CS107e
Computer Systems from the Ground Up

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Maria Fernandez, Blake Jones,
Liana Keesing, Anna Mistele

Autumn 2022

https://cs107e.github.io/

Chris

Maria

Blake

Liana

Anna

Who is Chris Gregg?

- Career:
- Johns Hopkins University Bachelor's of Science in Electrical and Computer Engineering
- Seven years active duty, U.S. Navy (14+ years reserves)
- Harvard University, Master's of Education
- Seven years teaching high school physics (Brookline, MA and Santa Cruz, CA)
- University of Virginia, Ph.D. in Computer Engineering
- Three years teaching computer science at Tufts University
- Senior Lecturer at Stanford (arrived, Fall 2016)
- Personal website: https://web.stanford.edu/~cgregg

Learning Goal 1

Understand how computers
represent data,
execute programs,
and control peripherals

OK

```
int myvar;
int calc() {...}
```

Not OK

```
int calc() {
   int myvar;
   ...
}
```

OK

```
int a = 20;
unsigned int b = 6;
if (a < b) {...}
```

Not OK

```
int a = -20;
unsigned int b = 6;
if (a < b) {...}
```

OK

```
volatile long counter;
for (counter = 0;
     counter < 10000000000;
     counter++) {}
```

Not OK

```
long counter;
for (counter = 0;
     counter < 10000000000;
     counter++) {}
```

Why?

OK

```
int myvar;
int calc() {...}
```

Not OK

```
int calc() {
   int myvar;
   ...
}
```

```
int a = 20;
unsigned int b = 6;
if (a < b) {...}
```

```
int a = -20;
unsigned int b = 6;
if (a < b) {...}
```

```
volatile long counter;
for (counter = 0;
     counter < 10000000000;
     counter++) {}
```

```
long counter;
for (counter = 0;
     counter < 10000000000;
     counter++) {}
```

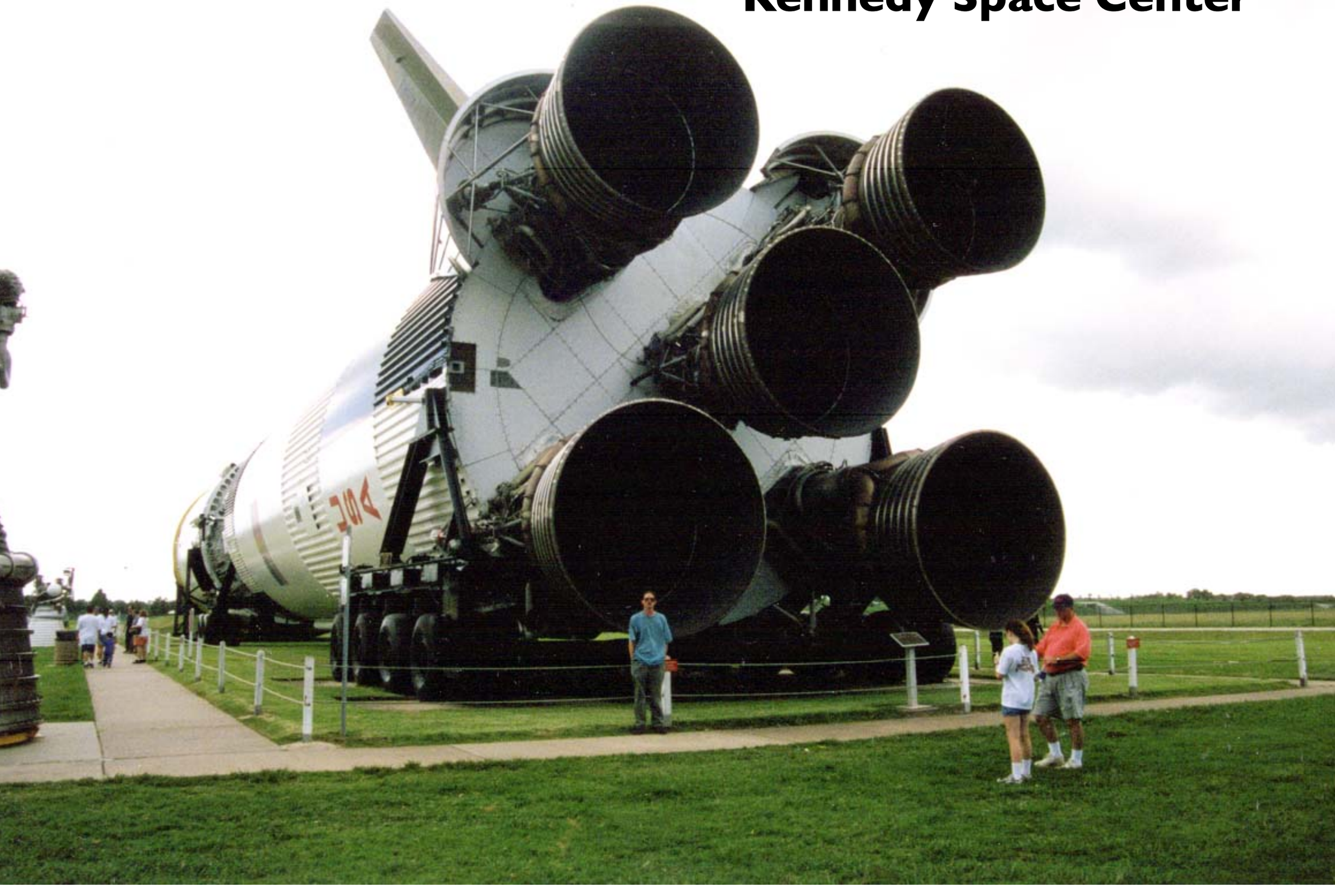
```
int main() {
    ...
}
```

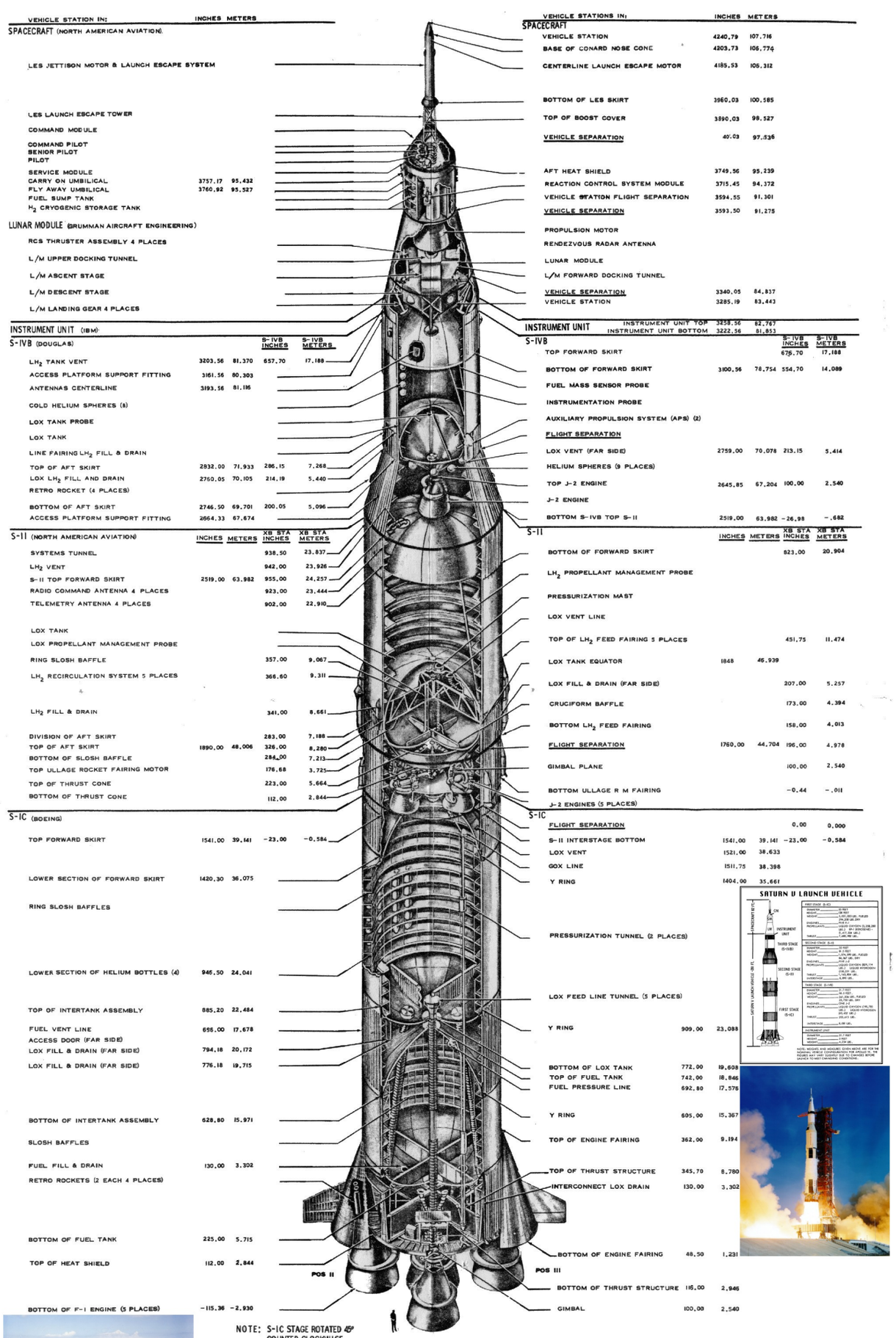
How does your program start at the first instruction of main()?
Or does it really?

First steps are often the hardest

That's why we're here!

Saturn V
Kennedy Space Center





Command Module
64,000 lbs

Saturn V
6,200,000 lbs

Payload
1.5% of total weight

Falcon 9

Engineer for Excellence!

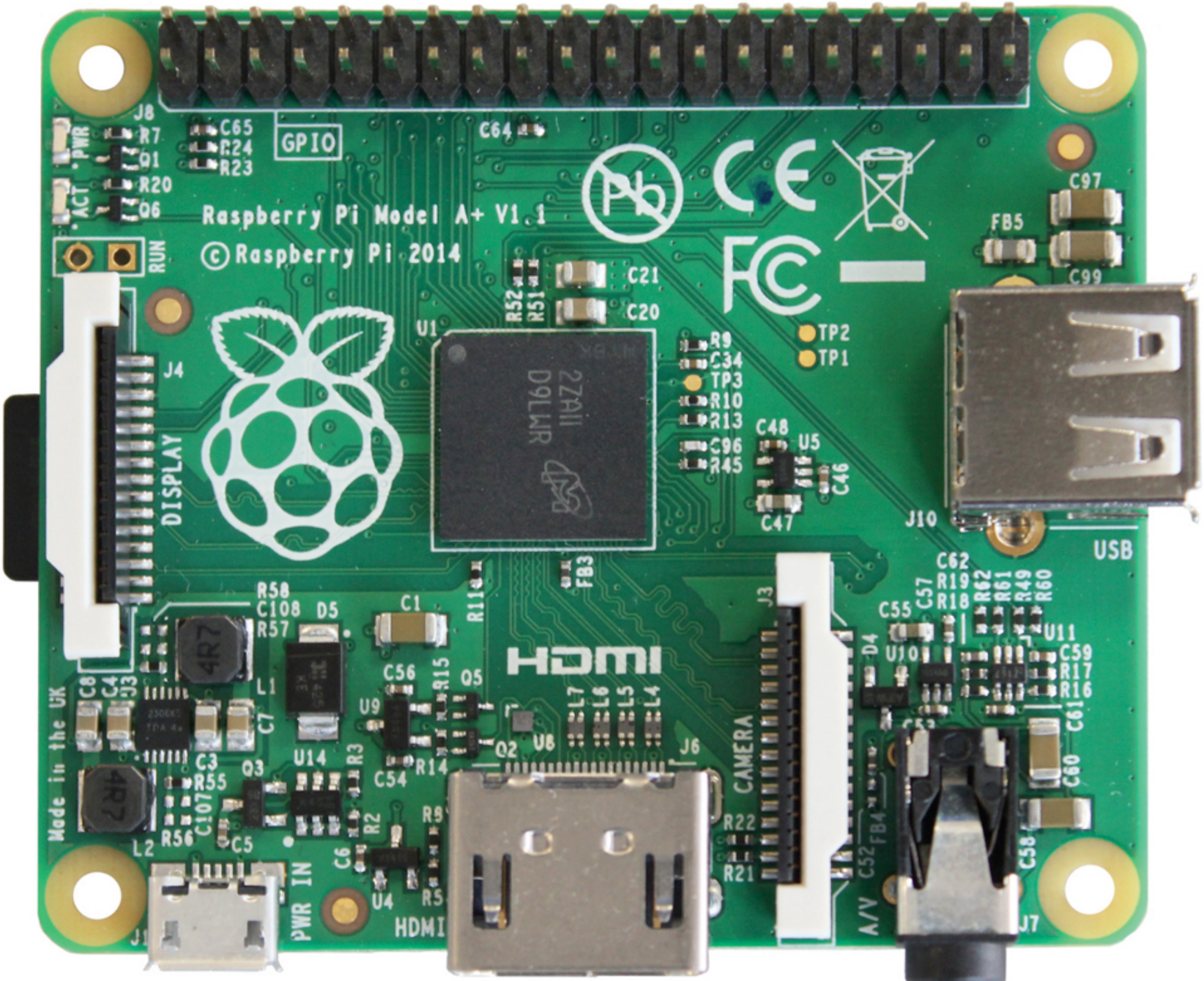
Perseverance!

Bare Metal on the Raspberry Pi

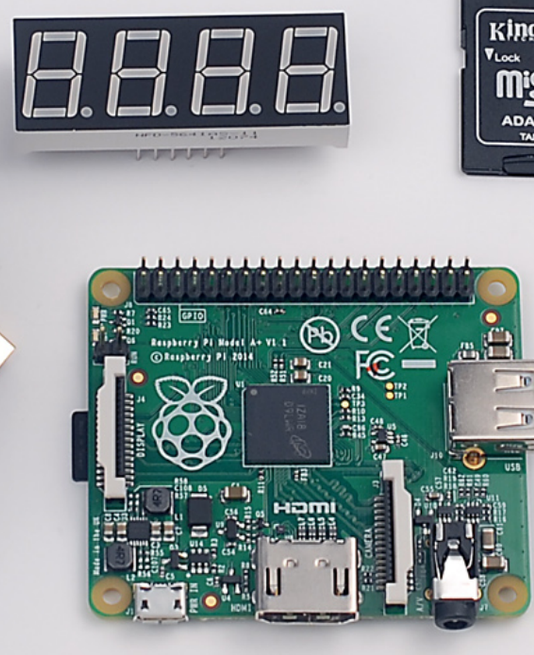
Definition: Bare metal programming involves no operating system (programmer constructs libraries)

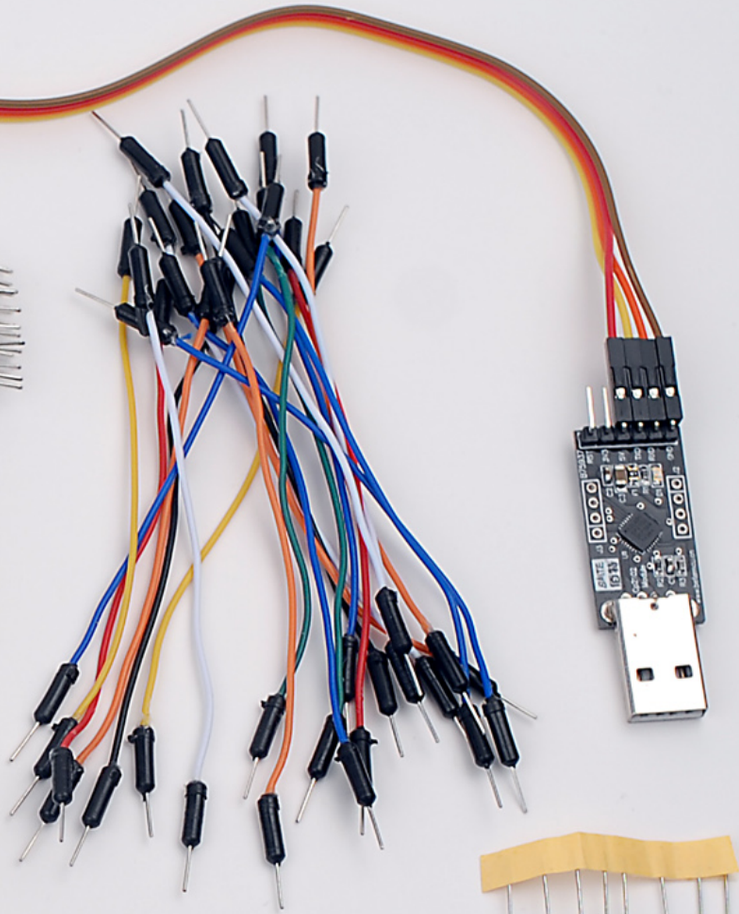
Bare metal programs boot and startup on their own, and directly control peripherals

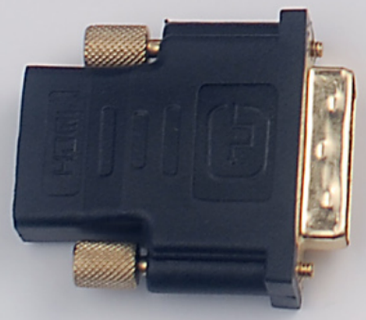
You'll understand every line of code in the system.

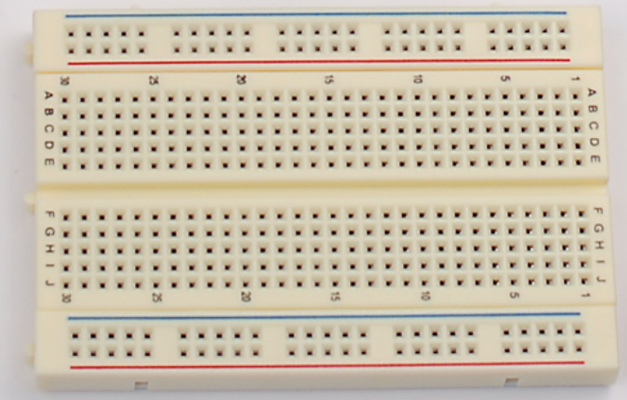

Raspberry Pi Model A+ V1.1
© Raspberry Pi 2014
GPIO
J8
PWR
ACT
RUN
J4
DISPLAY
U1
J6
CAMERA
HDMI
J3
USB
J10
PWR IN
J1
A/V
J7
U5
U14
U9
U8
U4
U10
U11
D4
D5
L1
L2
Made in the UK
TP1
TP2
TP3
FB3
FB4
FB5

Raspberry Pi Kit









Raspberry Pi Shell

```
Raspberry Pi System Monitor

*
00008000- 07 DA A0 E3 1B 00 00 EB
*
00008008- B9 1B 00 EA 18 F0 9F E5
*
00008010- 18 F0 9F E5 18 F0 9F E5
*7000
00007000- 00
*
00007000- 00 00 00 00 00 00 00 00
*
00007008- 00 00 00 00 00 00 00 00
*
00007010- 00 00 00 00 00 00 00 00
*7000:01 00 a0 e3 1e ff 2f e1
*7000,7007
00007000- 01 00 A0 E3 1E FF 2F E1
*7000@
1
*7000/7007
e3a00001: mov r0, #1
e12fff1e: bx lr
*
```

Almost every instruction will be code you've written!

Learning Goal 2

Master your tools
Learn their value

Software Tools

UNIX command line: `bash, cd, ls, …`

Programming languages: C, …

`gcc`

`as`

`ld`

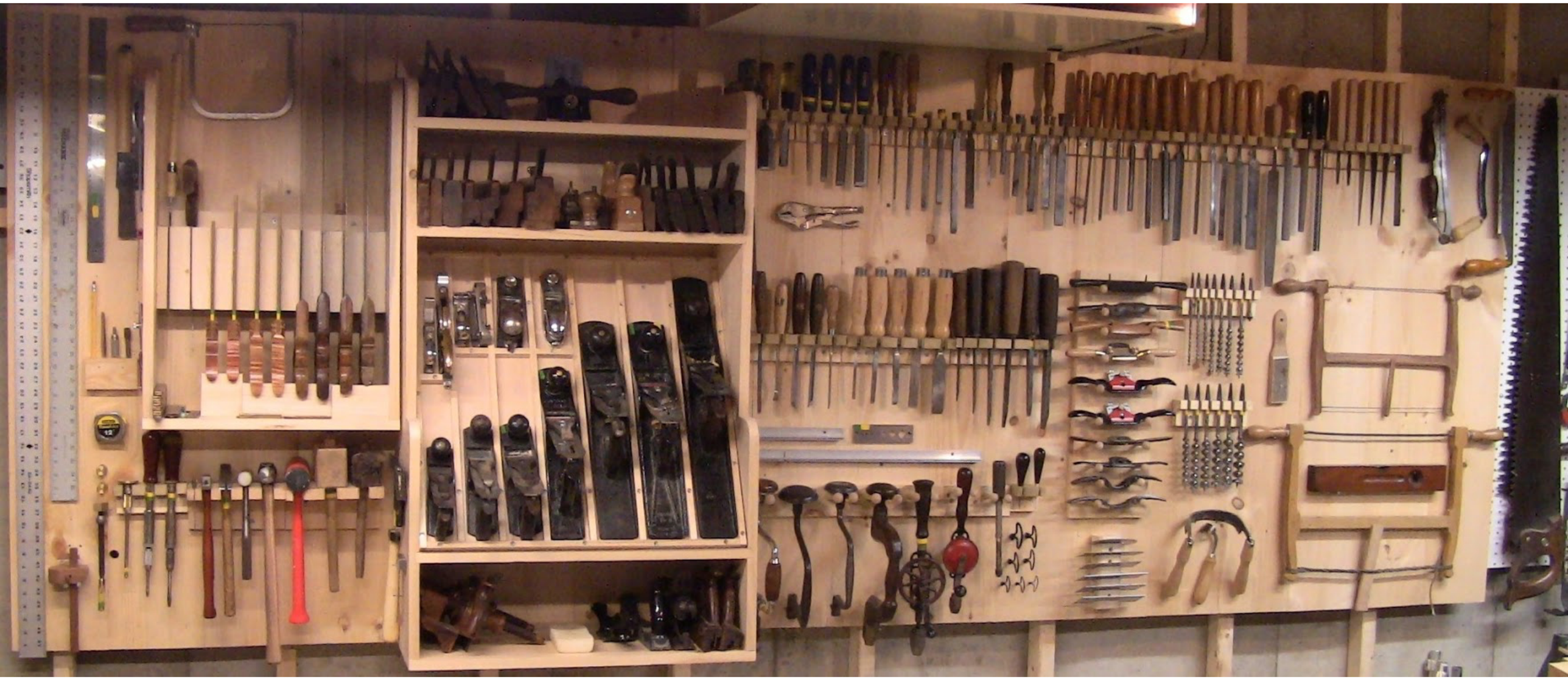
binutils: `nm, objcopy, objdump`, …

`make`

`git` and github.com

documentation: markdown

Different Tools for Different Jobs



http://dans-woodshop.blogspot.com/

Organized Development Environment

http://amhistory.si.edu/juliachild/

Don't Avoid Activation Energy

$$CO_{(g)} + NO_{2(g)} \longrightarrow CO_{2(g)} + NO_{(g)}$$

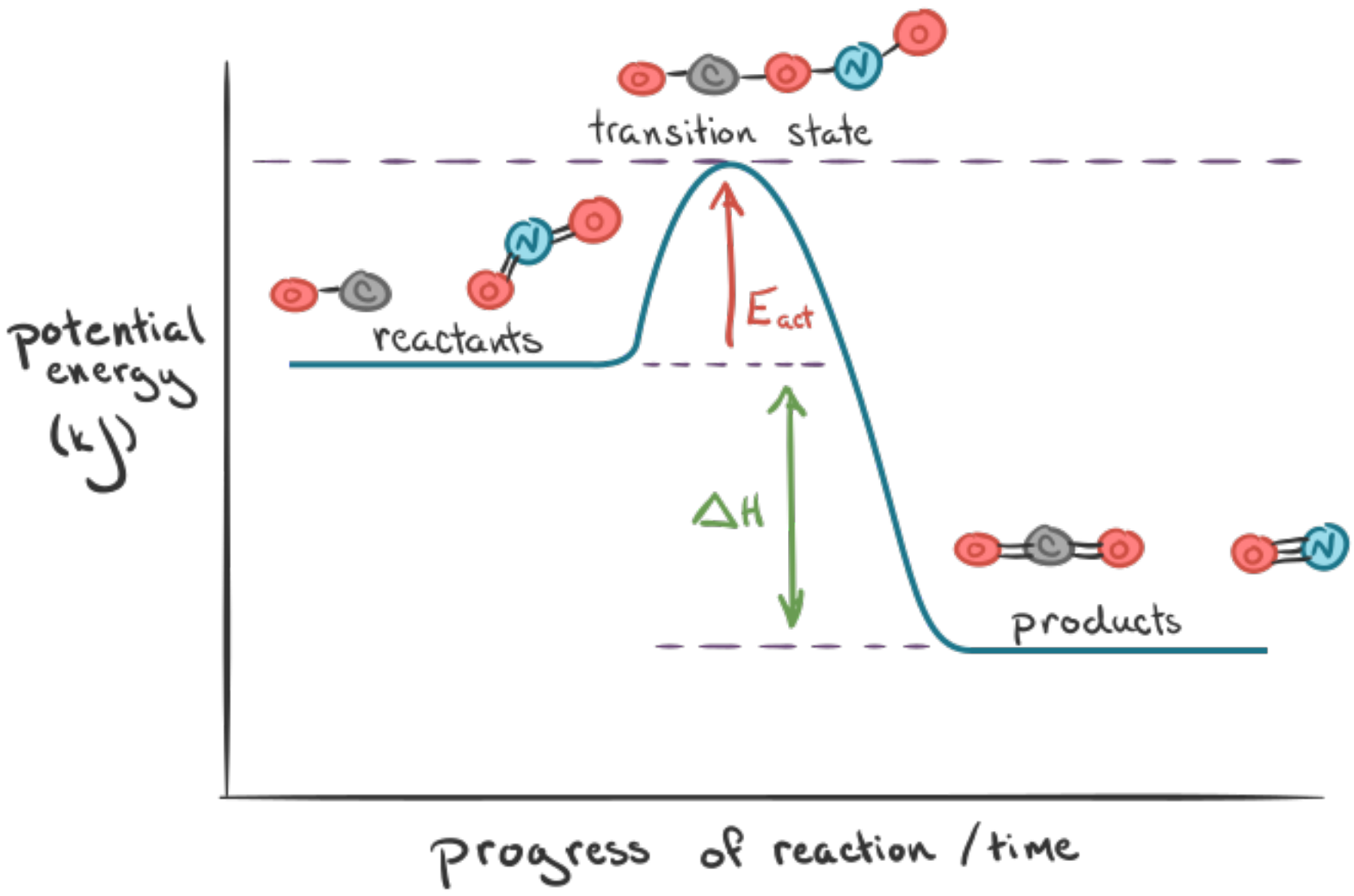


Figure from Khan Academy

https://www.khanacademy.org/test-prep/mcat/chemical-processes/thermochemistry/a/endothermic-vs-exothermic-reactions

Don't Avoid Activation Energy

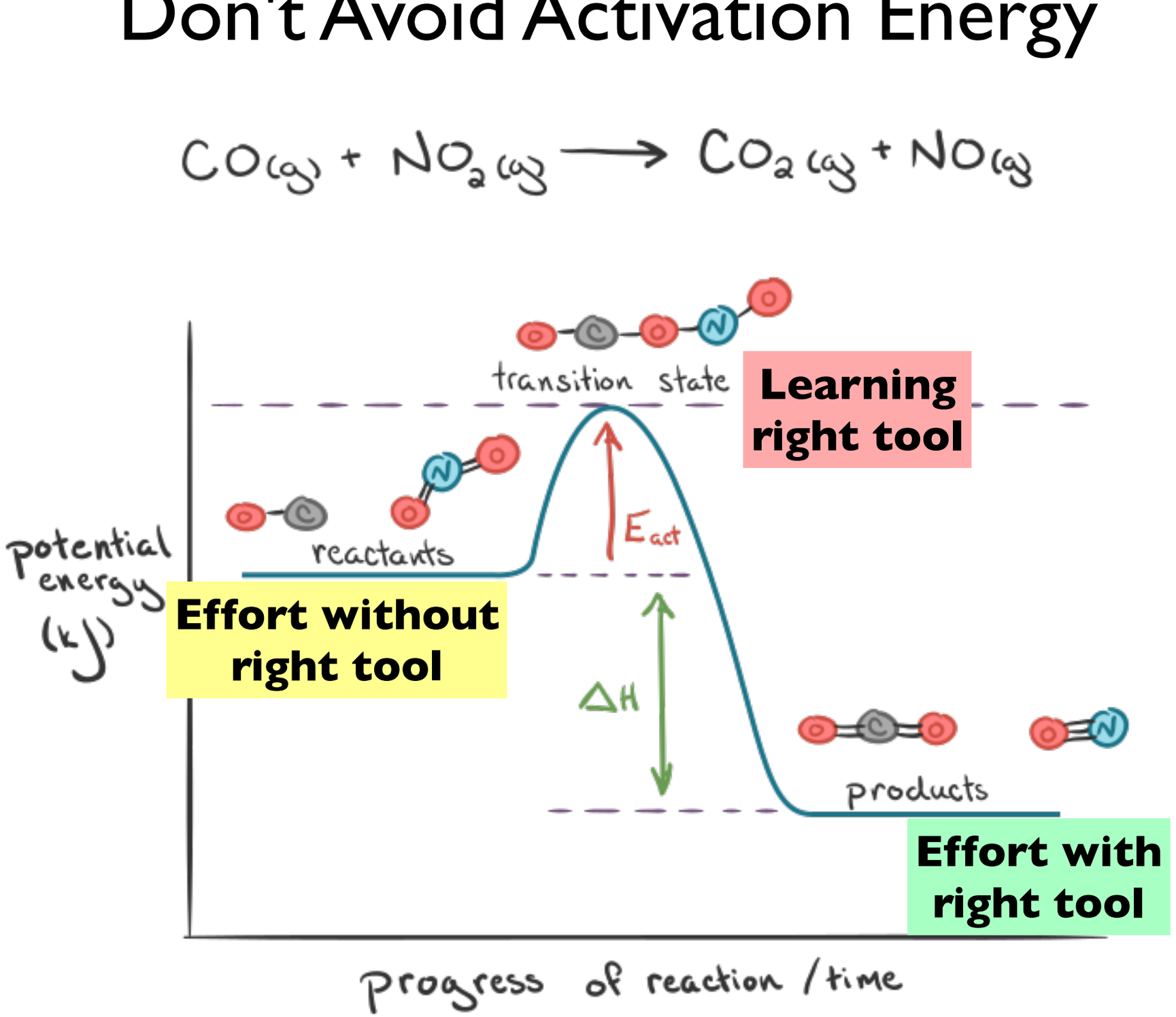
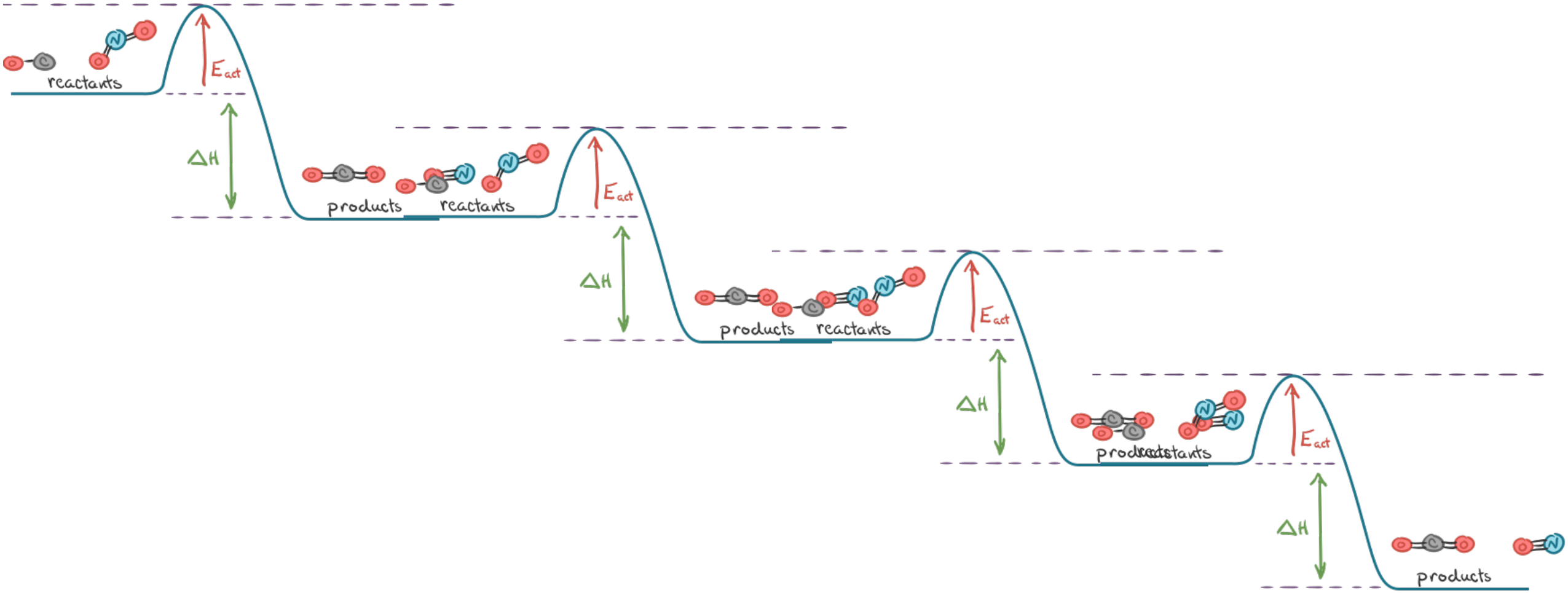


Figure from Khan Academy

https://www.khanacademy.org/test-prep/mcat/chemical-processes/thermochemistry/a/endothermic-vs-exothermic-reactions

Practice, Practice, Practice

https://paulsellers.com/tag/gouge/



It never ends... 1000x improvements possible!

Figure from Khan Academy

https://www.khanacademy.org/test-prep/mcat/chemical-processes/thermochemistry/a/endothermic-vs-exothermic-reactions

Debugging and Troubleshooting

Administration

Weekly Cadence

Each week has a focus topic

Pair of coordinated lectures on Fri and Mon

Mandatory lab on Wednesdays (either 10:30am-12:30pm, or 1:30pm-3:30pm)

Assignment handed out Wed evening (after lab), YEAH hours on Thu, assignment due following Tue at 6 pm.

Laboratories

Attendance is mandatory

Do exercises and complete check-list

Leave lab ready for assignment: walks you through tricky bit (hardware/software interface) to get you started

Philosophy: lots-of-help, hands-on, collaborative

We will organize your lab into small (2-3 person) breakout groups so you can do the lab with mute off and chat/collaborate. Initially groups are randomly assigned, later in the quarter we will let you choose partners if you want to.

Assignments

7 assignments

- Build on each other

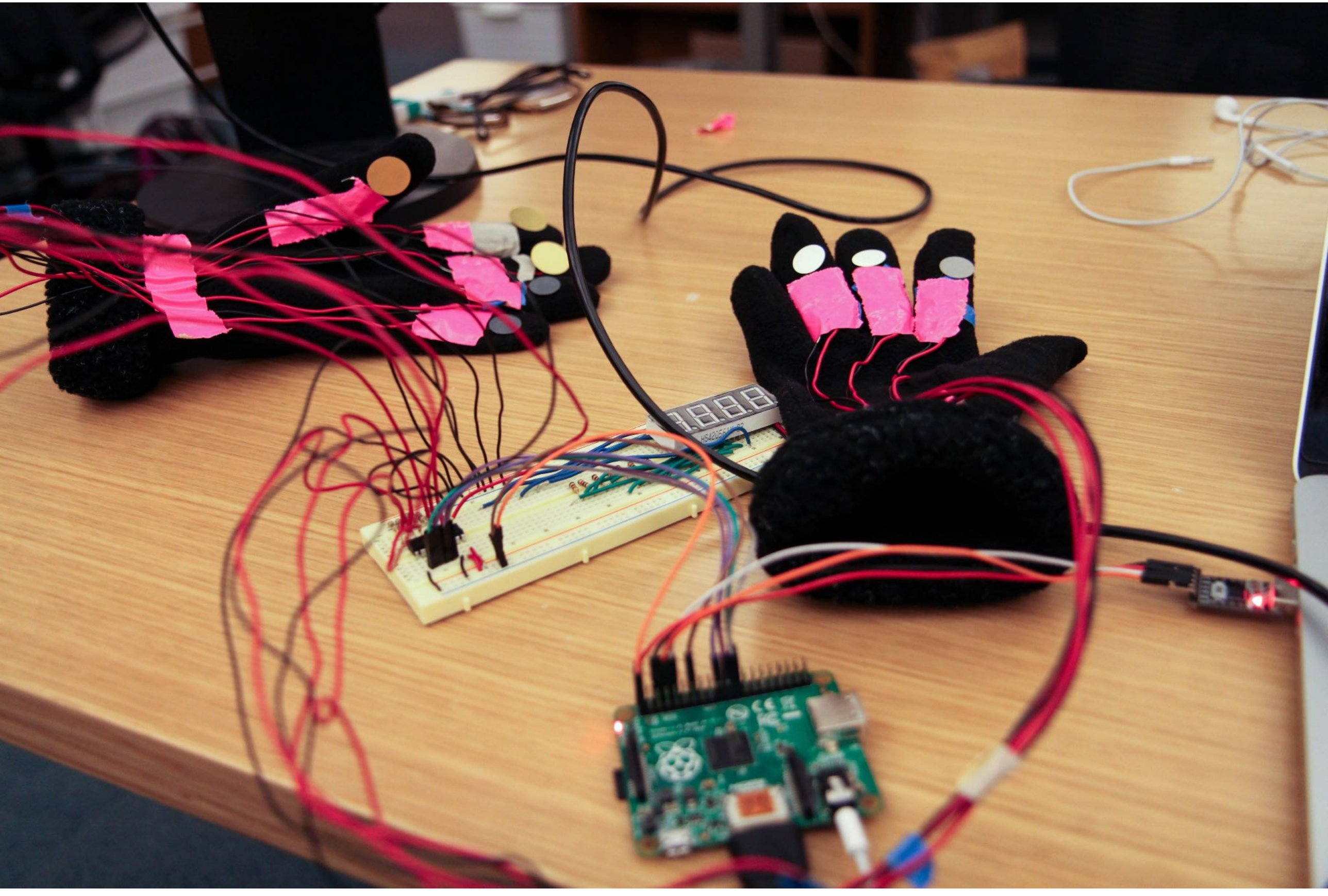
Two parts for each assignment

- Basic (required, tight spec, guided steps)
- Extension (optional, opportunity for your exploration/creativity)

Final project demonstrations on Thursday, December 9

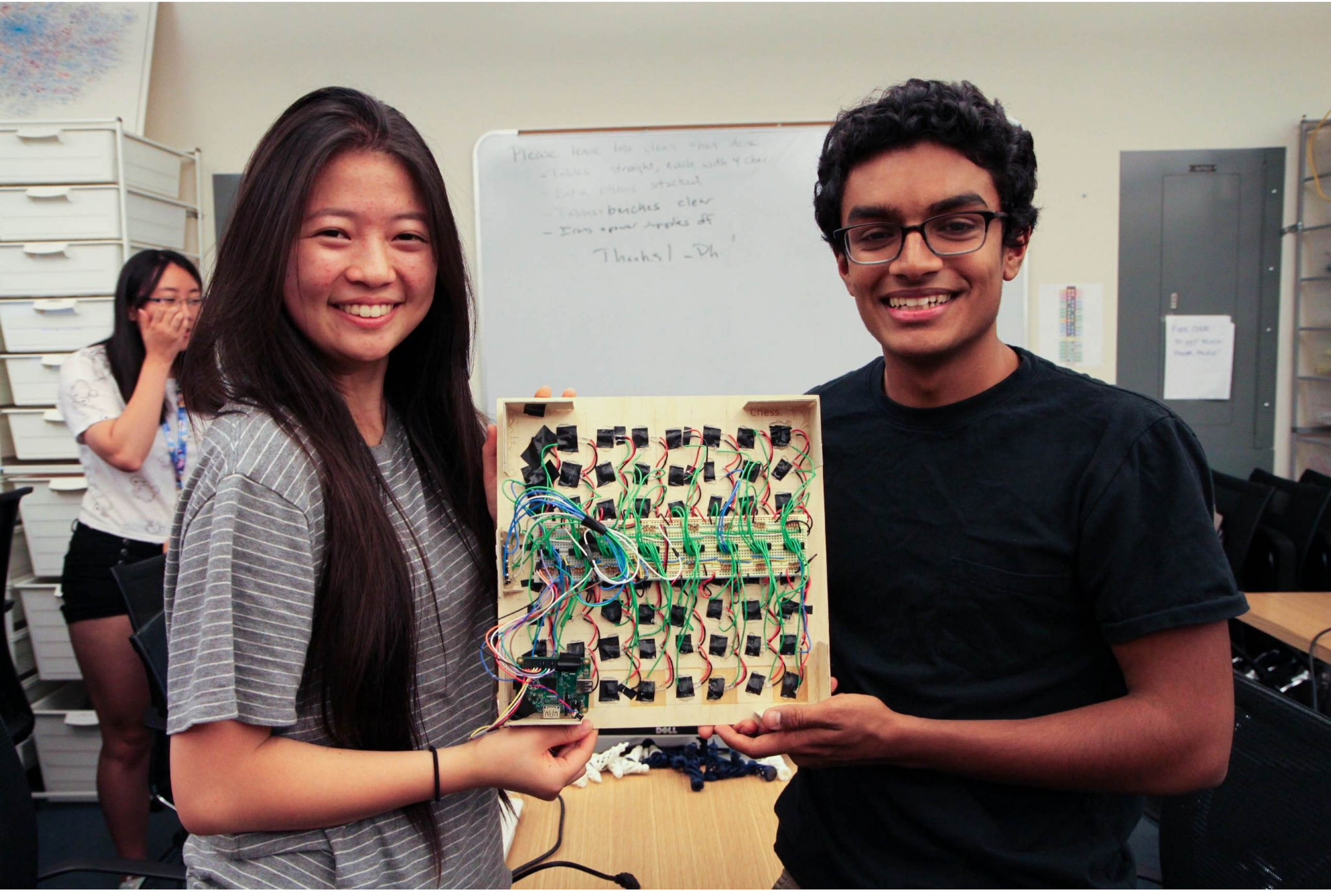
Scaled back due to lack of exam period, physical lab resources

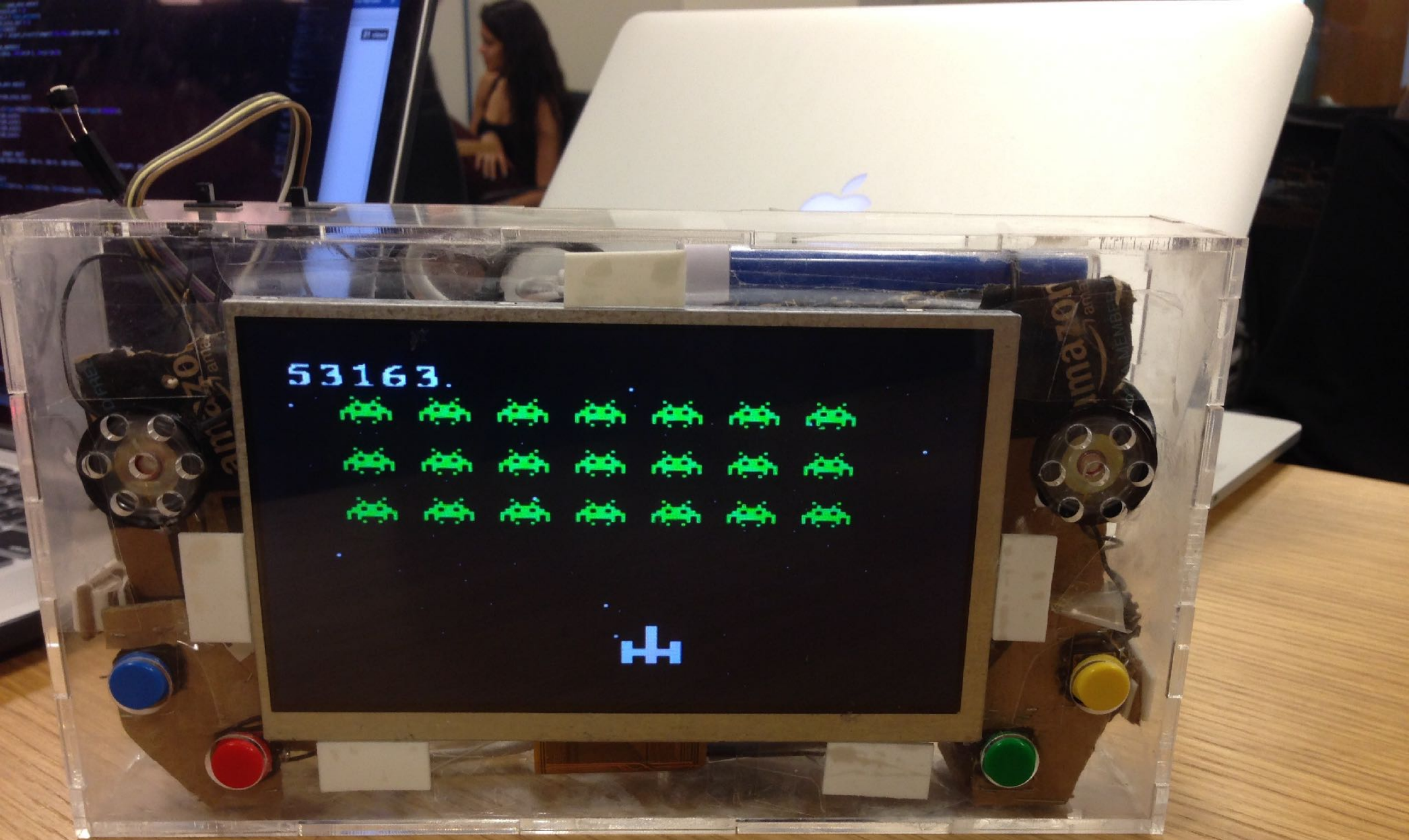
- Encourage you to play with some hardware (e.g. sensors)




a new CS
twitch
STANFORD


game mode
DELL


Please leave lab clean when done
- Tables straight, each with 4 chairs
- Extra chairs stacked
- Trash/benches clear
- Iron, spray bottles off
Thanks! -Dh
Chess
DELL


53163.

First Week

Today

Fill out course application if you haven't already:

https://web.stanford.edu/class/cs107e/

We will decide on enrollment (capped at 40) by Tuesday, September 27th (tomorrow). You will receive an email about enrollment by then.

Assignment 0

- Join forum https://edstem.org/us/courses/29339/discussion/

- Read and understand our guides on basic topics: electricity, numbers, and UNIX

- Create github account and send us your GitHub id

- Install/setup your development environment

- Fill out lab time poll (will be posted on EdStem)

Class Meeting Protocol 1

Class attendance is *expected*. The slides are not intended to be a replacement for being in class. There are a lot of conceptually difficult topics, and having you there to ask us to stop and clarify is important.

In our experience teaching this class, students who stop regularly attending lectures struggle greatly and spend the last two weeks trying to earn more points back by fixing bugs and resubmitting.

Class Meeting Protocol 2

I will likely screencast the lectures, and they will *only* be available on a case-by-case basis for students who have a legitimate reason for missing class. Legitimate reasons include:

- COVID isolation
- Away sporting / academic event

Illegitimate reasons include:

- Don't want to attend lecture / too tired
- Leaving for returning from a weekend trip that isn't sports/academic

Dealing with COVID

Stanford requires masks are worn inside at all times unless you are speaking in a class. We will be masked in lab.

- Please wear them well and carefully! Even if you are alone in lab.

If you feel sick or have been exposed, get tested.

What is a computer?

You've taking CS106A / 106B, and possibly some hardware-esque classes (e.g., ENGR 40M, EE 101A/B, EE108, etc.), but you probably haven't taken a course where you discussed what a computer really is.

Almost all computers you use today (including the Raspberry Pi, your phone, and your laptop/desktop, but not FPGAs) are built using the *von Neumann architecture*, which was laid out by John von Neumann et al. in a 1945 paper on the EDVAC computer.

The von Neumann architecture

The original architecture designed by von Newmann has the following features (see Wikipedia)

- A processing unit that contains an arithmetic logic unit and processor registers
- A control unit that contains an instruction register and program counter
- Memory that stores data and instructions
- External mass storage
- Input and output mechanisms

A critical part is the idea that instructions and data are both kept in the same memory

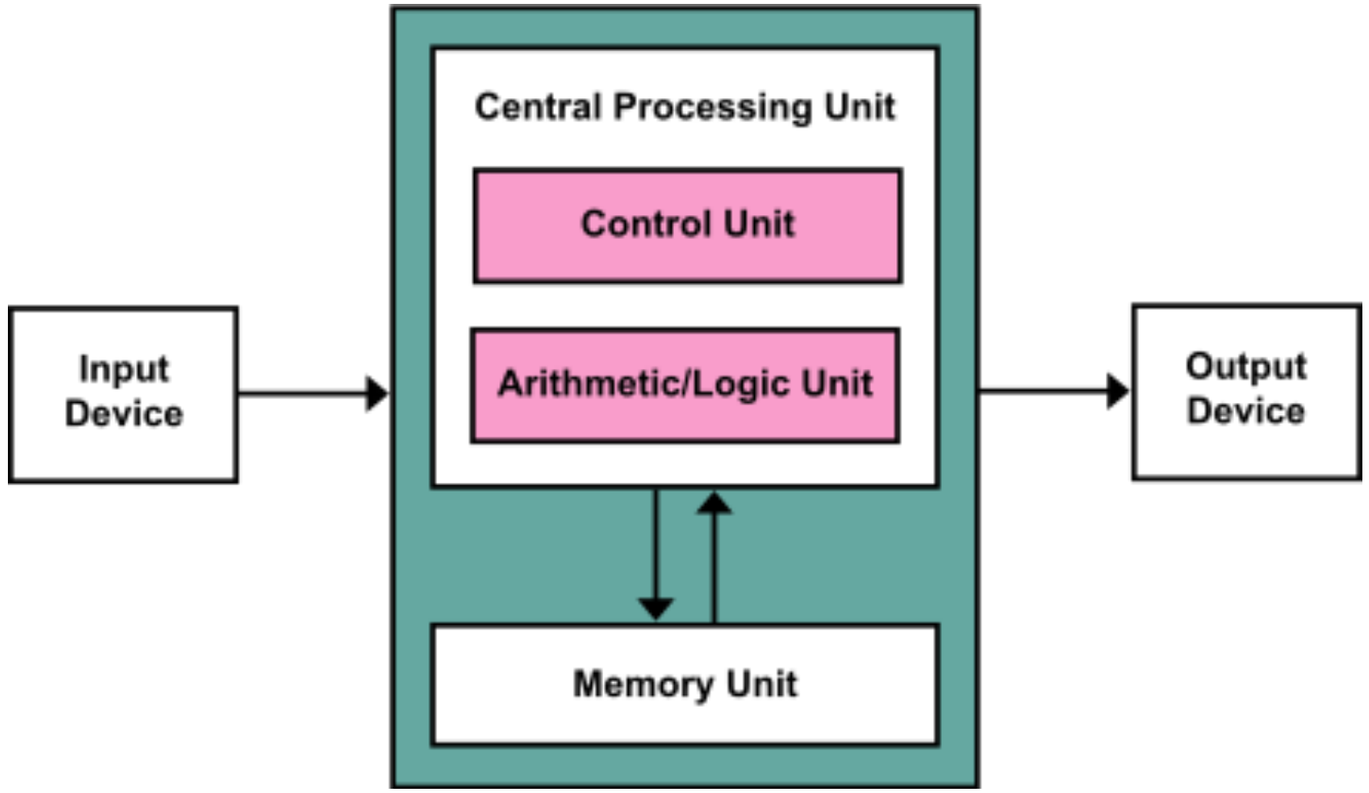
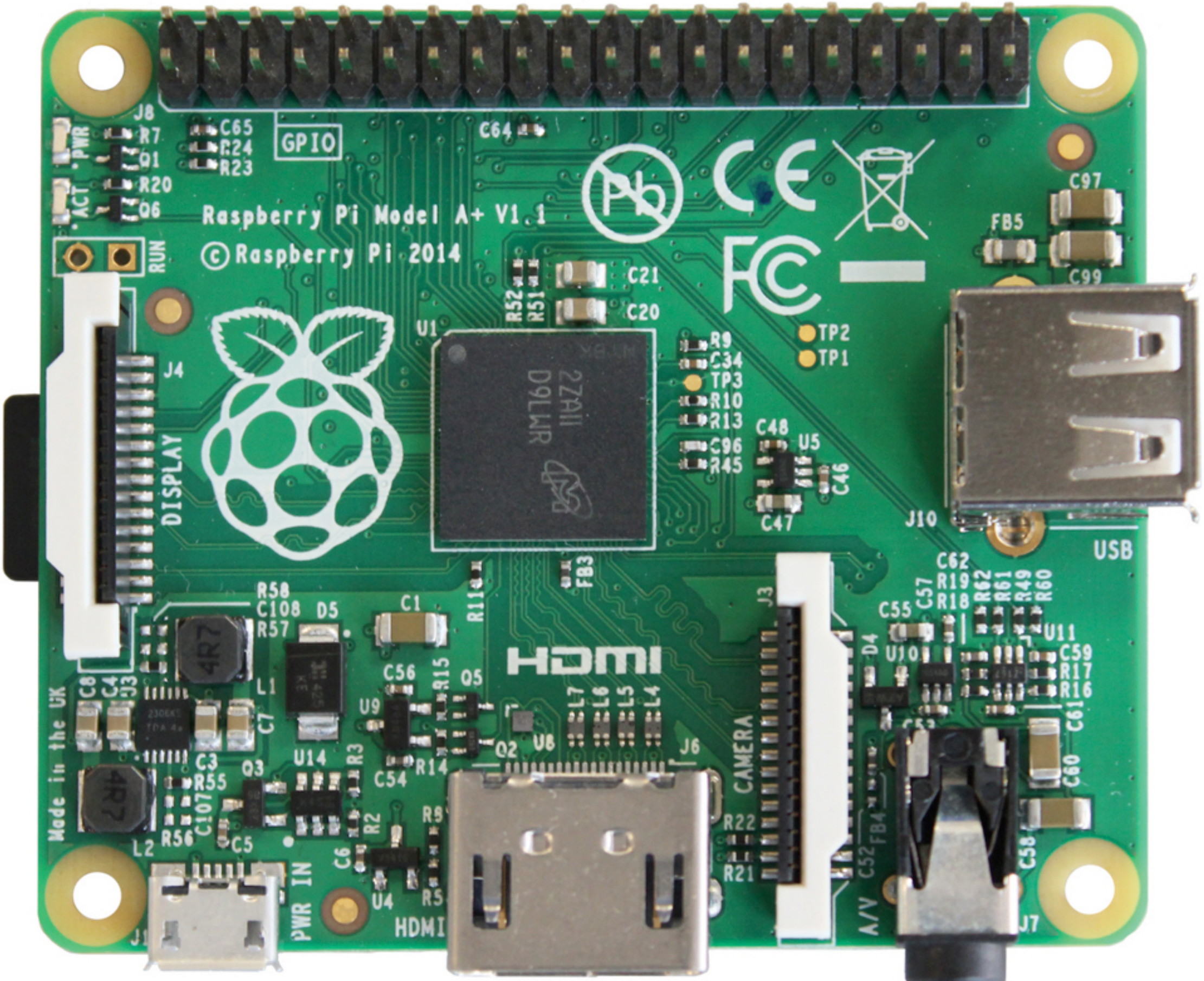
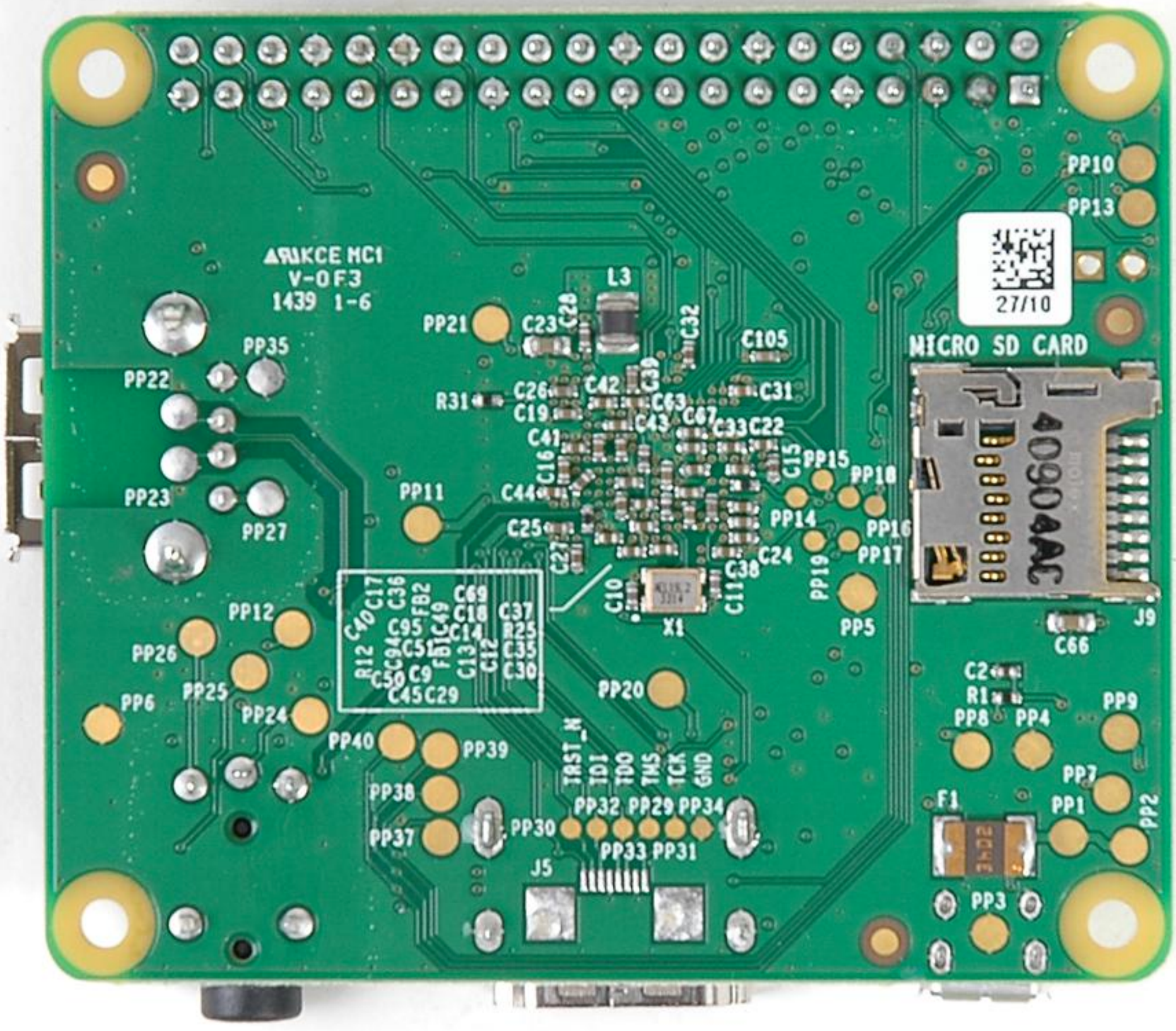


Image: https://en.wikipedia.org/wiki/Von_Neumann_architecture#/media/File:Von_Neumann_Architecture.svg

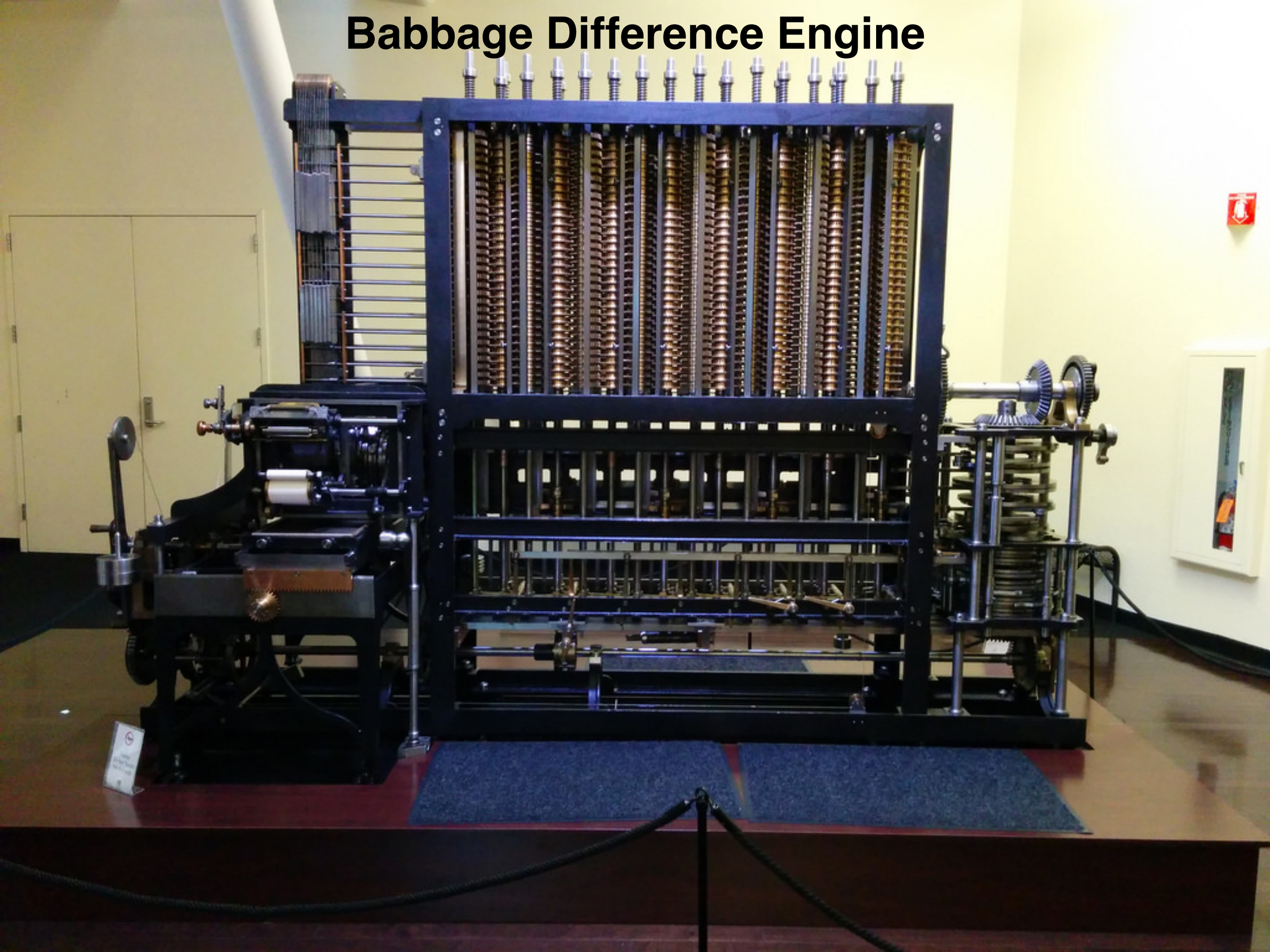
How is our Rasperry Pi a von Newmann architecture machine?

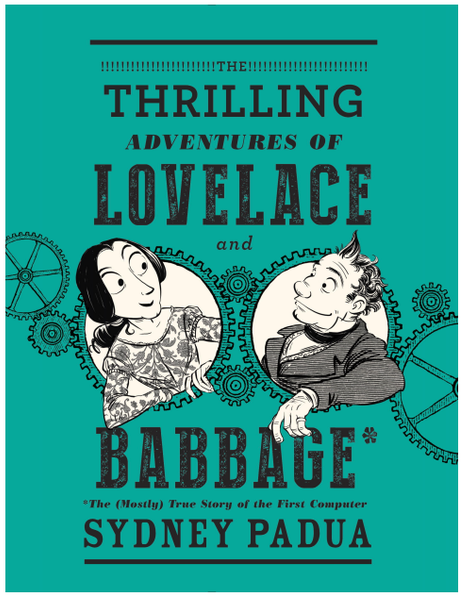
- A processing unit that contains an arithmetic logic unit and processor registers
  - The Raspberry Pi has an ARM processor with processor registers
- A control unit that contains an instruction register and program counter
  - The ARM processor has an instruction register (kind of — it is not something we can get access to) and a program counter ("r15")
- Memory that stores data and instructions
  - The Raspberry Pi A+ has 512MB of RAM
- External mass storage
  - The Raspberry Pi A+ has an SD card reader
- Input and output mechanisms
  - The Raspertty PI A+ has USB (we won't use it), HDMI (we will use it), and GPIO pins (you better believe we will use them)


Raspberry Pi Model A+ V1.1
© Raspberry Pi 2014
GPIO
J8
PWR
ACT
RUN
J4
DISPLAY
U1
J6
CAMERA
HDMI
J3
USB
J10
PWR IN
J1
A/V
J7
U5
U14
U9
U8
U4
U10
U11
D4
D5
L1
L2
Made in the UK
TP1
TP2
TP3
FB3
FB4
FB5


ARIKCE MC1
V-0 F3
1439 1-6
27/10
MICRO SD CARD
PP10
PP13
PP35
PP22
PP23
PP27
PP11
PP21
L3
C23
C28
C32
C105
C31
R31
C26
C42
C39
C63
C19
C43
C67
C33
C22
C41
C16
C15
C44
PP15
PP18
PP14
PP16
PP17
C25
C27
C38
C24
PP19
C10
C11
X1
PP5
J9
C66
C17
C36
FB2
C69
C40
C95
C49
C18
C37
R12
C94
C51
FB1
C14
R25
C13
C12
C35
C50
C9
C30
C45
C29
PP12
PP26
PP25
PP6
PP24
PP20
C2
R1
PP8
PP4
PP9
PP40
PP39
PP38
PP37
PP30
TRST_N
TDI
TDO
TMS
TCK
GND
PP32
PP29
PP34
PP33
PP31
J5
PP7
PP1
PP2
F1
PP3

Babbage Difference Engine



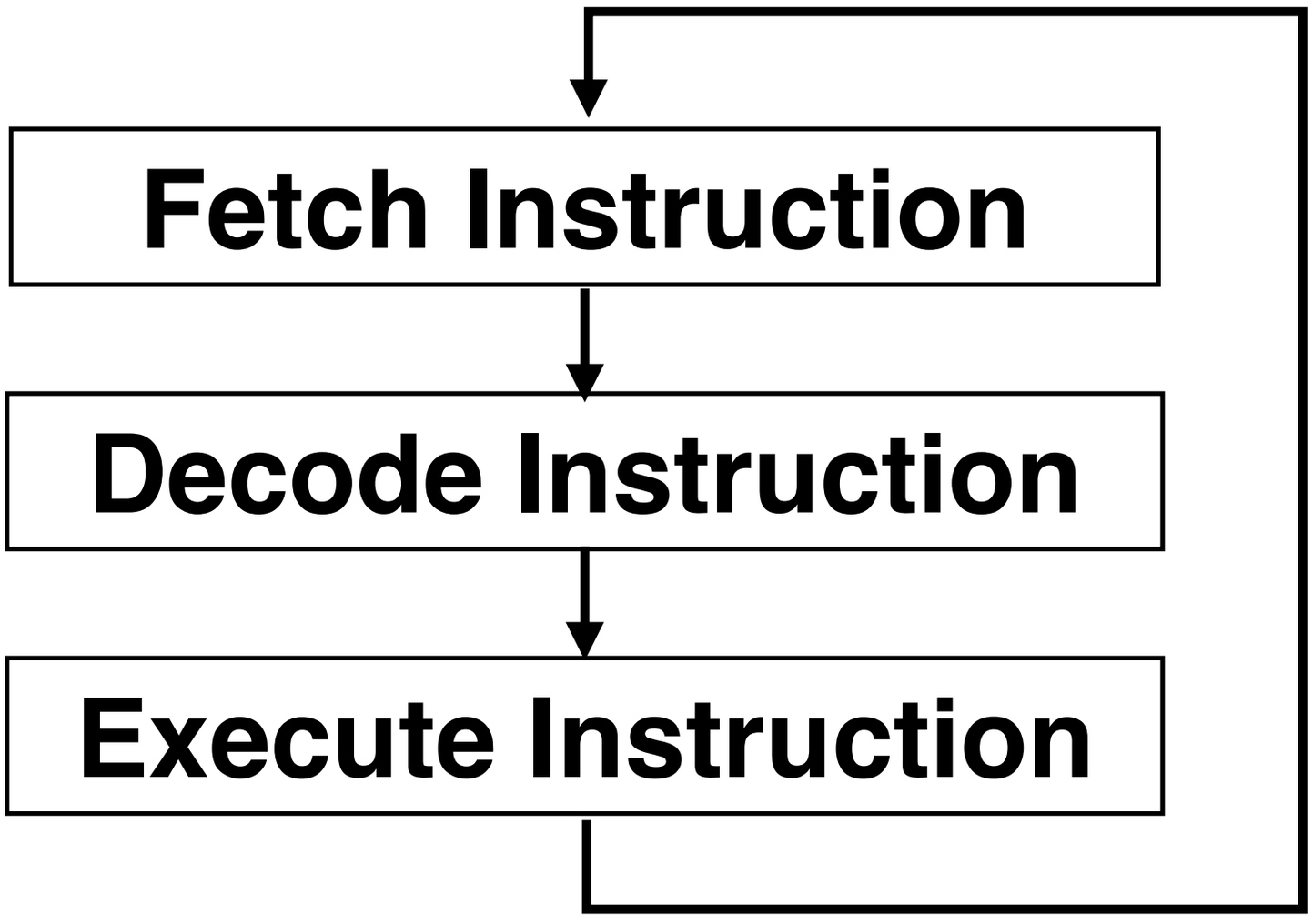


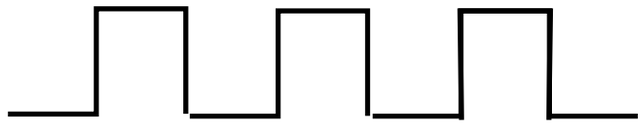
Analytical Engine

Universal Computer

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

Running a "Program"

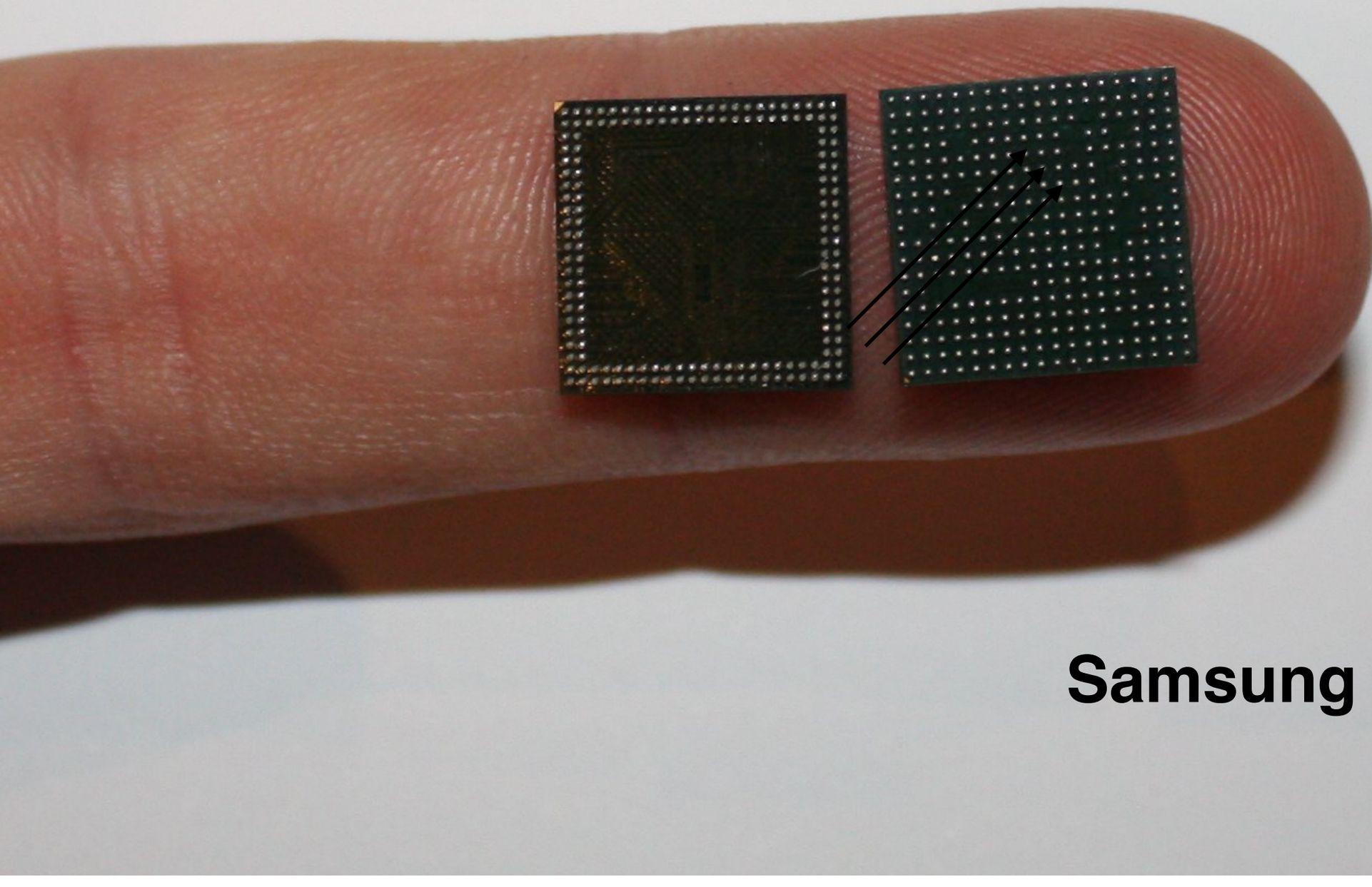




Clock

Package on Package

Broadcom 2865 ARM Processor



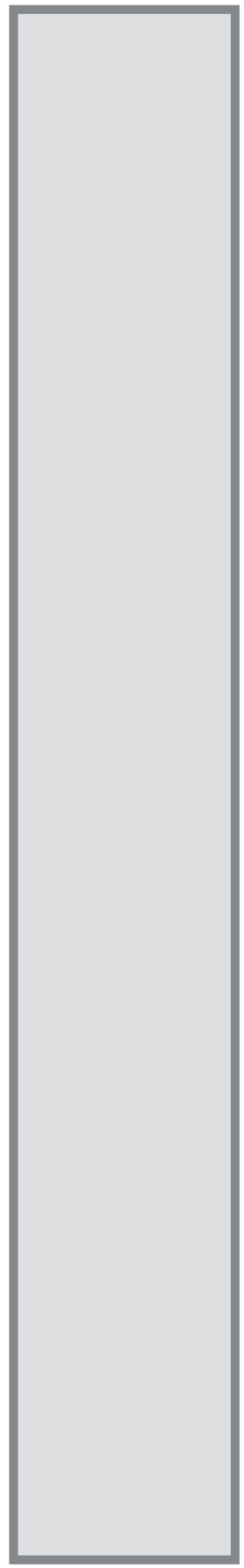
Samsung 4Gb SDRAM

Memory used to store both instructions and data

Storage locations are accessed using 32-bit addresses

Maximum addressable memory is 4 GB

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



100000000_{16}

Memory Map

00000000_{16}

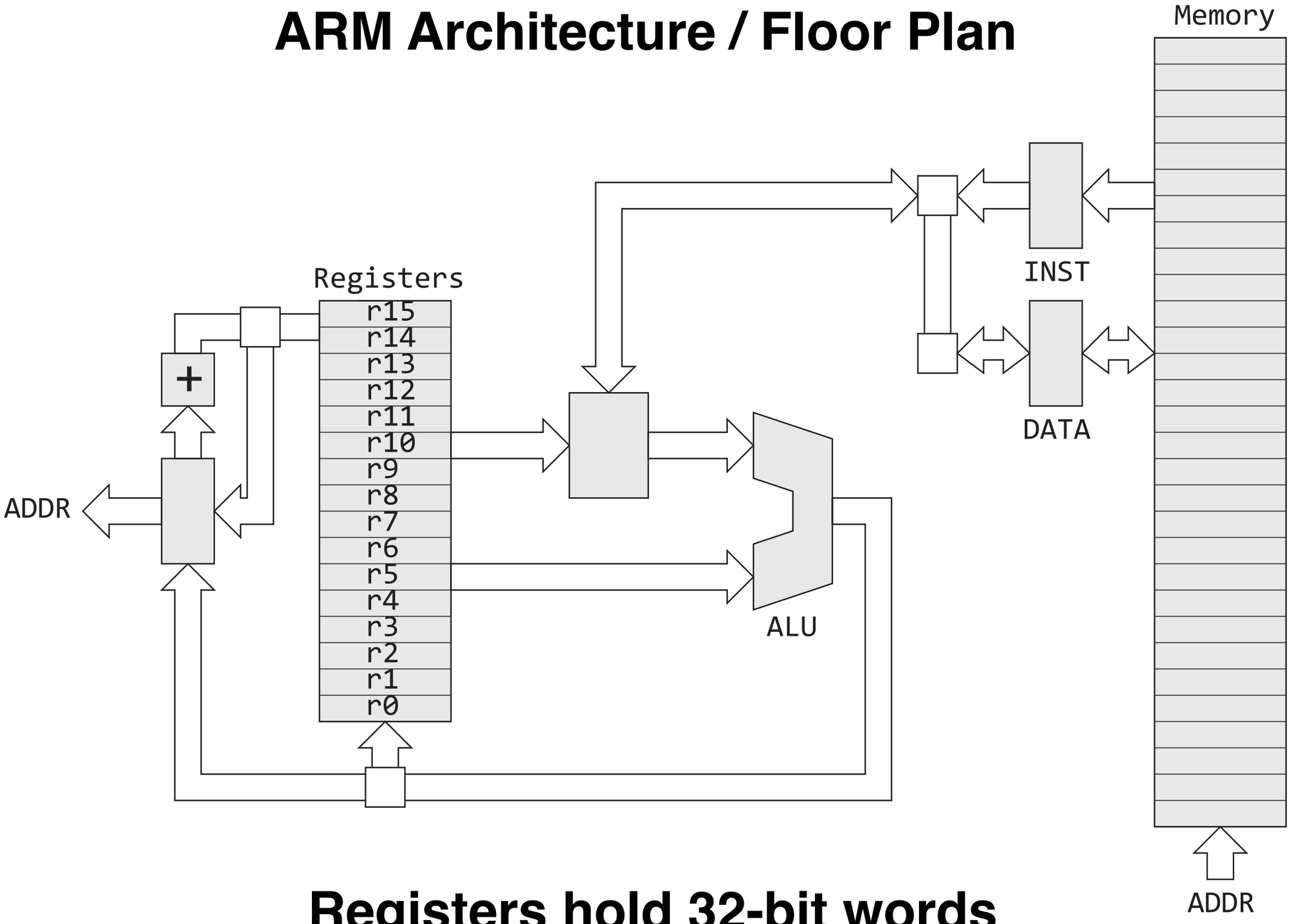
10000000_{16}

Memory Map

02000000_{16}

512 MB Actual Memory

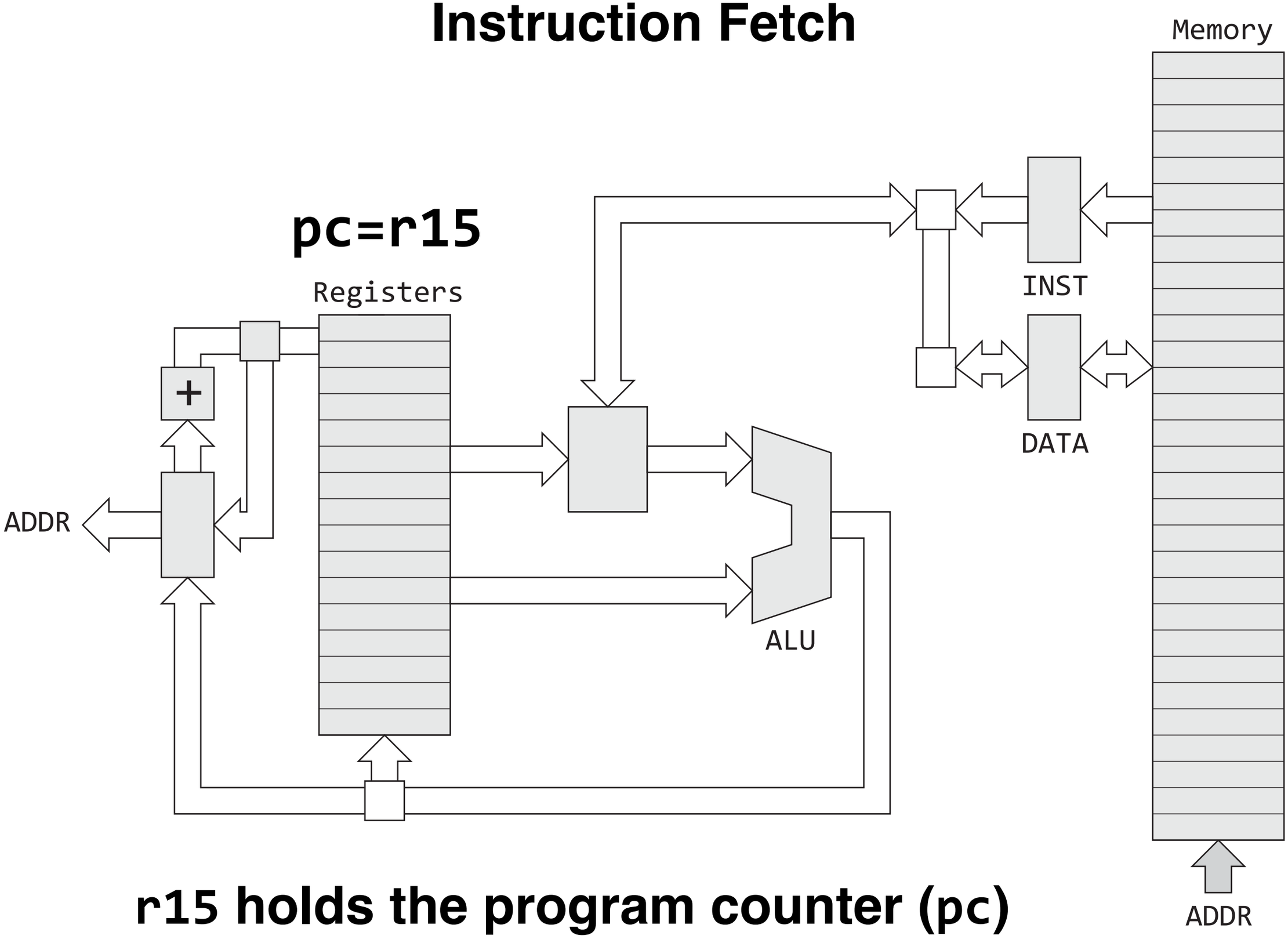
ARM Architecture / Floor Plan



Registers hold 32-bit words

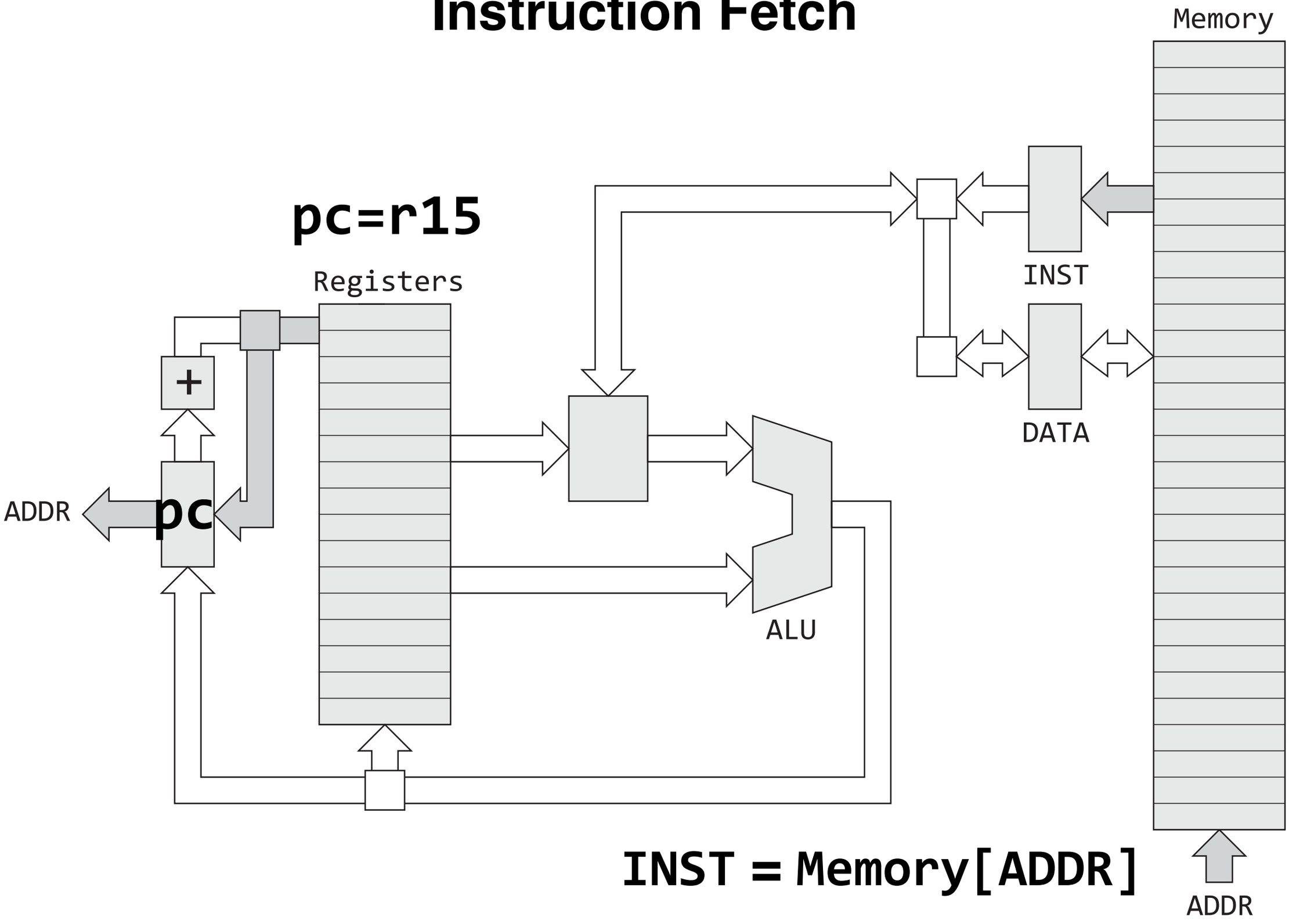
Arithmetic-Logic Unit (ALU) operates on 32-bit words

Instruction Fetch



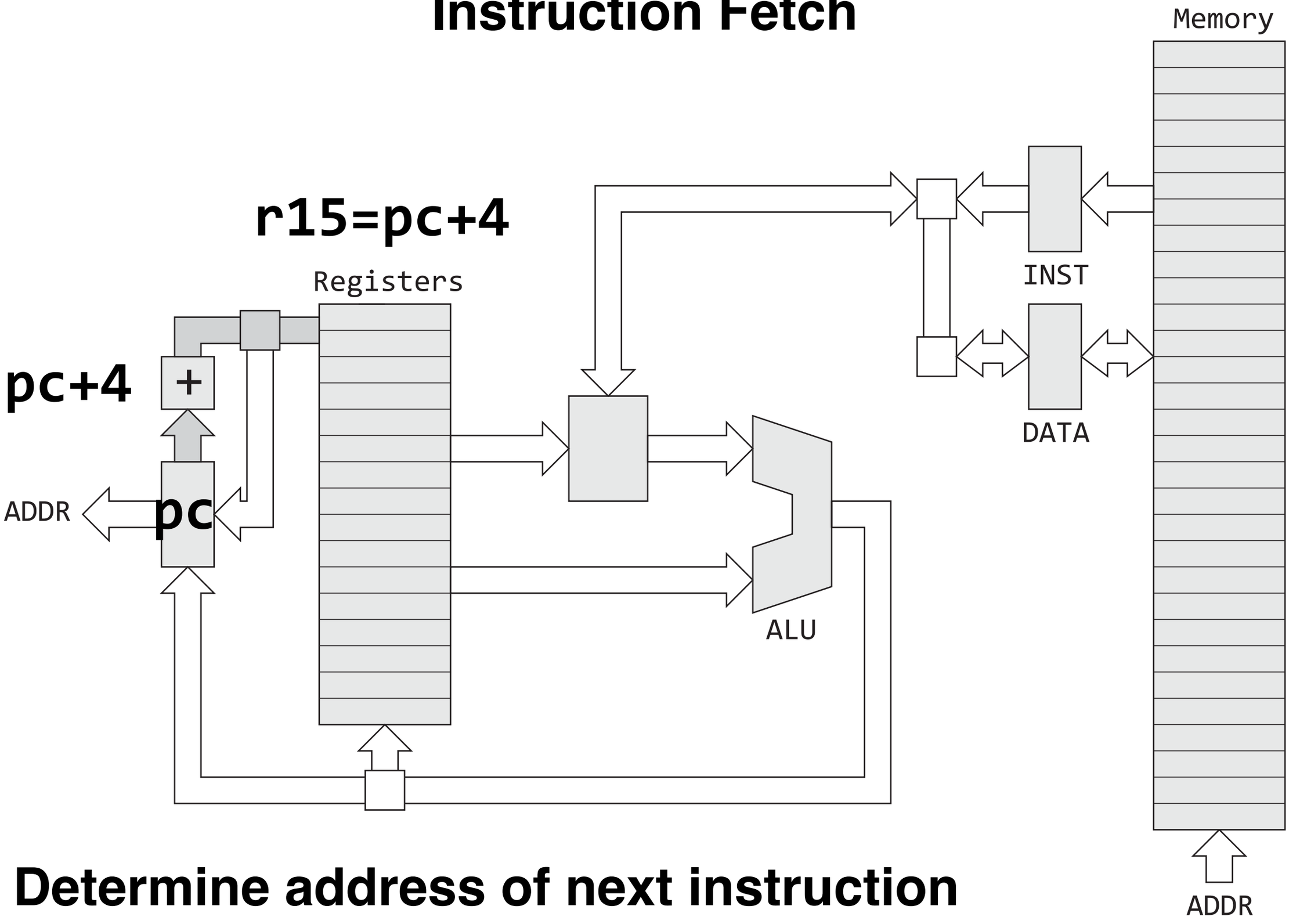
r15 holds the program counter (pc)

Instruction Fetch



Addresses and instructions are 32-bit words

Instruction Fetch



Determine address of next instruction

Why pc+4?