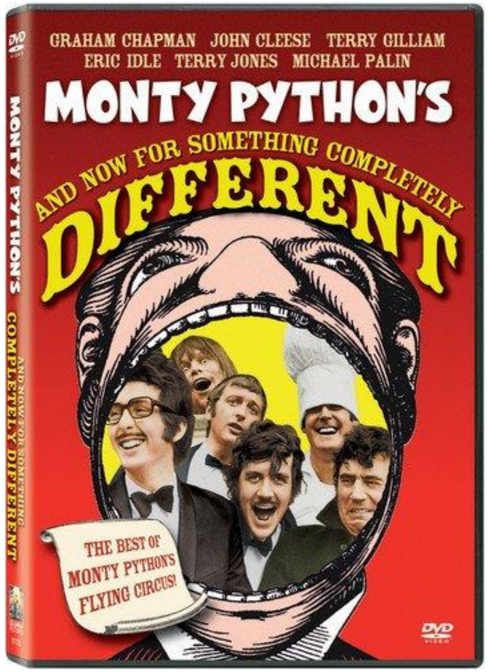
COS 217: Introduction to Programming Systems

Assembly Language

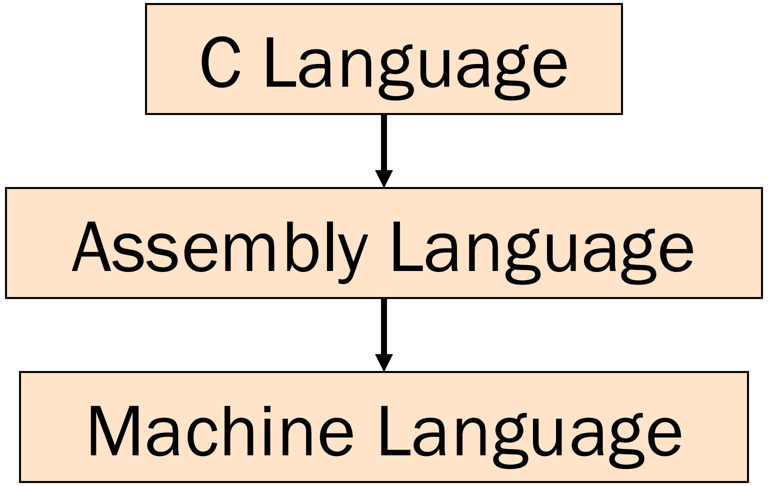
Part 1



PRINCETON UNIVERSITY

Context of this Lecture

"Under the hood"



C Language

Assembly Language

Machine Language

Agenda

Language Levels

Architecture

Assembly Language: Performing Arithmetic

Assembly Language: Load/Store and Defining Global Data

High-Level Languages

Characteristics

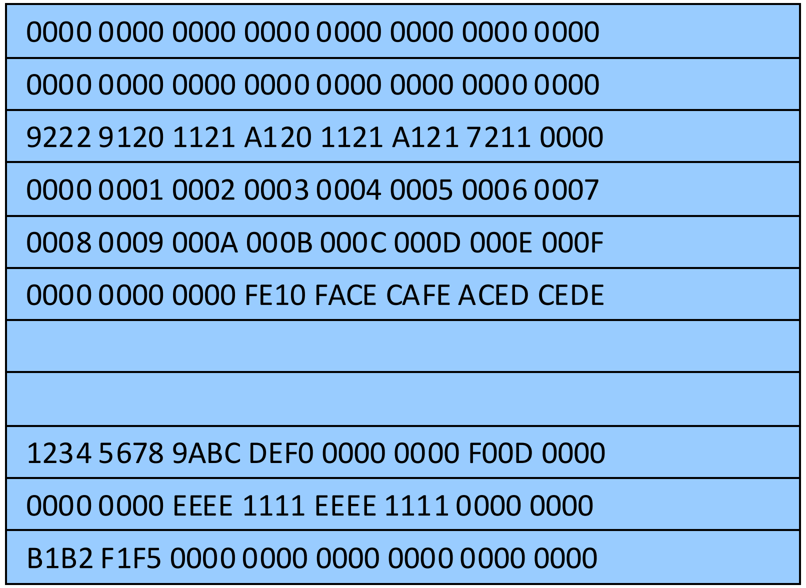
- Portable (to varying degrees)
- Complex
  - One statement can do a lot of work – good ratio of functionality to code size
- Human readable
  - Structured: if(), for(), while(), etc.
  - Variable names can hide details of where data is stored (stack, heap, etc.)
  - Type system allows compiler to check 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
  - Potentially even 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 architecture in the world (in your phone, in your Mac, 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?)

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

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”

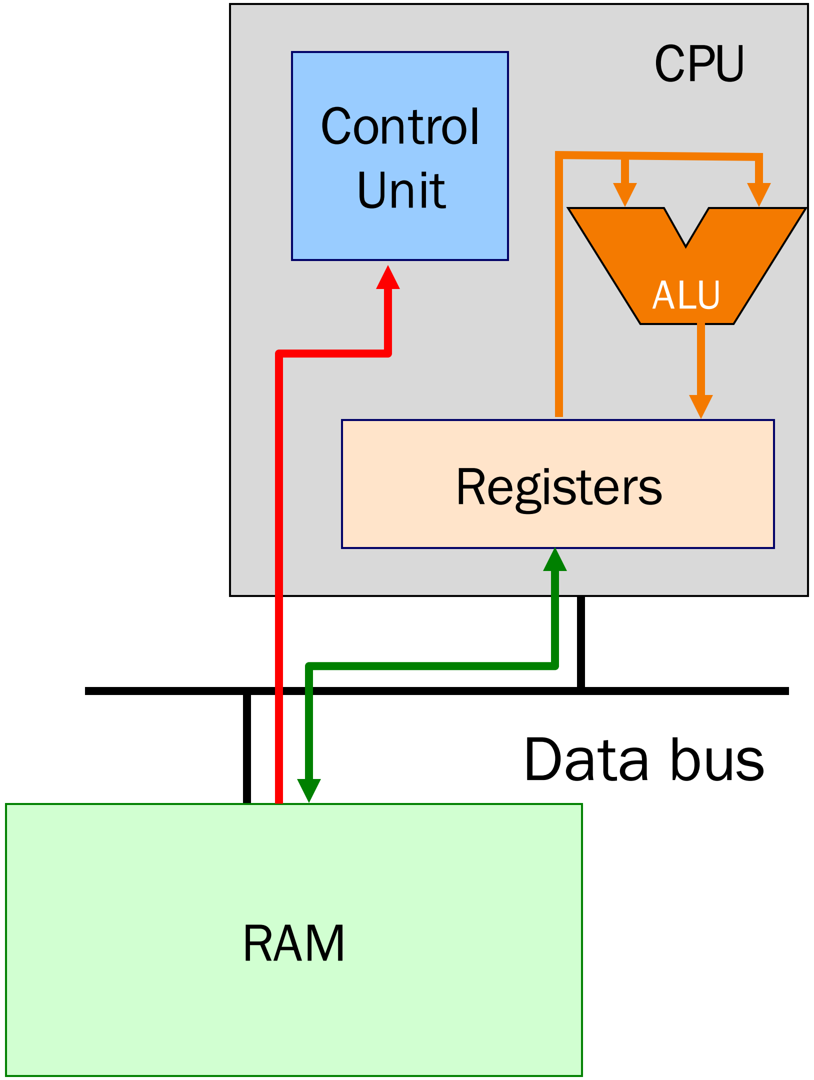
- In which (machine-language) programs are just data in memory
- a.k.a. “Princeton architecture” – contrast to the now-mostly-obsolete “Harvard architecture”

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



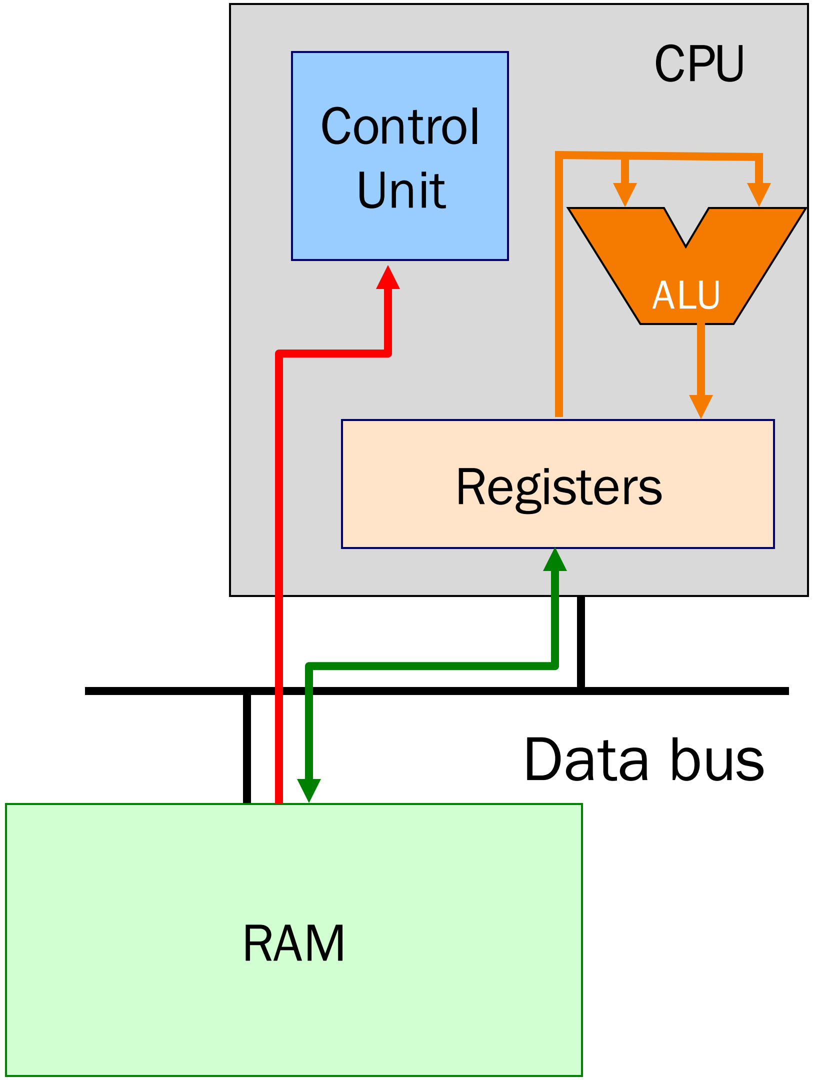
Von Neumann Architecture

Registers

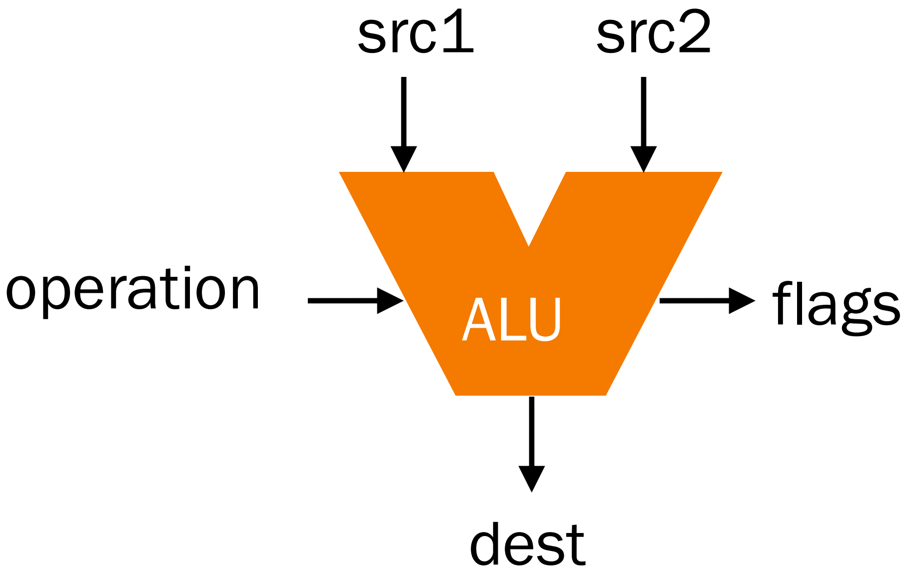
Small amount of storage on the CPU

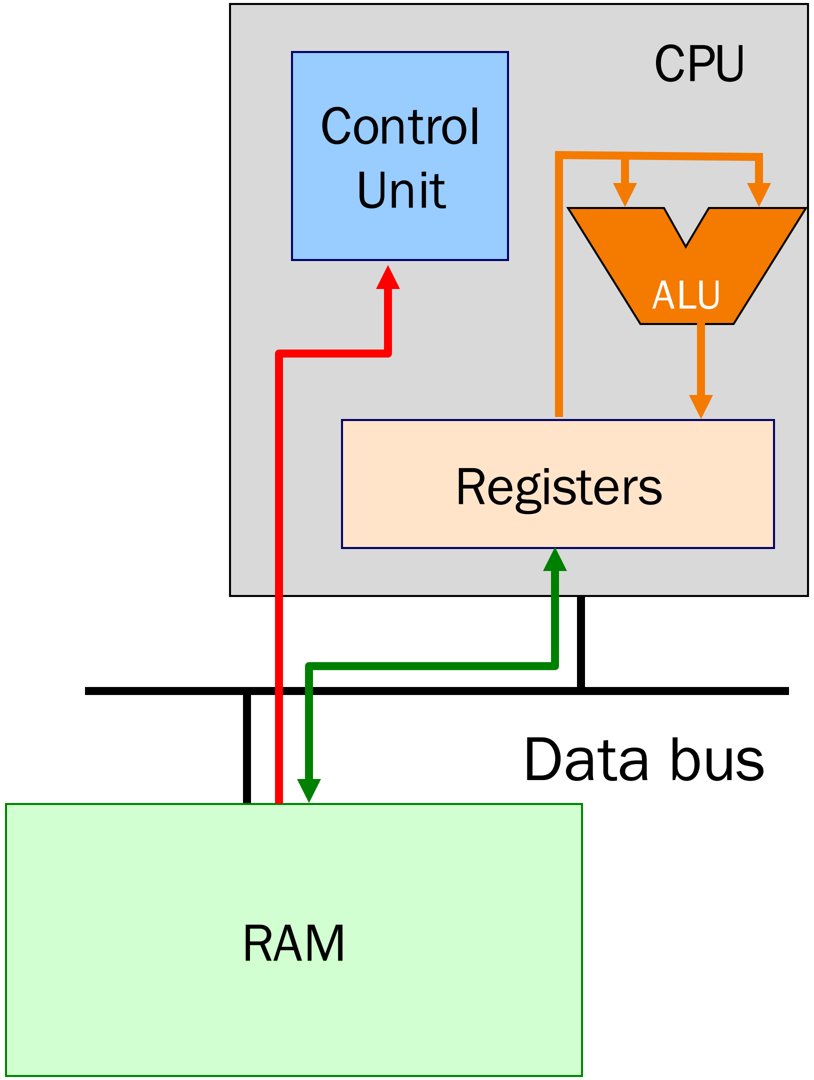
- Top of the “storage hierarchy”
- Very {small, expensive, fast}

ALU instructions operate on registers



ALU Arithmetic Example





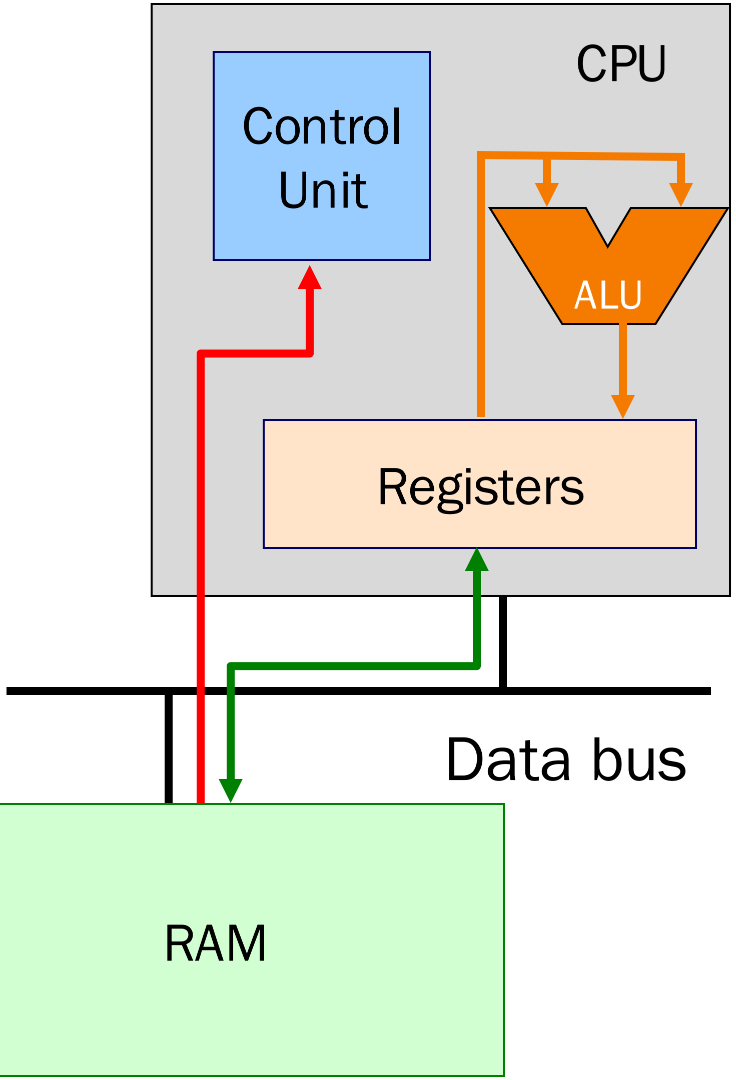
Von Neumann Architecture

RAM (Random Access Memory)

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

- Contains data
  (program variables, structs, arrays)
- and the program itself in machine code!

Instructions are fetched from RAM



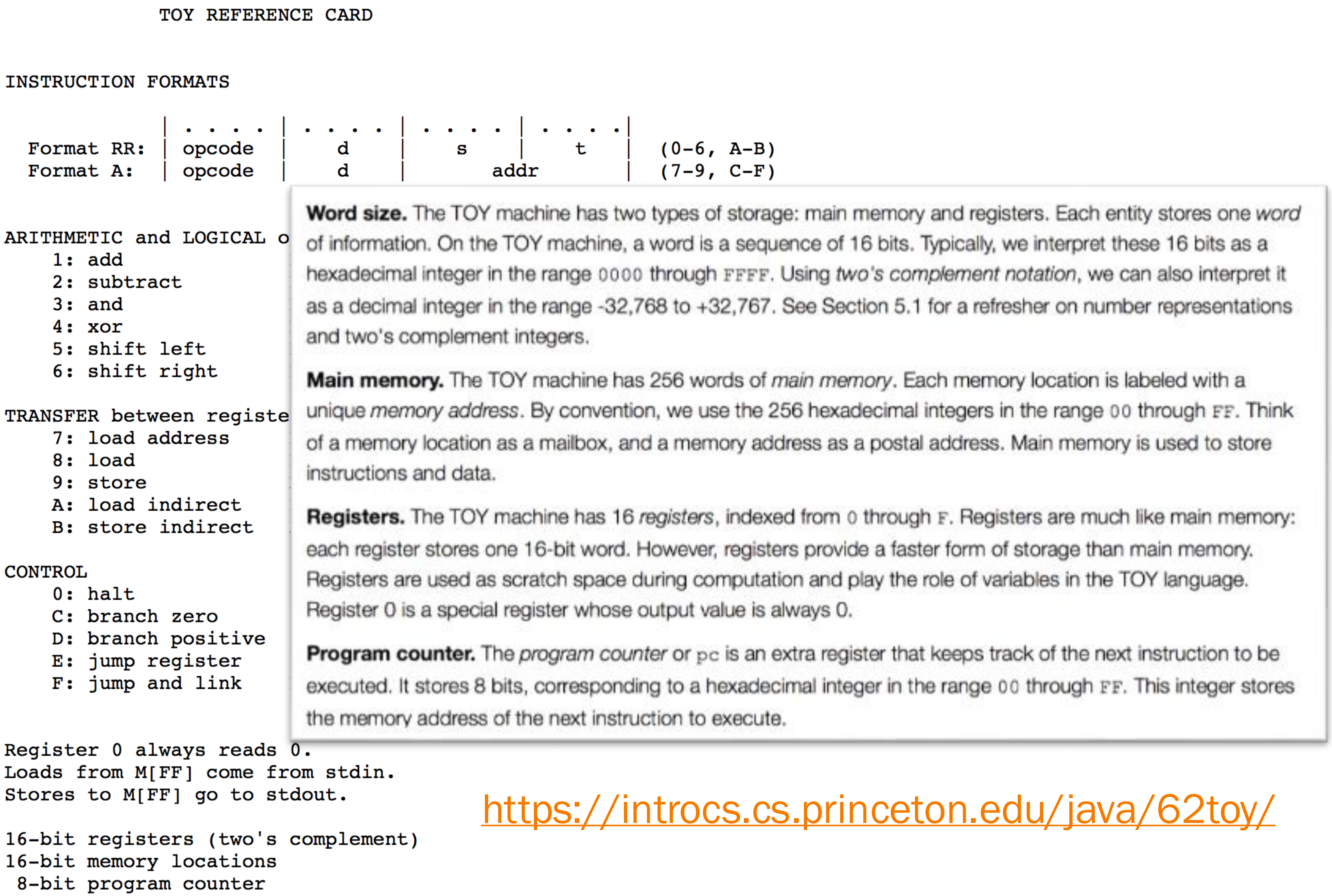
Time to reminisce about old TOYs

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


ARITHMETIC and LOGICAL o
    1: add
    2: subtract
    3: and
    4: xor
    5: shift left
    6: shift right

TRANSFER between registe
    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

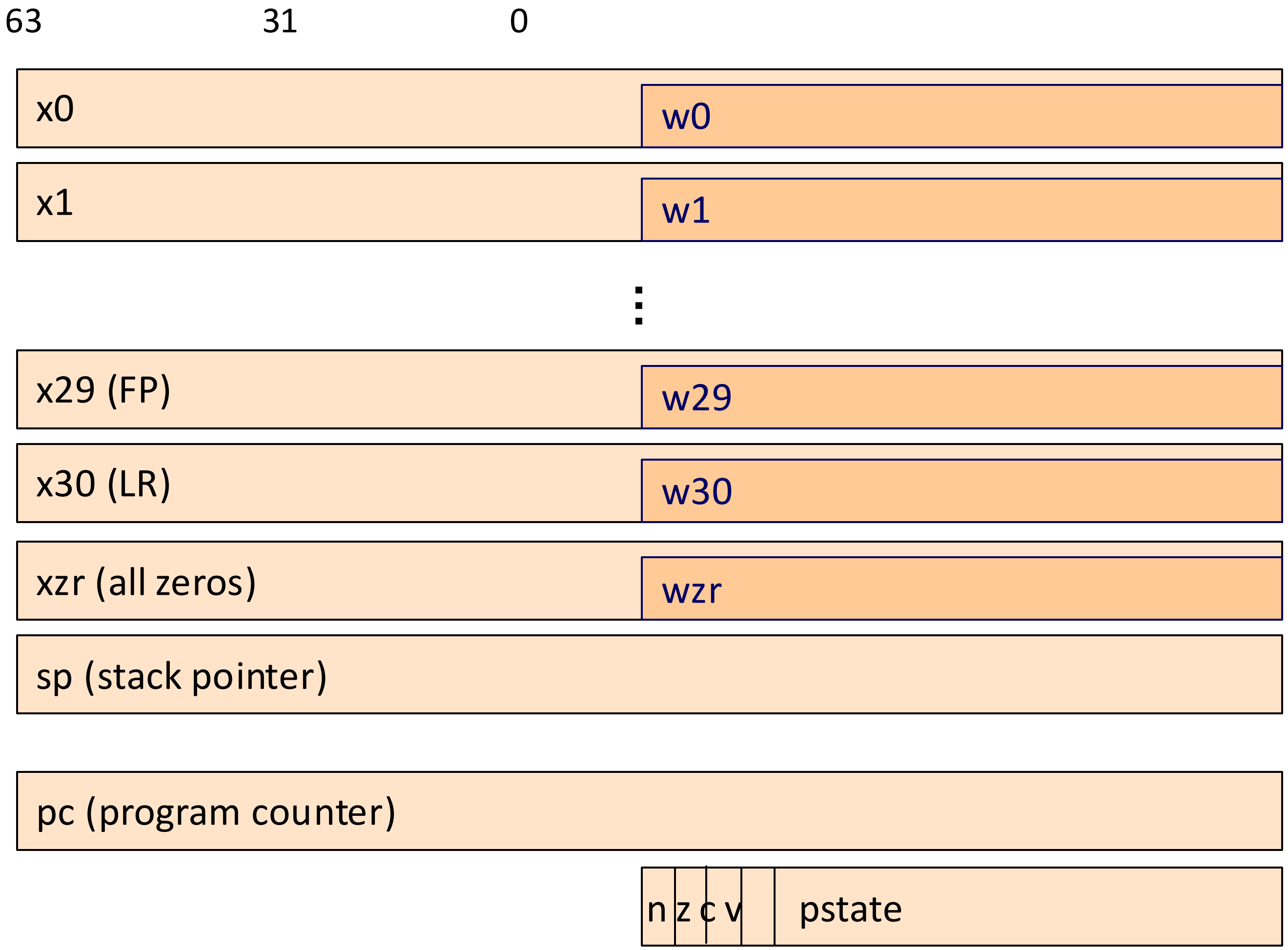
Typical pattern:

- **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)



63 31 0

x0 w0

x1 w1

⋮

x29 (FP) w29

x30 (LR) w30

xzr (all zeros) wzr

sp (stack pointer)

pc (program counter)

n z c v pstate

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

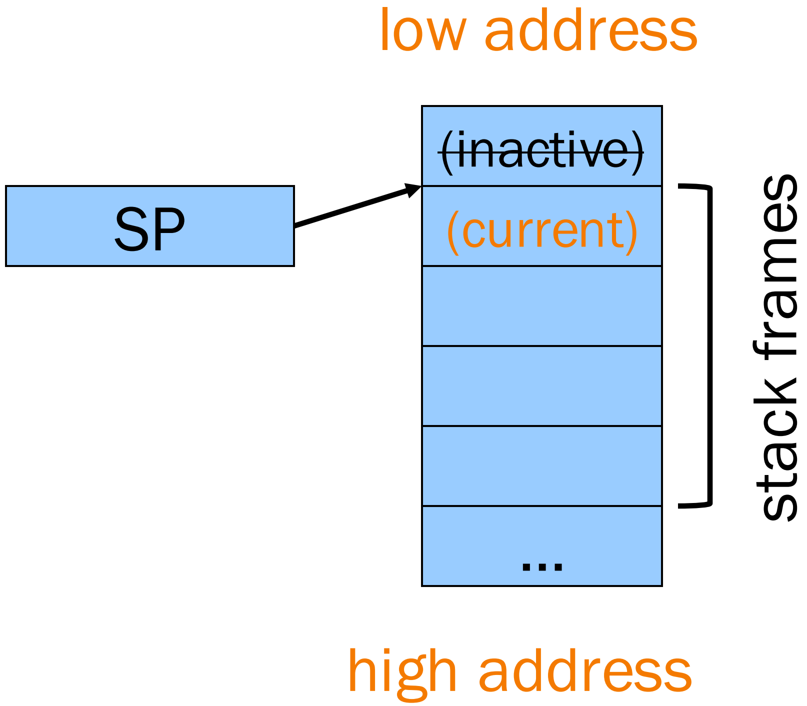
XZR

- 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



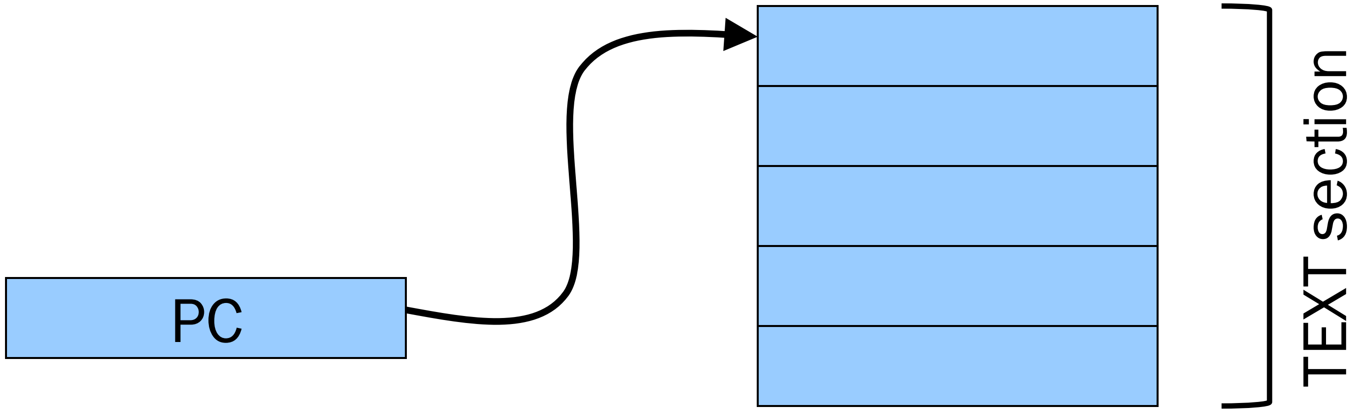
Allows use of the STACK section of memory

(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

n	z	c	v	(rest of pstate)

Special-purpose register…

- Contains **condition flags:**
  n (Negative), z (Zero), c (Carry), v (oVerflow)
- 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

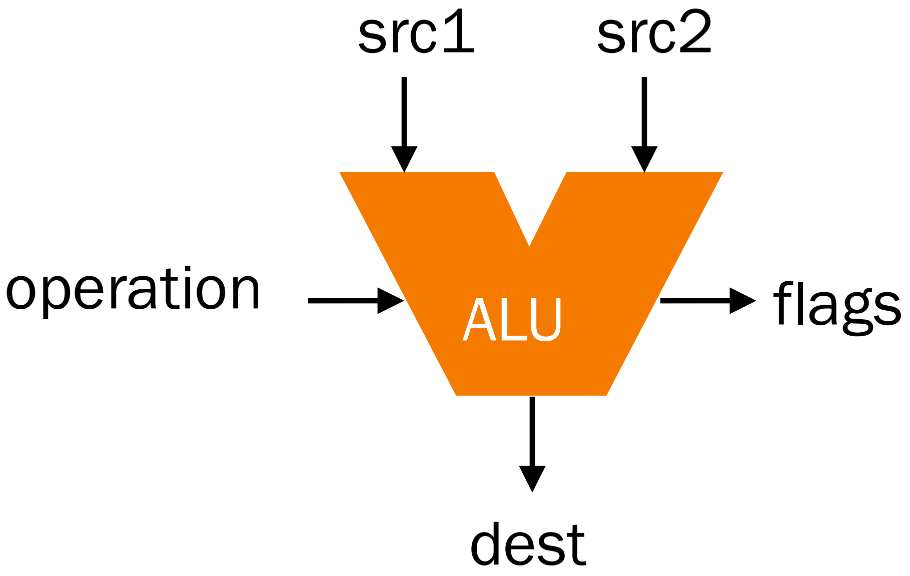
Language Levels

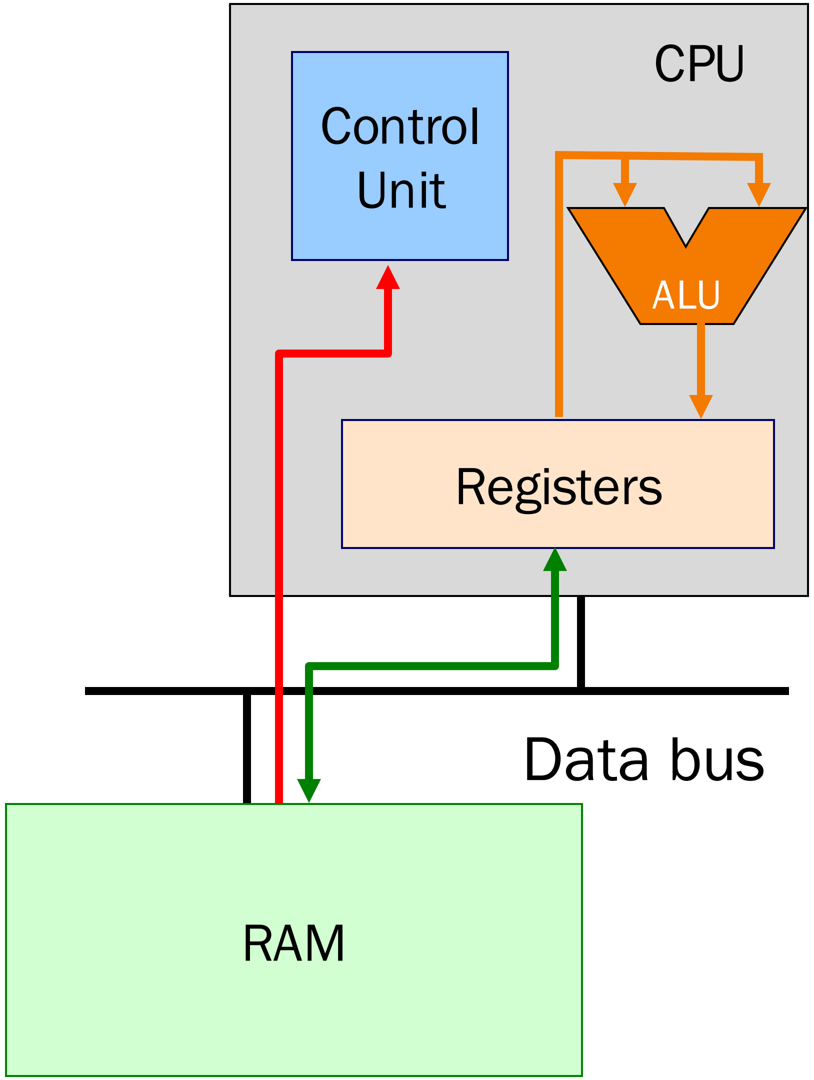
Architecture

Assembly Language: Performing Arithmetic

Assembly Language: Load/Store and Defining Global Data

ALU Arithmetic Example

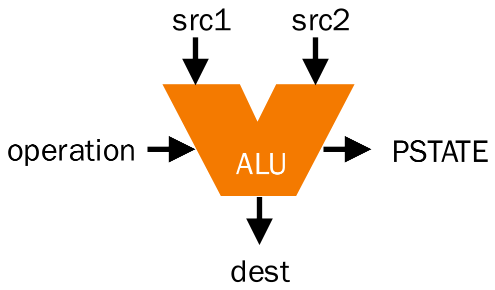




Instruction Format

Many instructions have this format:

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



- **name:** mnemonic 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
```

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
```

These are actually assembler shortcuts for instructions with XZR!

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

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 registers!
  - The addresses (src for ldr, dest for str) must be x-flavored
  - Other operands (dest for ldr, src for str) can be x-flavored or w-flavored
- 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!
  - The addresses (src for ldr, dest for str) must be x-flavored
  - Other operands (dest for ldr, src for str) can be x-flavored or w-flavored
- Contents of registers in [brackets] must be 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
ldrw1, [x0]
adr          x0, width
ldrw2, [x0]
add          w1, w1, w2
lsl w1, w1, 1
adr          x0, perim
strw1, [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;
}
```

```
    .section .data
length:     .word 1
width:      .word 2
perim:      .word 0
    .section .text
    .global main
main:
adr         x0, length
ldrw1, [x0]
adr         x0, width
ldrw2, [x0]
add         w1, w1, w2
lsl w1, w1, 1
adr         x0, perim
strw1, [x0]
mov         w0, 0
ret
```

Sections (Stack/heap are different!)

- .rodata: read-only
- .data: read-write
- .bss: read-write (initialized to 0)
- .text: read-only, program code

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
ldrw1, [x0]
adr         x0, width
ldrw2, [x0]
add         w1, w1, w2
lsl w1, w1, 1
adr         x0, perim
strw1, [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;
}
```

```
    .section .data
length:     .word 1
width:      .word 2
perim:      .word 0
    .section .text
    .global main
main:
adr         x0, length
ldrw1, [x0]
adr         x0, width
ldrw2, [x0]
add         w1, w1, w2
lsl w1, w1, 1
adr         x0, perim
strw1, [x0]
mov         w0, 0
ret
```

Global visibility

- .global: Declare "main" to be a globally-visible label

Make a “pointer”

```
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
ldrw1, [x0]
adr         x0, width
ldrw2, [x0]
add         w1, w1, w2
lsl w1, w1, 1
adr         x0, perim
strw1, [x0]
mov         w0, 0
ret
```

Generating addresses

adr: put address of a label in a register

Loads and Stores

```
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
ldrw1, [x0]
adr         x0, width
ldrw2, [x0]
add         w1, w1, w2
lsl w1, w1, 1
adr         x0, perim
strw1, [x0]
mov         w0, 0
ret
```

Load and store

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

Return

```
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
ldrw1, [x0]
adr         x0, width
ldrw2, [x0]
add         w1, w1, w2
lsl w1, w1, 1
adr         x0, perim
strw1, [x0]
mov         w0, 0
ret
```

Return a value

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

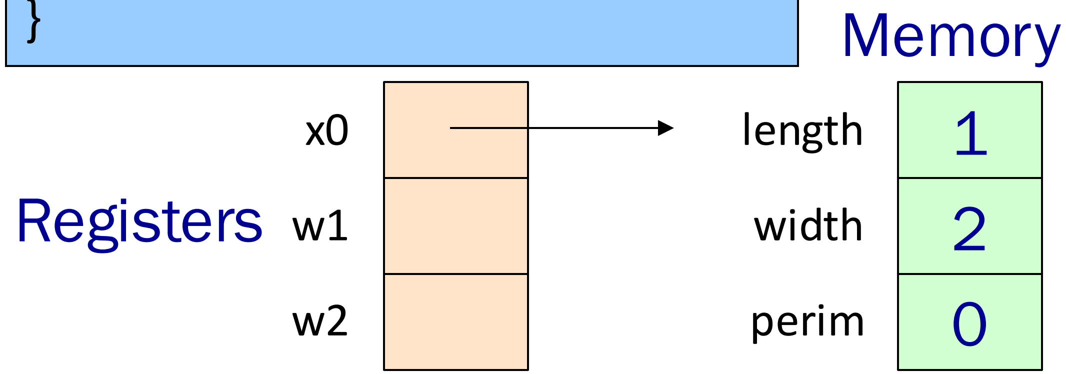
* w0 for int, x0 for long

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
ldrw1, [x0]
adr         x0, width
ldrw2, [x0]
add         w1, w1, w2
lsl w1, w1, 1
adr         x0, perim
strw1, [x0]
mov         w0, 0
ret
```

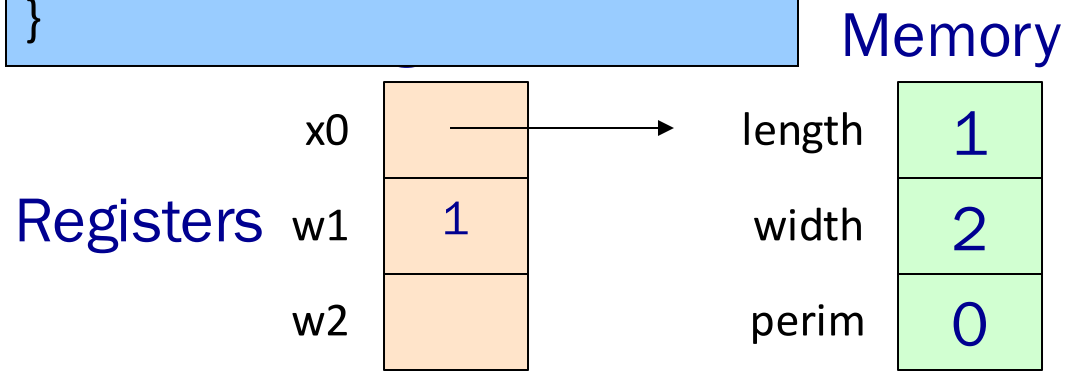


Trace

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

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

```
    .section .data
length:      .word 1
width:       .word 2
perim:       .word 0
    .section .text
    .global main
main:
adr          x0, length
ldrw1, [x0]
adr          x0, width
ldrw2, [x0]
add          w1, w1, w2
lsl w1, w1, 1
adr          x0, perim
strw1, [x0]
mov          w0, 0
ret
```

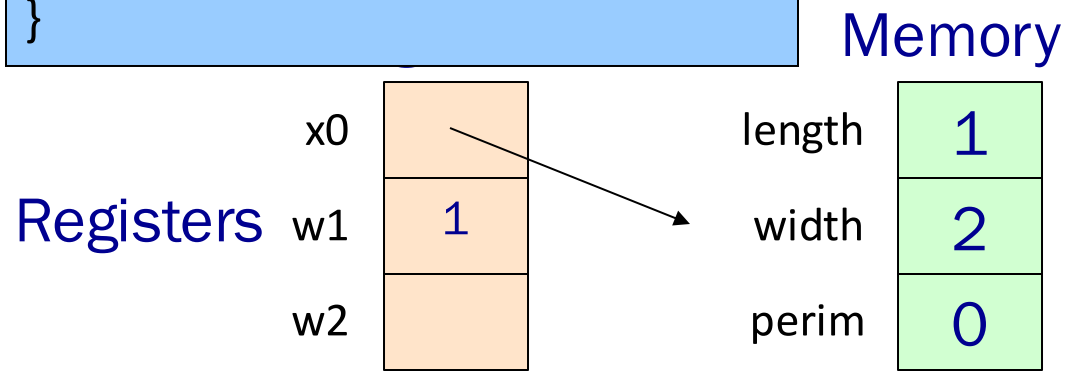


Trace

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

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

```
    .section .data
length:     .word 1
width:      .word 2
perim:      .word 0
    .section .text
    .global main
main:
adr         x0, length
ldrw1, [x0]
adr         x0, width
ldrw2, [x0]
add         w1, w1, w2
lsl w1, w1, 1
adr         x0, perim
strw1, [x0]
mov         w0, 0
ret
```

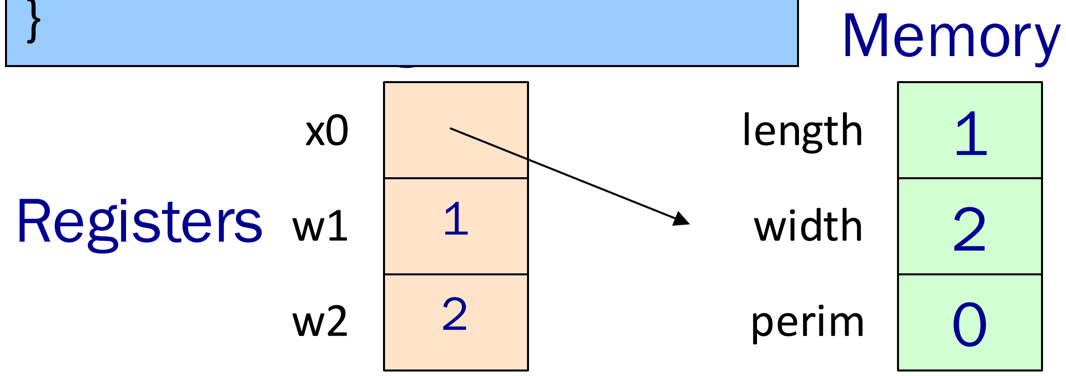


Trace

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

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

```
    .section .data
length:     .word 1
width:      .word 2
perim:      .word 0
    .section .text
    .global main
main:
adr         x0, length
ldrw1, [x0]
adr         x0, width
ldrw2, [x0]
add         w1, w1, w2
lsl w1, w1, 1
adr         x0, perim
strw1, [x0]
mov         w0, 0
ret
```

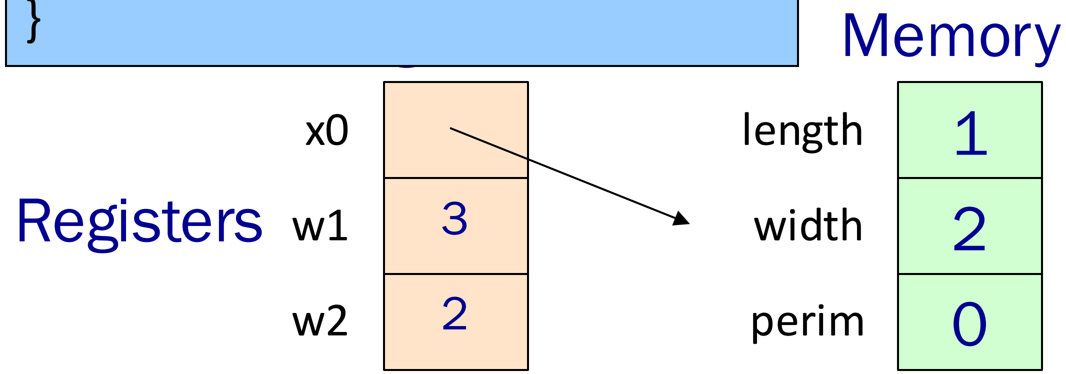


Trace

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

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

```
    .section .data
length:     .word 1
width:      .word 2
perim:      .word 0
    .section .text
    .global main
main:
adr         x0, length
ldrw1, [x0]
adr         x0, width
ldrw2, [x0]
add         w1, w1, w2
lsl w1, w1, 1
adr         x0, perim
strw1, [x0]
mov         w0, 0
ret
```



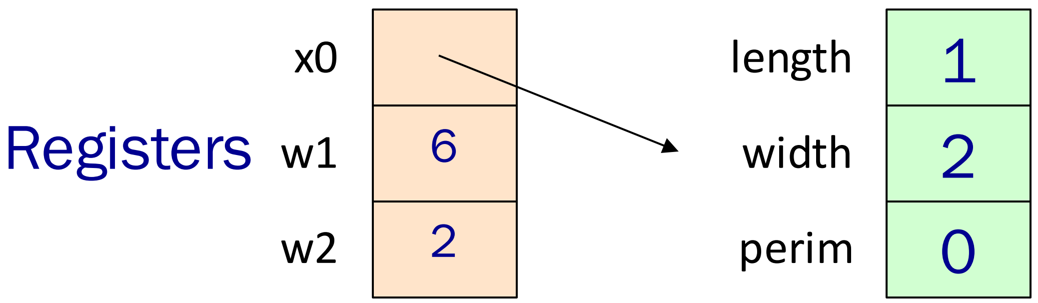
Trace

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

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

```
    .section .data
length:     .word 1
width:      .word 2
perim:      .word 0
    .section .text
    .global main
main:
adr         x0, length
ldrw1, [x0]
adr         x0, width
ldrw2, [x0]
add         w1, w1, w2
lsl w1, w1, 1
adr         x0, perim
strw1, [x0]
mov         w0, 0
ret
```

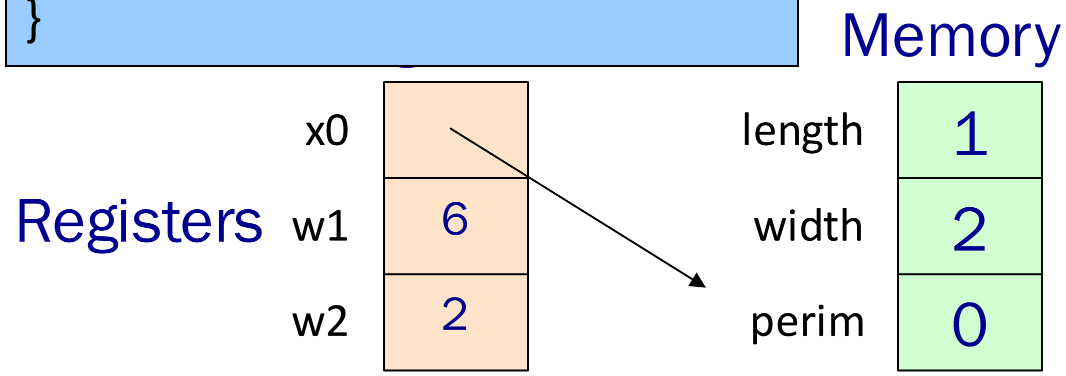
Memory



Trace

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

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



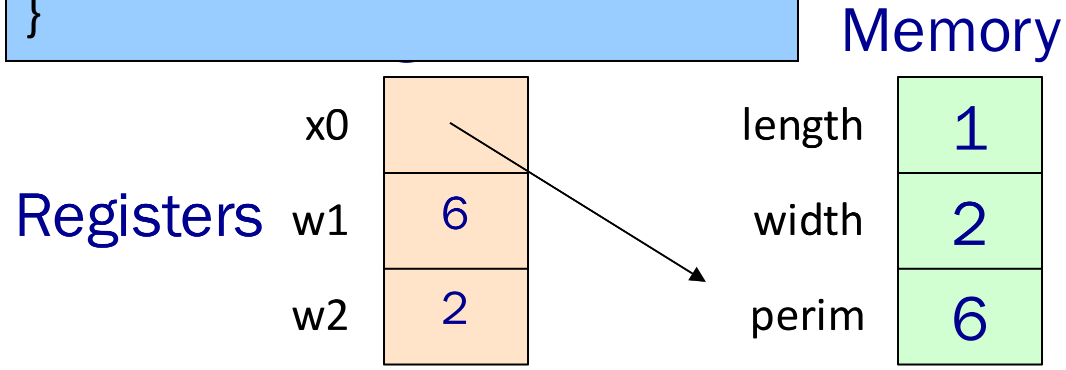
```
     .section .data
length:      .word 1
width:       .word 2
perim:       .word 0
     .section .text
     .global main
main:
adr          x0, length
ldrw1, [x0]
adr          x0, width
ldrw2, [x0]
add          w1, w1, w2
lsl w1, w1, 1
adr          x0, perim
strw1, [x0]
mov          w0, 0
ret
```

Trace

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

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

```
    .section .data
length:     .word 1
width:      .word 2
perim:      .word 0
    .section .text
    .global main
main:
adr         x0, length
ldrw1, [x0]
adr         x0, width
ldrw2, [x0]
add         w1, w1, w2
lsl w1, w1, 1
adr         x0, perim
strw1, [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;
}
```

```
    .section .data
length:      .word 1
width:       .word 2
perim:       .word 0
    .section .text
    .global main
main:
adr          x0, length
ldrw1, [x0]
adr          x0, width
ldrw2, [x0]
add          w1, w1, w2
lsl w1, w1, 1
adr          x0, perim
strw1, [x0]
mov          w0, 0
ret
```

Return value

- Passed back in register w0

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
ldrw1, [x0]
adr           x0, width
ldrw2, [x0]
add           w1, w1, w2
lsl w1, w1, 1
adr           x0, perim
strw1, [x0]
mov           w0, 0
ret
```

Return to caller

ret instruction

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
or directive

.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

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?

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