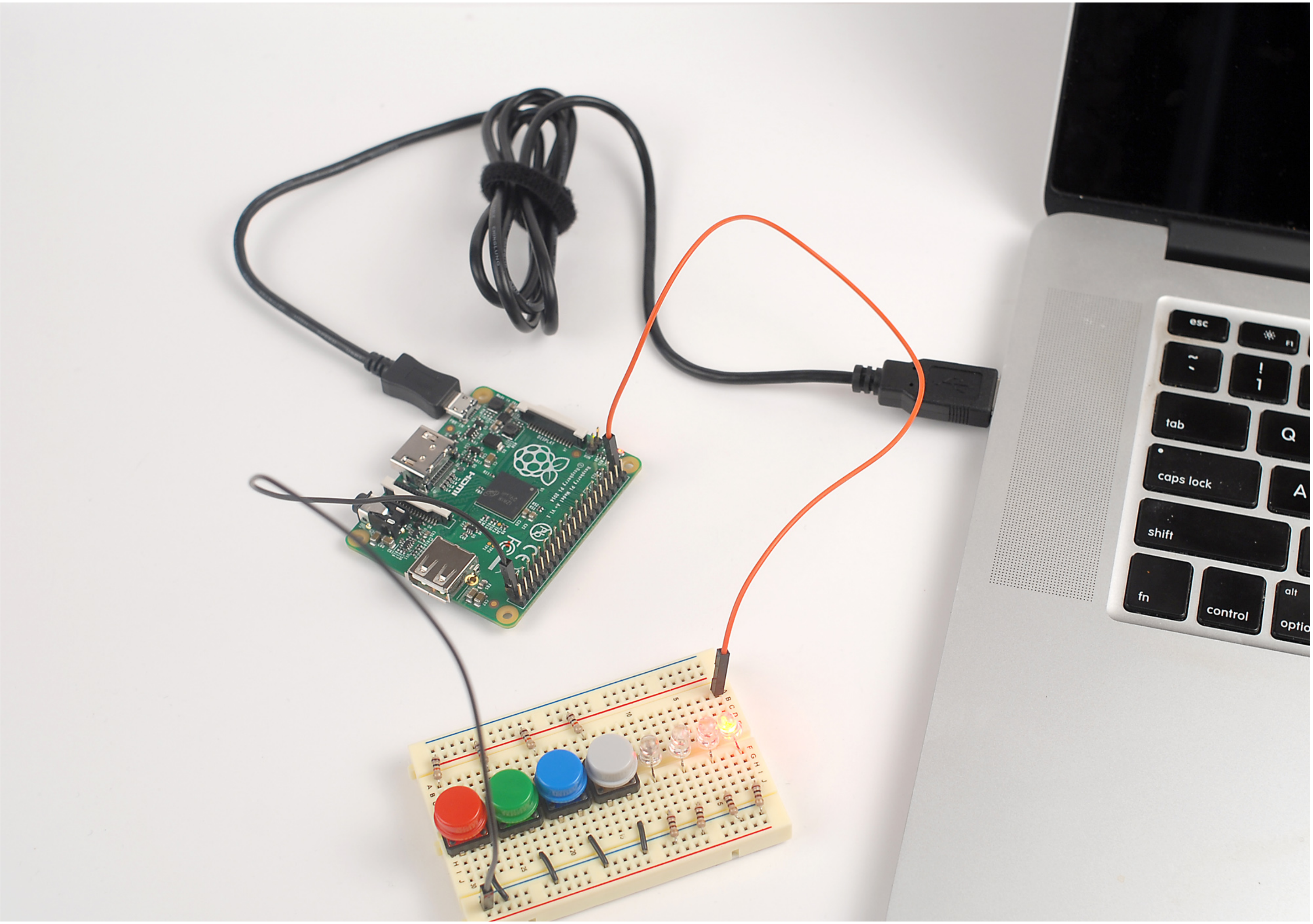
ARM

Processor and Memory Architecture

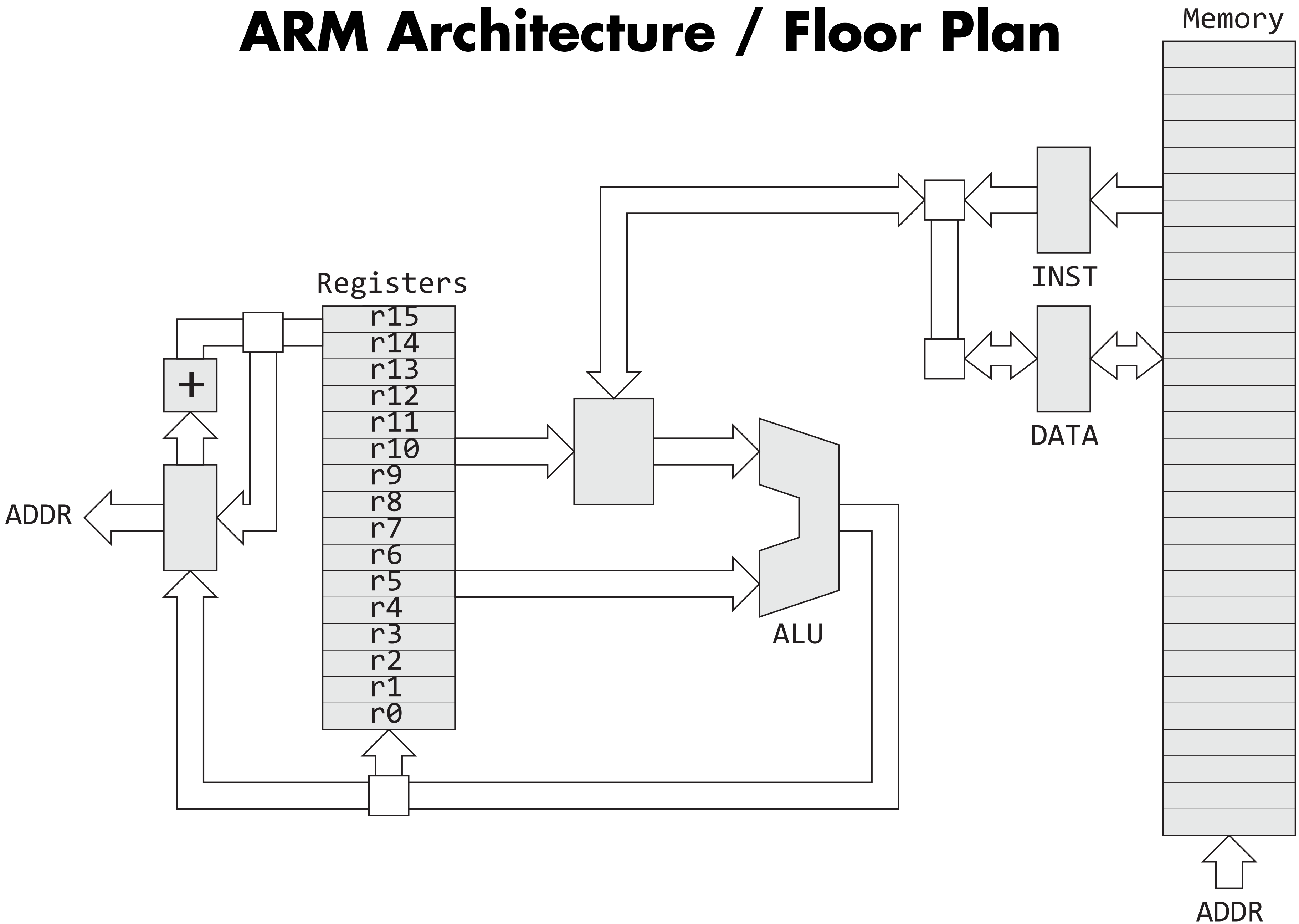
Goal: Turn on an LED


esc
tab
Q
caps lock
A
shift
fn
control
alt

Assignment 1

Knight Rider Display - Larson Scanner

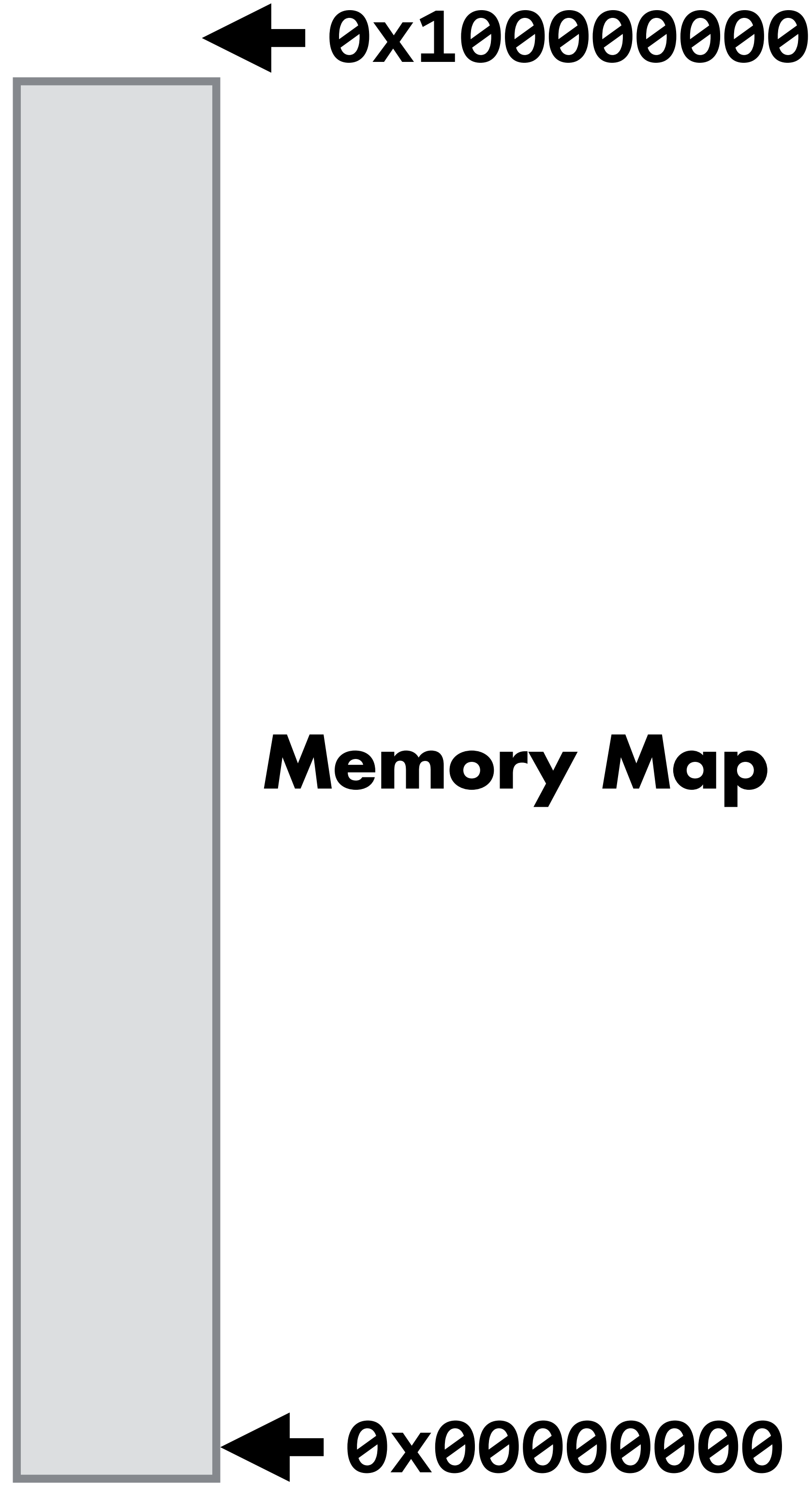
ARM Architecture / Floor Plan



Memory is a large array

Storage locations are accessed using a 32-bit index, called the *address*

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



Memory Map

Fred Brooks
1932-2022

Brooks was asked "What do you consider your greatest technological achievement?"

Brooks responded, "The most important single decision I ever made was to change the IBM 360 series from a 6-bit byte to an 8-bit byte, thereby enabling the use of lowercase letters. That change propagated everywhere."

https://www.wired.com/2010/07/ff-fred-brooks/

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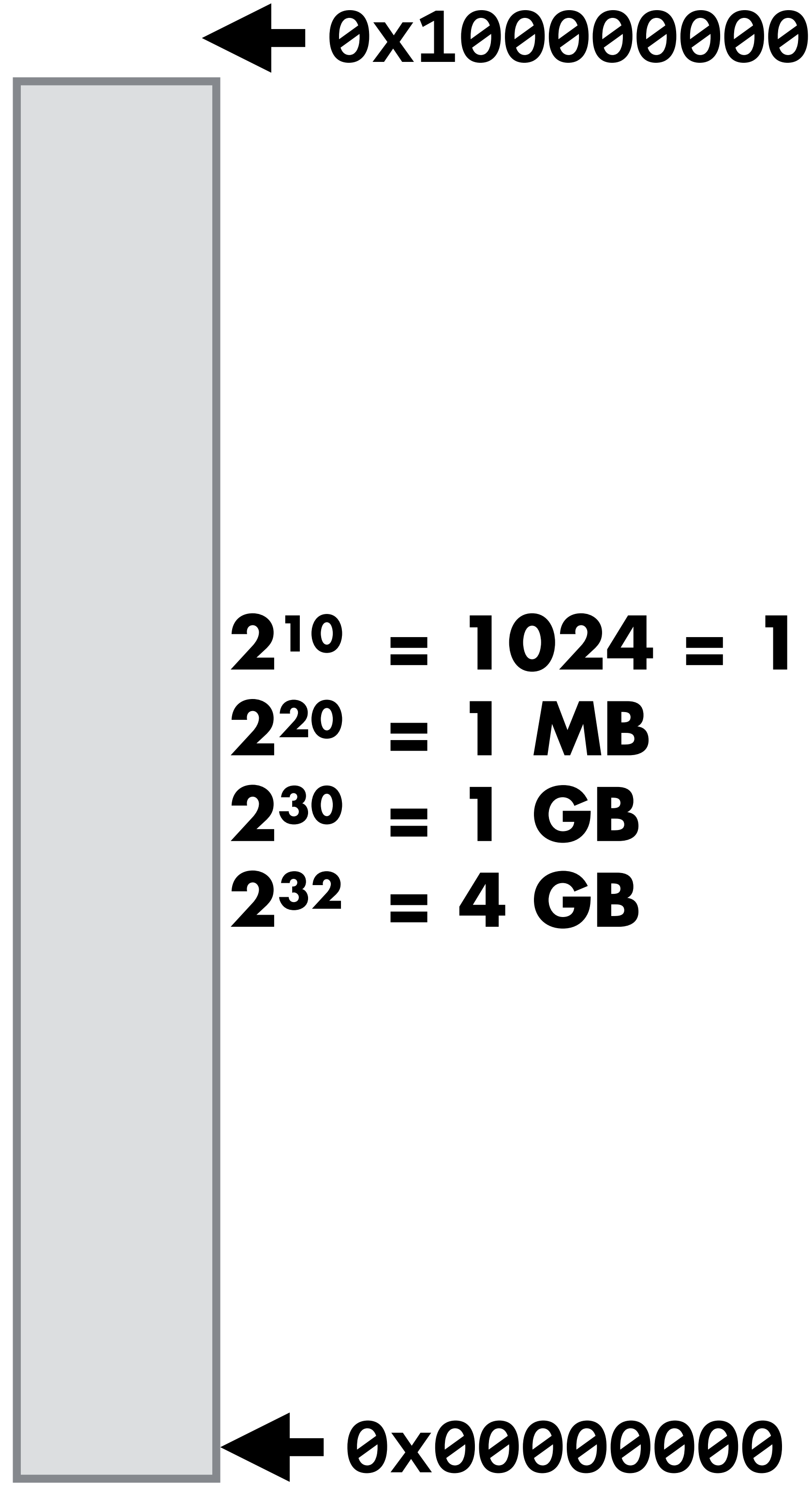
Address refers to a *byte* (8-bits)

4 consecutive bytes form a *word* (32-bits)

Maximum addressable memory is 4 GB (gigabyte)



2^{10} = 1024 = 1 KB
2^{20} = 1 MB
2^{30} = 1 GB
2^{32} = 4 GB

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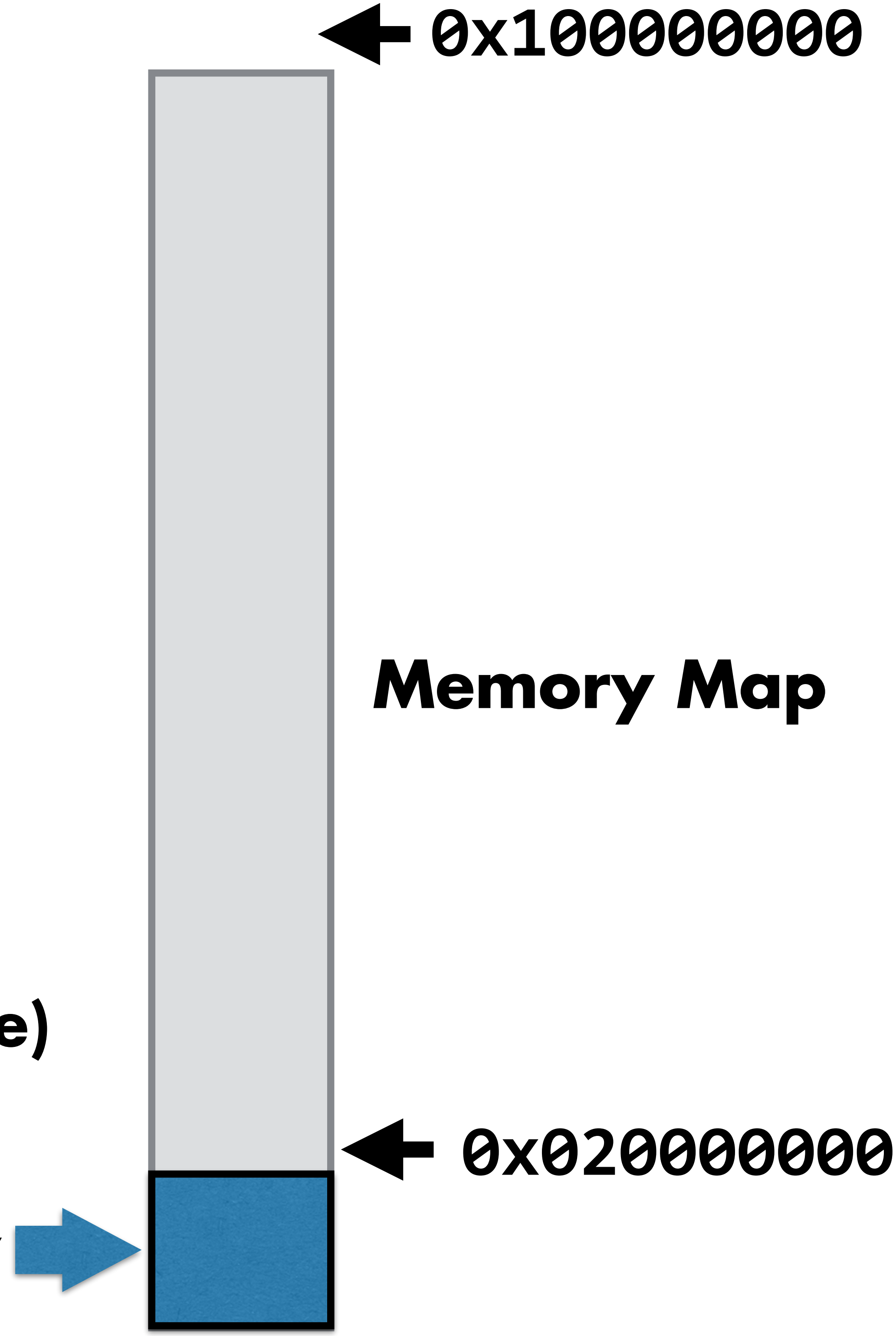
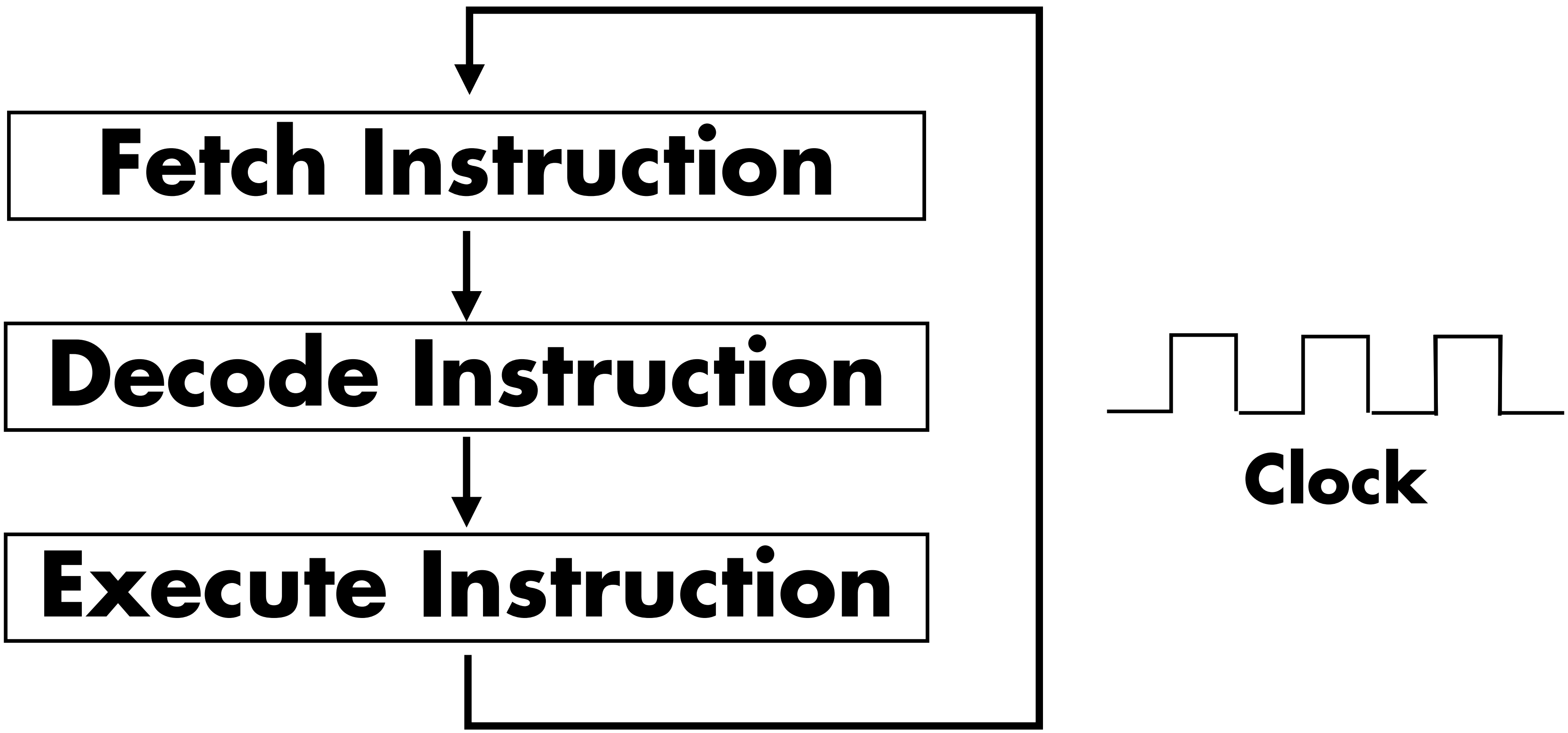
512 MB Actual Memory

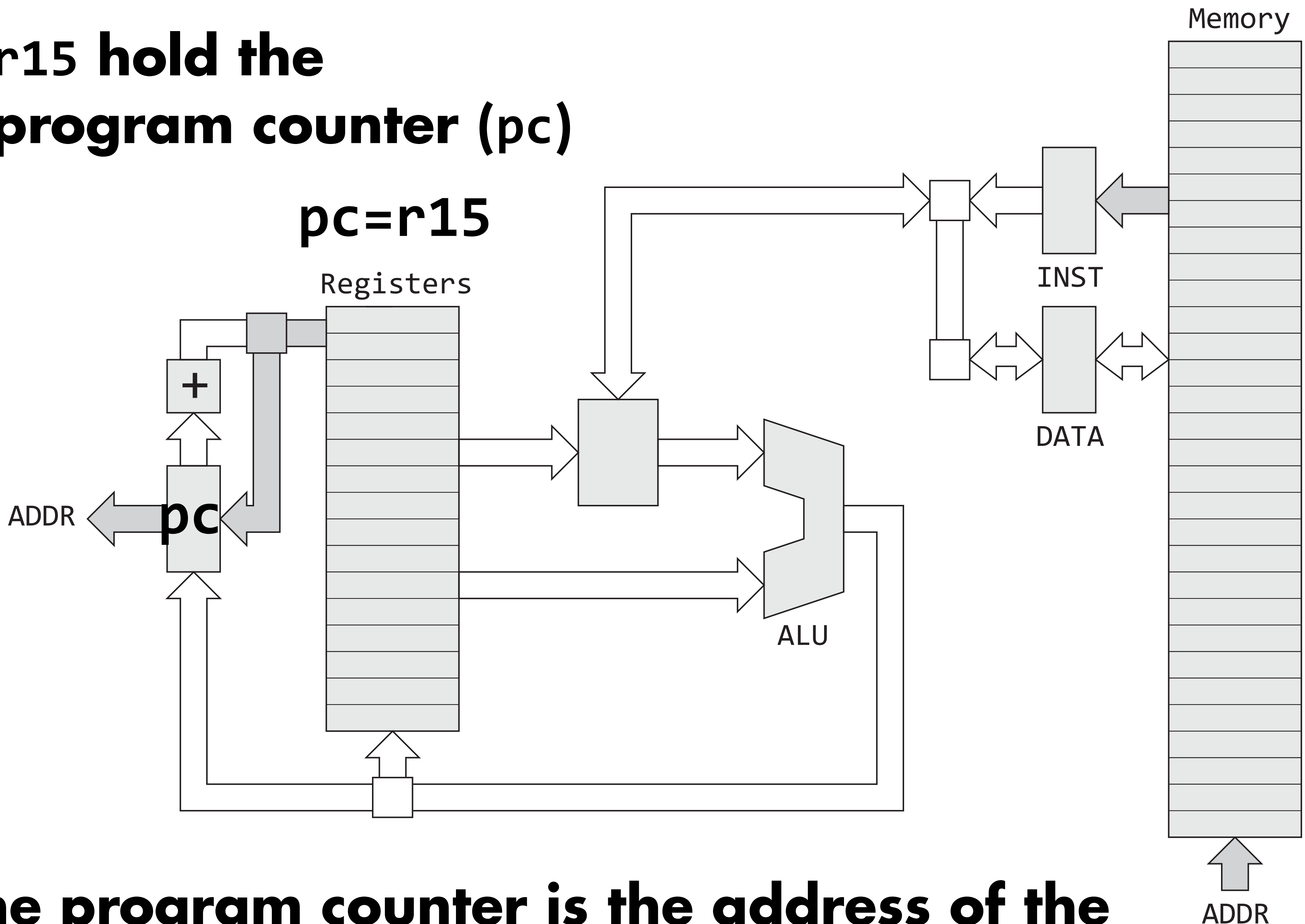


Running a Program



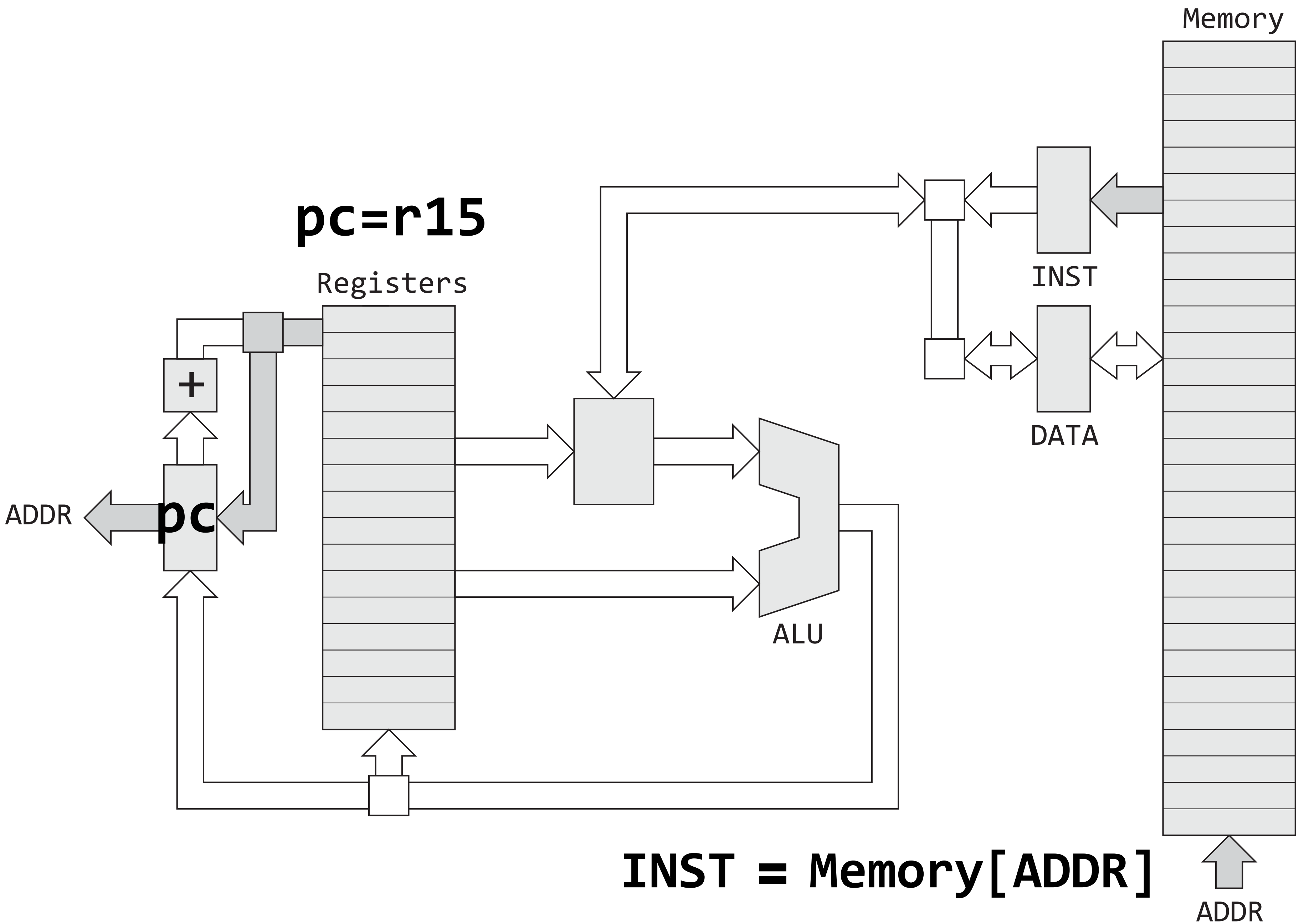
ARM Architecture / Floor Plan

`r15` hold the program counter (`pc`)



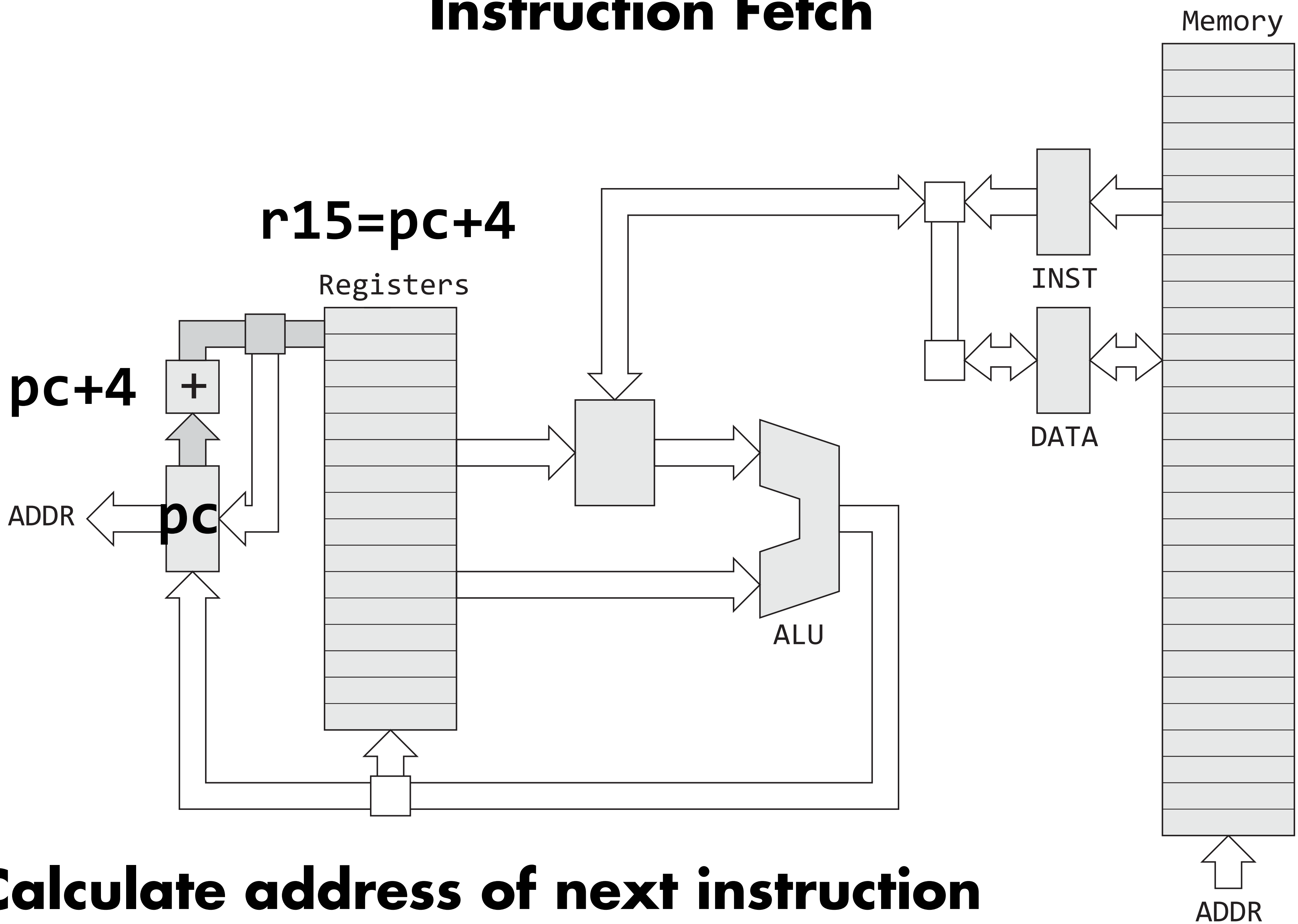
The program counter is the address of the next instruction to execute (not quite).

ARM Architecture / Floor Plan



Registers, addresses, and instructions are 32-bit words

Instruction Fetch

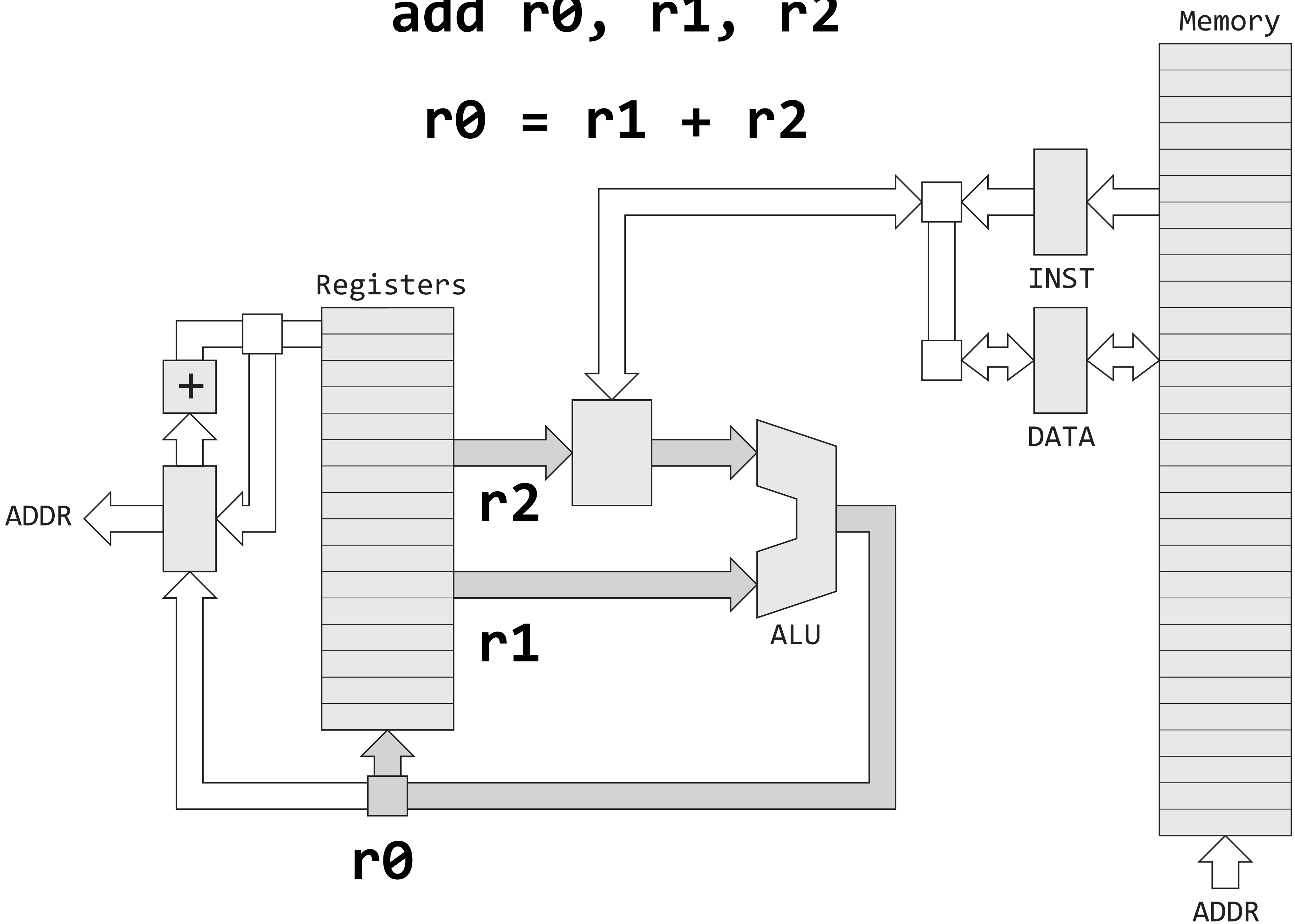


Calculate address of next instruction

Why pc+4?

Arithmetic-Logic Unit (ALU)

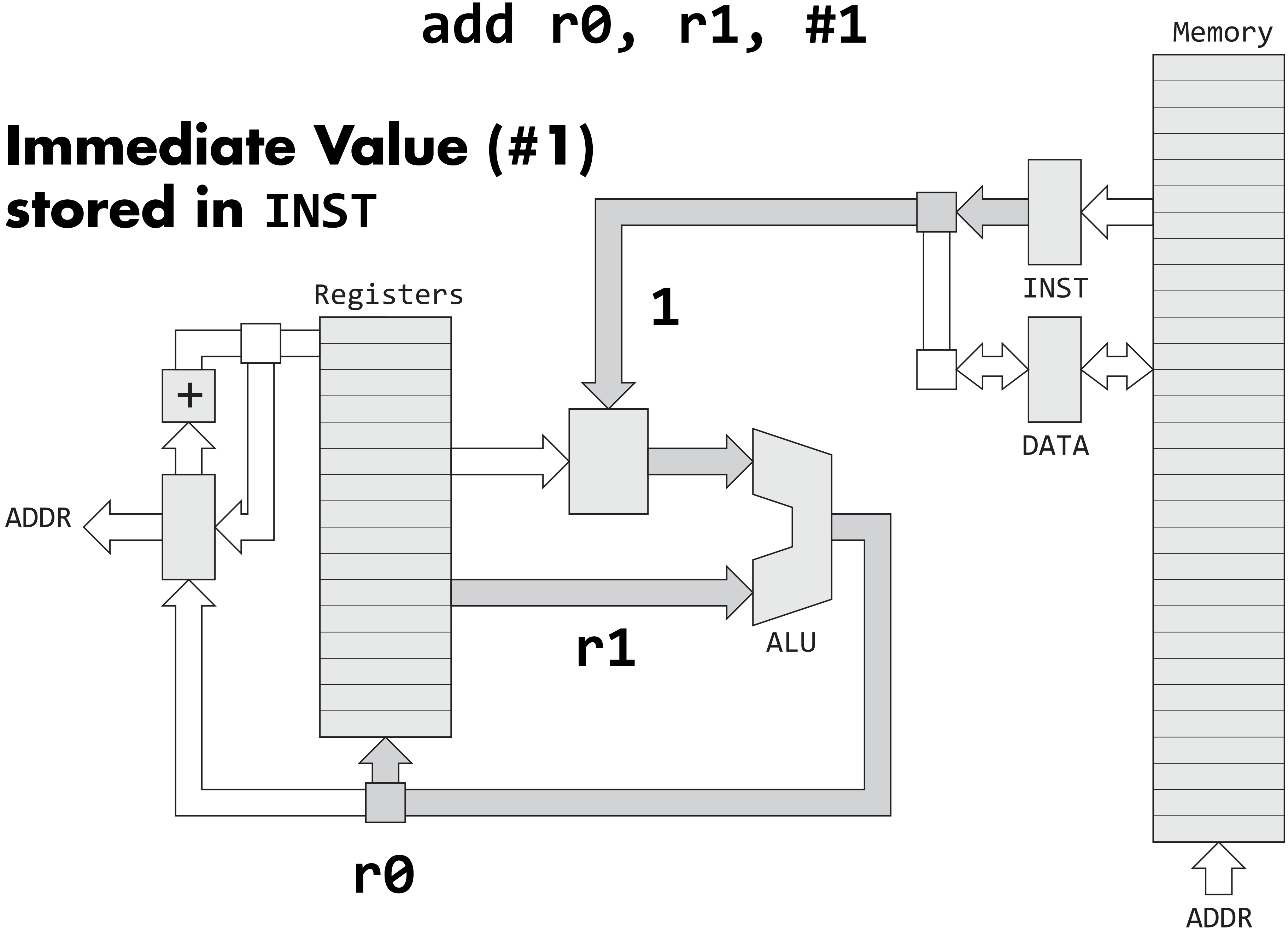
```
add r0, r1, r2

r0 = r1 + r2
```



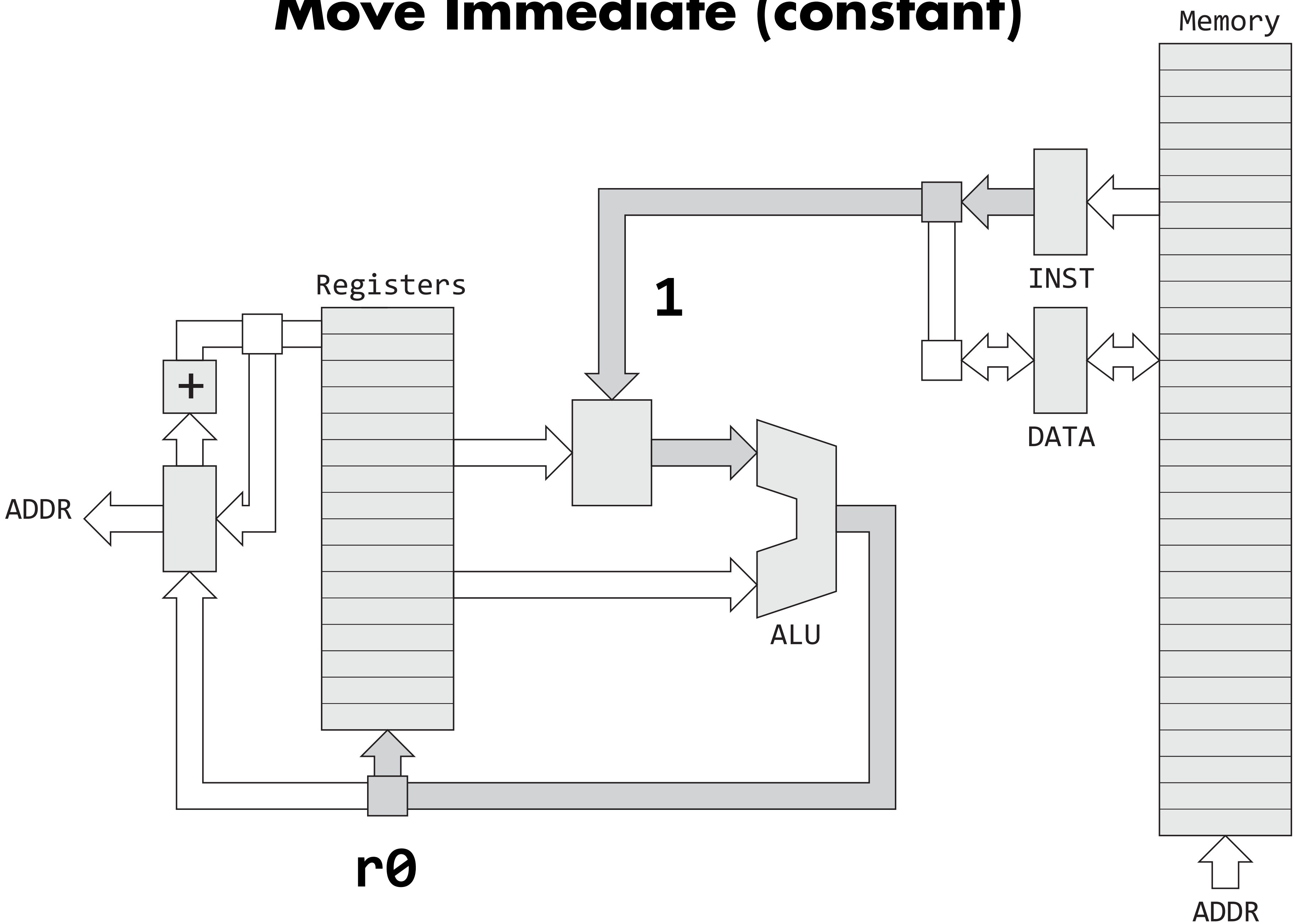
ALU only operates on data in registers

`add r0, r1, #1`

Immediate Value (#1) stored in `INST`

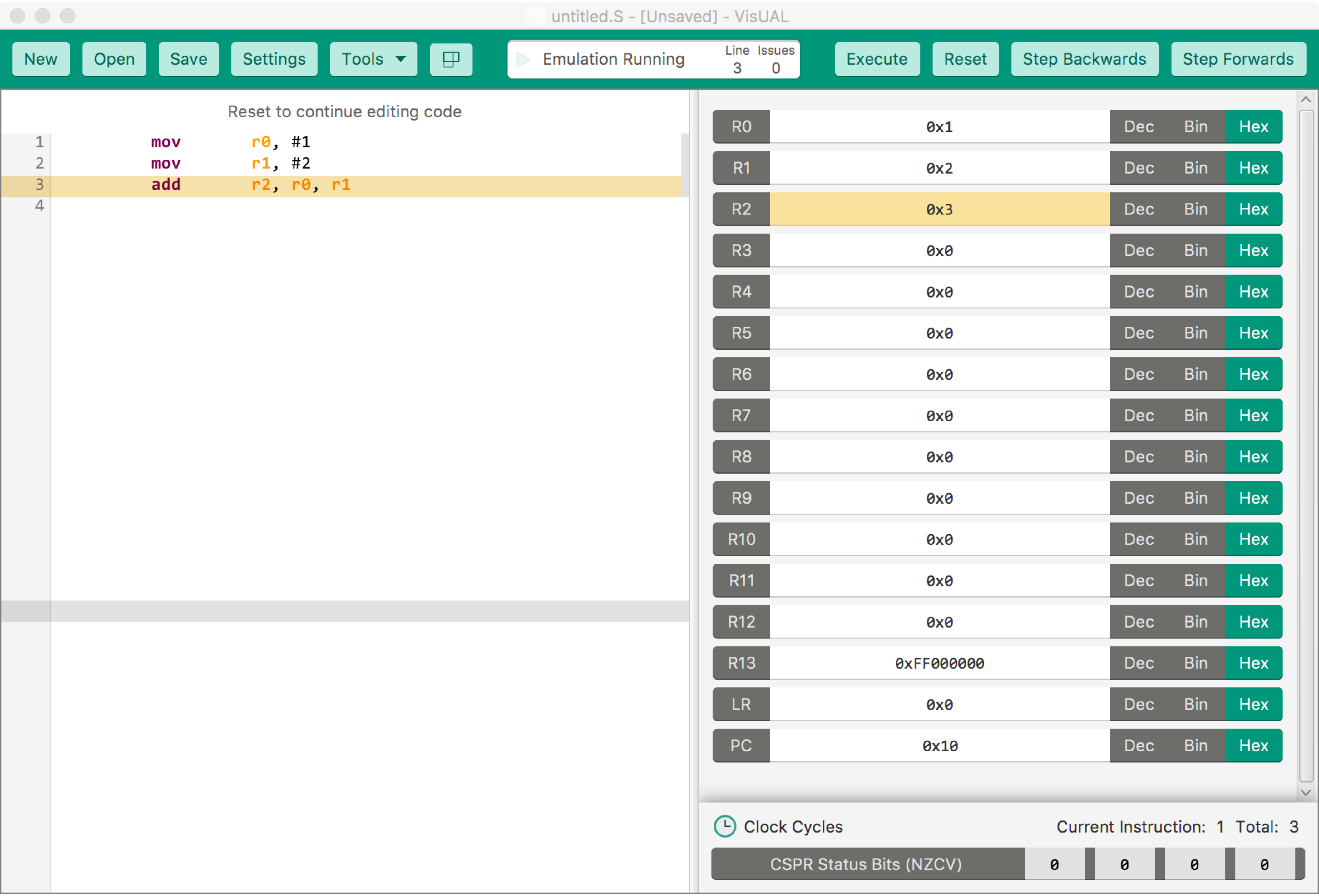


Move Immediate (constant)



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
mov r0, #1
mov r1, #2
add r2, r0, r1
R0 0x1
R1 0x2
R2 0x3
R3 0x0
R4 0x0
R5 0x0
R6 0x0
R7 0x0
R8 0x0
R9 0x0
R10 0x0
R11 0x0
R12 0x0
R13 0xFF000000
LR 0x0
PC 0x10
Dec Bin Hex
Clock Cycles
Current Instruction: 1 Total: 3
CSPR Status Bits (NZCV) 0 0 0 0

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)

```
02 00 81 e0
```

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

# Extract instructions into a binary (.bin)
% arm-none-eabi-objcopy add.o -O binary add.bin

# Find size (in bytes)
% ls -l add.bin
-rw-r--r--+ 1 hanrahan  staff  4 add.bin

# Display binary contents as bytes in hex
% xxd -g 1 add.bin
0000000: 02 00 81 e0
```

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.

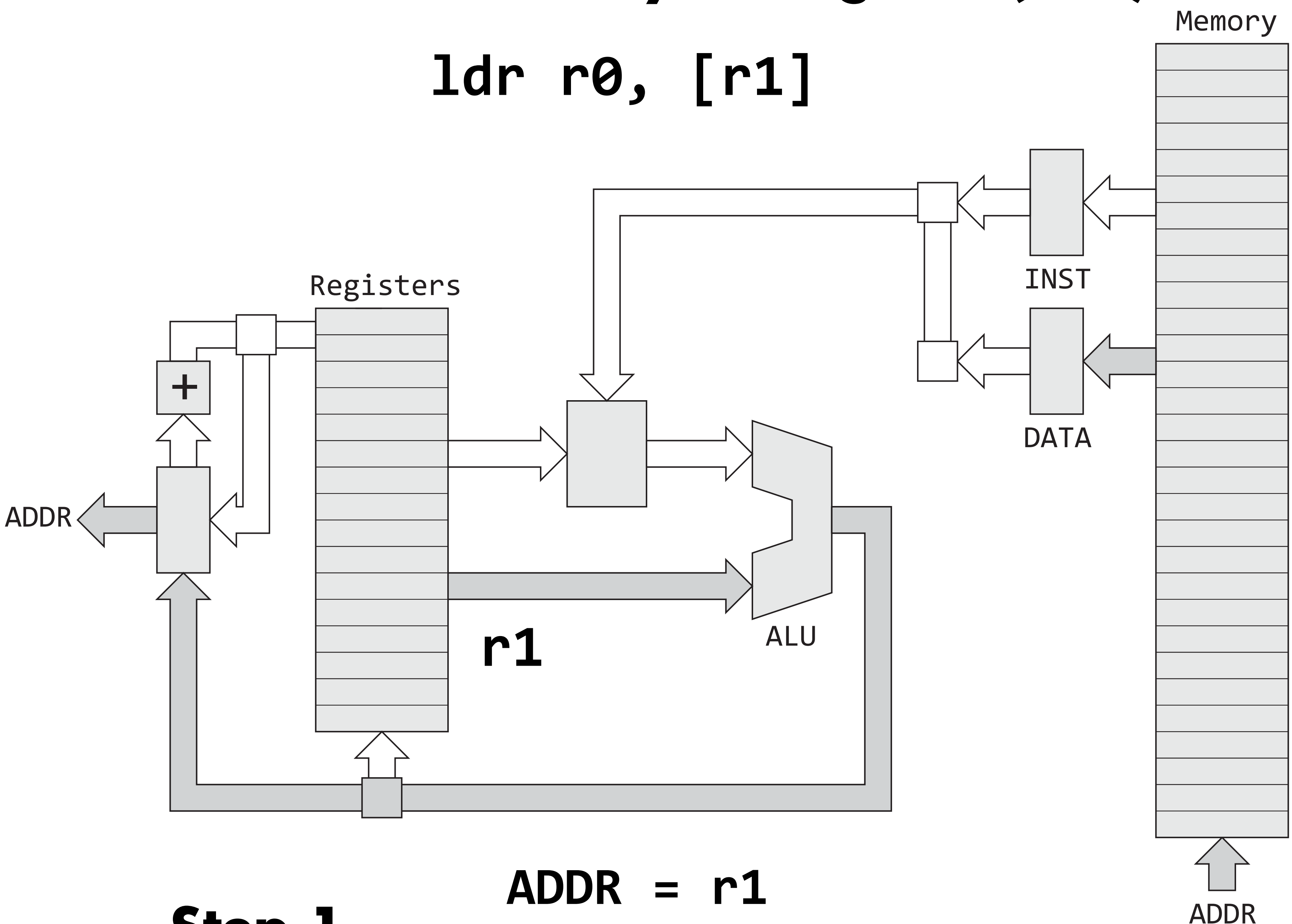
2. If all instructions are 32-bits, can you move any 32-bit constant value into a register using a single `mov` instruction?

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

Load and Store Instructions

Load from Memory to Register (LDR)

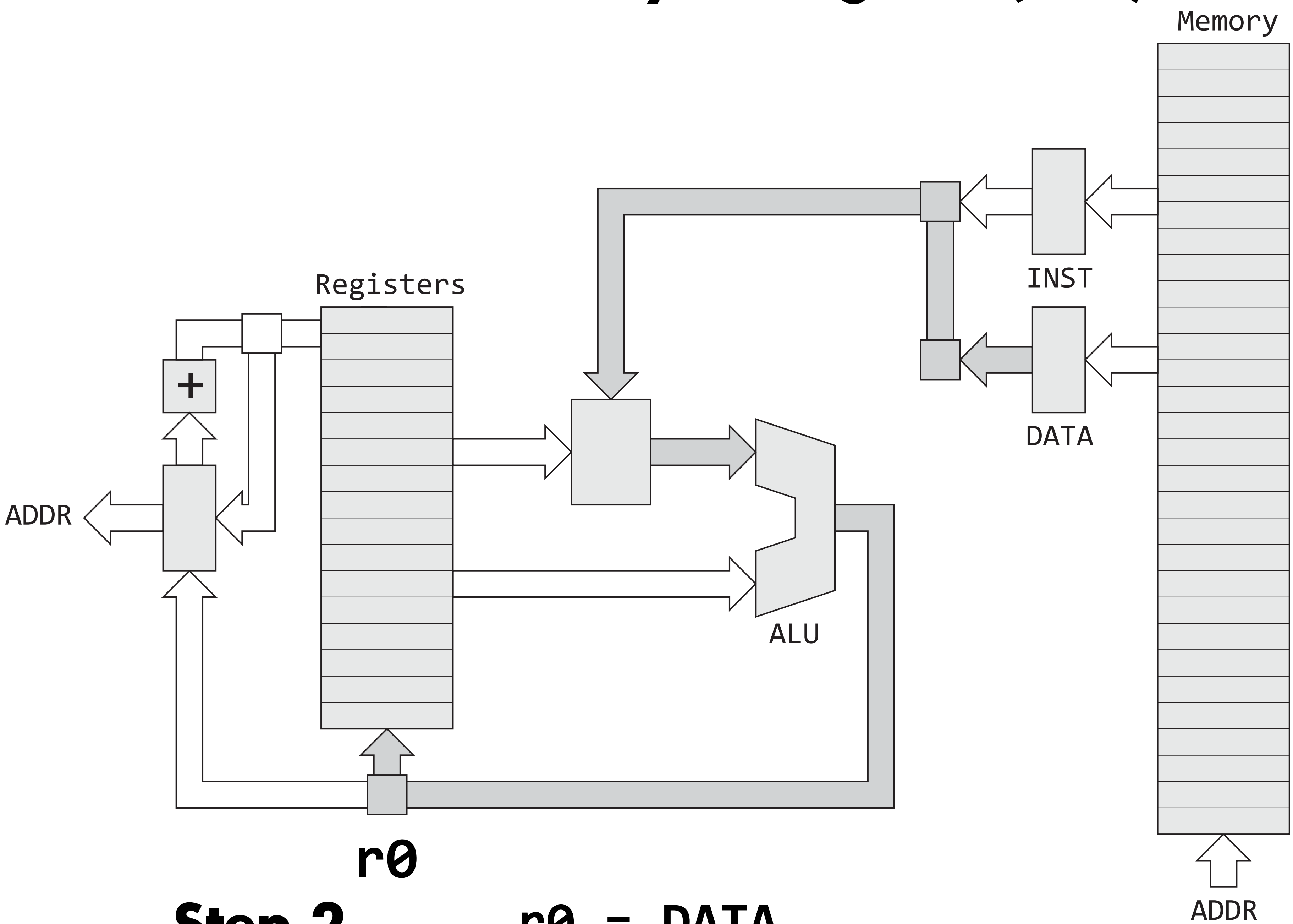
```
ldr r0, [r1]
```



Step 1

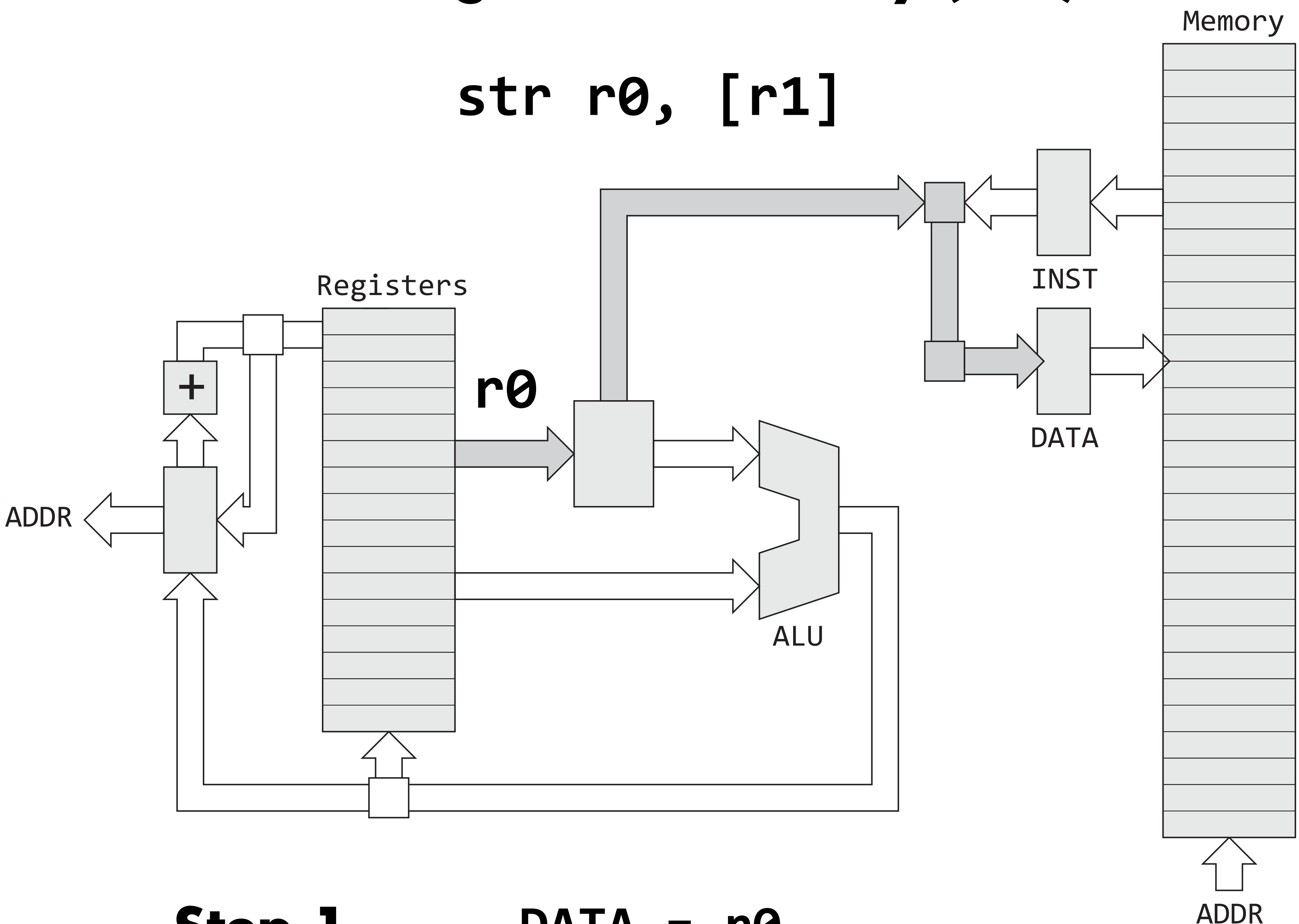
```
ADDR = r1
DATA = Memory[ADDR]
```

Load from Memory to Register (LDR)



Step 2 r0 = DATA

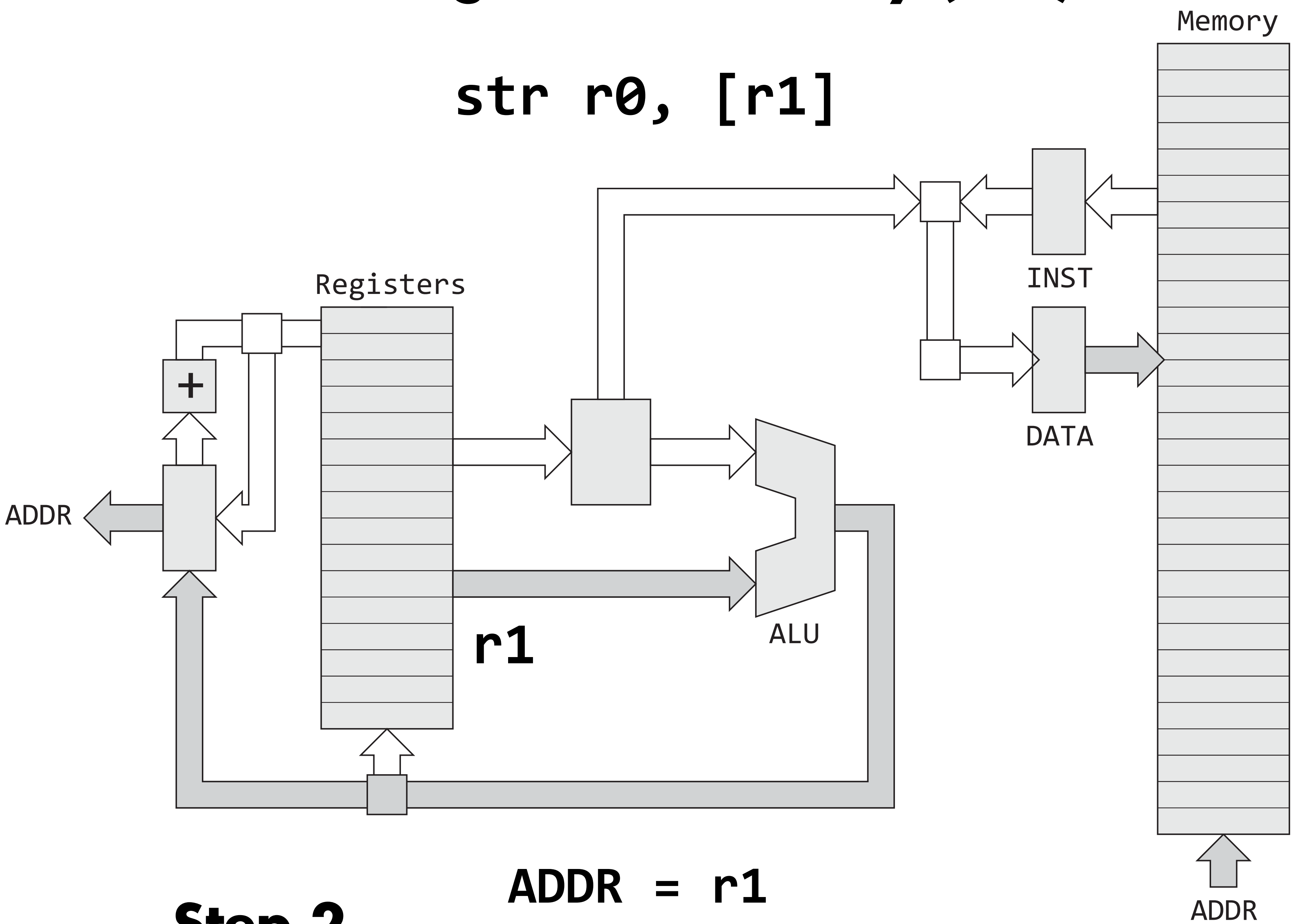
Store Register in Memory (STR)



Step 1 DATA = r0

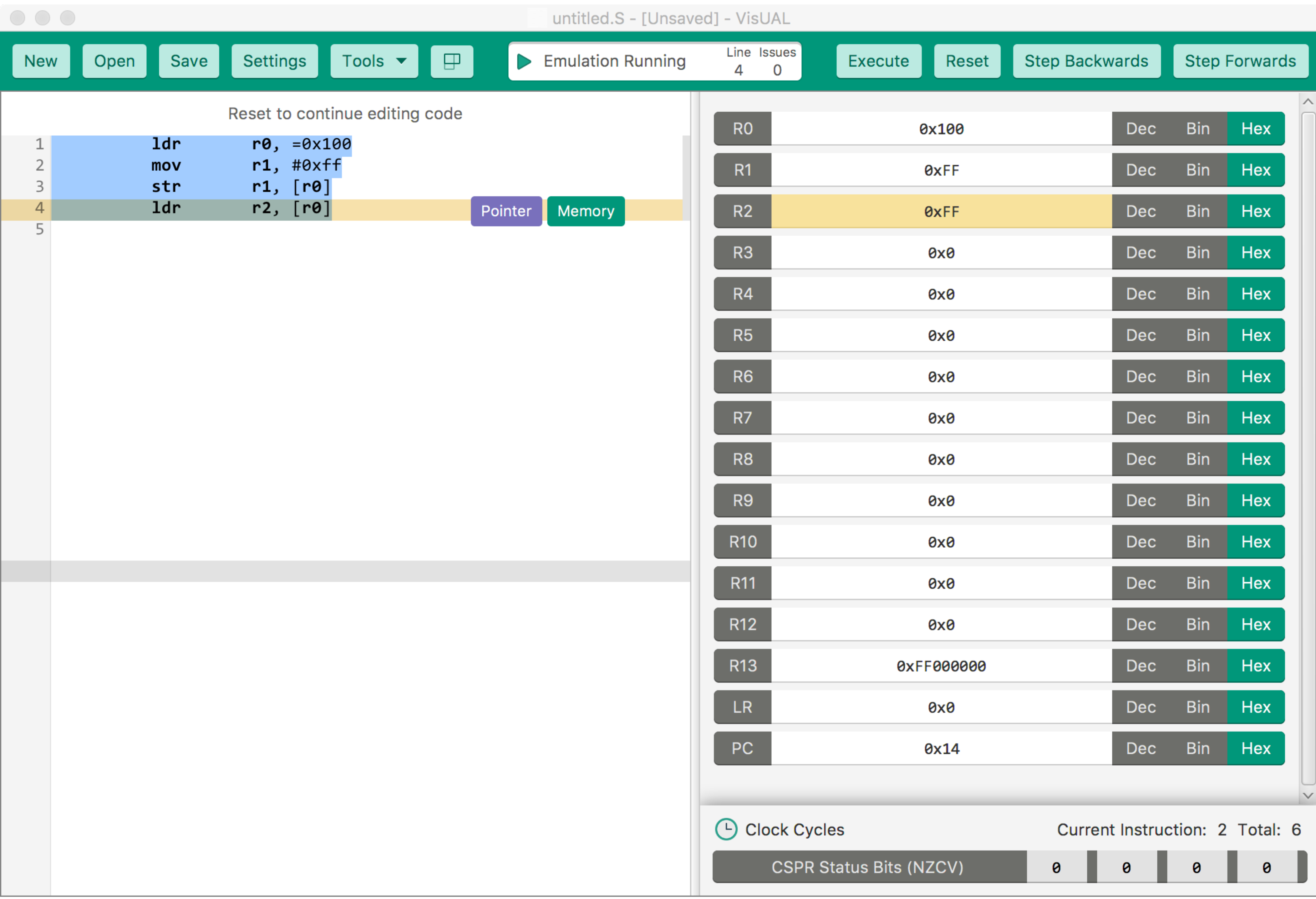
Store Register in Memory (STR)

`str r0, [r1]`

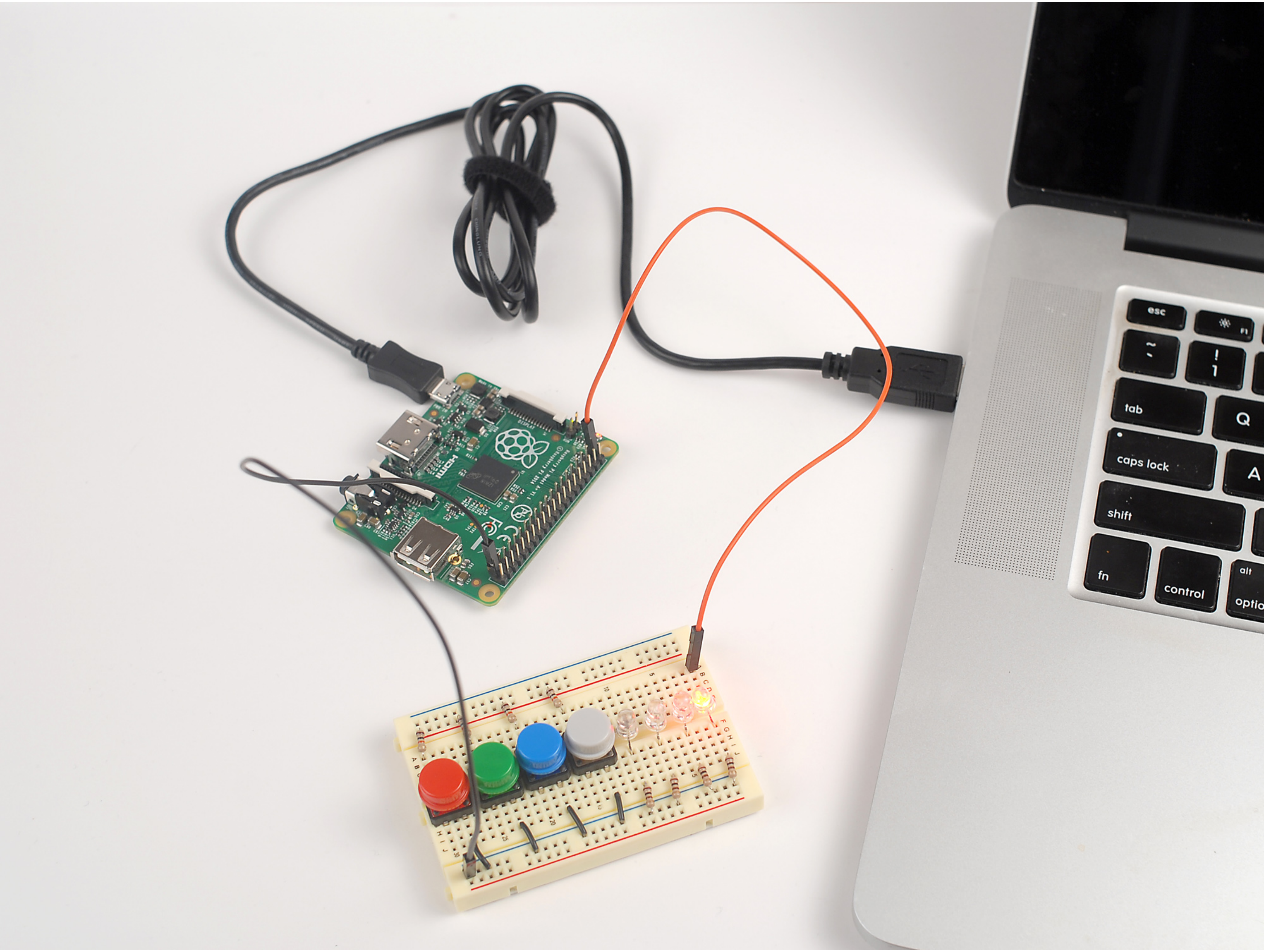


Step 2

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
R1 0xFF
R2 0xFF
R3 0x0
R4 0x0
R5 0x0
R6 0x0
R7 0x0
R8 0x0
R9 0x0
R10 0x0
R11 0x0
R12 0x0
R13 0xFF000000
LR 0x0
PC 0x14
Dec Bin Hex
Clock Cycles
Current Instruction: 2 Total: 6
CSPR Status Bits (NZCV) 0 0 0 0

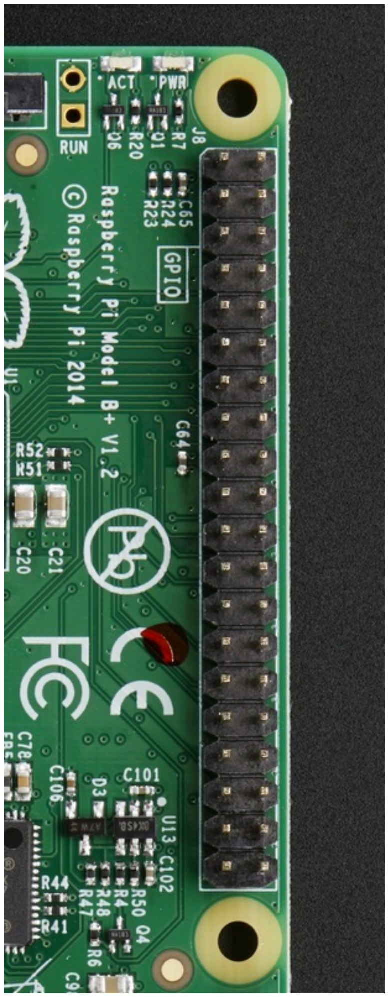
Turning on an LED

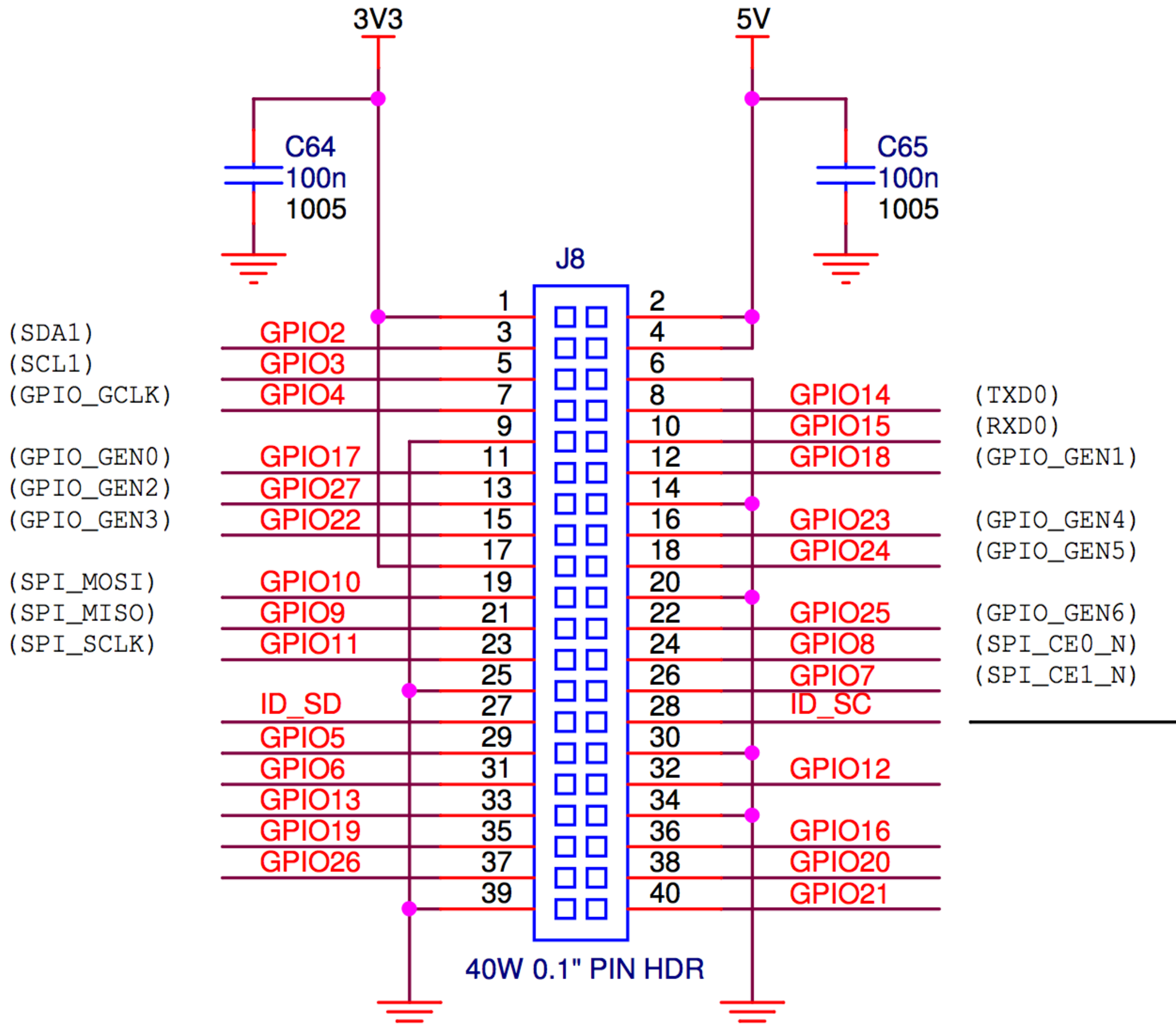

esc
tab
Q
caps lock
A
shift
fn
control
alt

Computers have Peripherals that Interface to the World

GPIO Pins are Peripherals

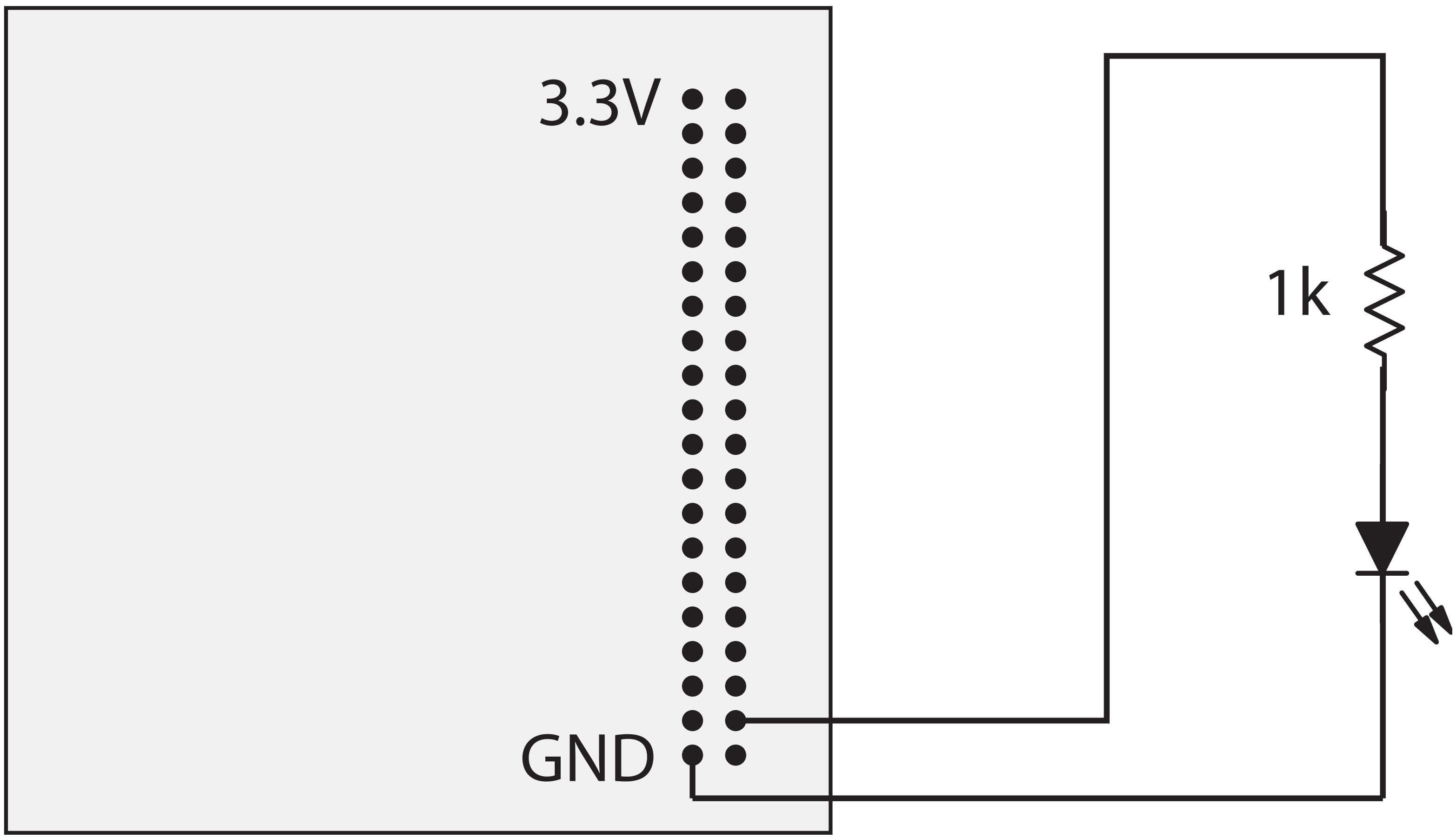
General-Purpose Input/Output (GPIO) Pins





54 GPIO Pins

Connect LED to GPIO 20



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

Peripherals are Controlled
by
Special Memory Locations

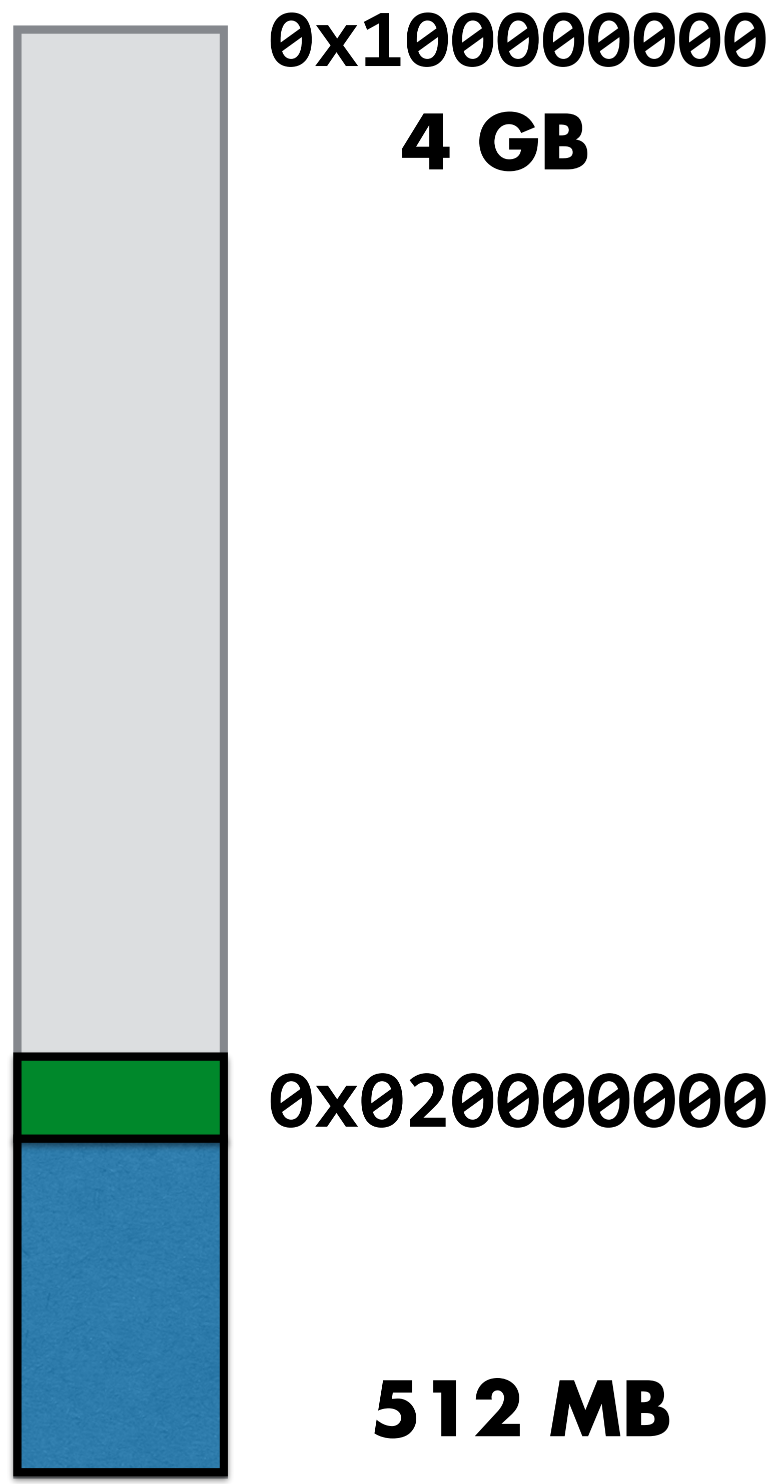
"Peripheral Registers"

Memory Map

Peripheral registers are *mapped* into address space

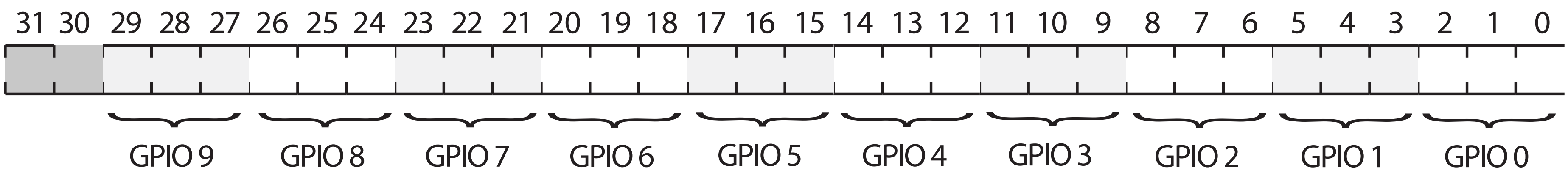
Memory-Mapped IO (MMIO)

MMIO space is above physical memory



Ref: BCM2835-ARM-Peripherals.pdf

GPIO Function Select Register

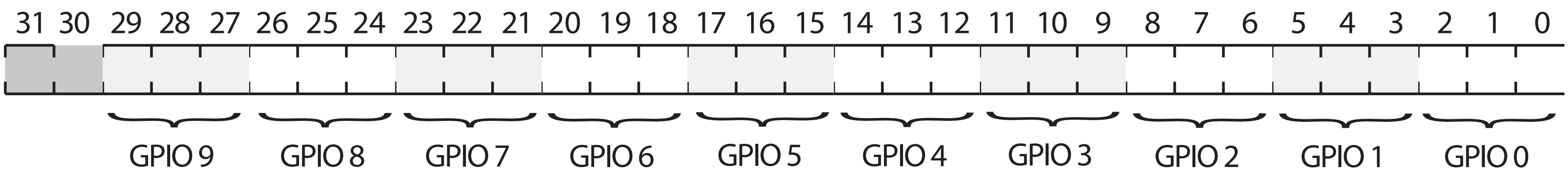


"Function" is INPUT, OUTPUT (or ALT0-5)

8 functions requires 3 bits to specify

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

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)

Pi has 54 GPIOs - 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 …

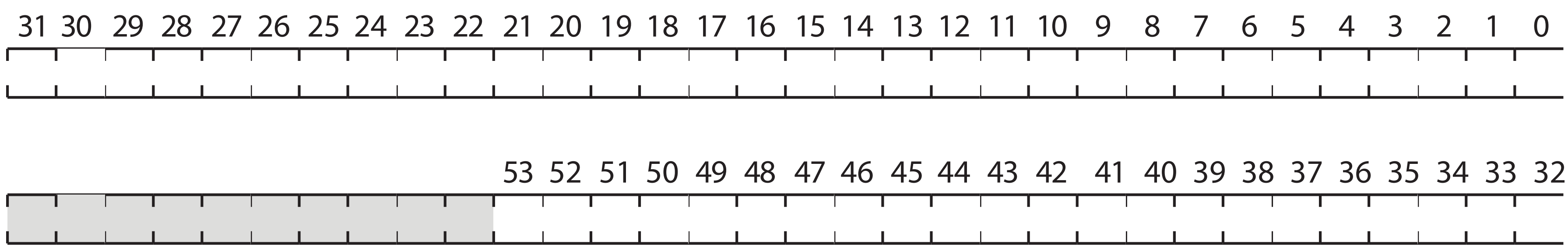
```
Manual says: 0x7E200000
Replace 7E with 20: 0x20200000
```

Ref: BCM2835-ARM-Peripherals.pdf

```
// Set GPIO20 to be an output

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

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

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

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

```
//  Set GPIO20 output High (3.3V)

// FSET0 = 0x2020001c

mov r0, #0x20
lsl r1, r0, #24
lsl r2, r0, #16
orr r1, r1, r2
orr r1, r1, #0x1c

mov r1, #1         // 0x00000001
lsl r1, r1, #20    // 0x00100000
str r1, [r0]       // store 1<<20 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/
ON  Macintosh HD

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

Key Concepts

Bits are bits; bitwise operations

Memory addresses refer to bytes (8-bits), words are 4 bytes

Memory stores both instructions and data

Computer:s repeatedly fetch, decode, and execute instructions

Different types of ARM instructions

- **ALU**
- **Loads and Stores**
- **Branches**

General purpose IO (GPIO), peripheral registers, and MMIO