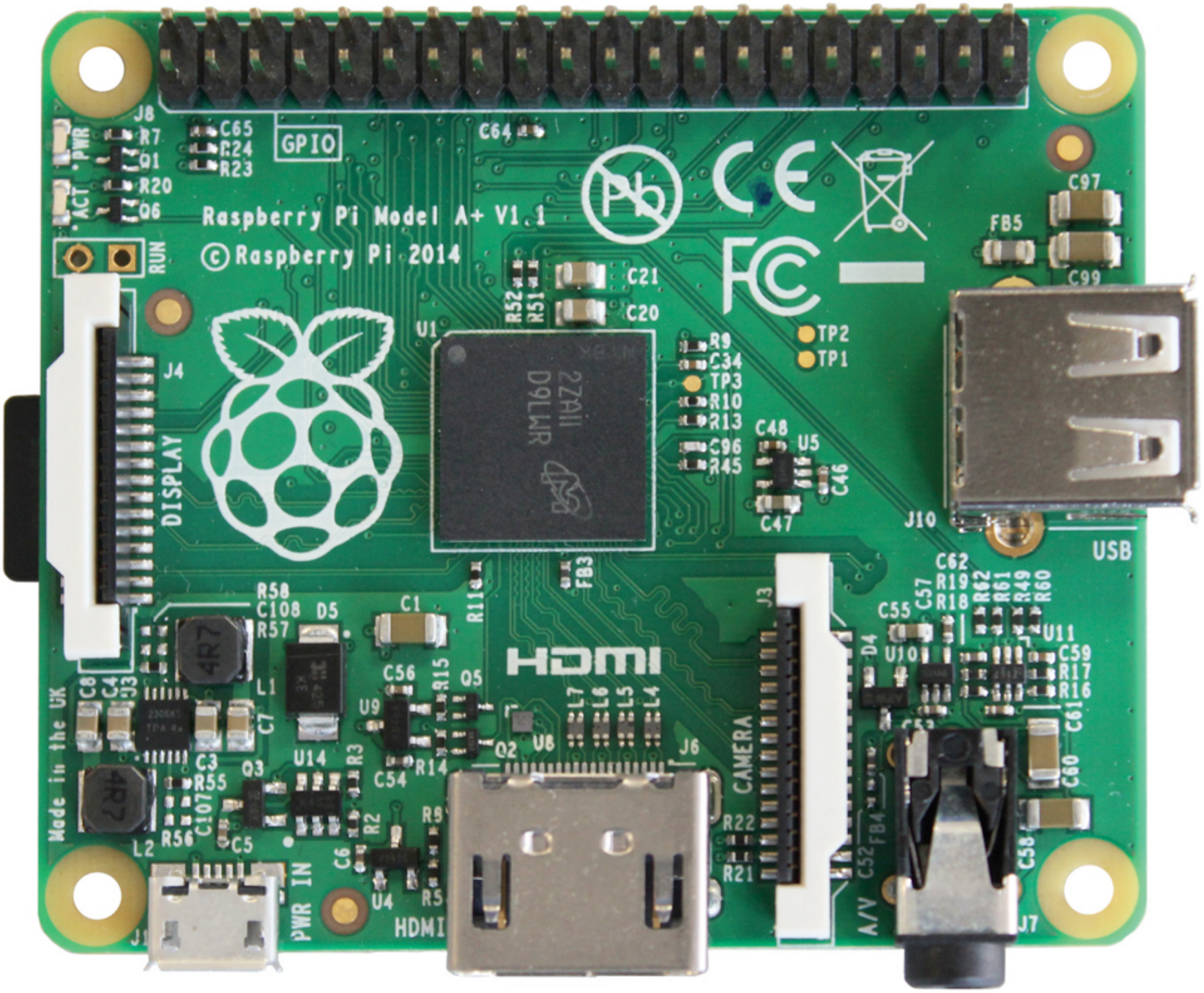
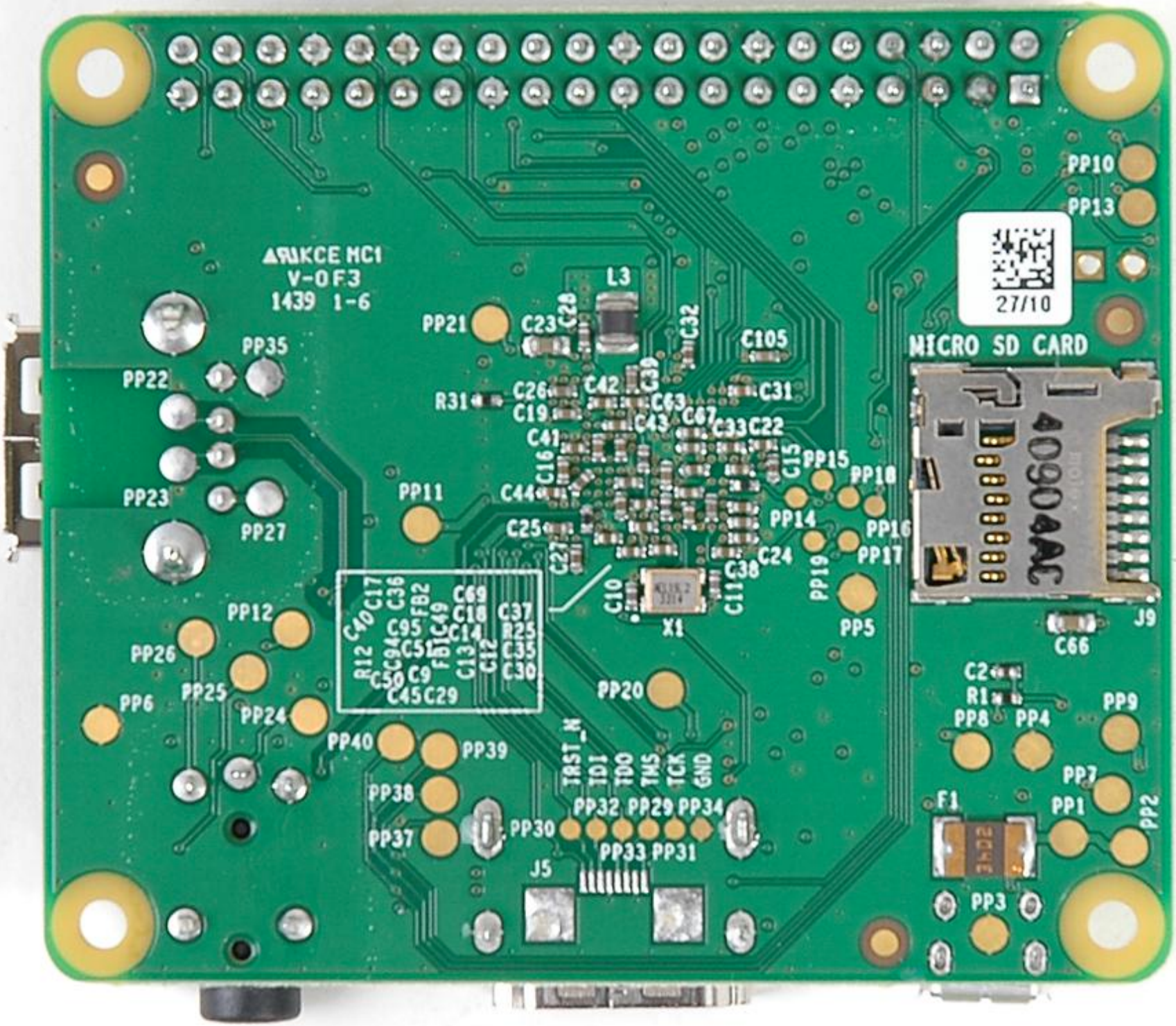
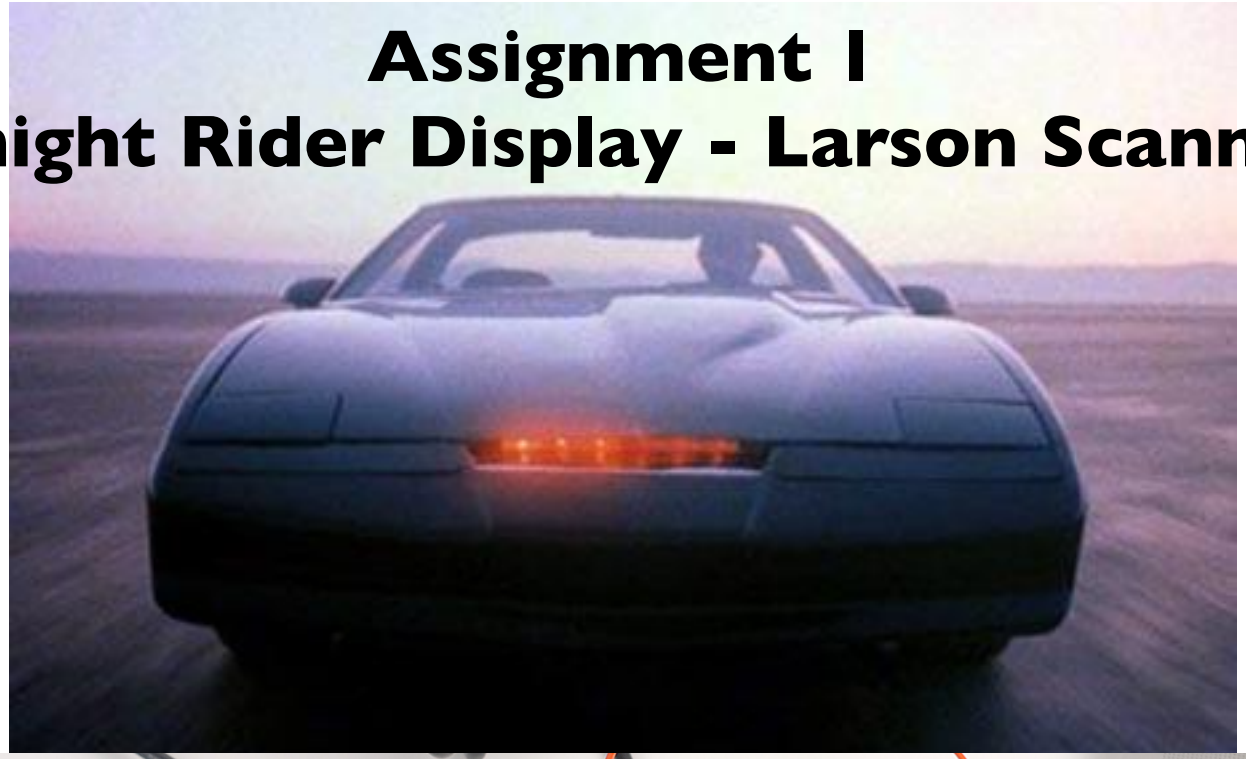
ARM
Processor and Memory Architecture

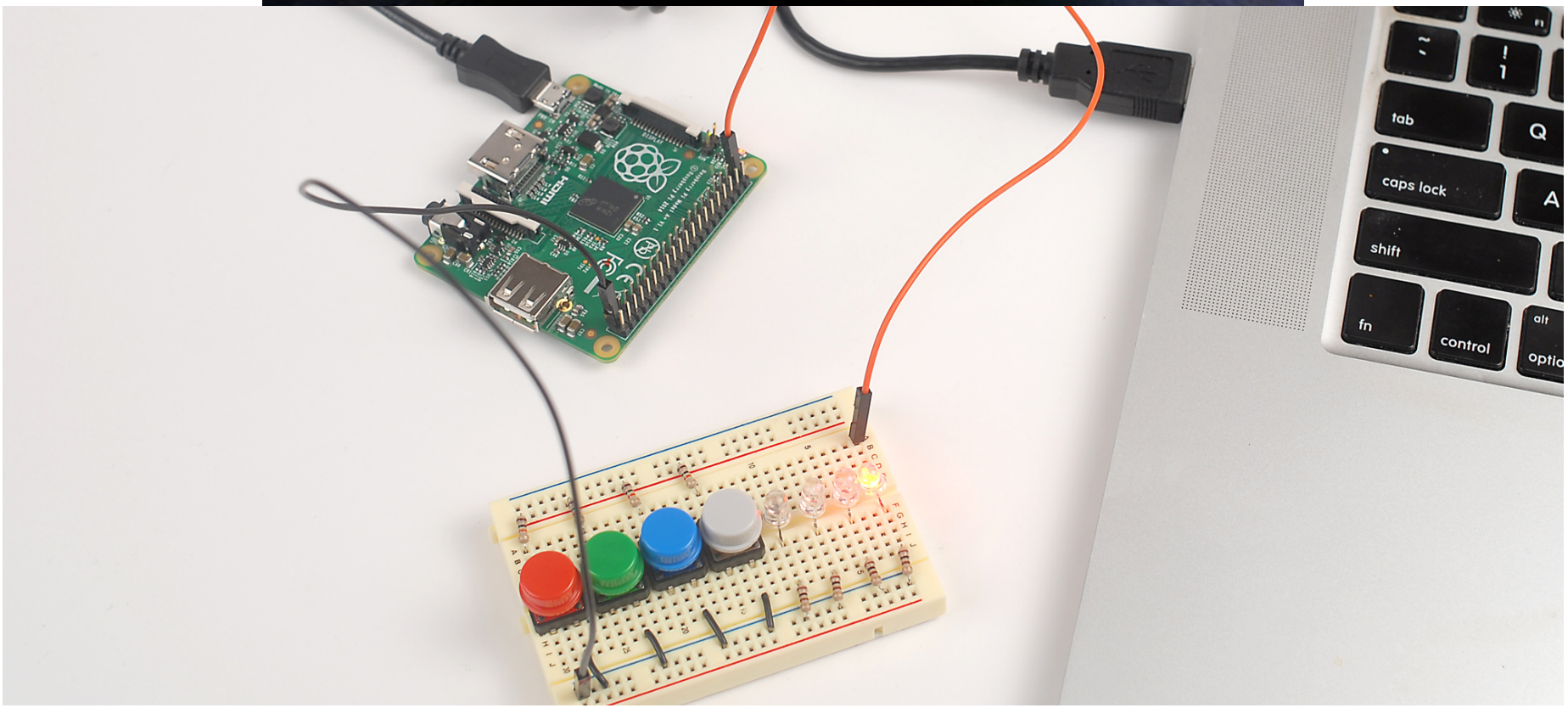
Goal: Turn on an LED


GPIO
Raspberry Pi Model A+ V1.1
© Raspberry Pi 2014
DISPLAY
HDMI
CAMERA
USB
A/V
PWR IN
HDMI
Made in the UK

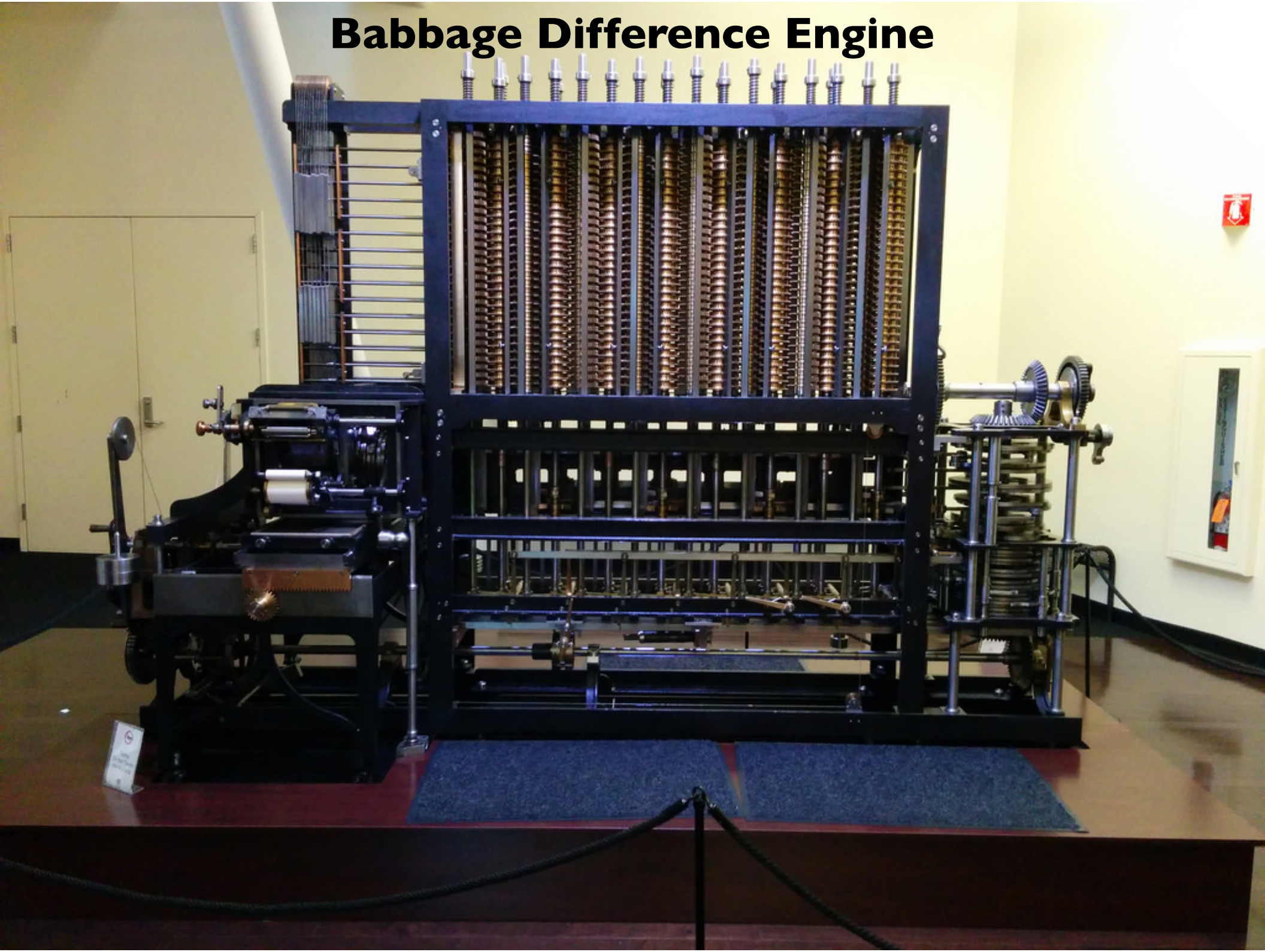

ARIKCE MC1
V-0 F3
1439 1-6
27/10
MICRO SD CARD
40904AC
L3
X1
J5
J9
F1
PP10
PP13
PP35
PP22
PP23
PP27
PP11
PP21
PP12
PP26
PP25
PP6
PP24
PP40
PP39
PP38
PP37
PP30
PP20
PP32
PP29
PP34
PP33
PP31
PP15
PP18
PP14
PP16
PP17
PP19
PP5
PP8
PP4
PP9
PP7
PP1
PP2
PP3
C66
TRST_N
TDI
TDO
TMS
TCK
GND

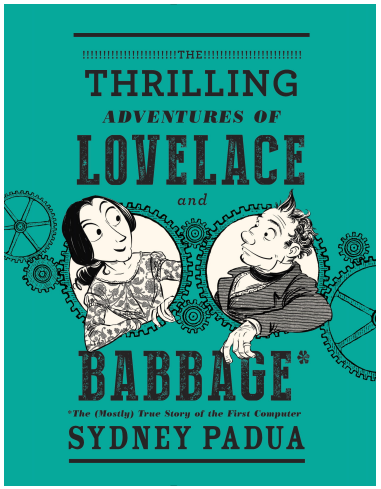
Assignment 1
Knight Rider Display - Larson Scanner





Babbage Difference Engine



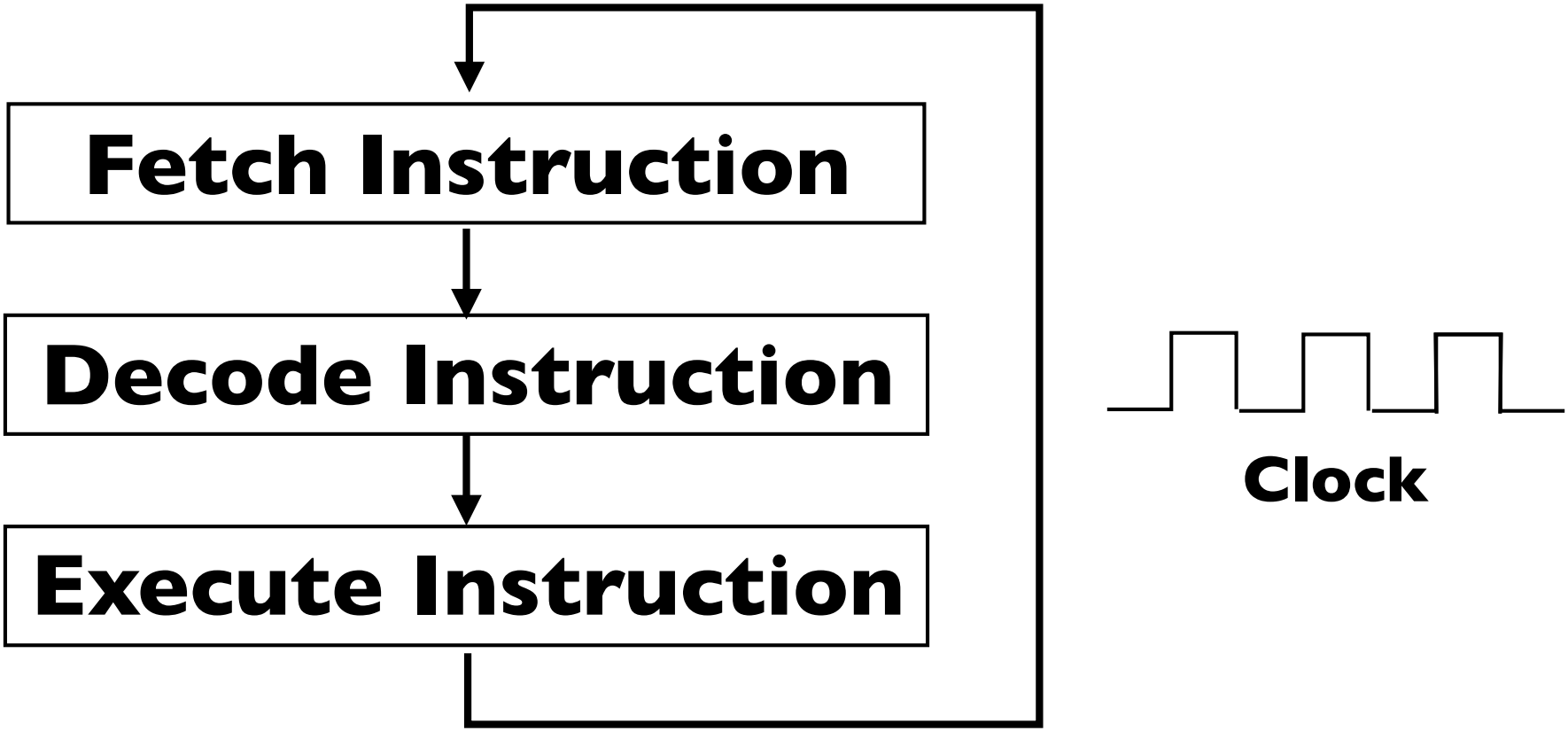


Analytical Engine

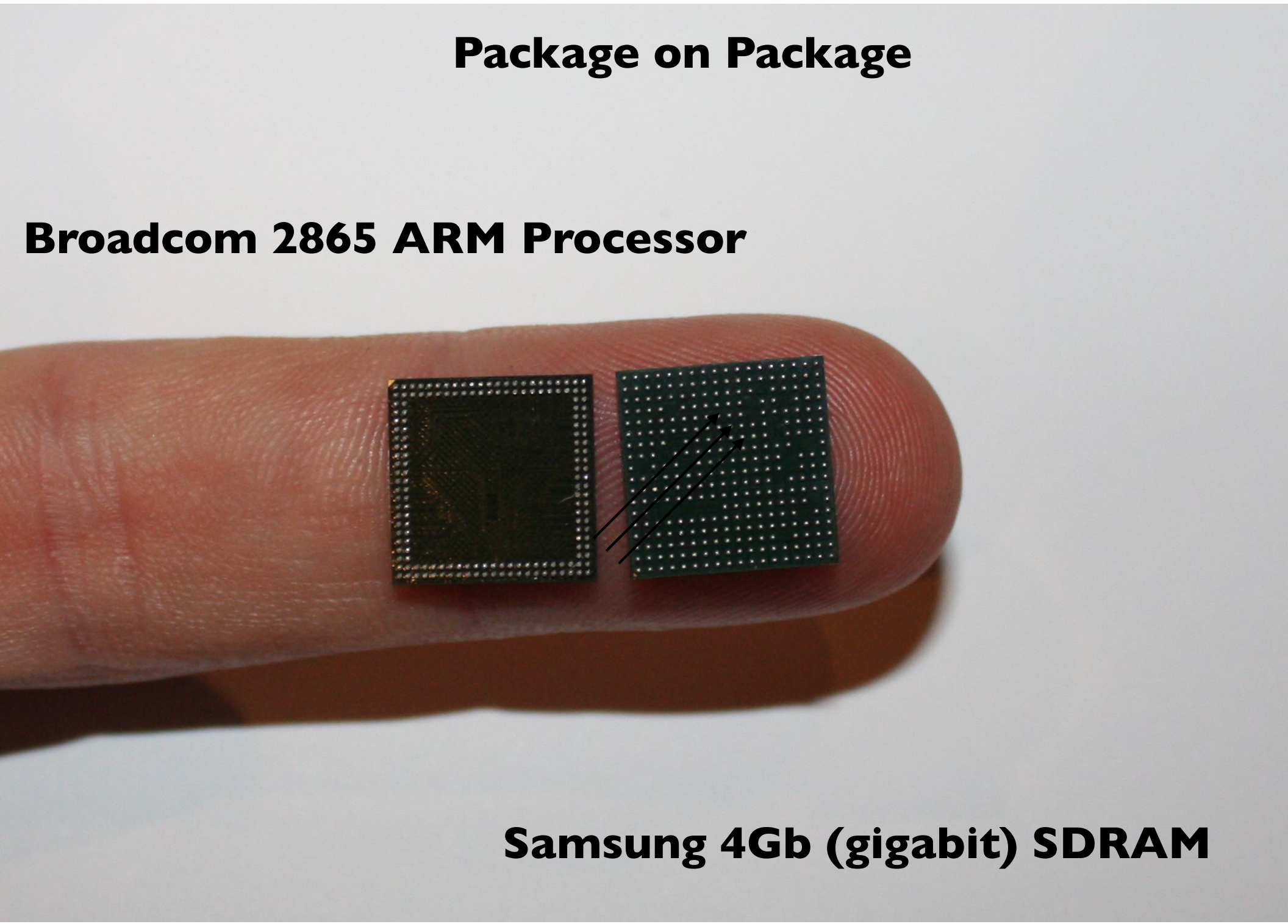
Universal Computer

http://www.theguardian.com/technology/2015/apr/12/thrilling-adventures-ada-lovelace-charles-babbage-sydney-padua

Running a Program



Package on Package

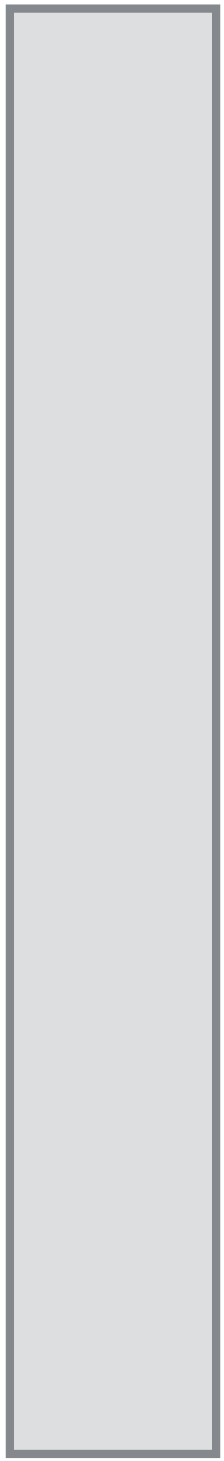


Memory used to store both instructions and data

Storage locations are accessed using 32-bit addresses

Maximum addressable memory is 4 GB (gigabyte)

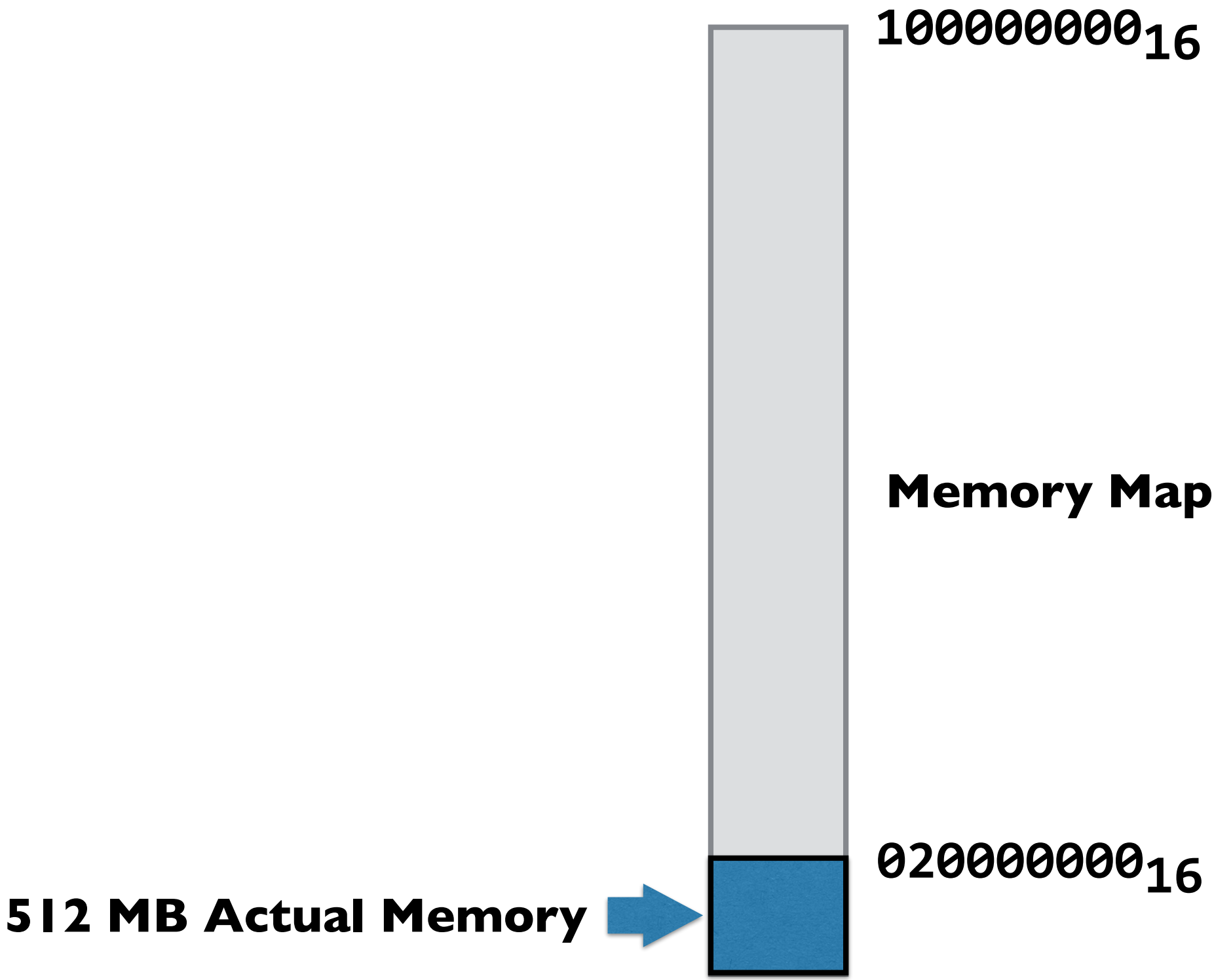
Address refers to a *byte (8-bits)*



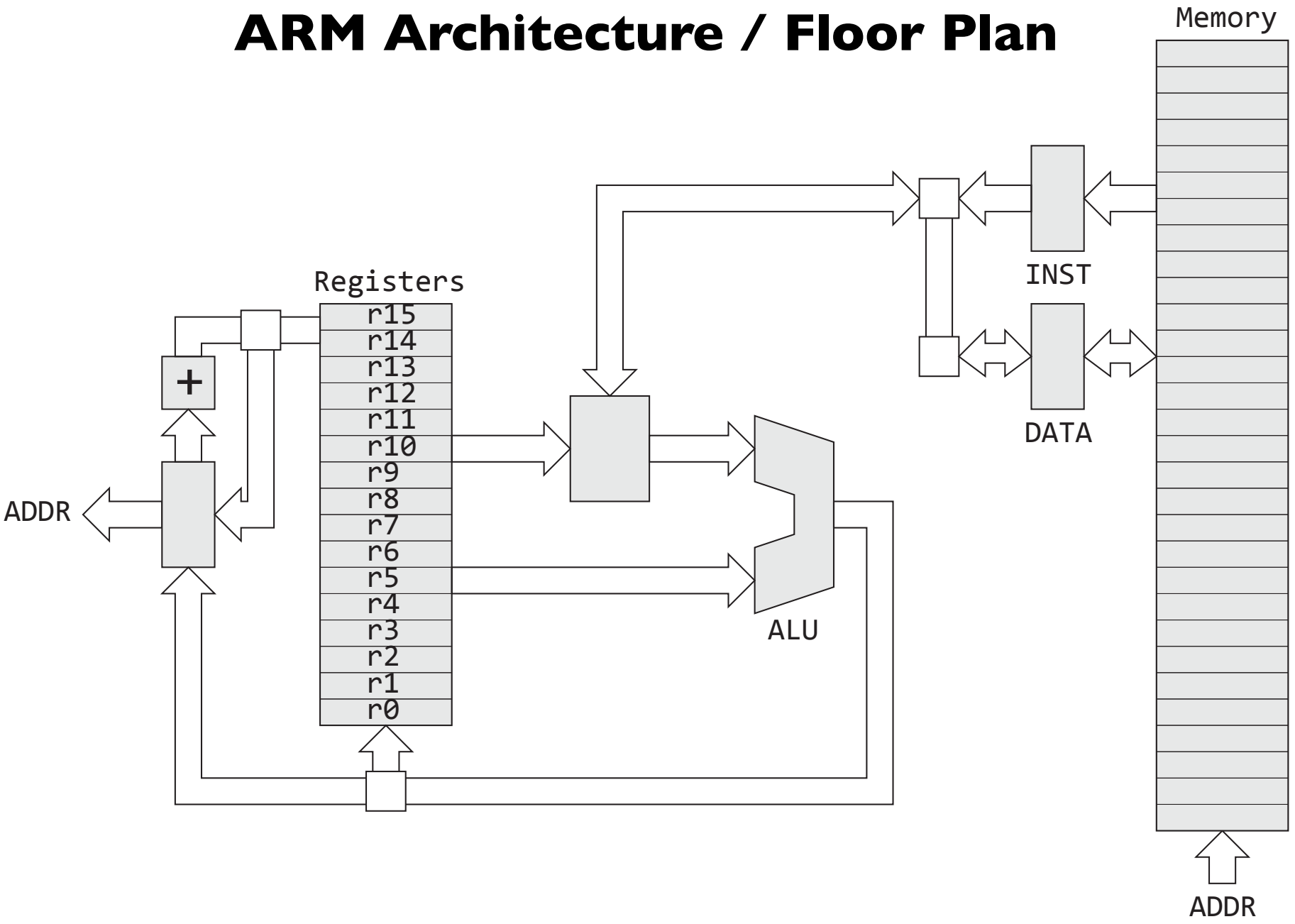
100000000_{16}

Memory Map

00000000_{16}

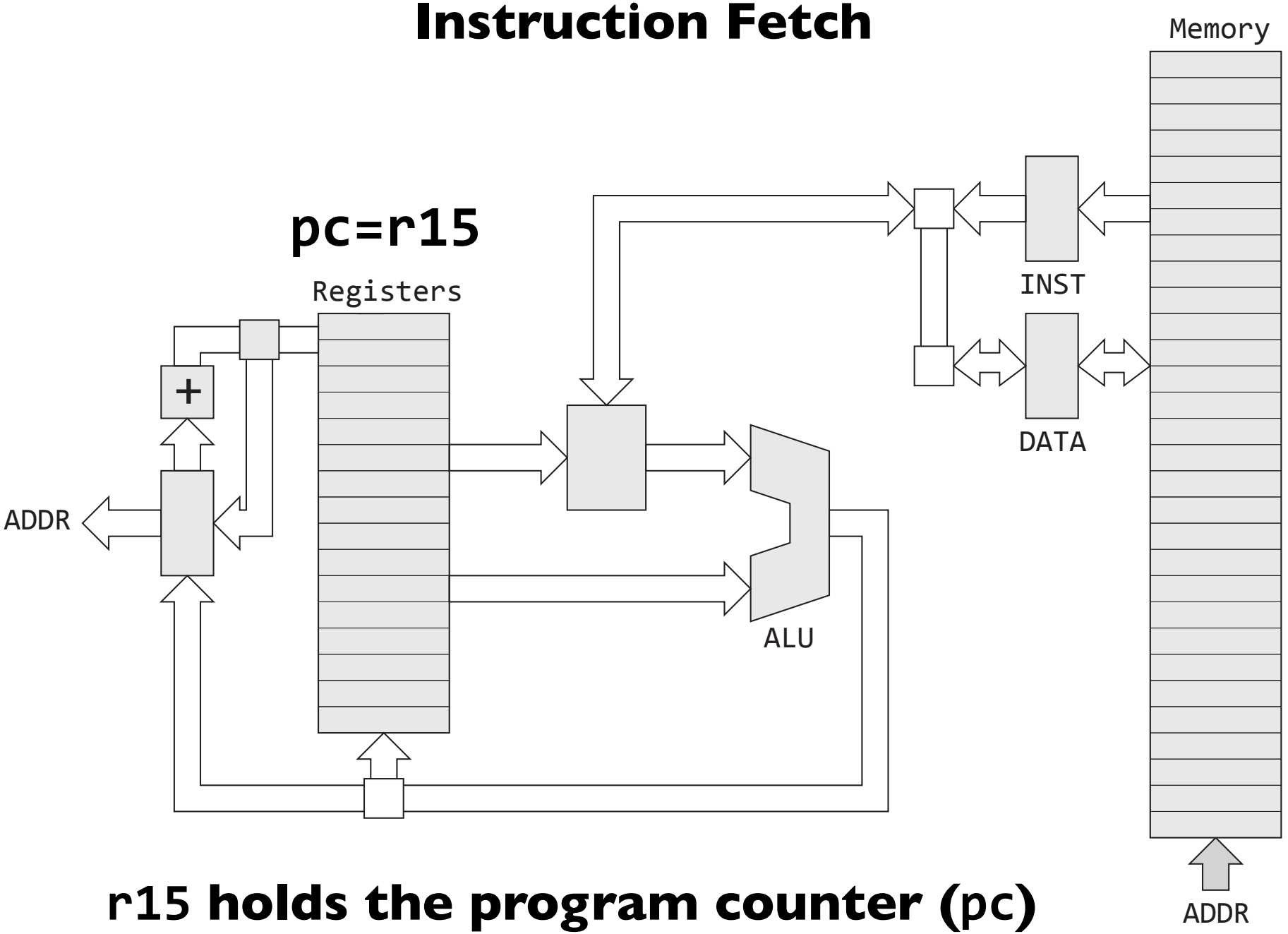

100000000_{16}
Memory Map
020000000_{16}
512 MB Actual Memory

ARM Architecture / Floor Plan



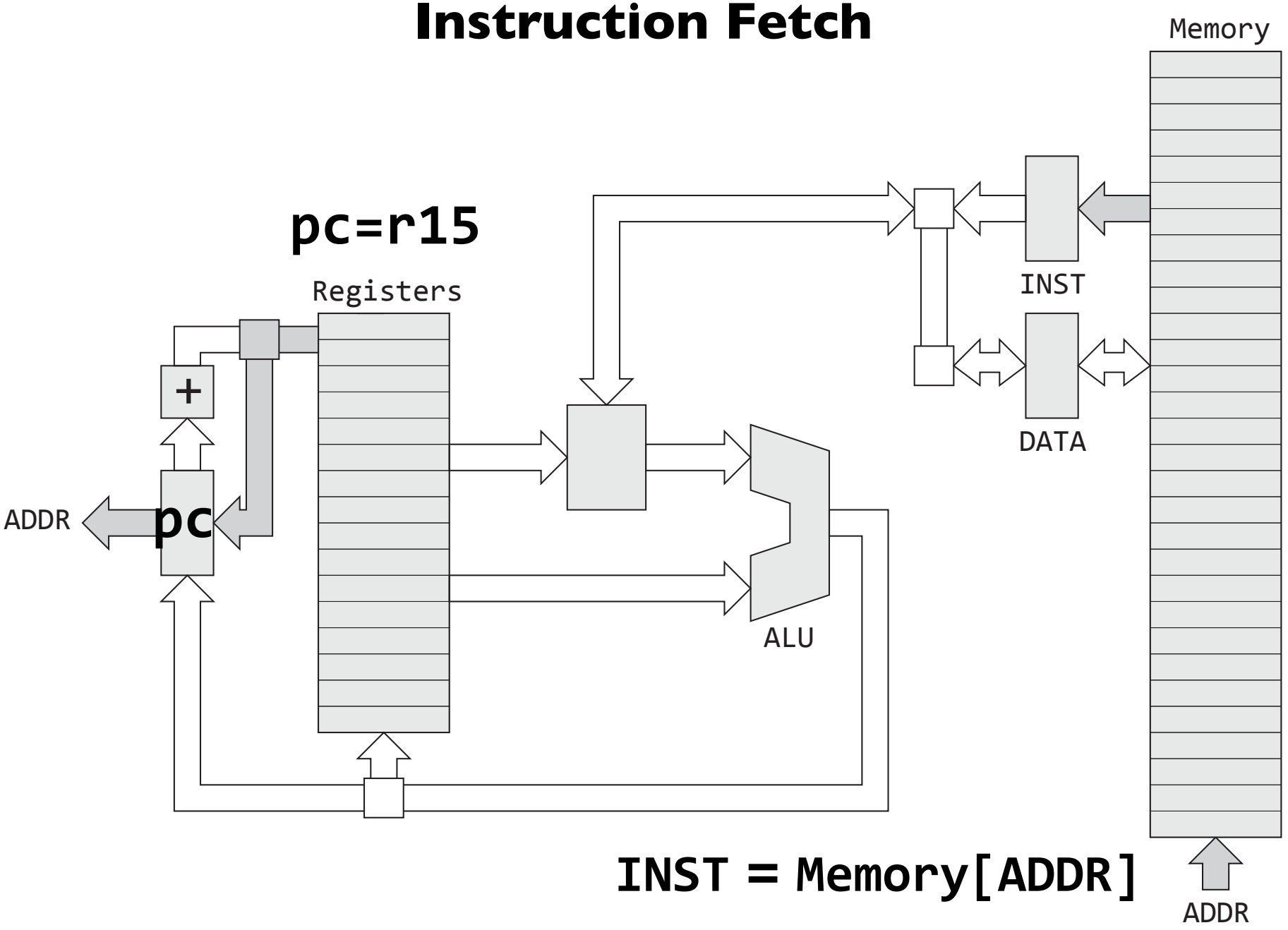
Key Fact: Everything is organized into 32-bit words

Instruction Fetch



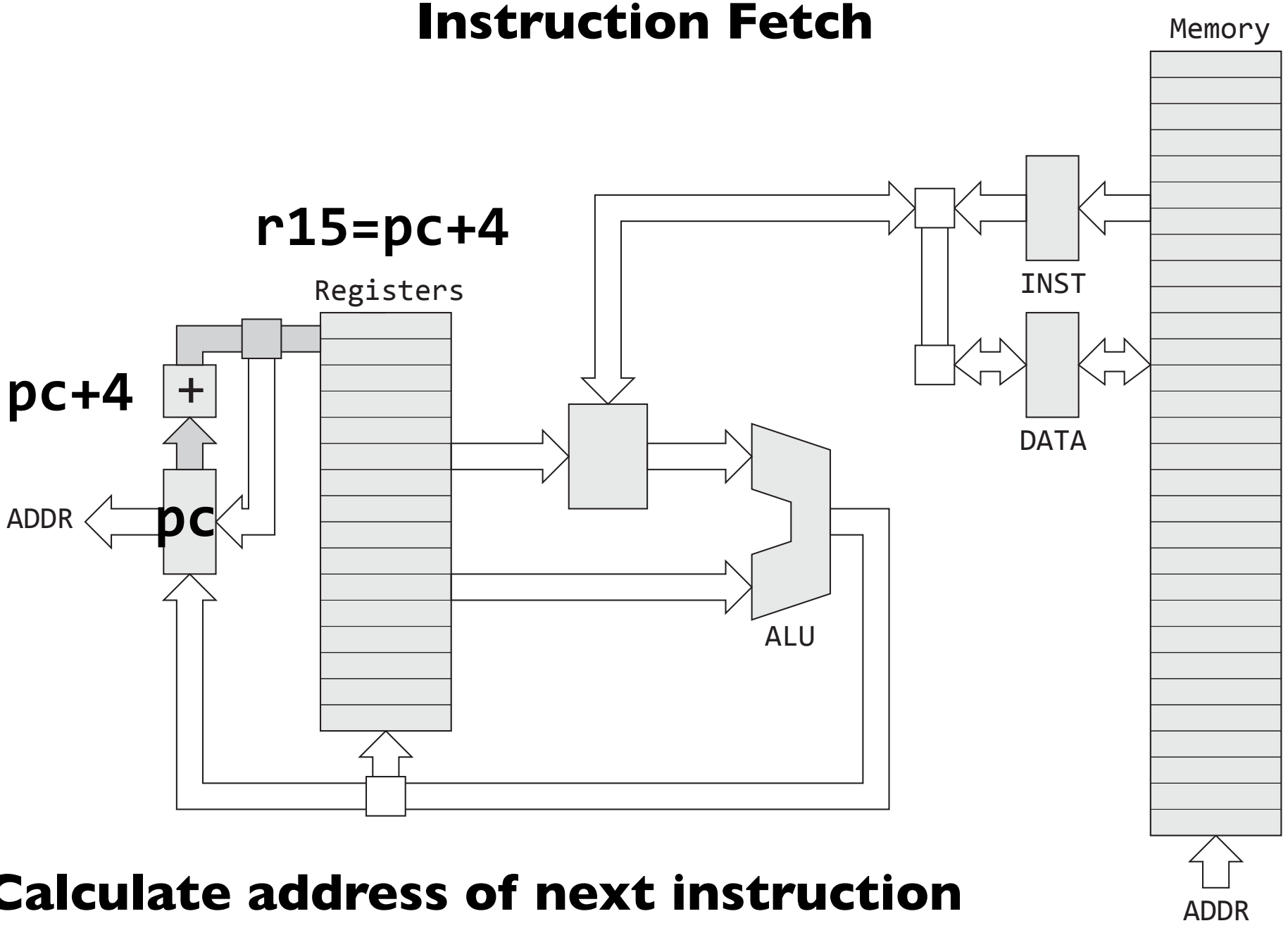
r15 holds the program counter (pc)

Instruction Fetch



Addresses and instructions are 32-bit words

Instruction Fetch



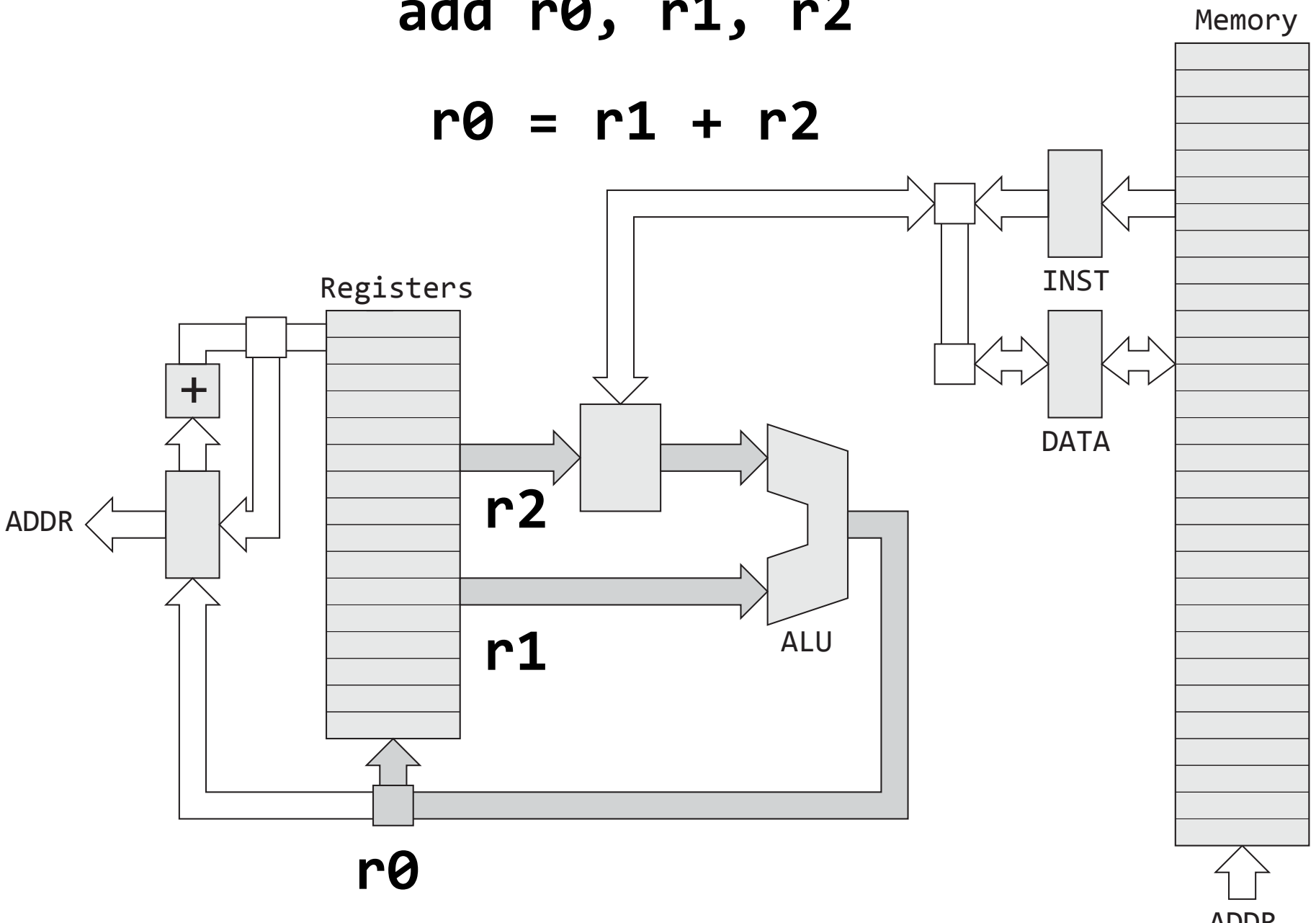
Calculate address of next instruction

Why pc+4?

Arithmetic-Logic Unit (ALU)

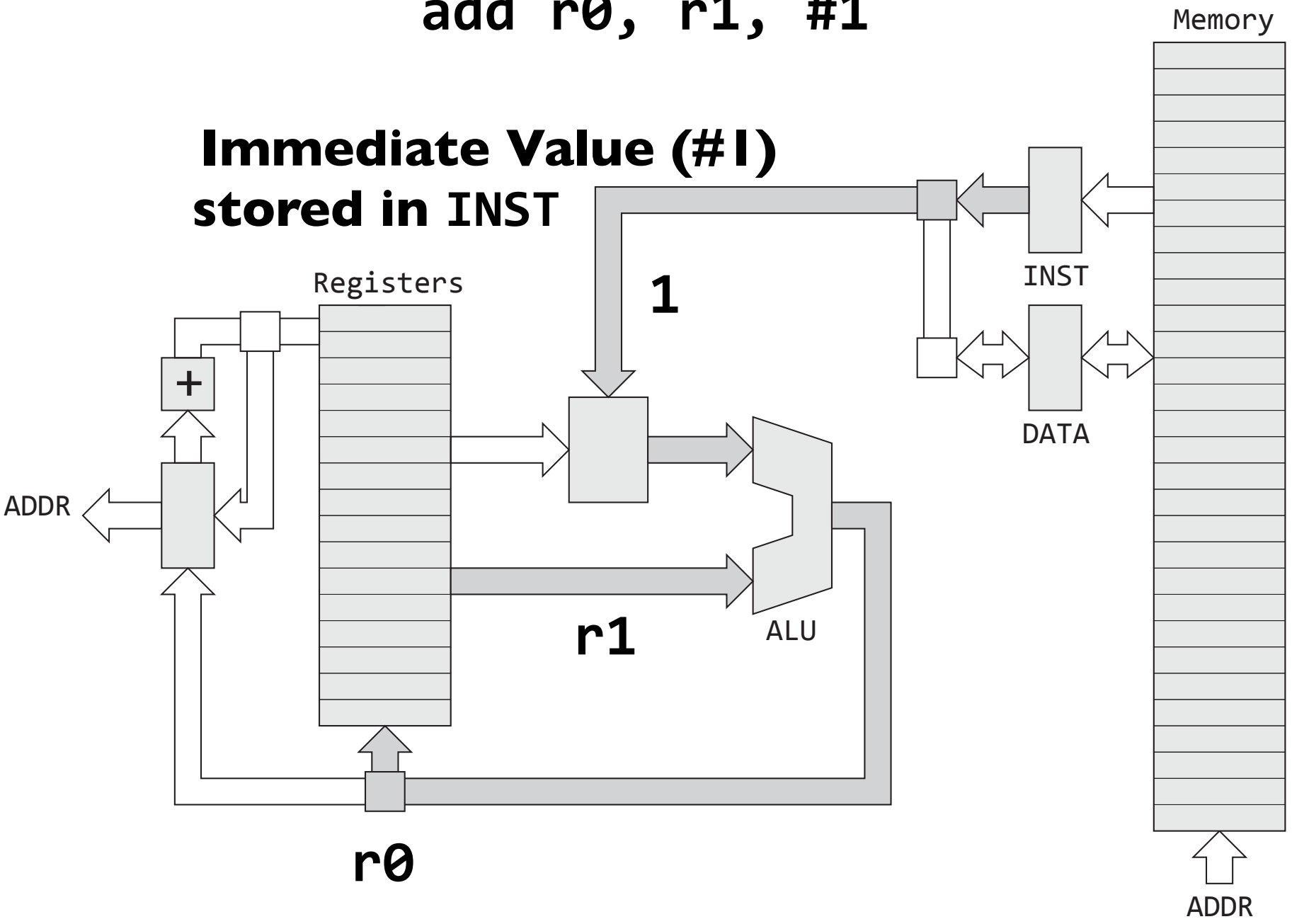
```
add r0, r1, r2

r0 = r1 + r2
```



ALU only operates on registers
Registers are also 32-bit words

add r0, r1, #1


Memory
Immediate Value (#1)
stored in INST
Registers
1
INST
DATA
+
ADDR
r1
ALU
r0
ADDR

Add Instruction

Meaning (defined as math or C code)

```
r0 = r1 + r2
```

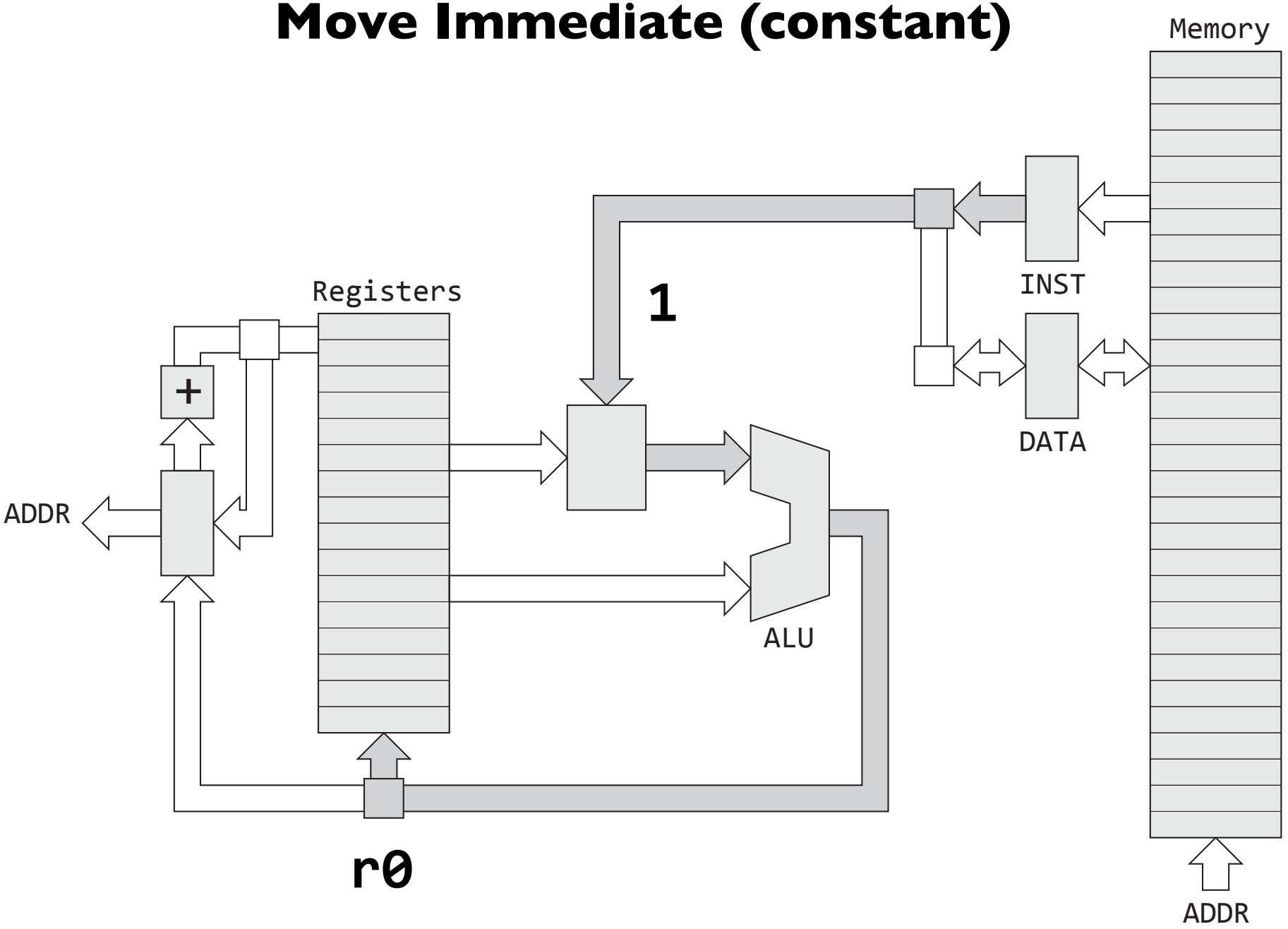
Assembly language (result is leftmost register)

```
add r0, r1, r2
```

Machine code (more on this later)

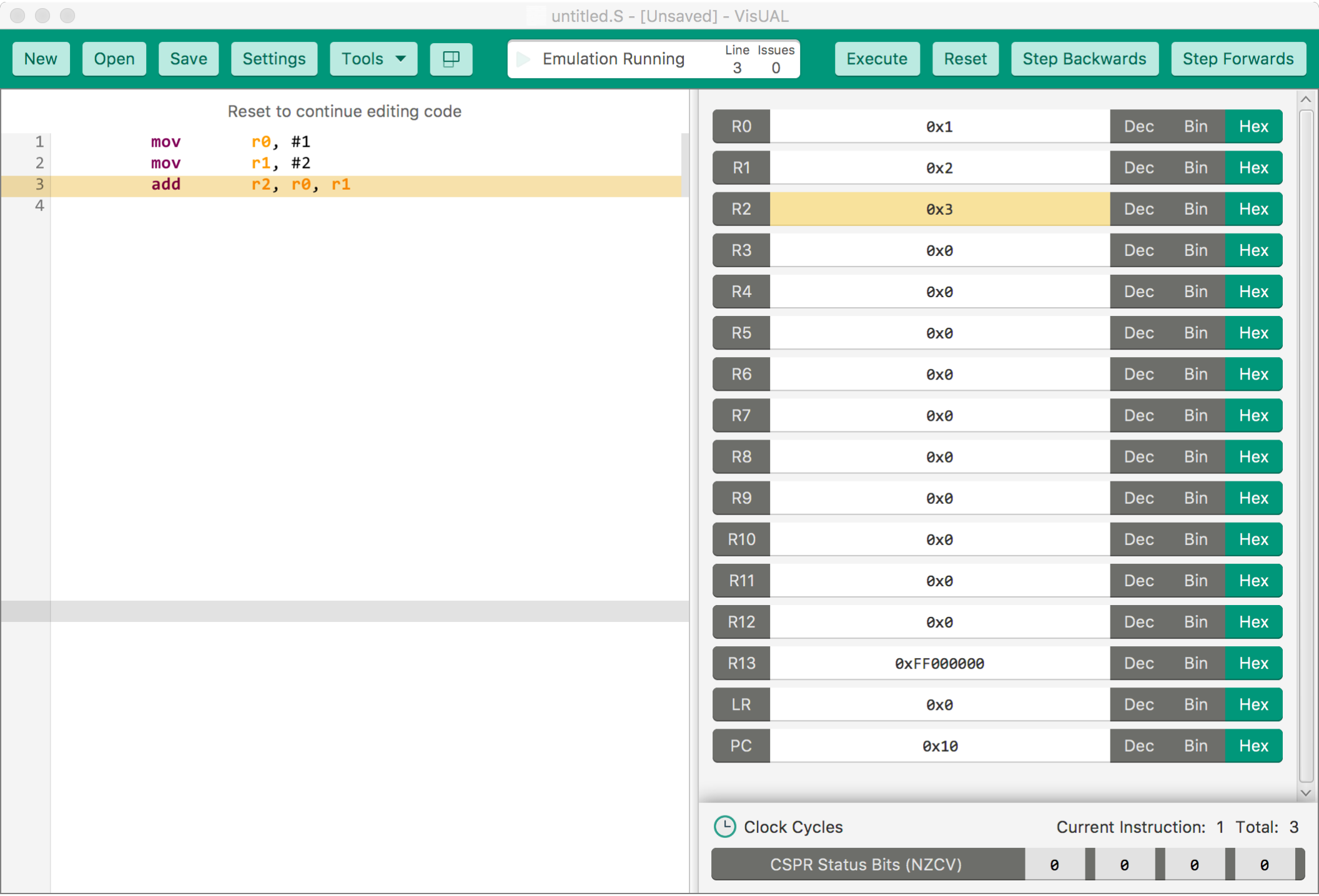
```
E0 81 00 02
```

Move Immediate (constant)




```
mov r0, #1
```

VisUAL


untitled.S - [Unsaved] - VisUAL
New
Open
Save
Settings
Tools
Emulation Running
Line 3
Issues 0
Execute
Reset
Step Backwards
Step Forwards
Reset to continue editing code
1 mov r0, #1
2 mov r1, #2
3 add r2, r0, r1
4
R0 0x1 Dec Bin Hex
R1 0x2 Dec Bin Hex
R2 0x3 Dec Bin Hex
R3 0x0 Dec Bin Hex
R4 0x0 Dec Bin Hex
R5 0x0 Dec Bin Hex
R6 0x0 Dec Bin Hex
R7 0x0 Dec Bin Hex
R8 0x0 Dec Bin Hex
R9 0x0 Dec Bin Hex
R10 0x0 Dec Bin Hex
R11 0x0 Dec Bin Hex
R12 0x0 Dec Bin Hex
R13 0xFF000000 Dec Bin Hex
LR 0x0 Dec Bin Hex
PC 0x10 Dec Bin Hex
Clock Cycles
Current Instruction: 1 Total: 3
CSPR Status Bits (NZCV) 0 0 0 0

Conceptual Questions

1. Suppose your program starts at `0x8000`, what assembly language instruction could you execute to jump to and start executing instructions at that location.

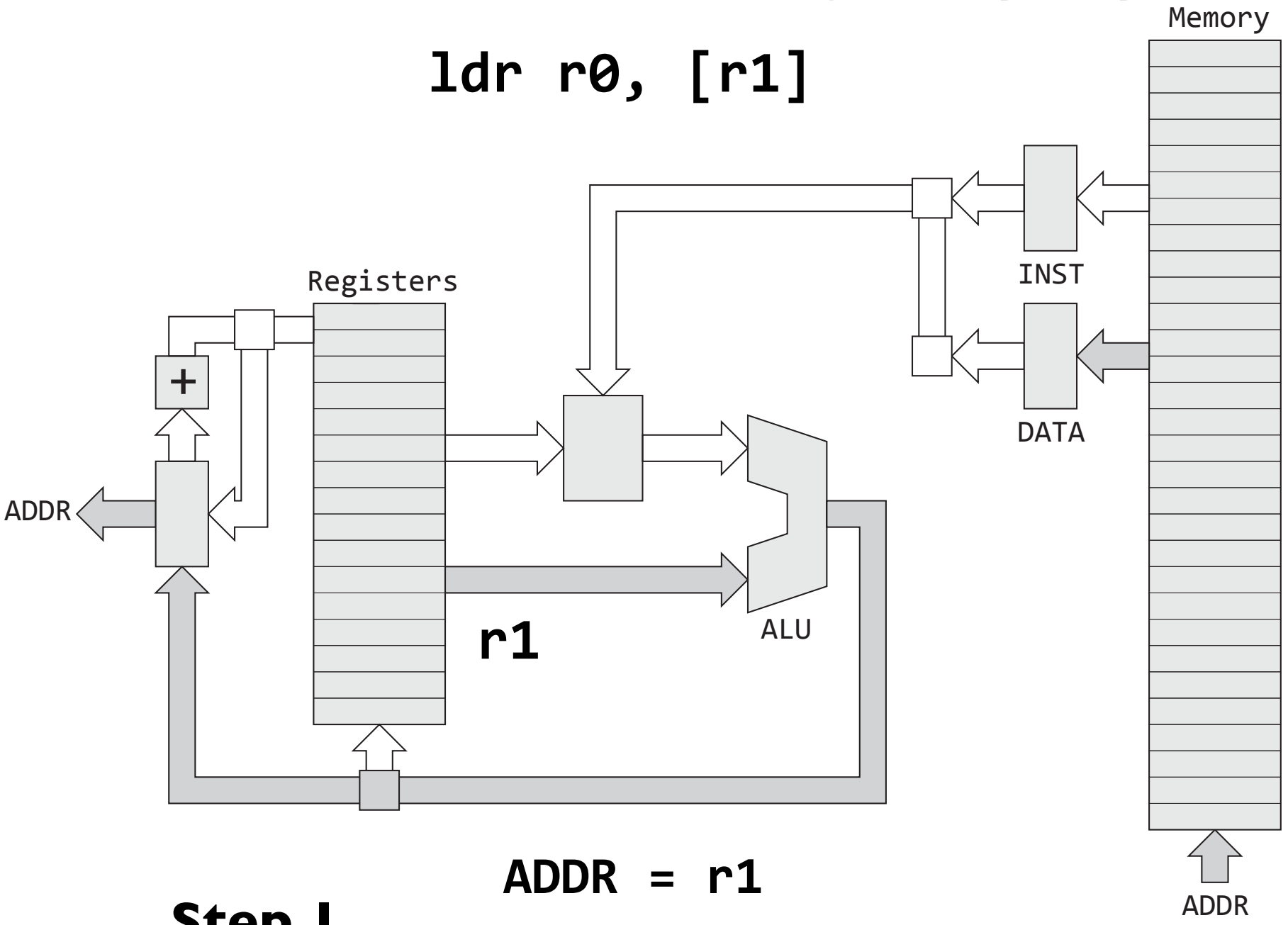
2. If all instructions are 32-bits, can you move any 32-bit constant value into a register using a single `mov` instruction?

3. What is the difference between a memory location and a register?

Load and Store Instructions

Load from Memory to Register (LDR)

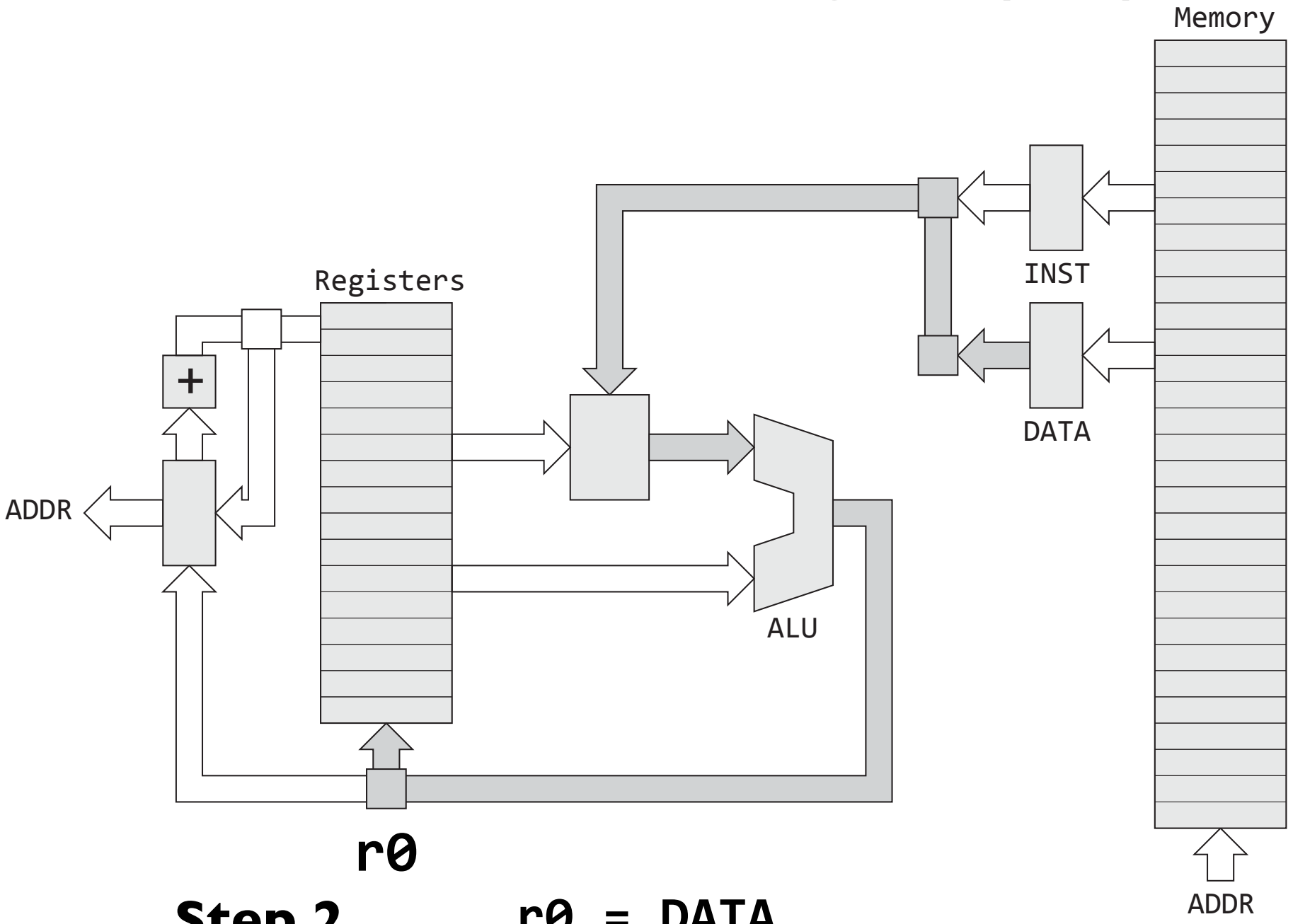
```
ldr r0, [r1]
```



Step 1

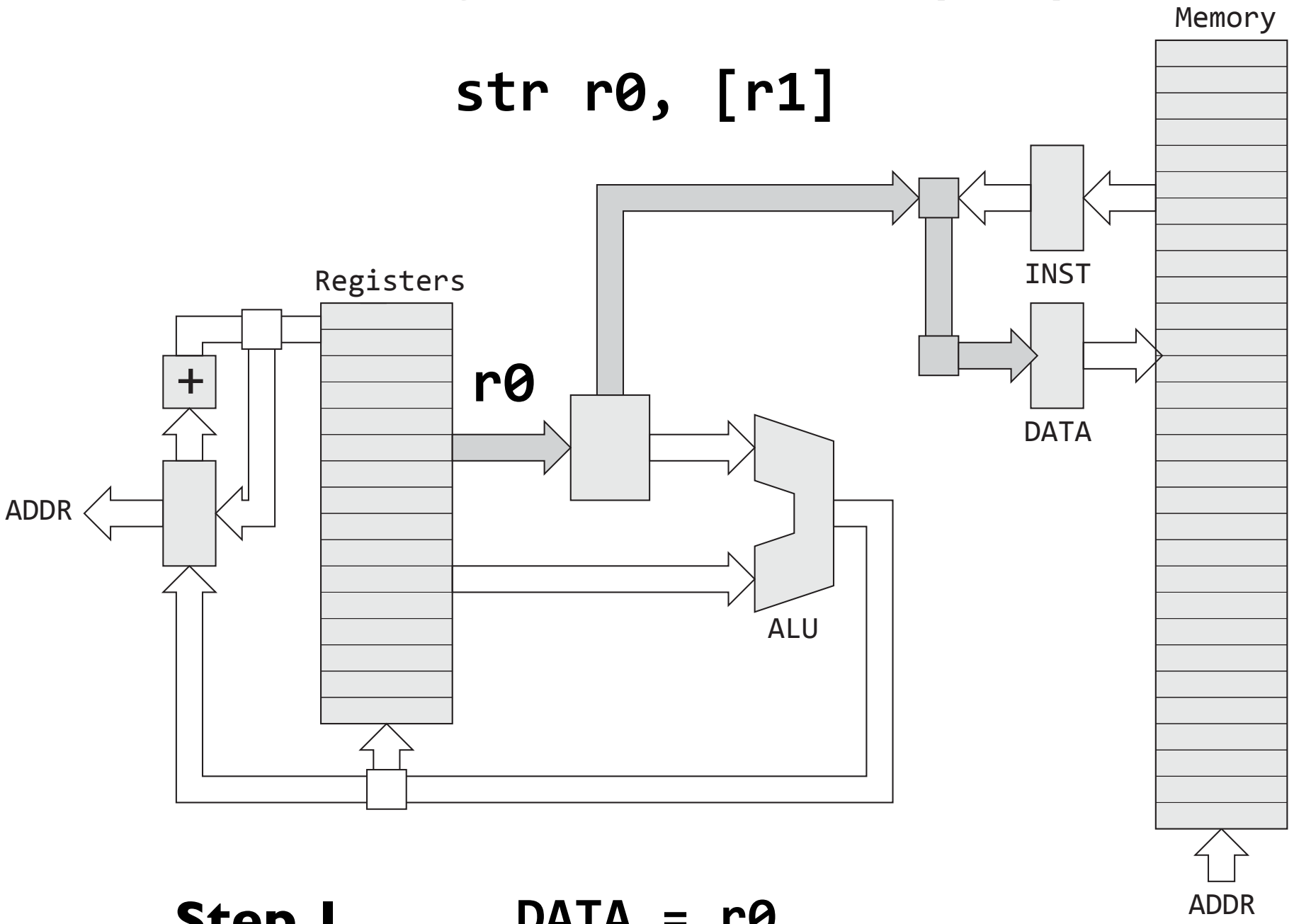
```
ADDR = r1
DATA = Memory[ADDR]
```

Load from Memory to Register (LDR)



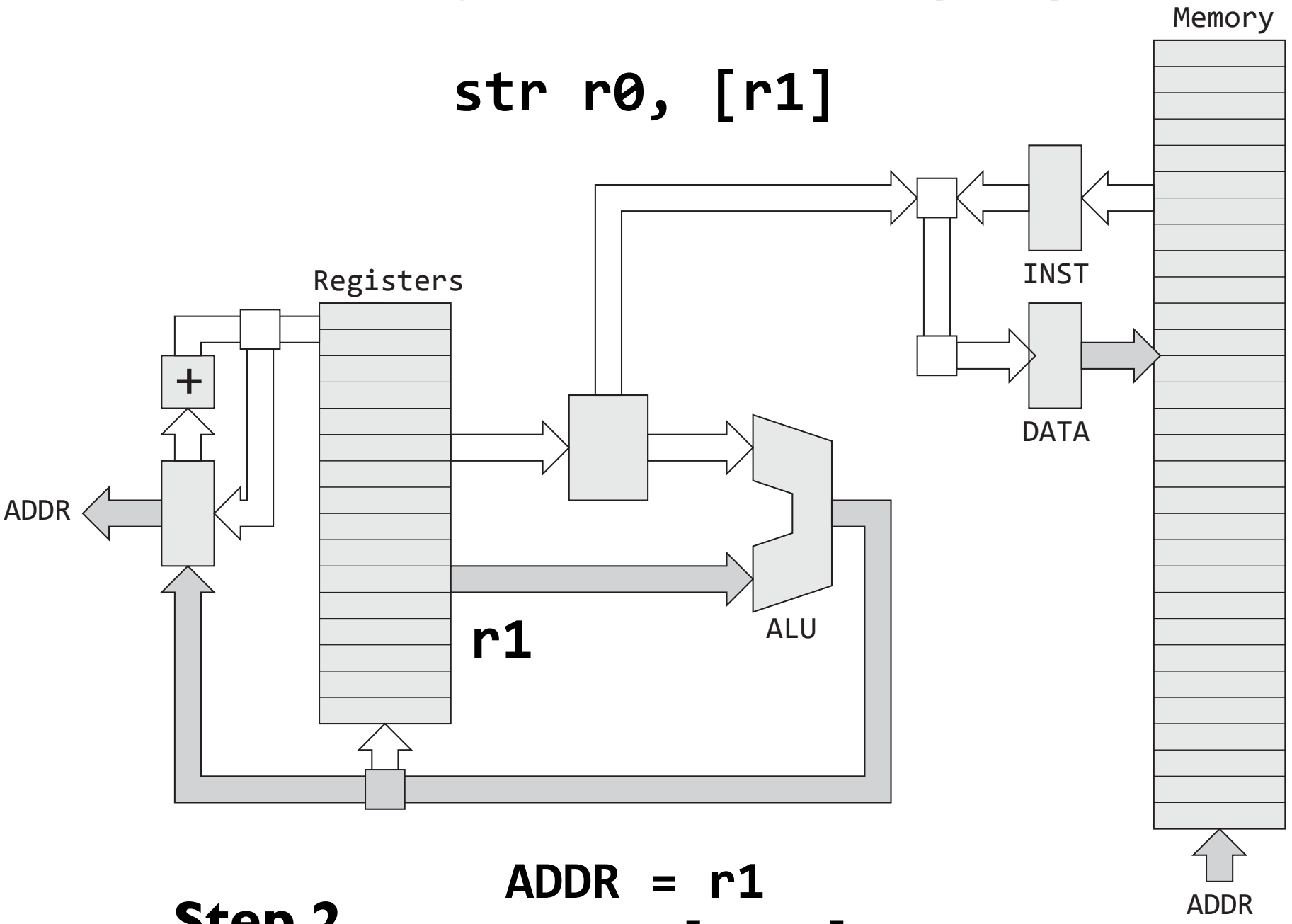
Step 2 `r0 = DATA`

Store Register in Memory (STR)



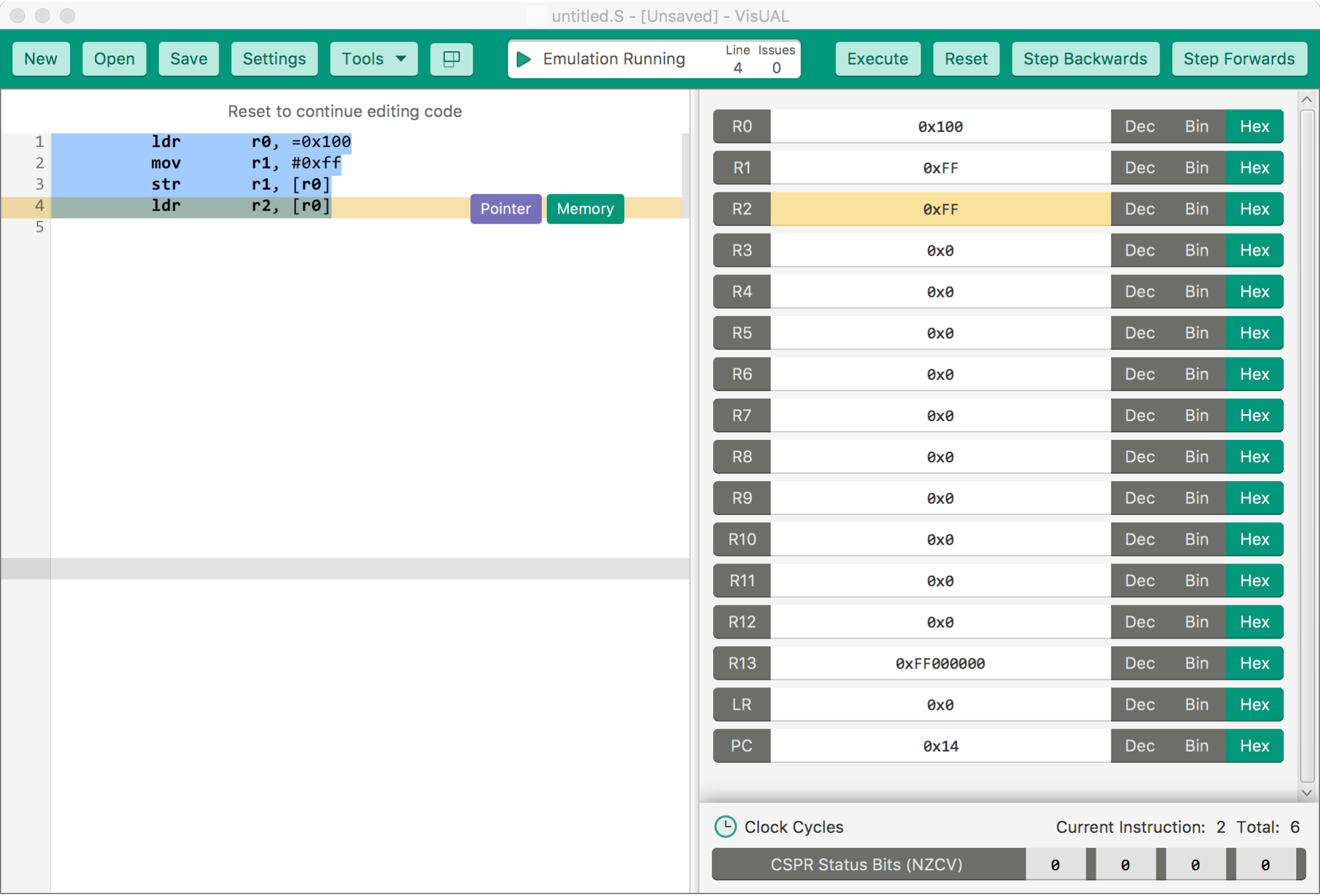
Step 1 DATA = r0

Store Register in Memory (STR)



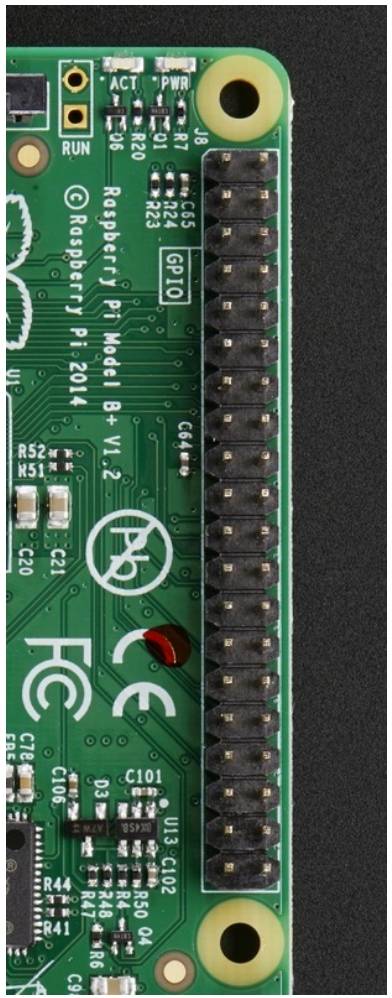
Step 2

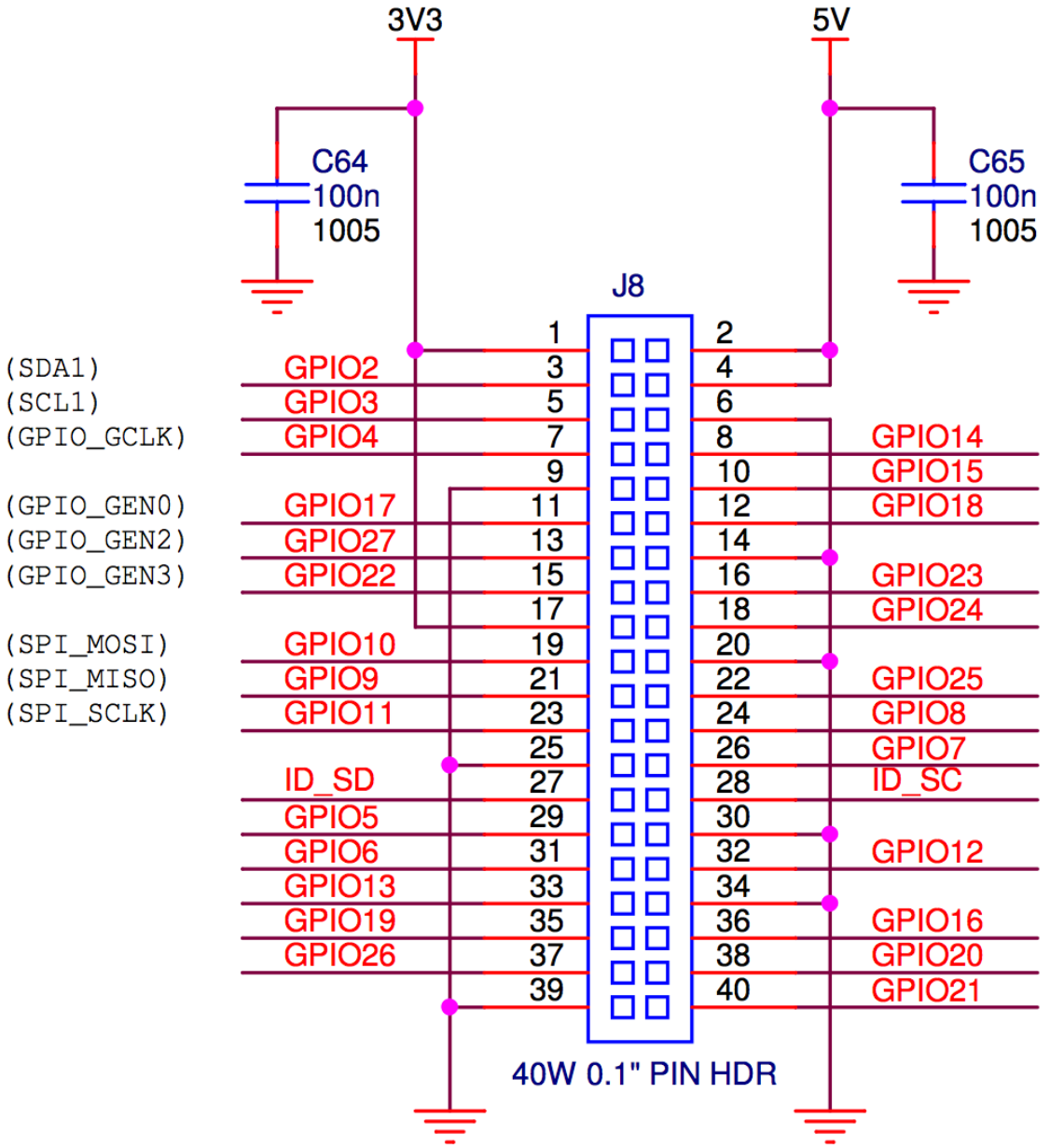
```
ADDR = r1
Memory[ADDR] = DATA
```


untitled.S - [Unsaved] - VisUAL
New
Open
Save
Settings
Tools
Emulation Running
Line 4
Issues 0
Execute
Reset
Step Backwards
Step Forwards
Reset to continue editing code
1 ldr r0, =0x100
2 mov r1, #0xff
3 str r1, [r0]
4 ldr r2, [r0]
5
Pointer
Memory
R0 0x100 Dec Bin Hex
R1 0xFF Dec Bin Hex
R2 0xFF Dec Bin Hex
R3 0x0 Dec Bin Hex
R4 0x0 Dec Bin Hex
R5 0x0 Dec Bin Hex
R6 0x0 Dec Bin Hex
R7 0x0 Dec Bin Hex
R8 0x0 Dec Bin Hex
R9 0x0 Dec Bin Hex
R10 0x0 Dec Bin Hex
R11 0x0 Dec Bin Hex
R12 0x0 Dec Bin Hex
R13 0xFF000000 Dec Bin Hex
LR 0x0 Dec Bin Hex
PC 0x14 Dec Bin Hex
Clock Cycles
Current Instruction: 2 Total: 6
CSPR Status Bits (NZCV) 0 0 0 0

Turning on an LED

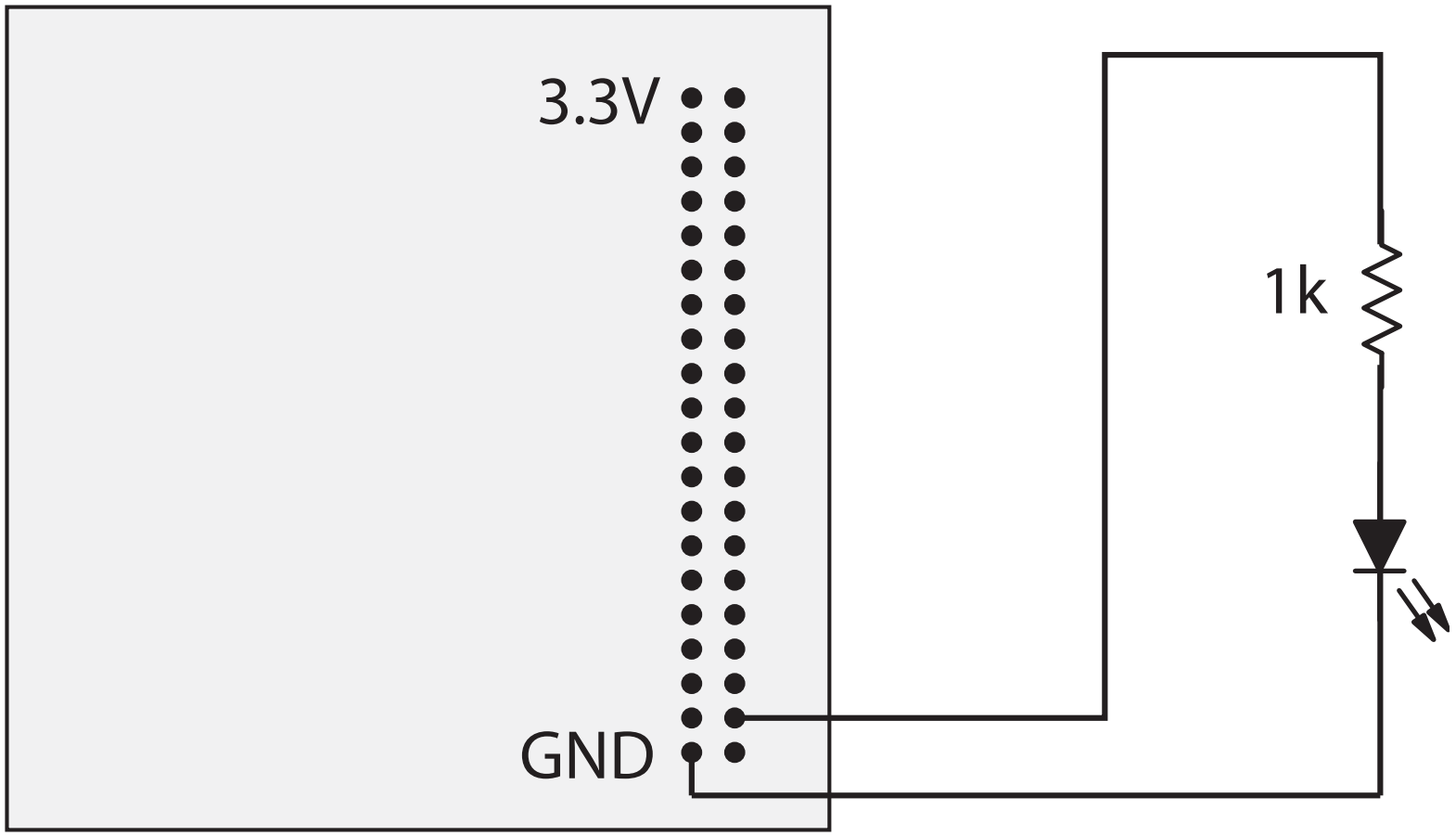
General-Purpose Input/Output (GPIO) Pins



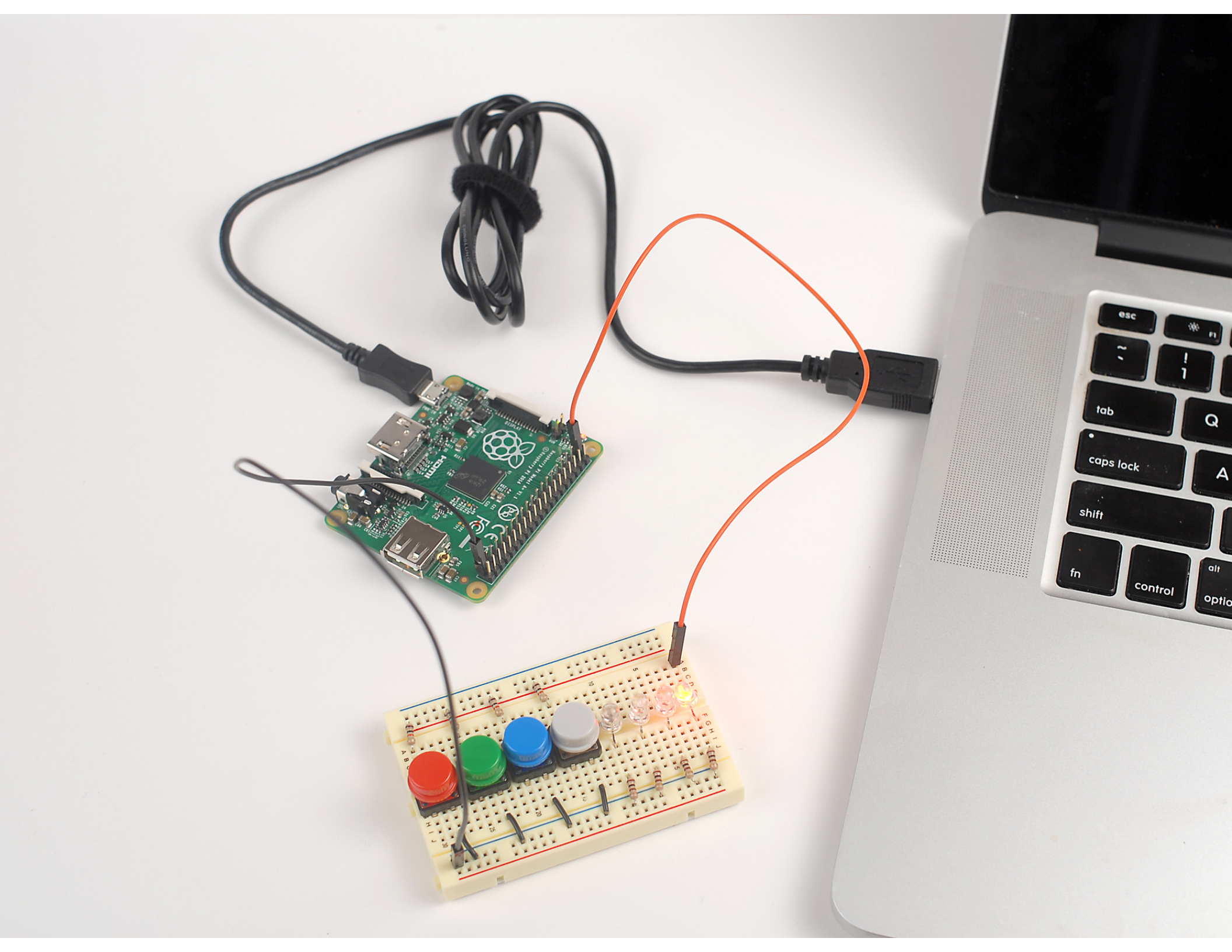


54 GPIO Pins

Connect LED to GPIO 20



1 -> 3.3V
0 -> 0.0V (GND)


esc
tab
caps lock
shift
fn
control

GPIO Pins are *Peripherals*

Peripherals are Controlled by Special Memory Locations

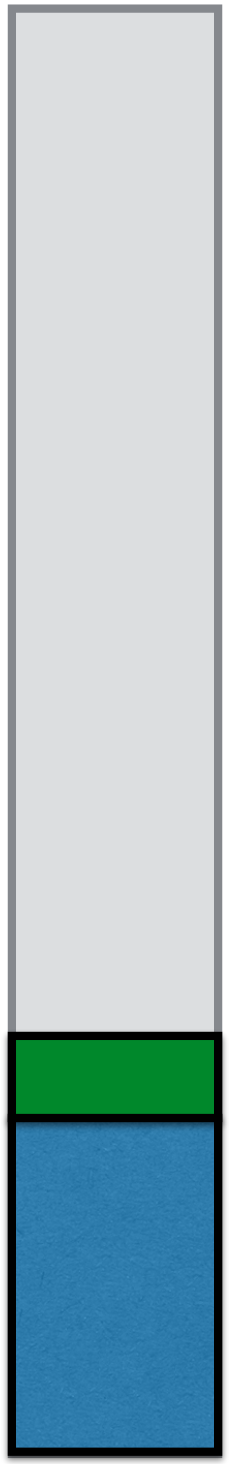
"Peripheral Registers"

Memory Map

Peripheral registers are mapped into address space

Memory-Mapped IO (MMIO)

MMIO space is above physical memory



100000000_{16}

4 GB

020000000_{16}

512 MB

Ref: BCM2835-ARM-Peripherals.pdf

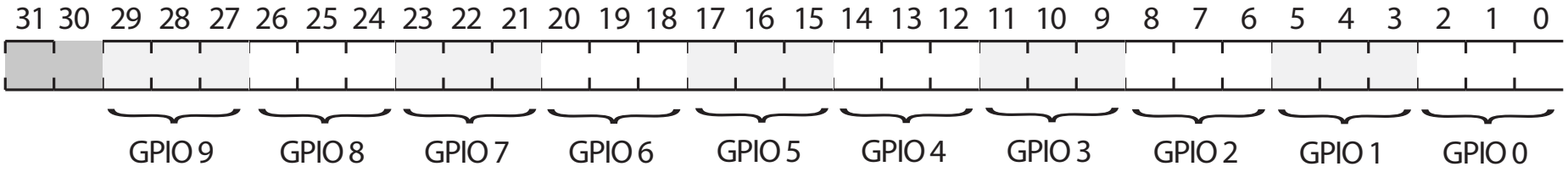
General-Purpose IO Function

GPIO Pins can be configured to be INPUT, OUTPUT, or ALT0-5

Bit pattern	Pin Function
000	The pin in an input
001	The pin is an output
100	The pin does alternate function 0
101	The pin does alternate function 1
110	The pin does alternate function 2
111	The pin does alternate function 3
011	The pin does alternate function 4
010	The pin does alternate function 5

3 bits required to select function

GPIO Function Select Register



"Function" is INPUT, OUTPUT (or ALT0-5)

8 functions requires 3 bits to specify

10 pins times 3 bits = 30 bits

32-bit register (2 wasted bits)

54 GPIOs pins requires 6 registers

GPIO Function Select Registers Addresses

Address	Field Name	Description	Size	Read/ Write
0x 7E20 0000	GPFSEL0	GPIO Function Select 0	32	R/W
0x 7E20 0000	GPFSEL0	GPIO Function Select 0	32	R/W
0x 7E20 0004	GPFSEL1	GPIO Function Select 1	32	R/W
0x 7E20 0008	GPFSEL2	GPIO Function Select 2	32	R/W
0x 7E20 000C	GPFSEL3	GPIO Function Select 3	32	R/W
0x 7E20 0010	GPFSEL4	GPIO Function Select 4	32	R/W
0x 7E20 0014	GPFSEL5	GPIO Function Select 5	32	R/W
0x 7E20 0018	-	Reserved	-	-

```
Watch out for …
  Manual says: 0x7E200000
  Replace 7E with 20: 0x20200000
```

Ref: BCM2835-ARM-Peripherals.pdf

```
// Set GPIO20 to be an output

// FSEL2 = 0x20200008
mov r0, #0x20      // r0 = #0x00000020
lsl r1, r0, #24    // r1 = #0x20000000
lsl r2, r0, #16    // r2 = #0x00200000
orr r1, r1, r2     // r1 = #0x20200000
orr r0, r1, #0x08 // r0 = #0x20200008

mov r1, #1     // 1 indicates OUTPUT
str r1, [r0]  // store 1 to 0x20200008
```

Note this also makes GPIO 21-29 into inputs

GPIO Pin Output Set Registers (GPSETn)

SYNOPSIS The output set registers are used to set a GPIO pin. The SET{n} field defines the respective GPIO pin to set, writing a "0" to the field has no effect. If the GPIO pin is being used as in input (by default) then the value in the SET{n} field is ignored. However, if the pin is subsequently defined as an output then the bit will be set according to the last set/clear operation. Separating the set and clear functions removes the need for read-modify-write operations

Bit(s)	Field Name	Description	Type	Reset
31-0	SETn (n=0..31)	0 = No effect 1 = Set GPIO pin *n*	R/W	0

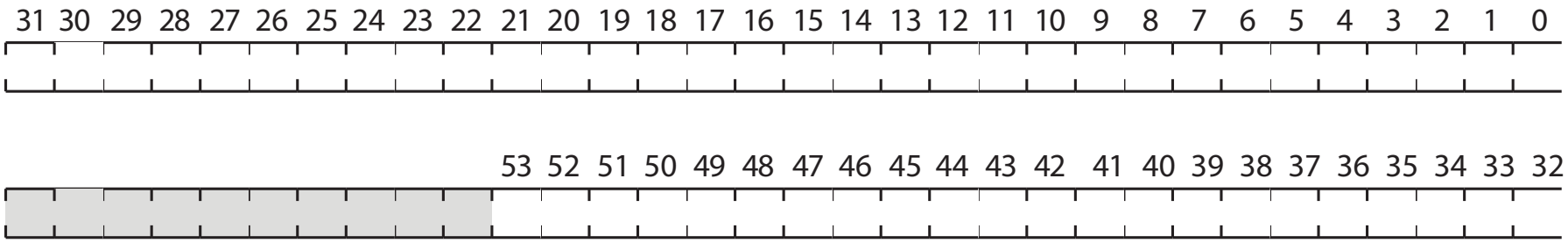
Table 6-8 – GPIO Output Set Register 0

Bit(s)	Field Name	Description	Type	Reset
31-22	-	Reserved	R	0
21-0	SETn (n=32..53)	0 = No effect 1 = Set GPIO pin *n.*	R/W	0

Table 6-9 – GPIO Output Set Register 1

GPIO Function SET Register

```
20 20 00 1C : GPIO SET0 Register
20 20 00 20 : GPIO SET1 Register
```



Notes

1. 1 bit per GPIO pin
2. 54 pins requires 2 registers

```
// Set GPIO20 output High (3.3V)
// Assumes GPIO 20 configured to be output
// FSET0 = 0x2020001c
mov r0, #0x20      // r0 = 0x00000020
lsl r1, r0, #24    // r1 = 0x20000000
lsl r2, r0, #16    // r2 = 0x00200000
orr r1, r1, r2     // r1 = 0x20200000
orr r0, r1, #0x1c // r0 = 0x2020001c

mov r1, #1         // r1 = 0x00000001
lsl r1, r1, #20    // r1 = 0x00100000
str r1, [r0]       // store r1 to 0x2020001c

// loop forever
loop:
b loop
```

```
# What to do on your laptop

# Assemble language to machine code
% arm-none-eabi-as on.s -o on.o

# Create binary from object file
% arm-none-eabi-objcopy on.o -O binary on.bin
```

```
# What to do on your laptop

# Insert SD card - Volume mounts
% ls /Volumes/
BOOT2020   Macintosh HD

# Copy to SD card
% cp on.bin /Volumes/BOOT2020/
kernel.img

# Eject and remove SD card
```

```
#
# Insert SD card into SDHC slot on pi
#
# Apply power using usb console cable.
# Power LED (Red) should be on.
#
# Raspberry pi boots. ACT LED (Green)
# flashes, and then is turned off
#
# LED connected to GPIO20 turns on!!
#
```

Assignment 0

- Join forum piazza.com/stanford/winter2020/cs107e

- Read and understand our guides on basic topics (electricity, numbers, unix). Practice unix command line

- Checkout the course directory from gitbub

- Checkout your assignment directory and answer the questionnaire, check-in to submit assignment

- Setup your development environment before lab

Key Concepts

- Bits are bits; fundamental bitwise operations
- Memory addresses refer to bytes (8-bits), words are 4 bytes
- Memory stores both instructions and data
- Computers repeatedly fetch, decode, and execute instructions
- Different types of ARM instructions: ALU, Loads and Stores, Branches
- General purpose IO (GPIO), peripheral registers, and MMIO

Further Reading

If you want to learn more about high-level computer organization and instructions, Chapter 2 of Computer Organization and Design: The Hardware/ Software Interface (Patterson and Hennessy) is an excellent place to start.