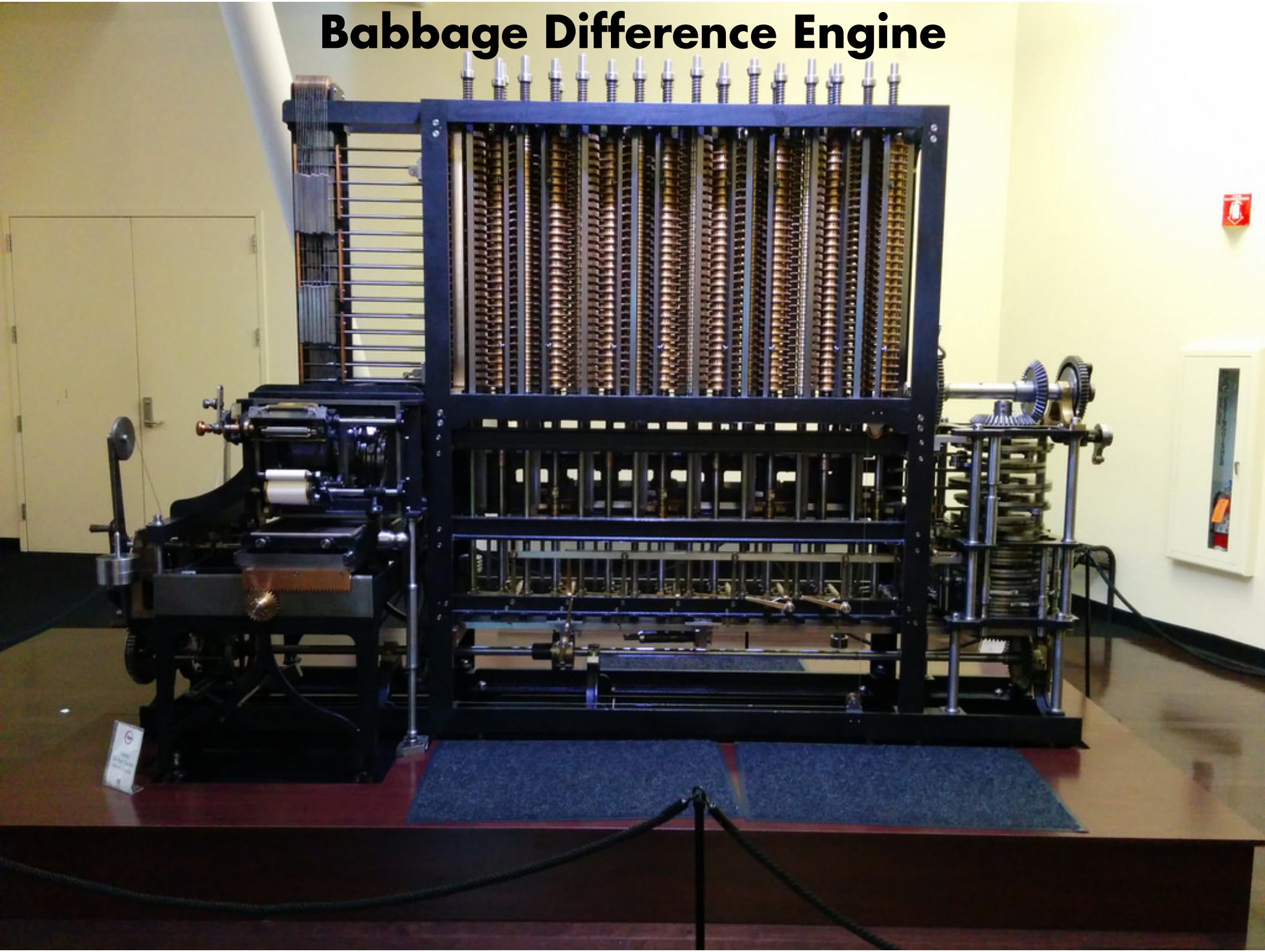
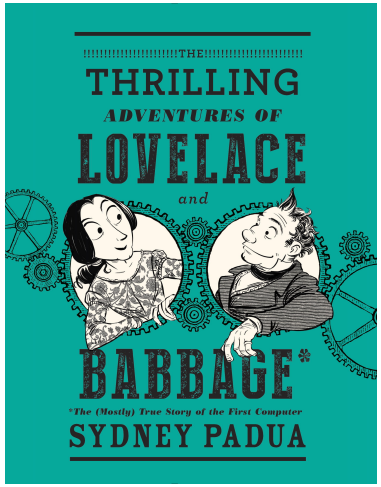
ARM
Processor and Memory Architecture

Goal: Turn on an LED

Babbage Difference Engine

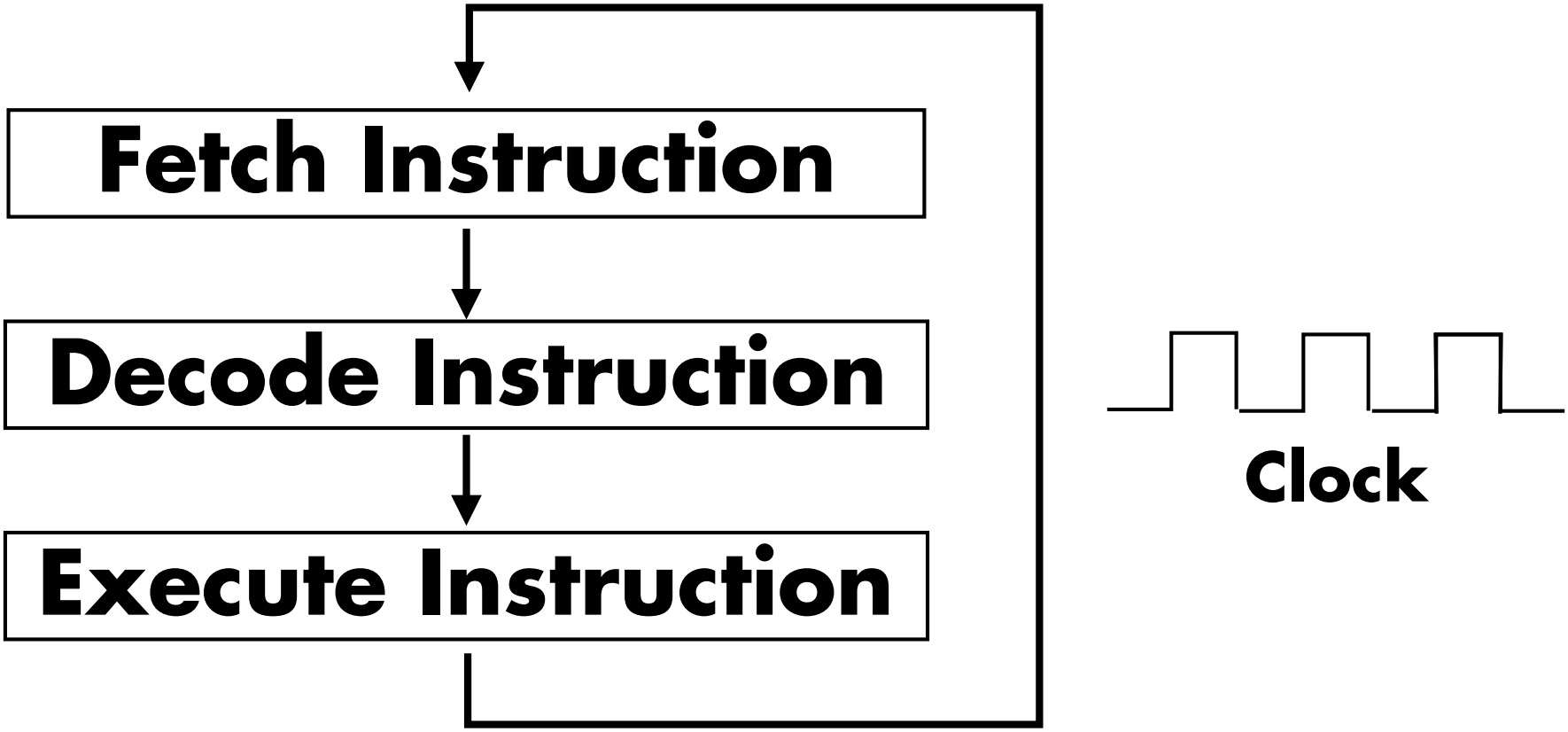


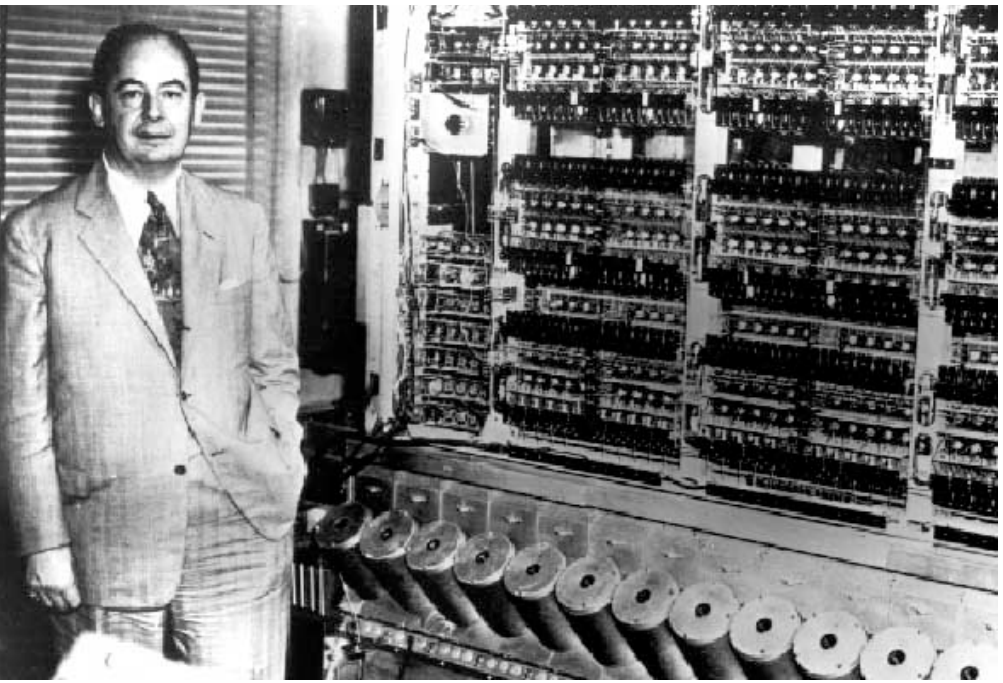


Analytical Engine

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

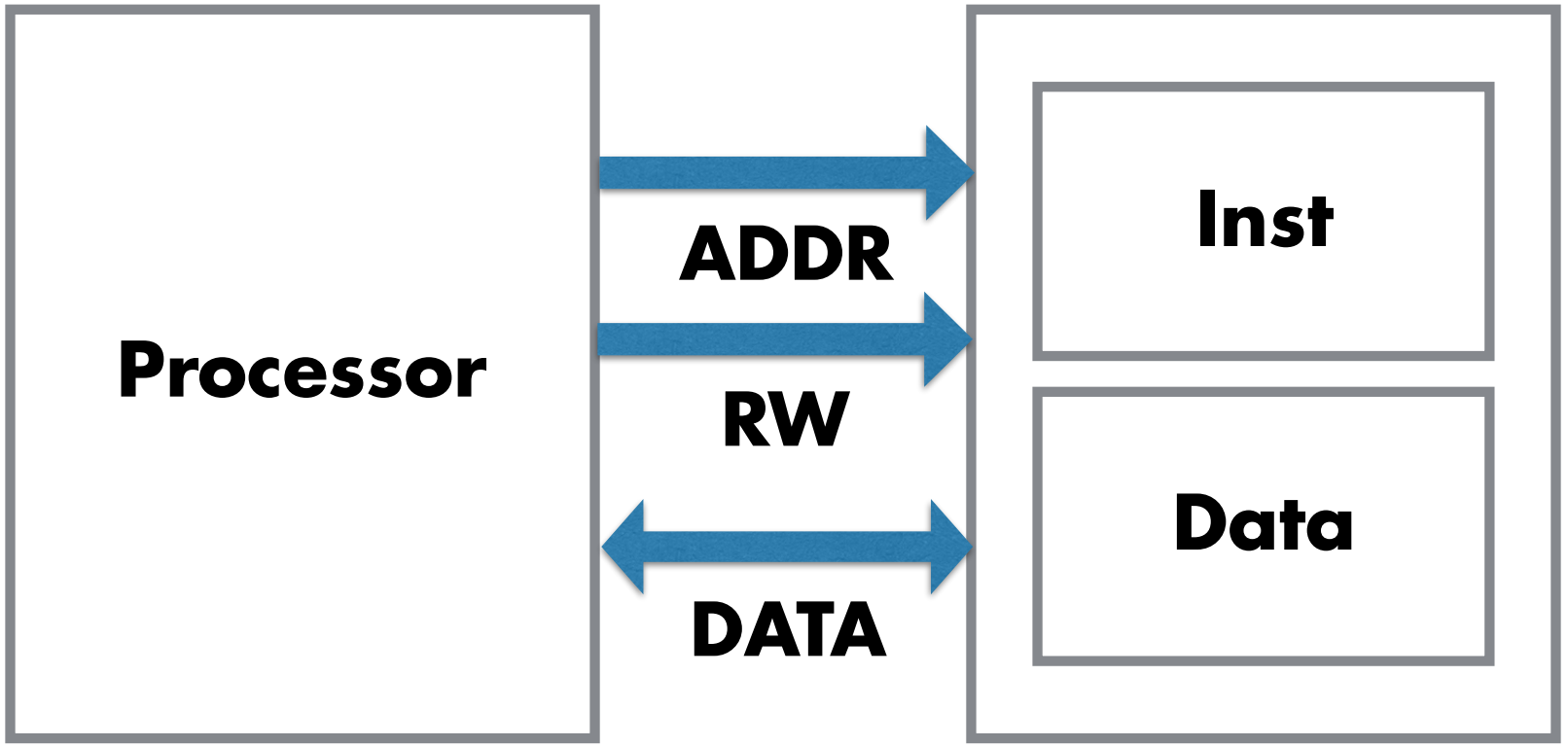
Running a "Program"



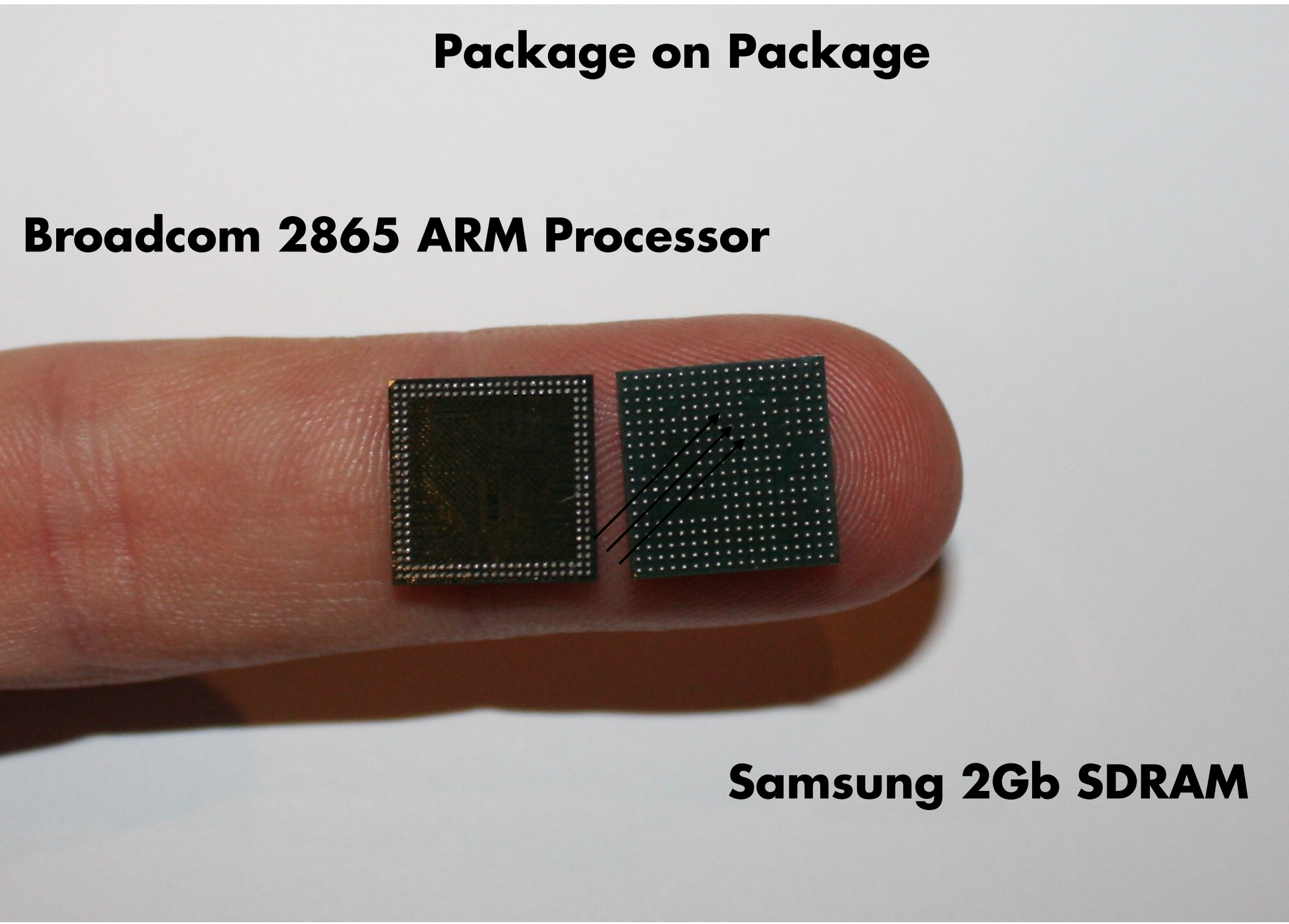


(John) von Neumann Architecture

Instructions and data stored in the same memory



Package on Package



Memory used to store information

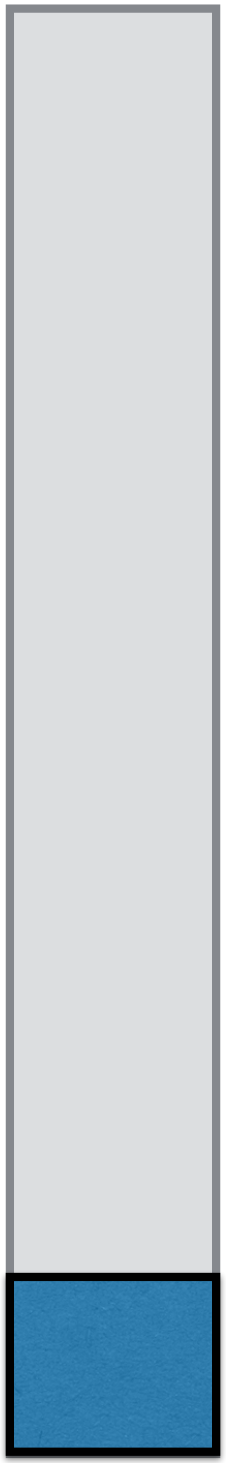
Stores both instructions and data

Storage locations are accessed using 32-bit addresses

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

Maximum addressable memory 4 GB

Actual memory is 256 MB



100000000_{16}

Memory Map

010000000_{16}

256 MB

ARM 32-bit Architecture

Processor designed around 32-bit "words"

Registers are 32-bits

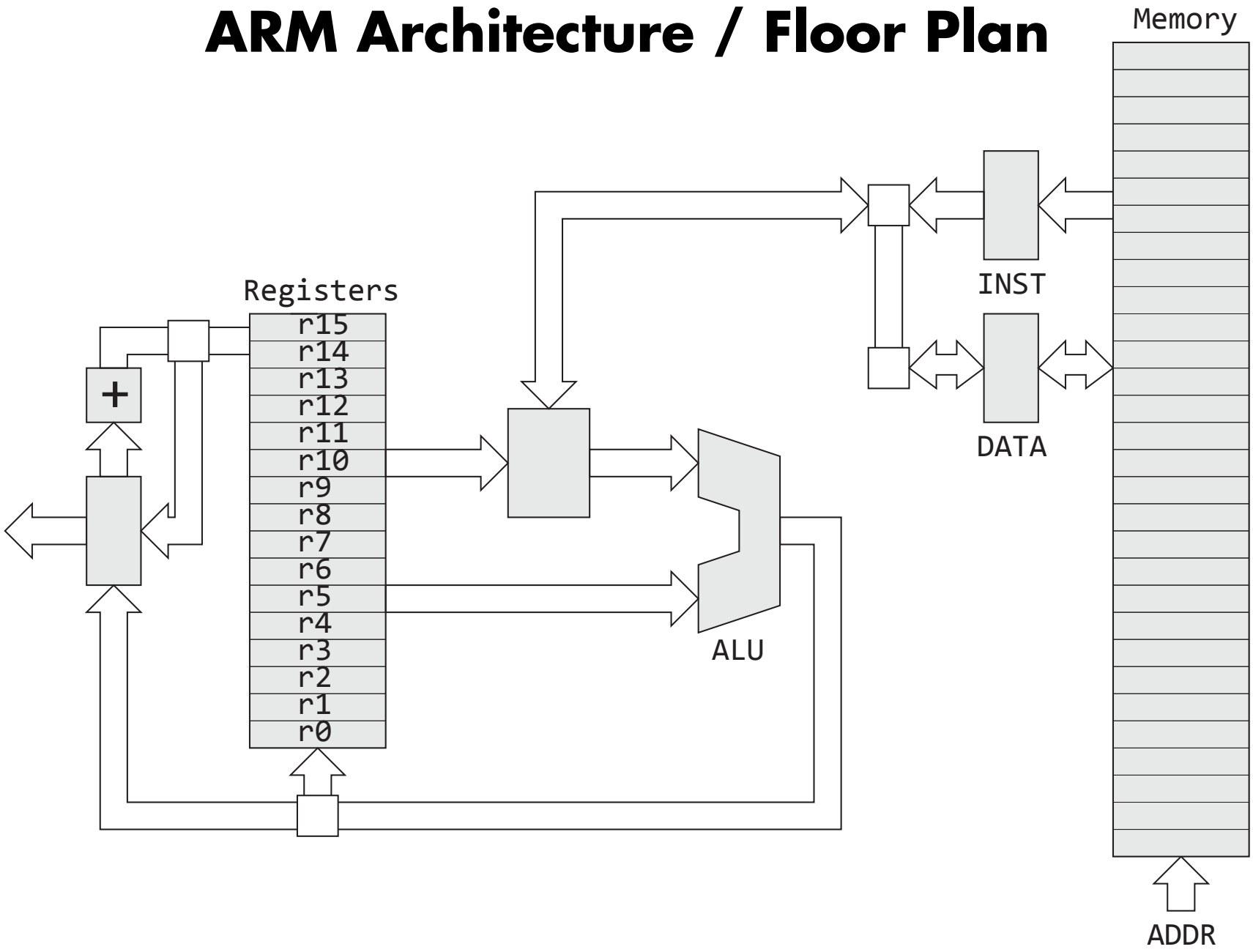
Arithmetic-Logic Unit (ALU) works on 32-bits

Addresses are 32-bits

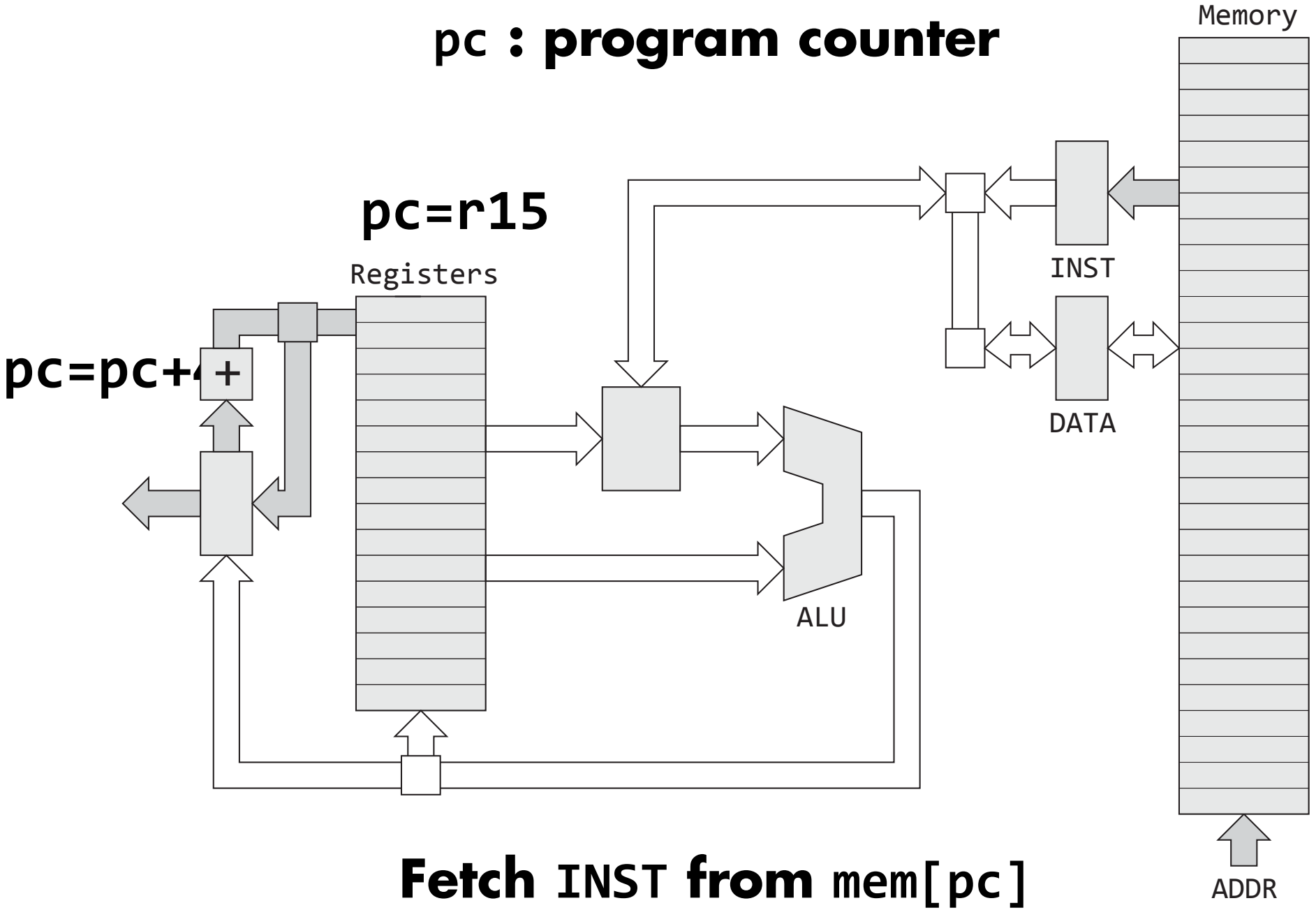
Instructions are 32-bits

The fact that everything is 32-bits simplifies things quite a bit!

ARM Architecture / Floor Plan



pc : program counter

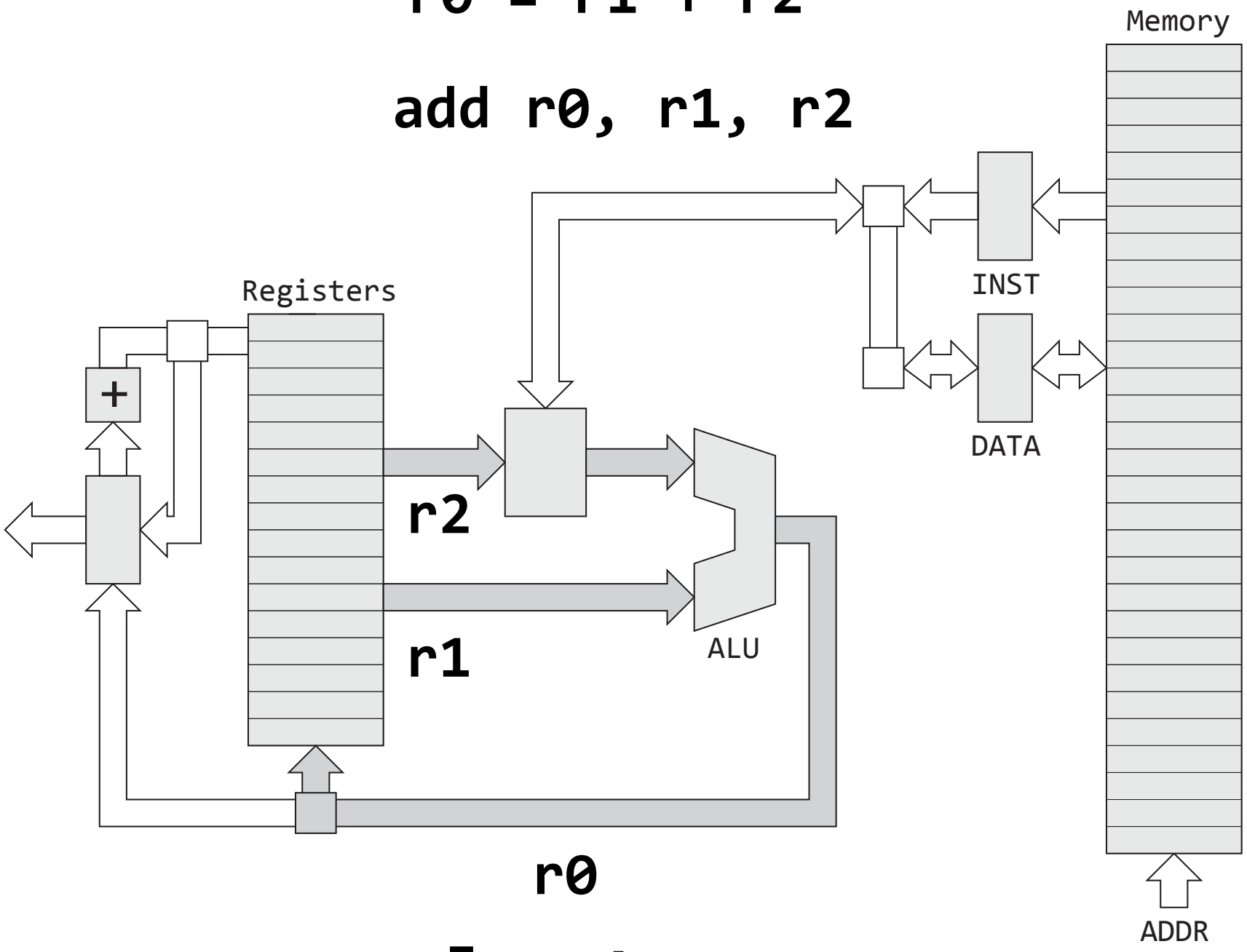


Fetch INST from mem[pc]

Decode

r0 = r1 + r2

add r0, r1, r2



Execute INST

Instructions

Meaning (C)

```
r0 = r1 + r2
```

Assembly language

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

Machine code

```
E0 81 00 02
```

```
// Single instruction program

add r0, r1, r2
```

```
# Assemble (.s) into 'object' file (.o)
% arm-none-eabi-as add.s -o add.o

# Create binary (.bin)
% arm-none-eabi-objdump add.o -O binary add.bin

# Size in bytes?
% ls -l add.bin
-rw-r--r--+ 1 hanrahan  staff  4 add.bin

# Dump binary in hex
% hexdump add.bin
0000000: 02 00 81 e0
```

Instructions

Meaning (C)

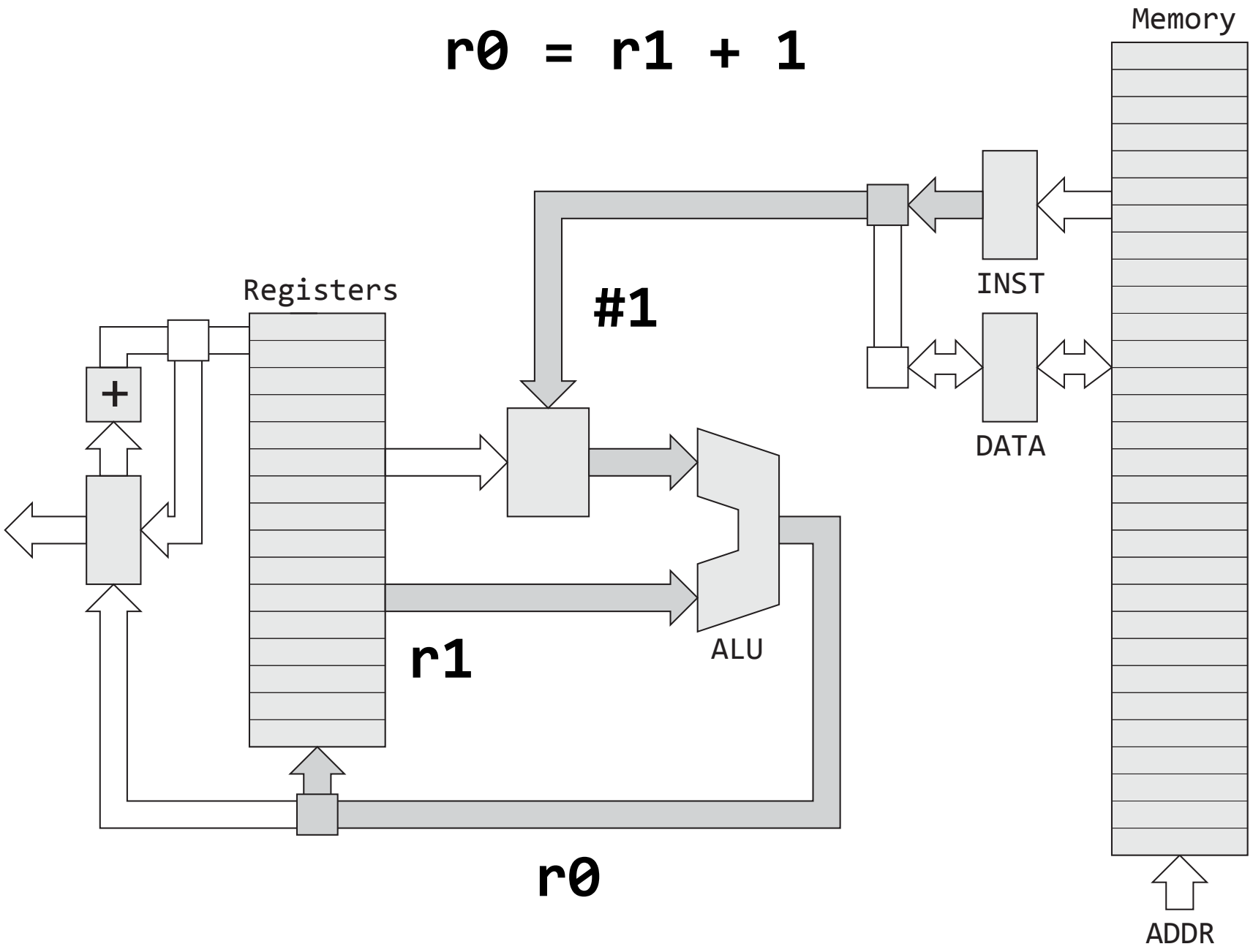
```
r0 = r1 + 1
```

Assembly language

```
add r0, r1, #1
```

Machine code

```
E2 81 00 01
```

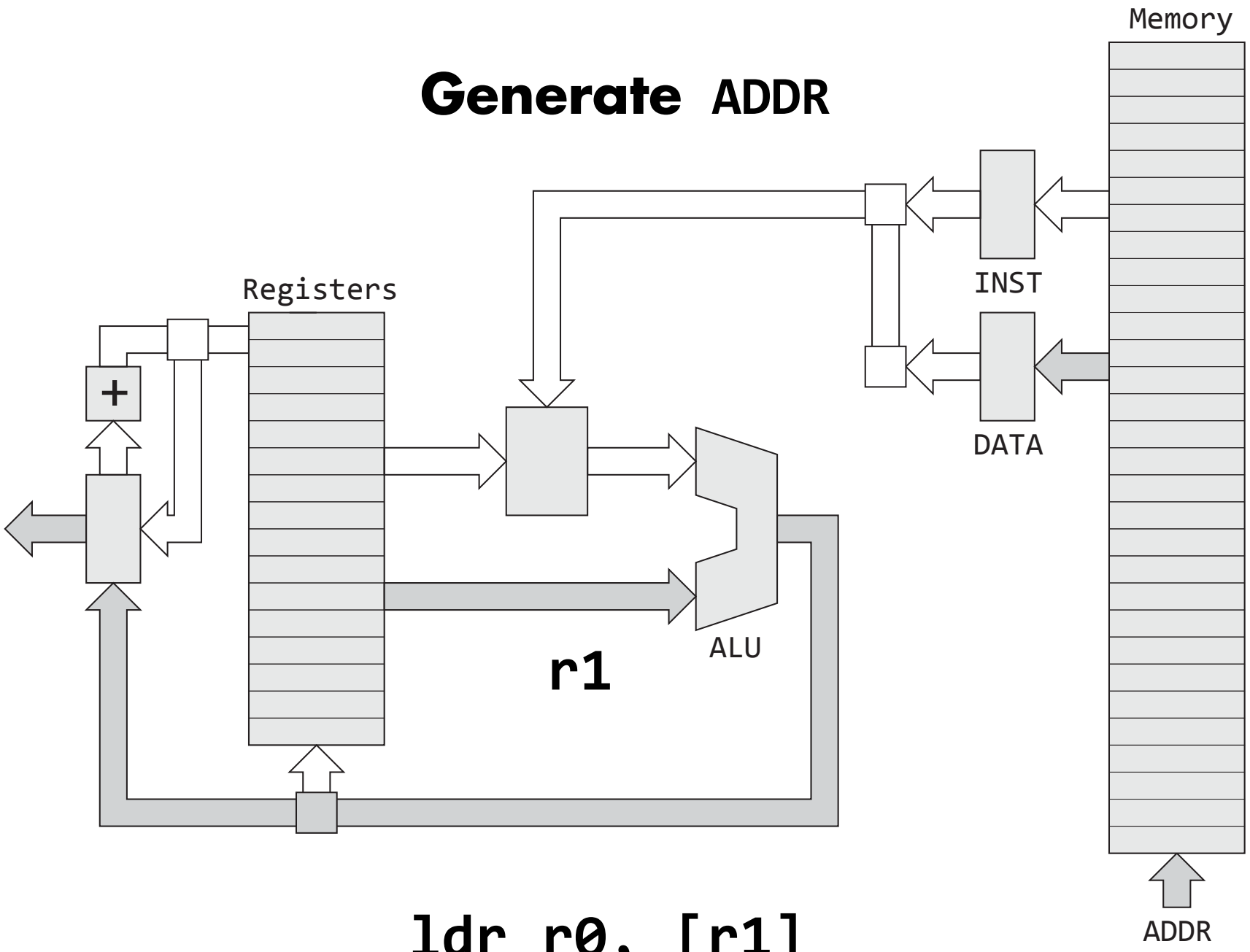

r0 = r1 + 1
Memory
INST
DATA
Registers
#1
+
r1
ALU
r0
ADDR
add r0, r1, #1

```
// Single instruction program

mov r0, #1
```

```
# Assemble (.s) into 'object' file (.o)
% arm-none-eabi-as mov.s -o mov.o

# Create binary (.bin)
% arm-none-eabi-objdump add.o -O binary mov.bin

# Size in bytes?
% ls -l mov.bin
-rw-r--r--+ 1 hanrahan  staff  4 mov.bin

# Dump binary in hex
% hexdump mov.bin
0000000: 01 00 a0 e3
```

Loads and Stores

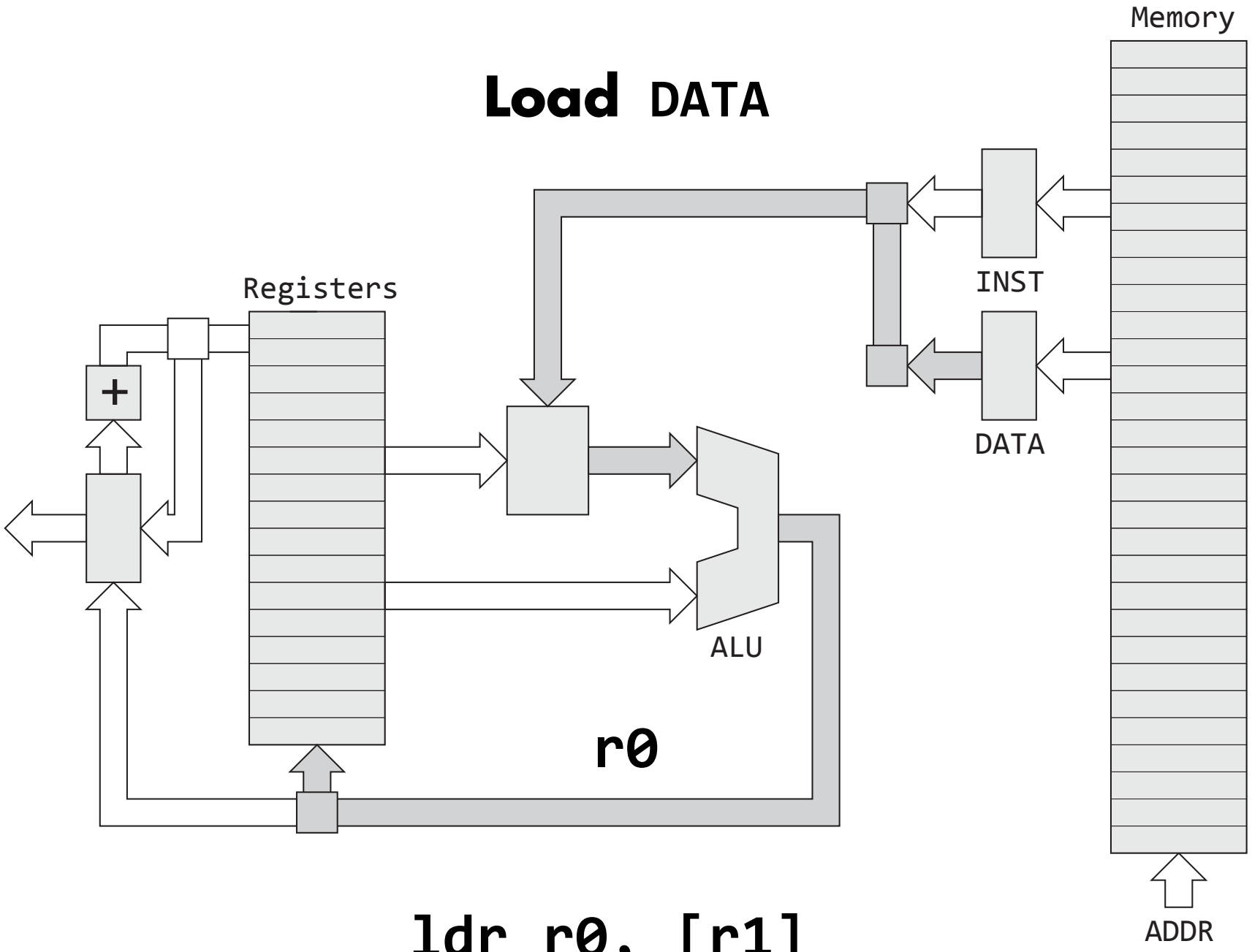
r0 = mem[r1]



ldr r0, [r1]

r0 = mem[r1]

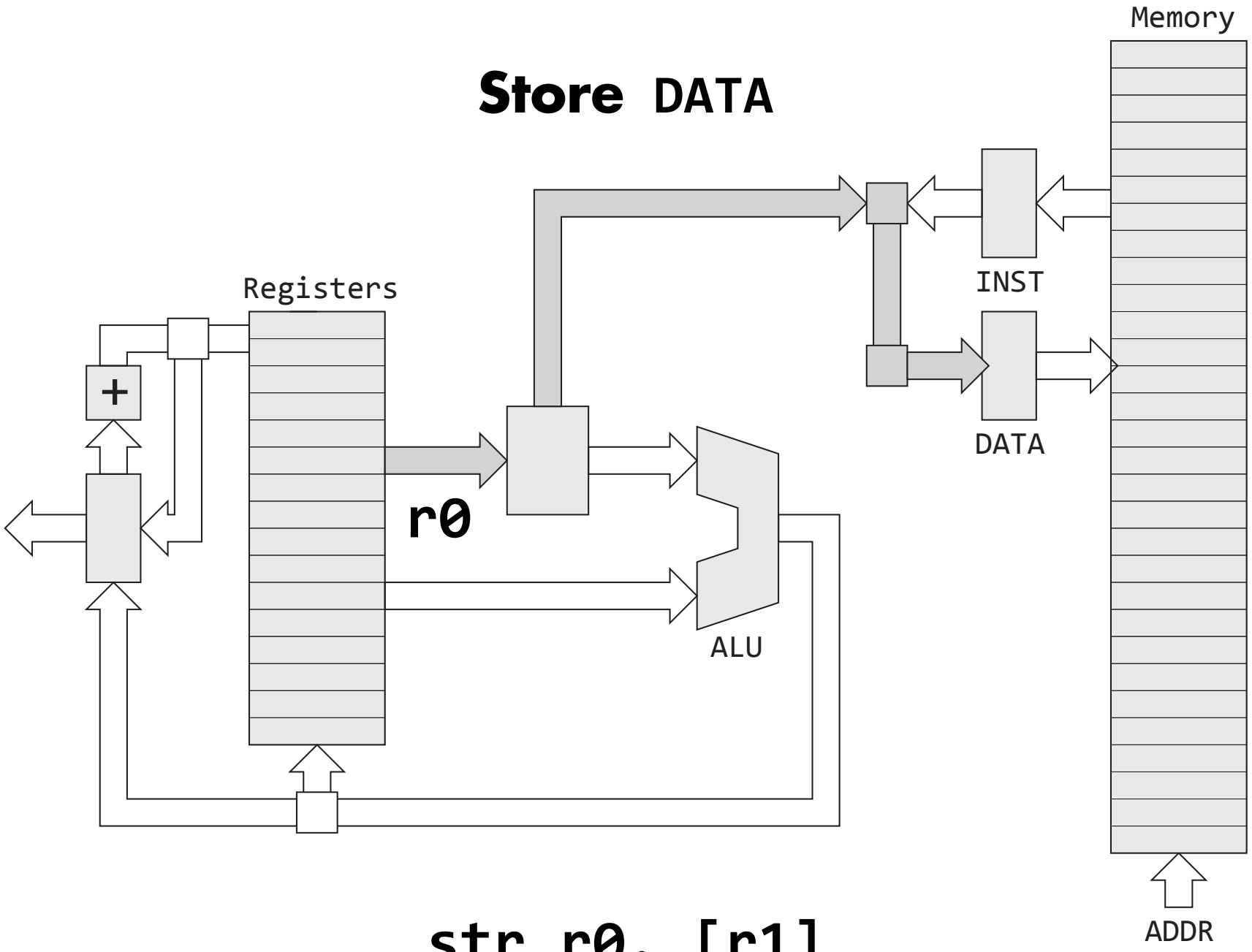
Load DATA



ldr r0, [r1]

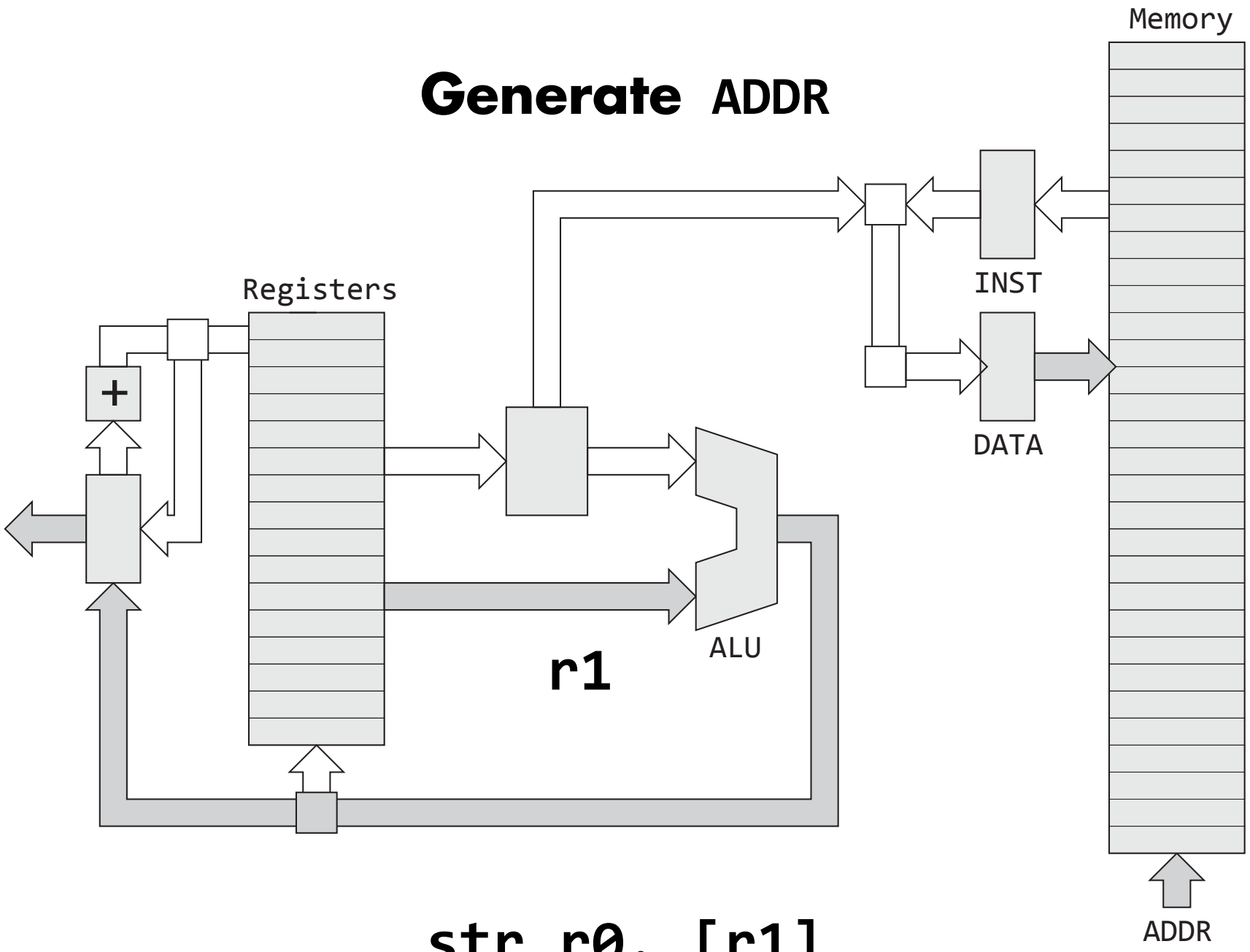
mem[r1] = r0

Store DATA



str r0, [r1]

mem[r1] = r0



str r0, [r1]

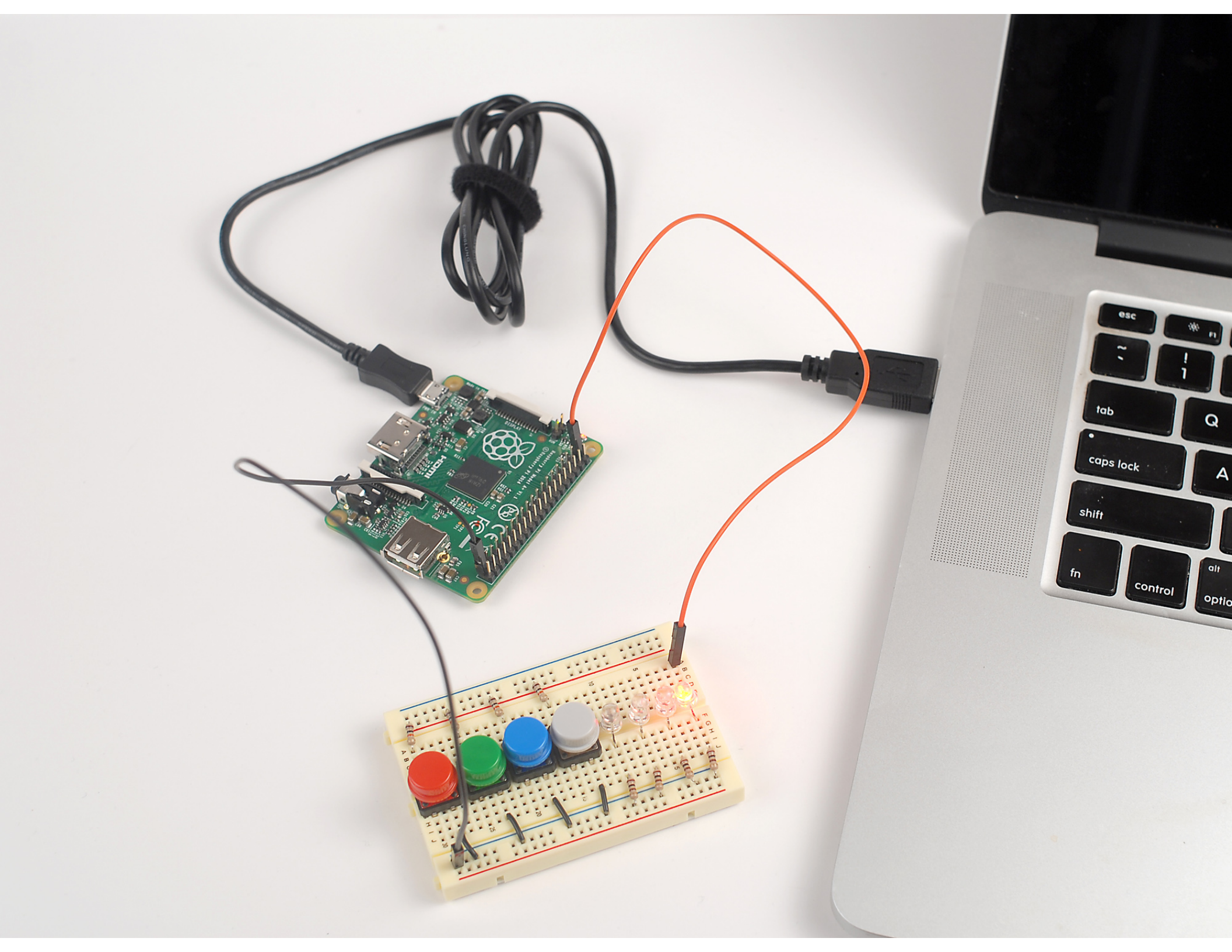
Conceptual Exercises

1. Suppose you have `0x8000` stored in `r0`, how could you jump and start executing instructions at that location?

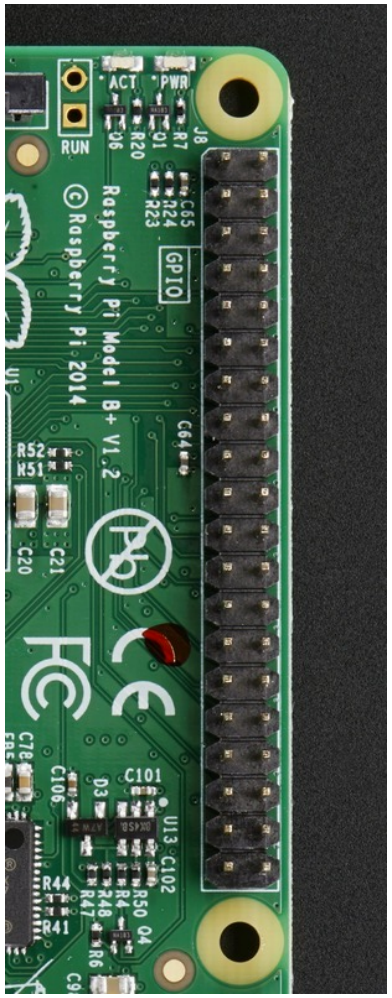
2. All instructions are 32-bits. Can you `mov` any 32-bit immediate constant to a register using the `mov` instruction?

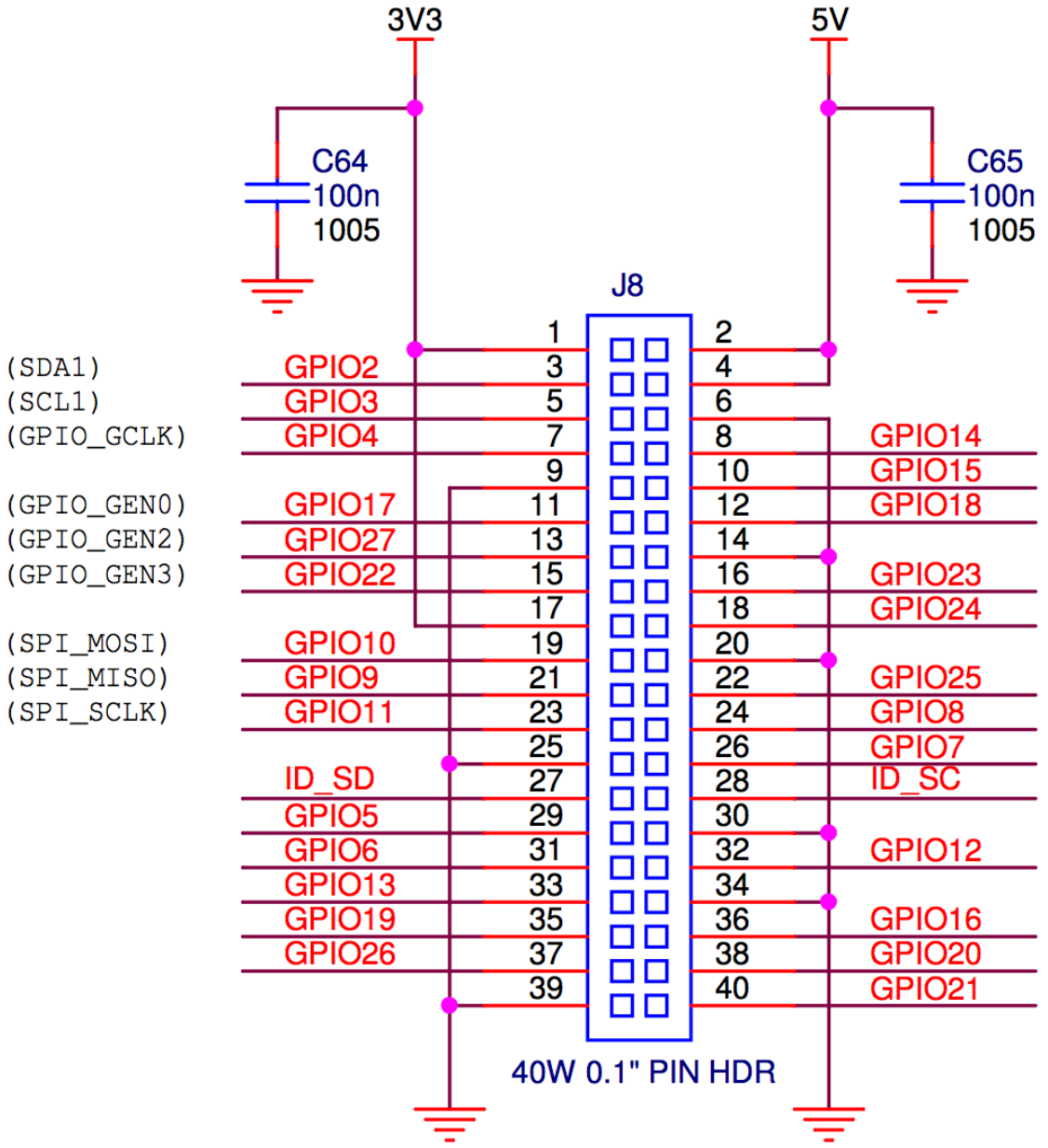
3. What instruction do you think takes longer to execute, `ldr` or `add`?

Turning on an LED


esc
tab
caps lock
shift
fn
control

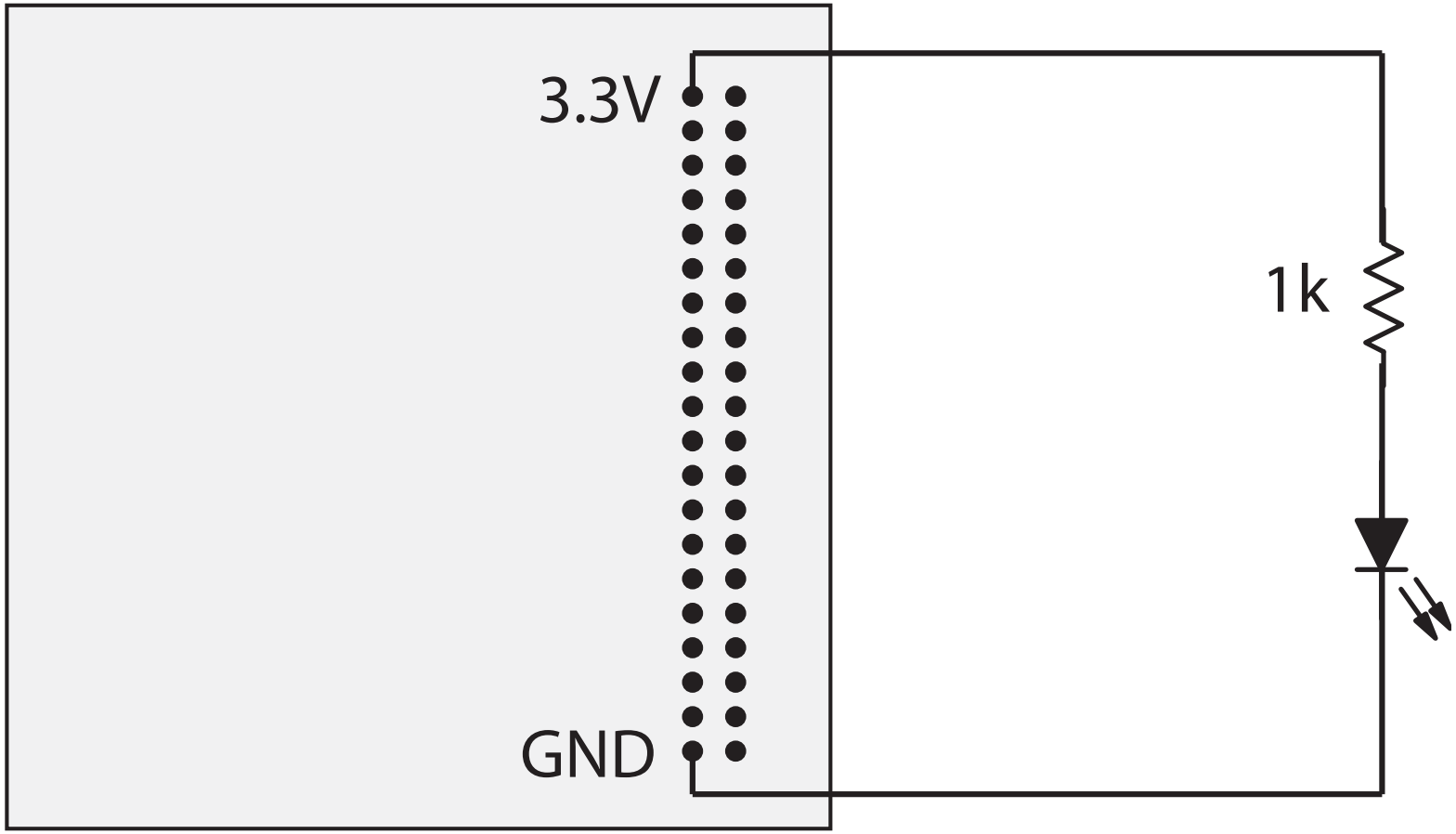
General-Purpose Input/Output (GPIO) Pins



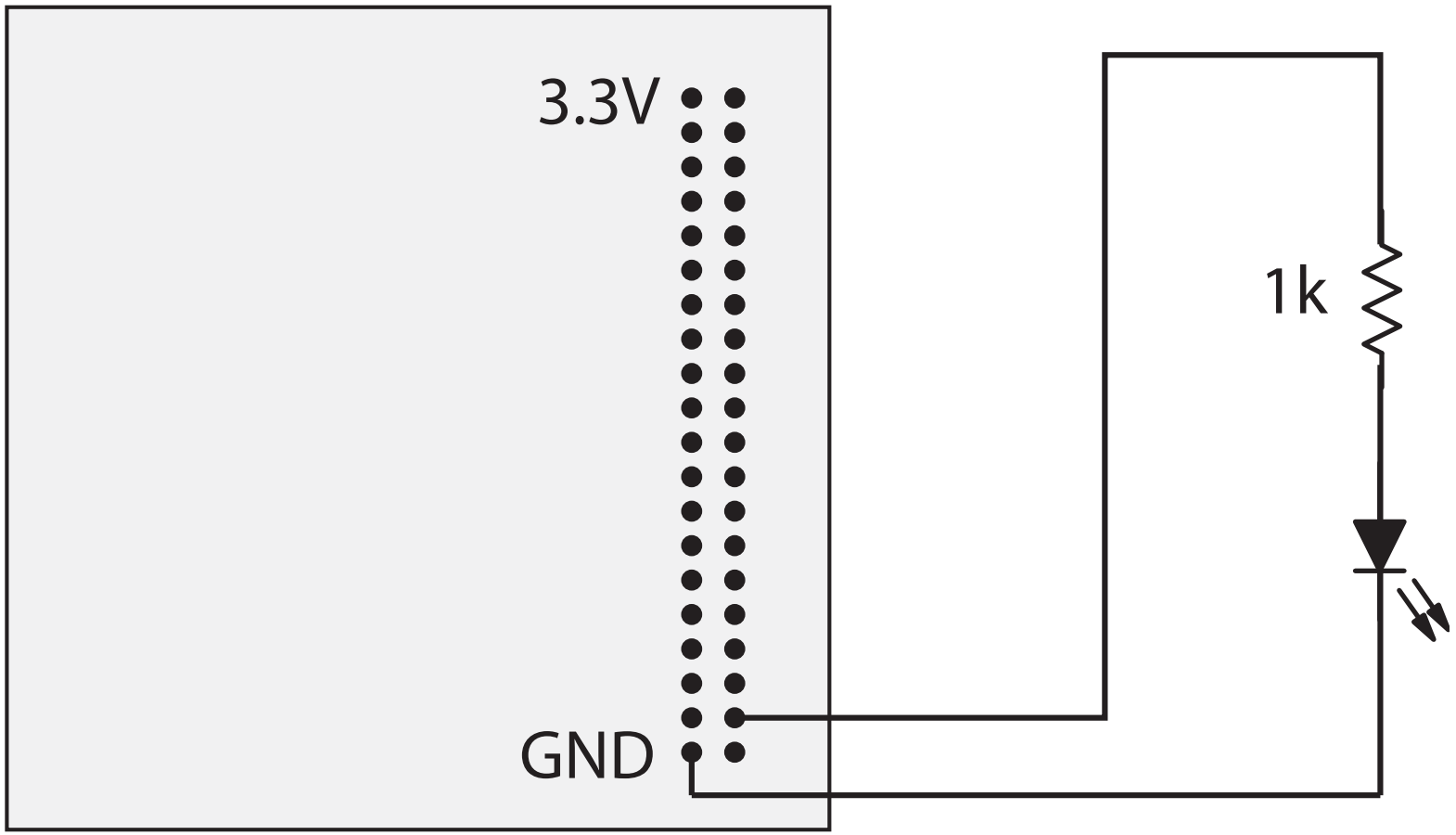


54 GPIO Pins

Powering an LED



Connect to GPIO 20

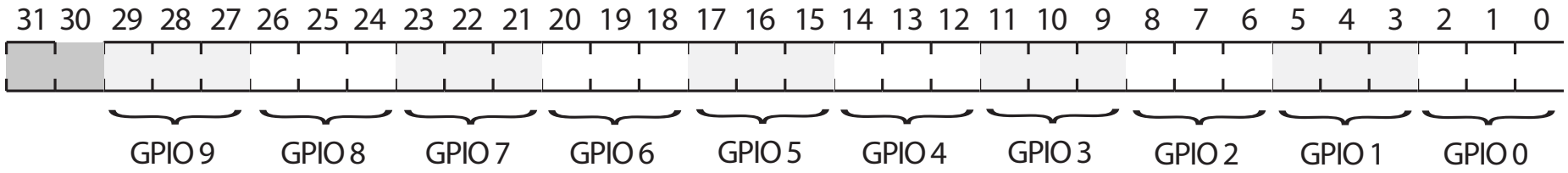


Logic 1 -> 3.3V (VCC)
Logic 0 -> 0.0V (GND)

Turn on an LED

1. Configure GPIO 20 for OUTPUT

GPIO Function Select Register



3 bits per GPIO pin

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

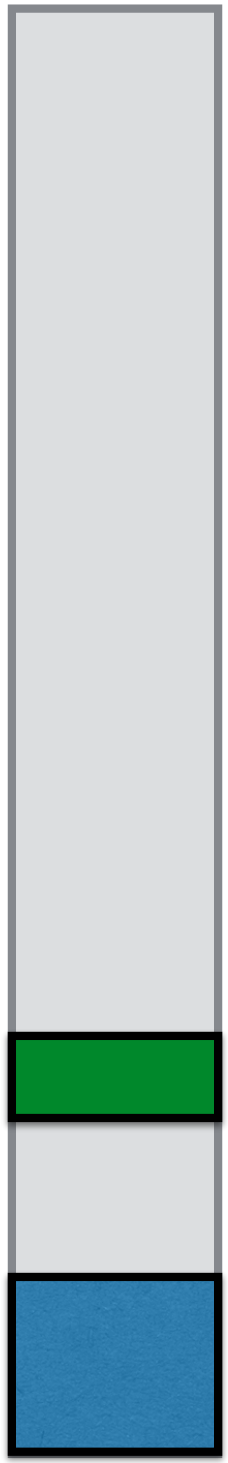
Max of 10 pins per 32-bit register

How to Control Peripherals?

Peripheral Registers
are
"Mapped" to Memory Addresses

Memory-Mapped Input-Output
MMIO

Memory Map



100000000_{16}

4 GB

Peripheral Registers

020000000_{16}

010000000_{16}

Ref: BCM2835-ARM-Peripherals.pdf

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	-	-

Notes

1. 0x 7E00 0000 -> 0x 2000 0000
2. 3-bits per GPIO pin, 54 GPIO pin
   => 6 GPIO function select registers

Ref: BCM2835-ARM-Peripherals.pdf

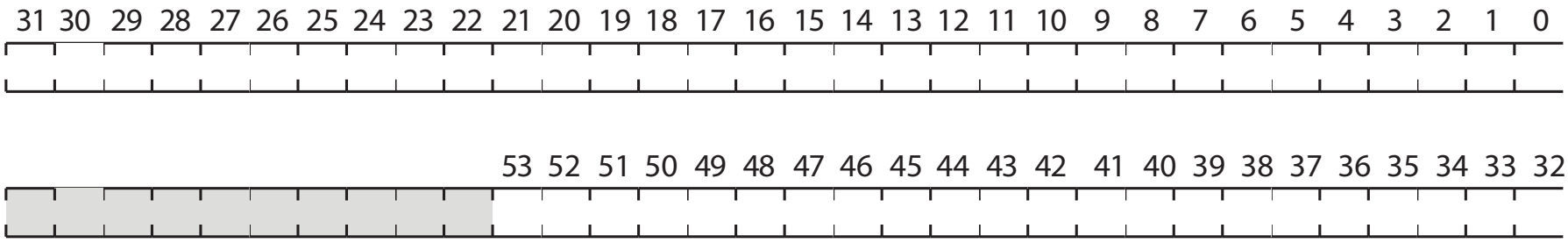
```
// Turn on an LED via GPIO 20

// FSEL2=0x20200008 controls pins 20-29

// load r0 with GPIO FSEL2 address
ldr r0, =0x20200008

// GPIO 20 function select is bits 0-2
// The value of 1 indicates OUTPUT
// load r1 with 1
mov r1, #1

// store value in r1 to address in r0
str r1, [r0]
```

Turn on an LED

1. Configure GPIO 20 for OUTPUT
2. Set GPIO 20 to 1 (HIGH, 3.3V)

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

```
…

// load r0 with GPIO SET0 register addr
ldr r0, =0x2020001C

// set bit 20 in r1
mov r1, #0x100000 // 0x100000 = 1 << 20

// store bit in GPIO SET0 register
str r1, [r0]
```

```
…

// load r0 with GPIO SET0 register addr
ldr r0, =0x2020001C

// set bit 20 in r1
mov r1, #0x100000 // 0x100000 = 1 << 20

// store bit in GPIO SET0 register
str r1, [r0]

// loop forever
hang: b hang
```

Turn on an LED

1. Configure GPIO 20 for OUTPUT
2. Set GPIO 20 to 1 (HIGH, 3.3V)
3. Install program as `kernel.img`

```
# 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

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

```
# What to do on your laptop

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

# Copy to SD card
% cp on.bin /Volumes/BARE/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!!
#
```

Definitive References

BCM2865 peripherals document + errata

Raspberry Pi schematic

ARMv6 architecture reference manual

see `Resources` **on cs107e.github.io**