COS 217: Introduction to Programming Systems

Assembly Language

Part 1

PRINCETON UNIVERSITY

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 much work – good ratio of functionality to code size
- Human readable
  - Structured – if(), for(), while(), etc.

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

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     w0, w0, #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!

Why Learn ARM Assembly Lang?

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

Pros

- ARM is the most widely used processor in the world
  (in your phone, in your Chromebook, in the internet-of-things, Armlab
  ... soon in Macs.)
- ARM has a modern and (relatively) elegant instruction set,
  compared to the big and ugly x86-64 instruction set

Cons

- x86-64 dominates the desktop/laptop (for now)

Agenda

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John von Neumann (1903-1957)

In computing

- Stored program computers
- Cellular automata
- Self-replication

Other interests

- Mathematics and statistics
- Inventor of game theory
- Nuclear physics

Princeton connection

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

Known for "Von Neumann architecture"

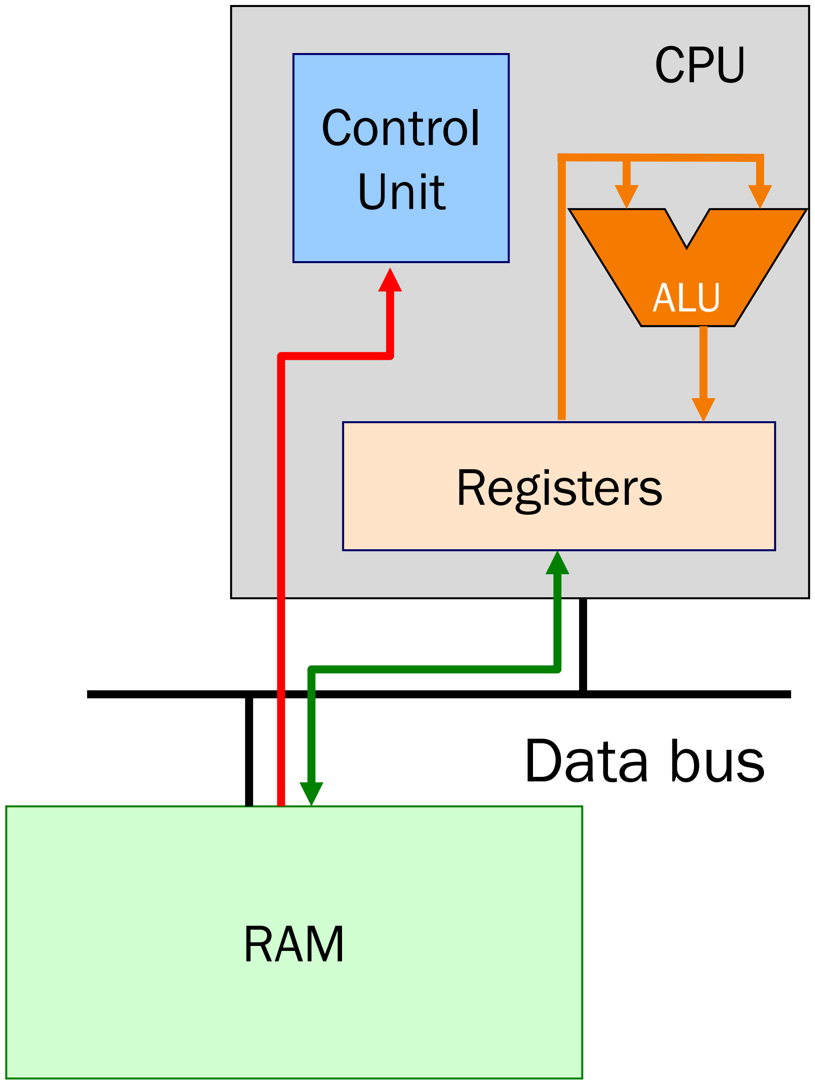
- In which programs are just data in the memory
- Contrast to the now-obsolete "Harvard architecture"

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



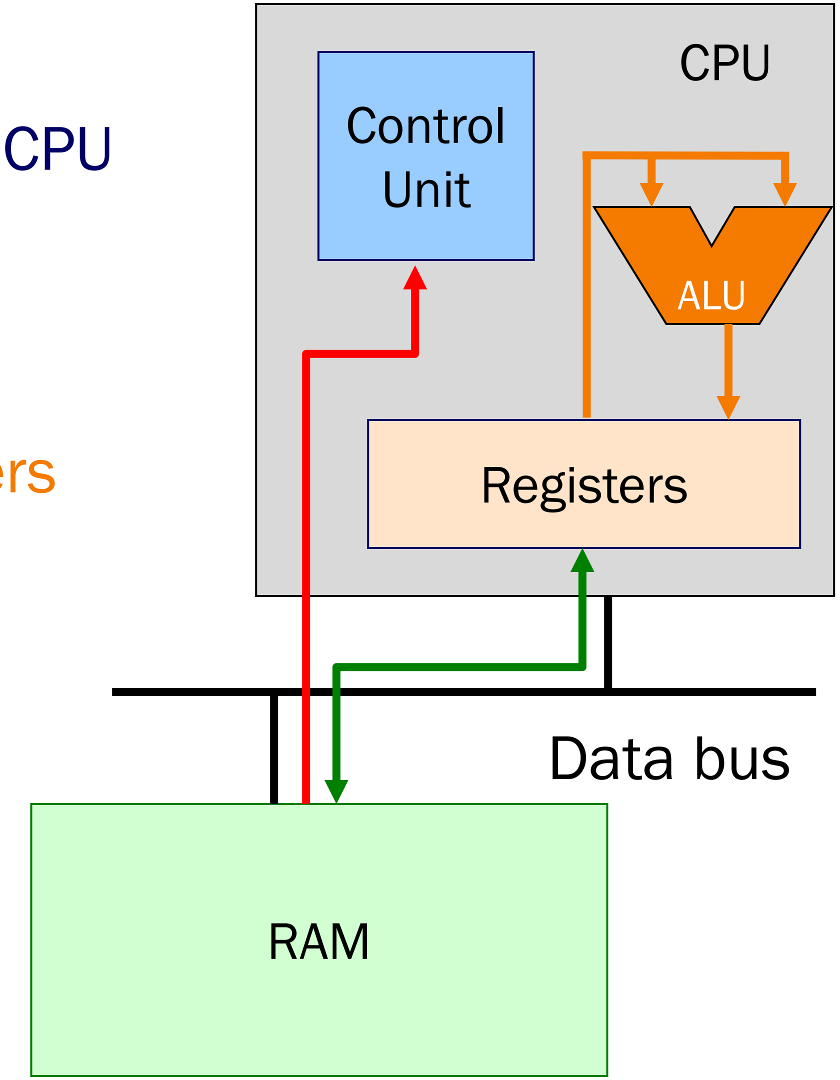
Von Neumann Architecture

Registers

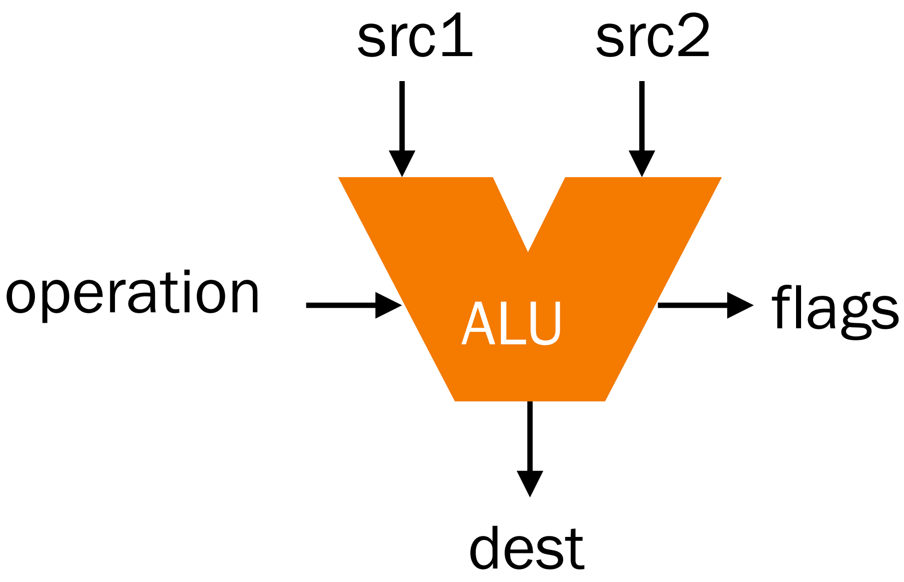
Small amount of storage on the CPU

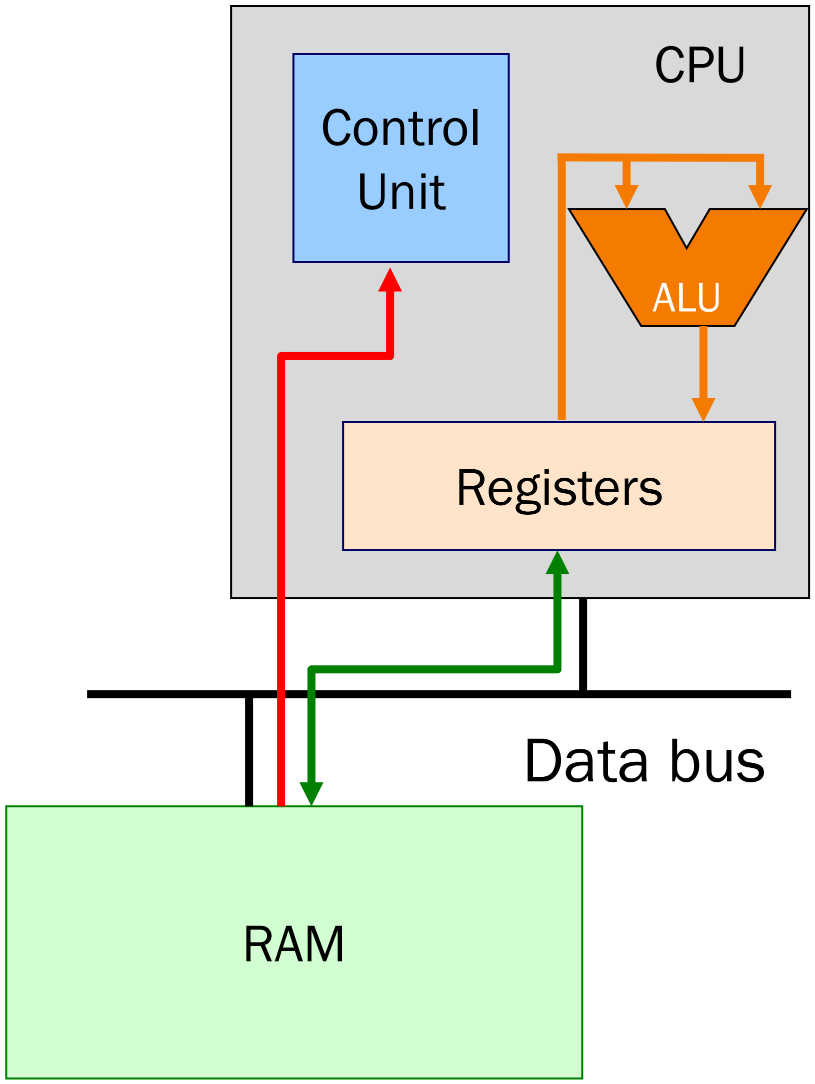
- Top of the “storage hierarchy”
- Very {small, expensive, fast}

ALU instructions operate on registers



ALU Arithmetic Example





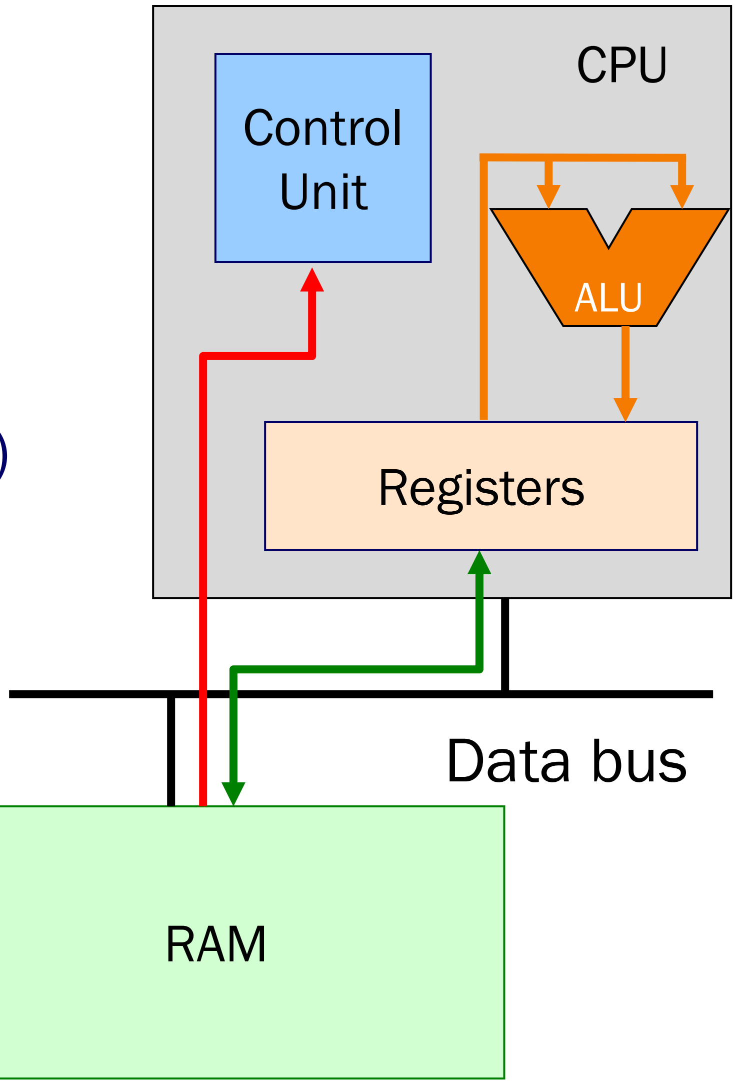
Von Neumann Architecture

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

```
               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

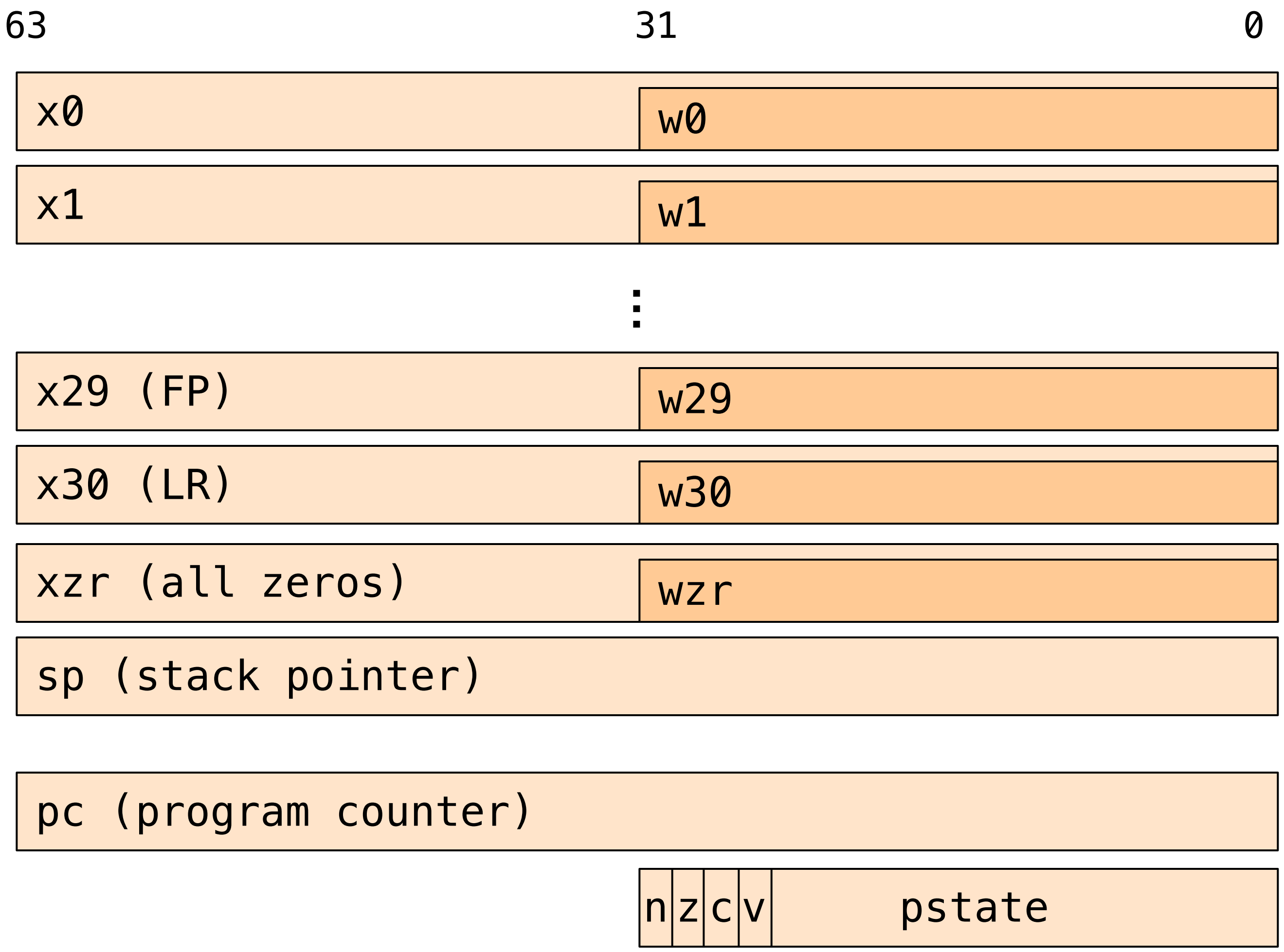
Typical pattern:

- **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)



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

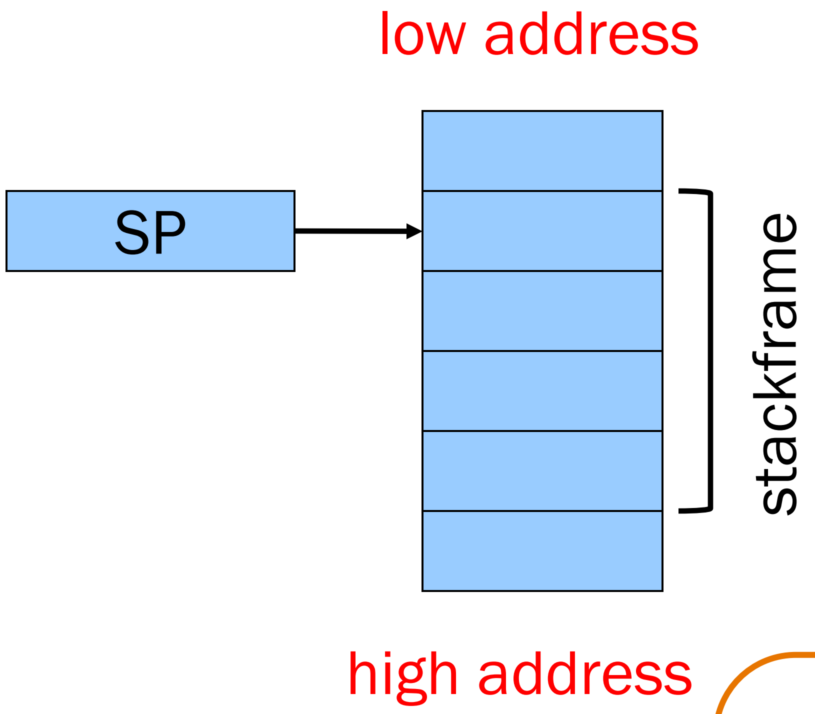
XZR

- 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 stackframe



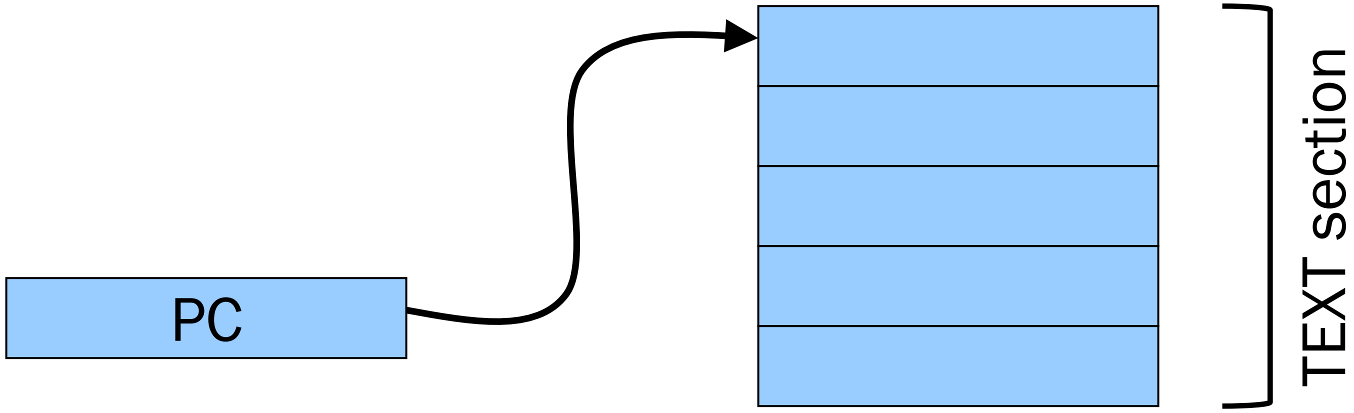
Allows use of the STACK section of memory

(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 instructions to be executed next
- Value changed:
  - Automatically to implement sequential control flow
  - By branch instructions to implement selection, repetition



PSTATE Register

n	z	c	v	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

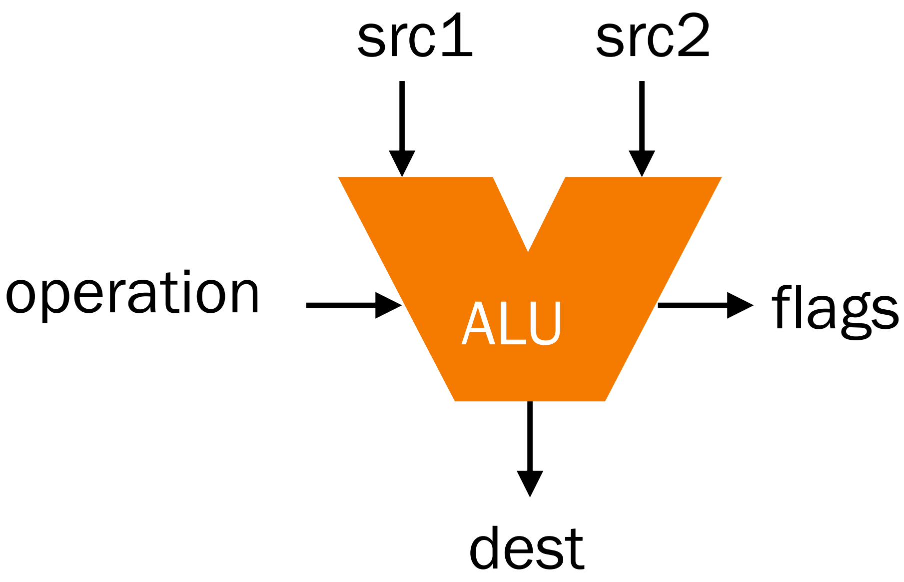
Language Levels

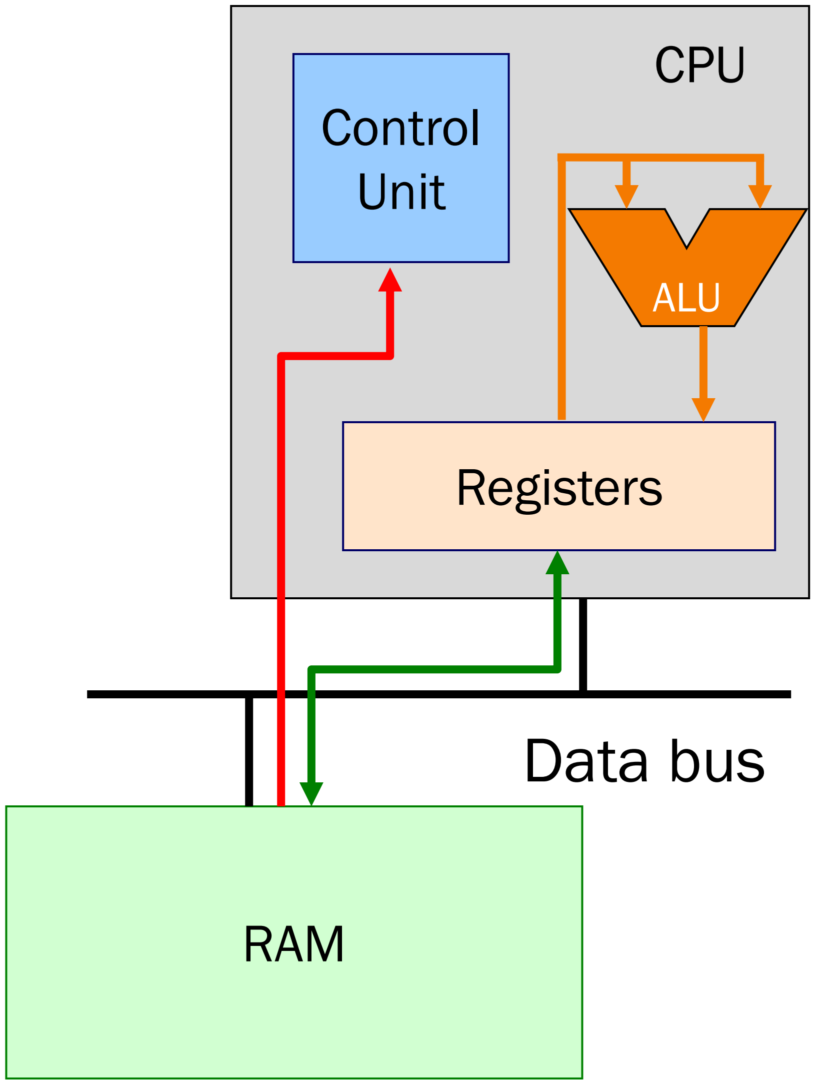
Architecture

Assembly Language: Performing Arithmetic

Assembly Language: Load/Store and Defining Global Data

ALU Arithmetic Example

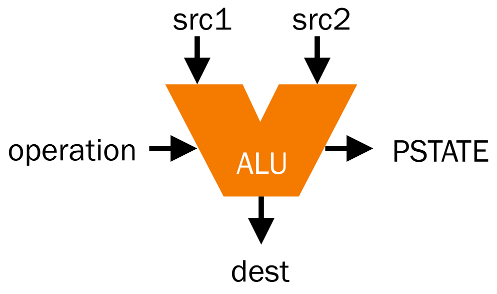




Instruction Format

Many instructions have this format:

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



- **name:** 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

- 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 stored in x1
- width stored in x2
- perim stored 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 stored in x1
- y stored in x2
- z stored in x3

We'll see later how to make this happen

```
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
```

Note arithmetic shift!
Logical right shift would be `lsr` instruction

More Arithmetic: Shortcuts

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

Assume that…

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

We'll see later how to make this happen

```
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 stored in x1
- y stored in x2

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

Mostly the same algorithms, same instructions!

- Can set different condition flags in PSTATE
- Exception is division: sdiv vs udiv instructions

32-bit Arithmetic

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

Assume that…

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

We'll see later how to make this happen

Assembly code using "w" registers:

```
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!
- 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 bytes (8 bit), shorts ("half-words": 16 bit)
  - See appendix of these slides for information on ordering: little-endian vs. big-endian
- Special instructions for signed reads
  - "Sign-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*

```c
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

```c
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

```c
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
```

Declaring data

- "Labels" for locations in memory
- .word: 32-bit int and initial value

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

main()

```c
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
```

Global visibility

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

Make a "pointer"

```c
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

```c
static int length = 1;
static int width = 2;
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int main()
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  perim =
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}
```

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length: .word 1
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  .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
```

Load and store

Use x0 as a "pointer" to load from and store to memory

Return

```c
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

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

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

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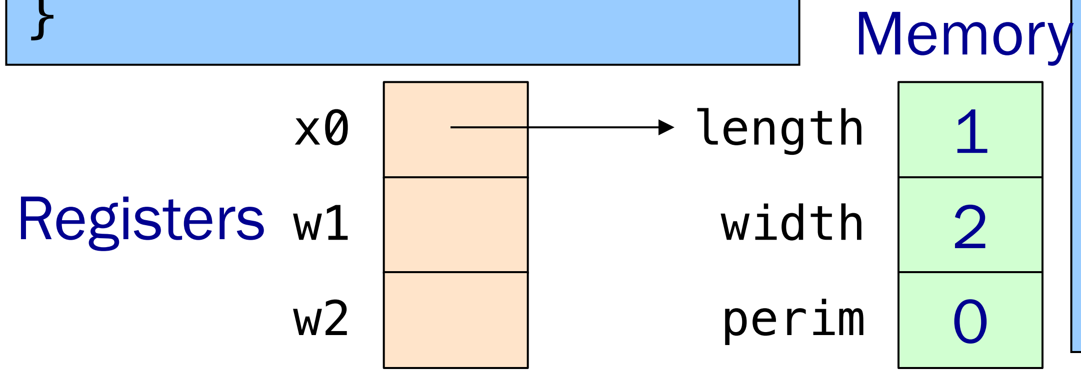
  .global main
main:
adr     x0, length
ldr     w1, [x0]
adr     x0, width
ldr     w2, [x0]
add     w1, w1, w2
lsl     w1, w1, 1
adr     x0, perim
str     w1, [x0]
mov     w0, 0
ret
```



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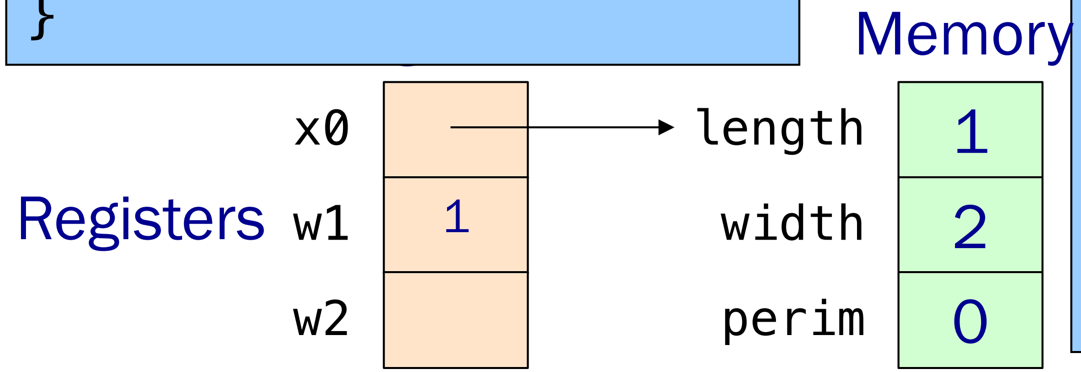
mov     w0, 0
ret
```



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adr     x0, width
ldr     w2, [x0]
add     w1, w1, w2
lsl     w1, w1, 1
adr     x0, perim
str     w1, [x0]
mov     w0, 0
ret
```

Registers

x0	
w1	1
w2	

Memory

length	1
width	2
perim	0

Trace

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static int perim = 0;

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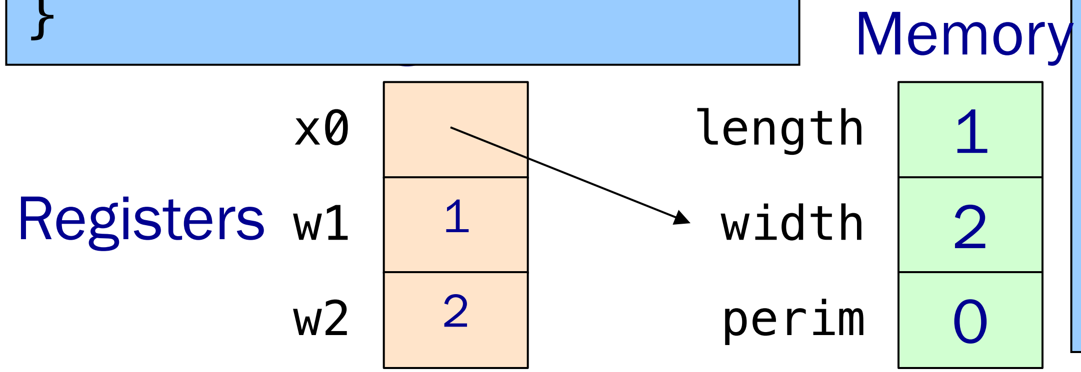
lsl     w1, w1, 1
adr     x0, perim
str     w1, [x0]
mov     w0, 0
ret
```



Trace

```c
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
```

Registers

x0	
w1	3
w2	2

Memory

length	1
width	2
perim	0

Trace

```c
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
```

Registers

x0	
w1	6
w2	2

Memory

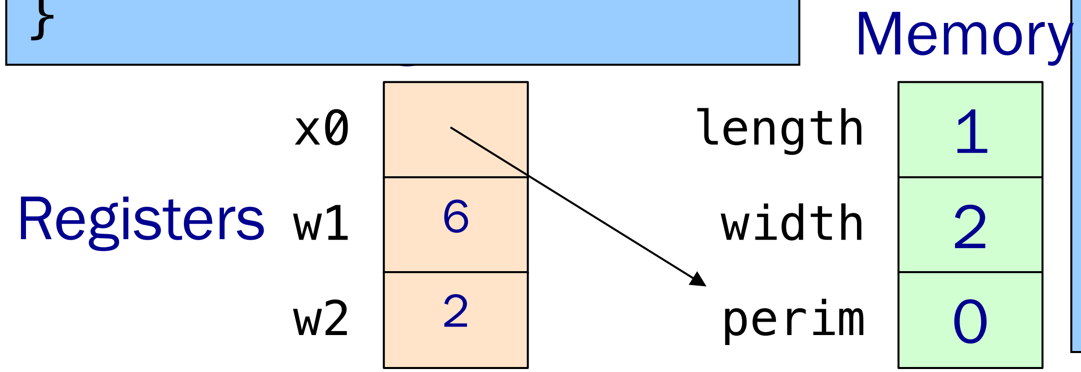
length	1
width	2
perim	0

Trace

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

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

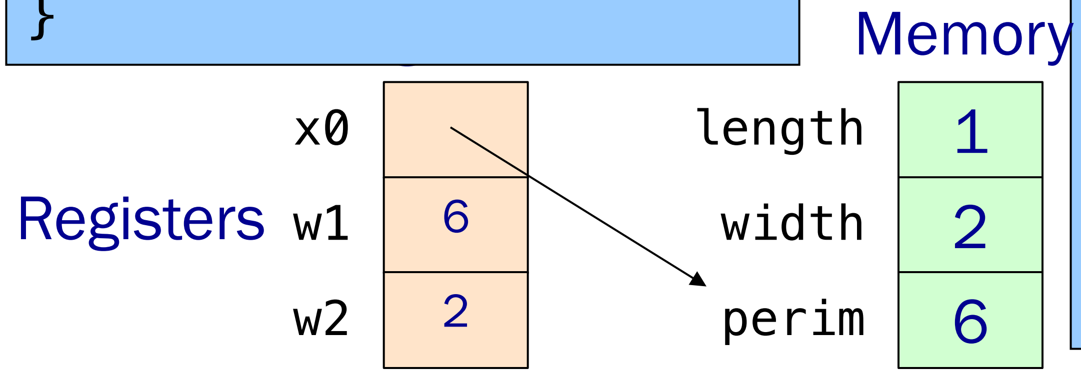
```
  .section .data
length: .word 1
width:  .word 2
perim:  .word 0
  .section .text
  .global main
main:
adr     x0, length
ldr     w1, [x0]
adr     x0, width
ldr     w2, [x0]
add     w1, w1, w2
lsl     w1, w1, 1
adr     x0, perim
str     w1, [x0]
mov     w0, 0
ret
```



Trace

```c
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
```

Trace

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

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

```asm
   .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 value

- Passed back in register w0

Trace

```c
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
```

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?

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 curated/hand-written assembly language examples
  - Chapters 2-5 of Pyeatt and Ughetta book
- Study compiler-generated assembly language code (complicated, YMMV)
  - `gcc217 –S somefile.c`