CS 31: Introduction to Computer Systems

05: C Functions & Computer Architecture

02-04-2025

Reading Quiz

- Note the red border!
- 1 minute per question
- No talking, no laptops, phones during the quiz

Check your frequency:

- Iclicker2: frequency AA
- Iclicker+: green light next to selection

For new devices this should be okay,
For used you may need to reset frequency

Reset:

1. hold down power button until blue light flashes (2secs)
2. Press the frequency code: AA vote status light will indicate success

What we will learn this week

1. Introduction to C
   - Data organization and strings
   - Functions

2. Computer Architecture
   - Machine memory models
   - Digital signals
   - Logic gates

Data Collections in C

- Many complex data types out there (CS 35)

- C has a few simple ones built-in:
  - Arrays
  - Structures (`struct`)
  - Strings (arrays of characters)

- Often combined in practice, e.g.:
  - An array of structs
  - A struct containing strings

Arrays and Strings

- C's support for collections of values
  - Array buckets store a single type of value
  - There is no "string" data type ☹
  - Specify max capacity (num buckets) when you declare an array variable (single memory chunk)

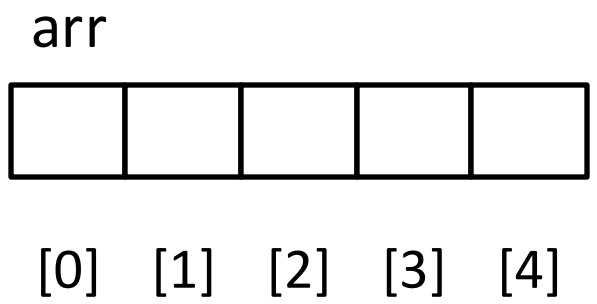
```
<type> <var_name>[<num buckets>];
int arr[5];  // an array of 5 integers
float rates[40]; // an array of 40 floats
```

Arrays

- C's support for collections of values
- Often accessed via a loop:

```
int arr[5];  // an array of 5 integers
float rates[40]; // an array of 40 floats
for (i=0; i < 5; i++) {
    arr[i] = i;
    rates[i] = arr[i]*2;
}
```


Get/Set value using brackets [] to index into array.

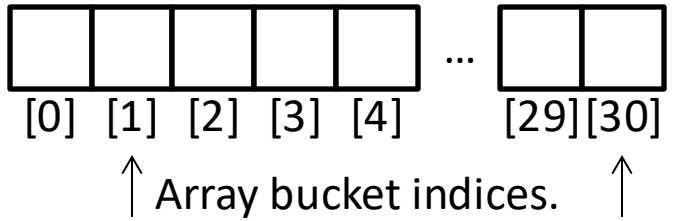


What does this for loop print?

Array Characteristics

```
int january_temps[31];   // Daily high temps
```

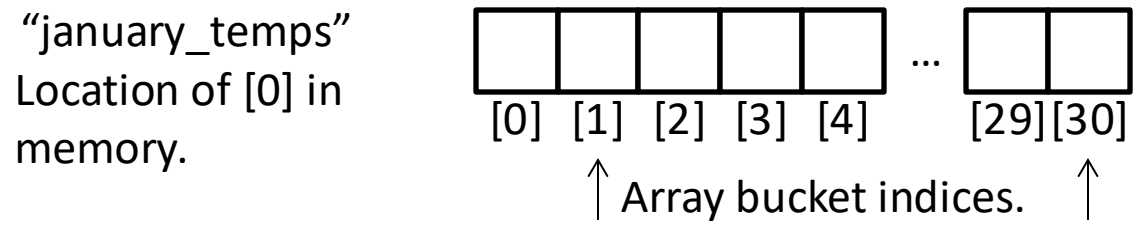
"january_temps"
Location of [0] in memory.



- Indices start at 0! Why?
- Array variable name means, to the compiler, the beginning of the memory chunk. (The memory address)
  - january_temps" (without brackets!) Location of [0] in memory.
  - Keep this in mind, we'll return to it soon (functions).

Array Characteristics

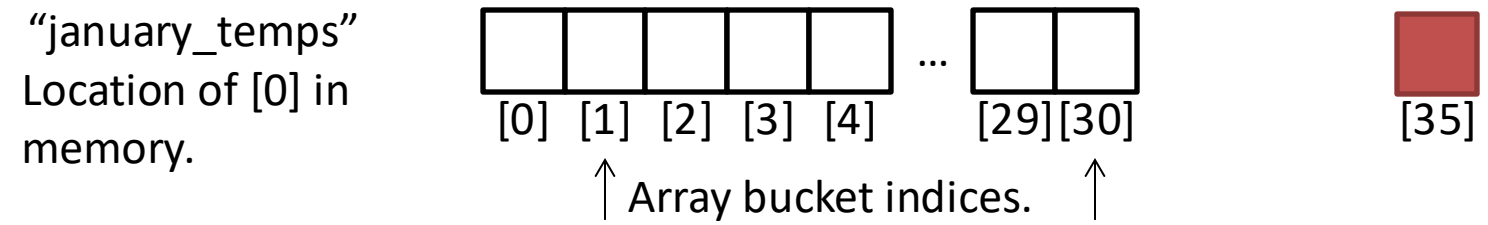
```
int january_temps[31]; // Daily high temps
```



- Indices start at 0! Why?
- The index refers to an offset from the start of the array
  - e.g., `january_temps`[3] means "three integers forward from the starting address of january_temps"

Array Characteristics

```
int january_temps[31]; // Daily high temps
```



- Asking for january_temps[35]?

C does NOT do bounds checking.

- Python: error
- C: "Sure! I don't care .." <ominous silence while bad things happen>

Characters and Strings

A character (type **`char`**) is numerical value that holds one letter.

```
char my_letter = 'w';   // Note: single quotes
```

What is the numerical value?

- printf("%d %c", my_letter, my_letter);
- Would print: 119 w

Why is 'w' equal to 119?

- ASCII Standard says so.
- American Standard Code for Information Interchange

Dec	Hex	Char	Dec	Hex	Char	Dec	Hex	Char	Dec	Hex	Char
0	00	Null	32	20	Space	64	40	@	96	60	`
1	01	Start of heading	33	21	!	65	41	A	97	61	a
2	02	Start of text	34	22	"	66	42	B	98	62	b
3	03	End of text	35	23	#	67	43	C	99	63	c
4	04	End of transmit	36	24	$	68	44	D	100	64	d
5	05	Enquiry	37	25	%	69	45	E	101	65	e
6	06	Acknowledge	38	26	&	70	46	F	102	66	f
7	07	Audible bell	39	27	'	71	47	G	103	67	g
8	08	Backspace	40	28	(	72	48	H	104	68	h
9	09	Horizontal tab	41	29	)	73	49	I	105	69	i
10	0A	Line feed	42	2A	*	74	4A	J	106	6A	j
11	0B	Vertical tab	43	2B	+	75	4B	K	107	6B	k
12	0C	Form feed	44	2C	,	76	4C	L	108	6C	l
13	0D	Carriage return	45	2D	-	77	4D	M	109	6D	m
14	0E	Shift out	46	2E	.	78	4E	N	110	6E	n
15	0F	Shift in	47	2F	/	79	4F	O	111	6F	o
16	10	Data link escape	48	30	0	80	50	P	112	70	p
17	11	Device control 1	49	31	1	81	51	Q	113	71	q
18	12	Device control 2	50	32	2	82	52	R	114	72	r
19	13	Device control 3	51	33	3	83	53	S	115	73	s
20	14	Device control 4	52	34	4	84	54	T	116	74	t
21	15	Neg. acknowledge	53	35	5	85	55	U	117	75	u
22	16	Synchronous idle	54	36	6	86	56	V	118	76	v
23	17	End trans. block	55	37	7	87	57	W	119	77	w
24	18	Cancel	56	38	8	88	58	X	120	78	x
25	19	End of medium	57	39	9	89	59	Y	121	79	y
26	1A	Substitution	58	3A	:	90	5A	Z	122	7A	z
27	1B	Escape	59	3B	;	91	5B	[	123	7B	{
28	1C	File separator	60	3C	<	92	5C	\	124	7C	|
29	1D	Group separator	61	3D	=	93	5D	]	125	7D	}
30	1E	Record separator	62	3E	>	94	5E	^	126	7E	~
31	1F	Unit separator	63	3F	?	95	5F	_	127	7F	□

Characters and Strings

$ man ascii

119 = w

Characters and Strings

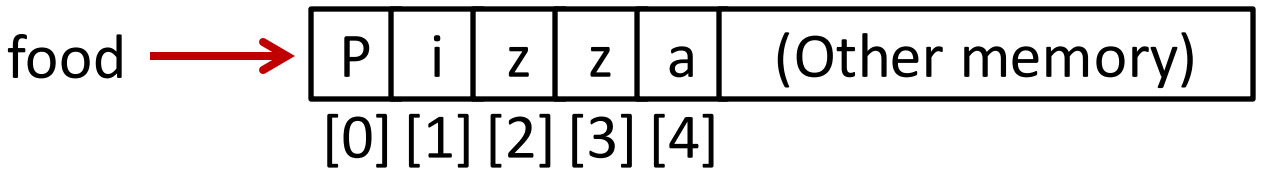
- A character (type **`char`**) is numerical value that holds one letter.
- A string is a memory block containing characters, one after another…

- Examples:

  char food[6] = “Pizza”;

Hmm, suppose we used printf and %s to print name.

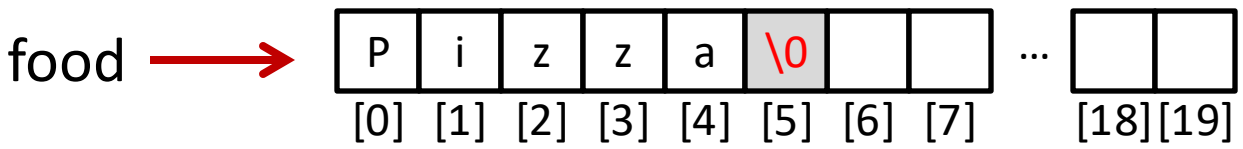
How does it know where the string ends and other memory begins?



Characters and Strings

- A character (type `char`) is numerical value that holds one letter.
- A string is a memory block containing characters, one after another, with a null terminator (numerical 0) at the end.
- Examples:

```
char food[20] = “Pizza”;
```



0 is the "Null character"

Special stuff over here in the lower values.

Dec	Hex	Char	Dec	Hex	Char	Dec	Hex	Char	Dec	Hex	Char
0	00	Null	32	20	Space	64	40	@	96	60	`
1	01	Start of heading	33	21	!	65	41	A	97	61	a
2	02	Start of text	34	22	"	66	42	B	98	62	b
3	03	End of text	35	23	#	67	43	C	99	63	c
4	04	End of transmit	36	24	$	68	44	D	100	64	d
5	05	Enquiry	37	25	%	69	45	E	101	65	e
6	06	Acknowledge	38	26	&	70	46	F	102	66	f
7	07	Audible bell	39	27	'	71	47	G	103	67	g
8	08	Backspace	40	28	(	72	48	H	104	68	h
9	09	Horizontal tab	41	29	)	73	49	I	105	69	i
10	0A	Line feed	42	2A	*	74	4A	J	106	6A	j
11	0B	Vertical tab	43	2B	+	75	4B	K	107	6B	k
12	0C	Form feed	44	2C	,	76	4C	L	108	6C	l
13	0D	Carriage return	45	2D	-	77	4D	M	109	6D	m
14	0E	Shift out	46	2E	.	78	4E	N	110	6E	n
15	0F	Shift in	47	2F	/	79	4F	O	111	6F	o
16	10	Data link escape	48	30	0	80	50	P	112	70	p
17	11	Device control 1	49	31	1	81	51	Q	113	71	q
18	12	Device control 2	50	32	2	82	52	R	114	72	r
19	13	Device control 3	51	33	3	83	53	S	115	73	s
20	14	Device control 4	52	34	4	84	54	T	116	74	t
21	15	Neg. acknowledge	53	35	5	85	55	U	117	75	u
22	16	Synchronous idle	54	36	6	86	56	V	118	76	v
23	17	End trans. block	55	37	7	87	57	W	119	77	w
24	18	Cancel	56	38	8	88	58	X	120	78	x
25	19	End of medium	57	39	9	89	59	Y	121	79	y
26	1A	Substitution	58	3A	:	90	5A	Z	122	7A	z
27	1B	Escape	59	3B	;	91	5B	[	123	7B	{
28	1C	File separator	60	3C	<	92	5C	\	124	7C	|
29	1D	Group separator	61	3D	=	93	5D	]	125	7D	}
30	1E	Record separator	62	3E	>	94	5E	^	126	7E	~
31	1F	Unit separator	63	3F	?	95	5F	_	127	7F	□

Characters and Strings

$ man ascii

Strings in C

- C String library functions: `#include <string.h>`
  - Common functions (`strlen`, `strcpy`, etc.) make strings easier
  - Less friendly than Python strings

- More on strings later, in labs.

- For now, remember about strings:
  - Allocate enough space for null terminator!
  - If you're modifying a character array (string), don't forget to set the null terminator!
  - If you see crazy, unpredictable behavior with strings, check these two things!

Functions and Stack Diagrams

Functions: Specifying Types

Need to specify the return type of the function, and the type of each parameter:

```
<return type> <func name> ( <param list> ) {
    // declare local variables first
    // then function statements
    return <expression>;
}

// my_function takes 2 int values and returns an int
int my_function(int x, int y) {
  int result;
  result = x;
  if(y > x) {
    result = y+5;
  }
  return result*2;
}
```

Compiler will yell at you if you try to pass the wrong type!

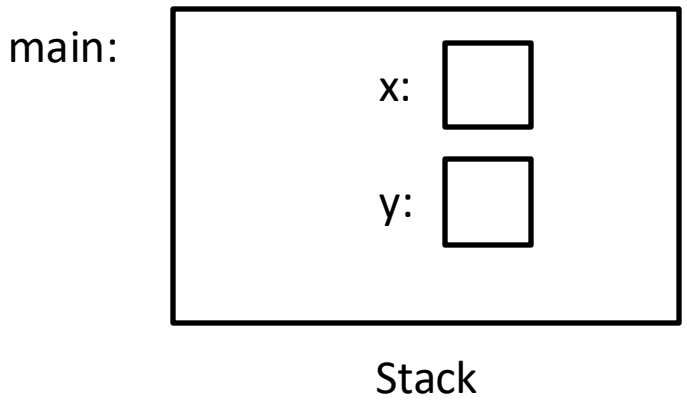
Function Arguments

Arguments are **passed by value**

- The function gets a separate copy of the passed variable

```
int func(int a, int b) {
    a = a + 5;
    return a - b;
}

int main() {
    // declare two integers
    int x, y;
    x = 4;
    y = 7;
    y = func(x, y);
    printf("%d, %d", x, y);
}
```



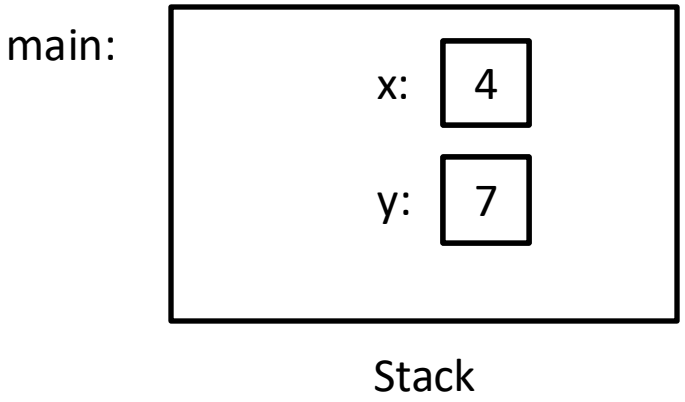
Function Arguments

Arguments are **passed by value**

- The function gets a separate copy of the passed variable

```
int func(int a, int b) {
    a = a + 5;
    return a - b;
}

int main() {
    // declare two integers
    int x, y;
    x = 4;
    y = 7;
    y = func(x, y);
    printf("%d, %d", x, y);
}
```



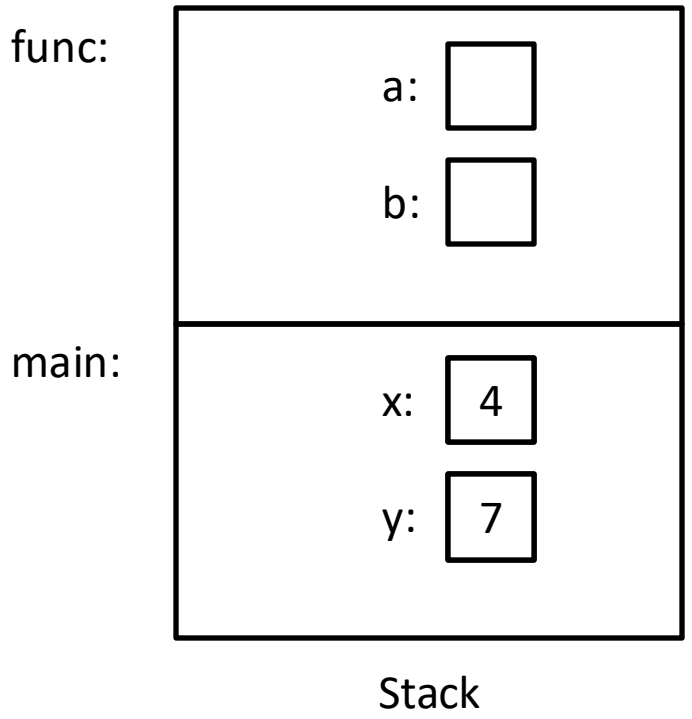
Function Arguments

Arguments are **passed by value**

- The function gets a separate copy of the passed variable

```
int func(int a, int b) {
    a = a + 5;
    return a - b;
}

int main() {
    // declare two integers
    int x, y;
    x = 4;
    y = 7;
    y = func(x, y);
    printf("%d, %d", x, y);
}
```



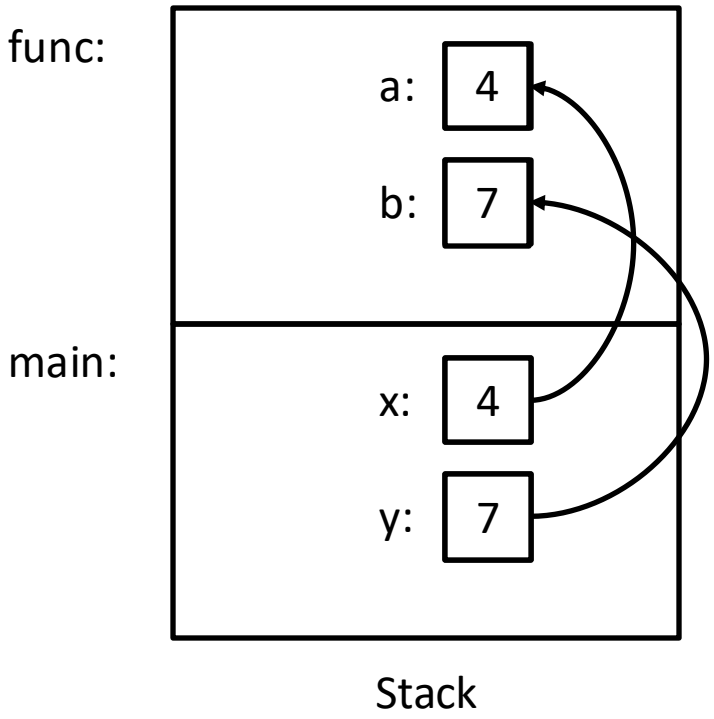
Function Arguments

Arguments are **passed by value**

- The function gets a separate copy of the passed variable

```
int func(int a, int b) {
    a = a + 5;
    return a - b;
}

int main() {
    // declare two integers
    int x, y;
    x = 4;
    y = 7;
    y = func(x, y);
    printf("%d, %d", x, y);
}
```



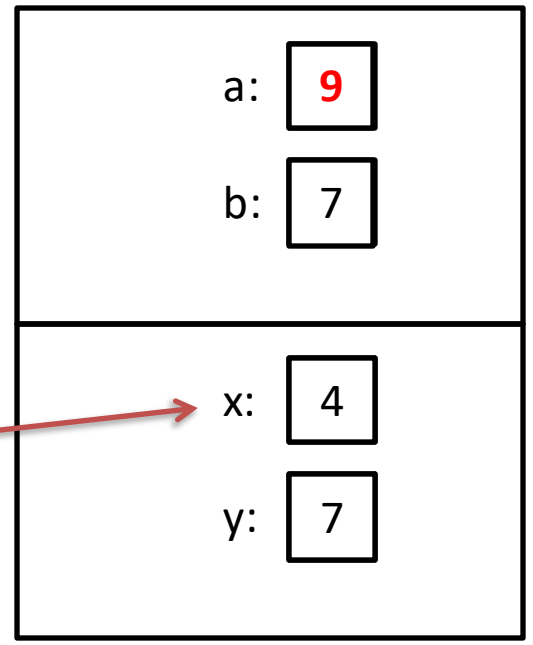
Function Arguments

Arguments are **passed by value**

- The function gets a separate copy of the passed variable

```
int func(int a, int b) {
    a = a + 5;
    return a - b;
}

int main() {
    // declare two integers
    int x, y;
    x = 4;
    y = 7;
    y = func(x, y);
    printf("%d, %d", x, y);
}
```



Note: This doesn't change!

No impact on values in main!

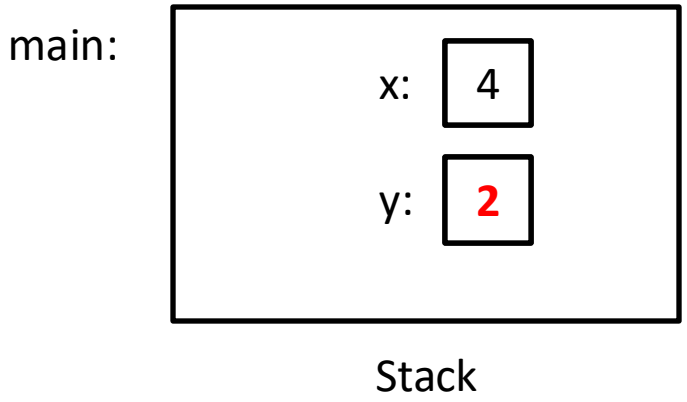
Function Arguments

Arguments are **passed by value**

- The function gets a separate copy of the passed variable

```
int func(int a, int b) {
    a = a + 5;
    return a - b;
}

int main() {
    // declare two integers
    int x, y;
    x = 4;
    y = 7;
    y = func(x, y);
    printf("%d, %d", x, y);
}
```



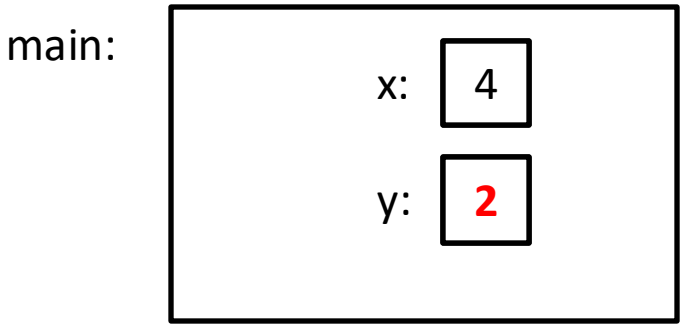
Function Arguments

Arguments are **passed by value**

- The function gets a separate copy of the passed variable

```
int func(int a, int b) {
    a = a + 5;
    return a - b;
}

int main() {
    // declare two integers
    int x, y;
    x = 4;
    y = 7;
    y = func(x, y);
    printf("%d, %d", x, y);
}
```



Output: 4, 2

What will this print?

```
int func(int a, int y, int my_array[]) {
    y = 1;
    my_array[a] = 0;
    my_array[y] = 8;//DRAW STACK DIAGRAM AT THIS POINT
    return y;
}

int main() {
    int x;
    int values[2];

    x = 0;
    values[0] = 5;
    values[1] = 10;

    x = func(x, x, values);

    printf("%d, %d, %d", x, values[0], values[1]);
}
```

A. 0, 5, 8
B. 0, 5, 10
C. 1, 0, 8
D. 1, 5, 8
E. 1, 5, 10

Hint: What does the name of an array mean to the compiler?

What will this print?

```
int func(int a, int y, int my_array[]) {
    y = 1;
    my_array[a] = 0;
    my_array[y] = 8;
    return y;
}

int main() {
    int x;
    int values[2];

    x = 0;
    values[0] = 5;
    values[1] = 10;

    x = func(x, x, values);

    printf("%d, %d, %d", x, values[0], values[1]);
}
```

A. 0, 5, 8
B. 0, 5, 10
C. 1, 0, 8
D. 1, 5, 8
E. 1, 5, 10

Hint: Still accessing the same memory location of array in func

What will this print?

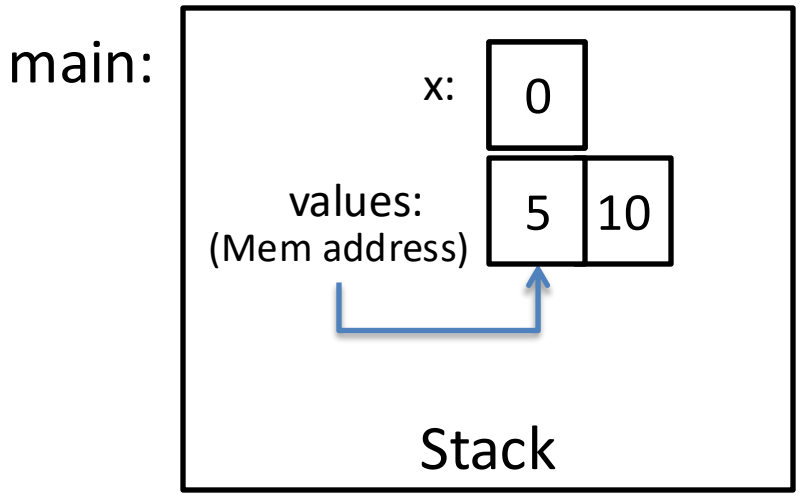
```
int func(int a, int y, int my_array[]) {
    y = 1;
    my_array[a] = 0;
    my_array[y] = 8;
    return y;
}

int main() {
    int x;
    int values[2];

    x = 0;
    values[0] = 5;
    values[1] = 10;

    x = func(x, x, values);

    printf("%d, %d, %d", x, values[0], values[1]);
}
```



What will this print?

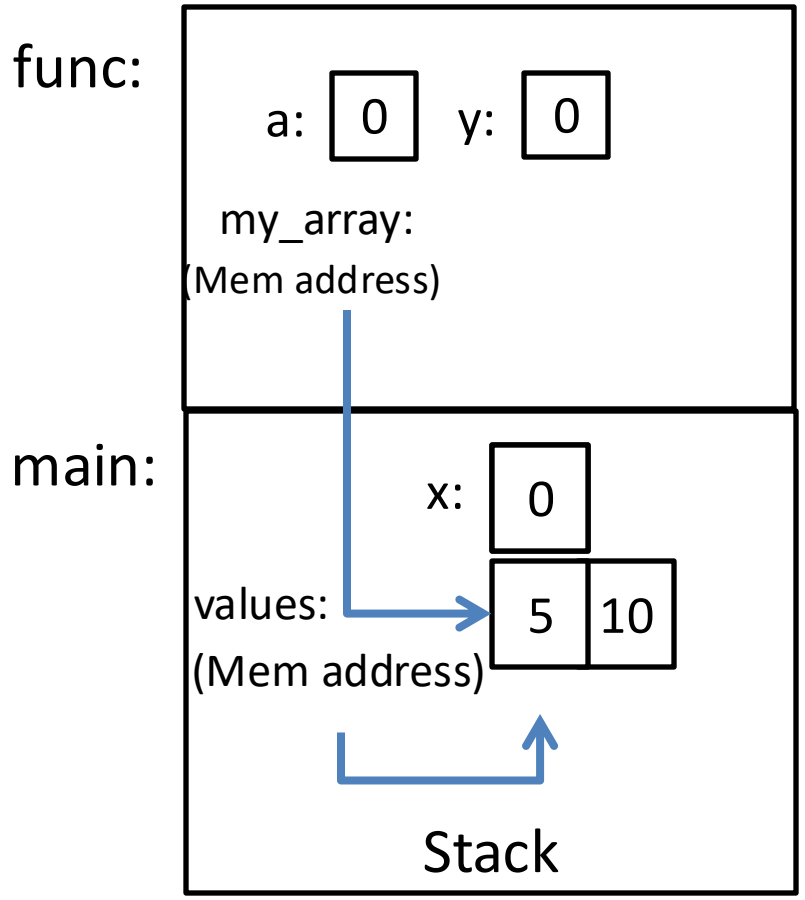
```
int func(int a, int y, int my_array[]) {
    y = 1;
    my_array[a] = 0;
    my_array[y] = 8;
    return y;
}

int main() {
    int x;
    int values[2];

    x = 0;
    values[0] = 5;
    values[1] = 10;

    x = func(x, x, values);

    printf("%d, %d, %d", x, values[0], values[1]);
}
```



What will this print?

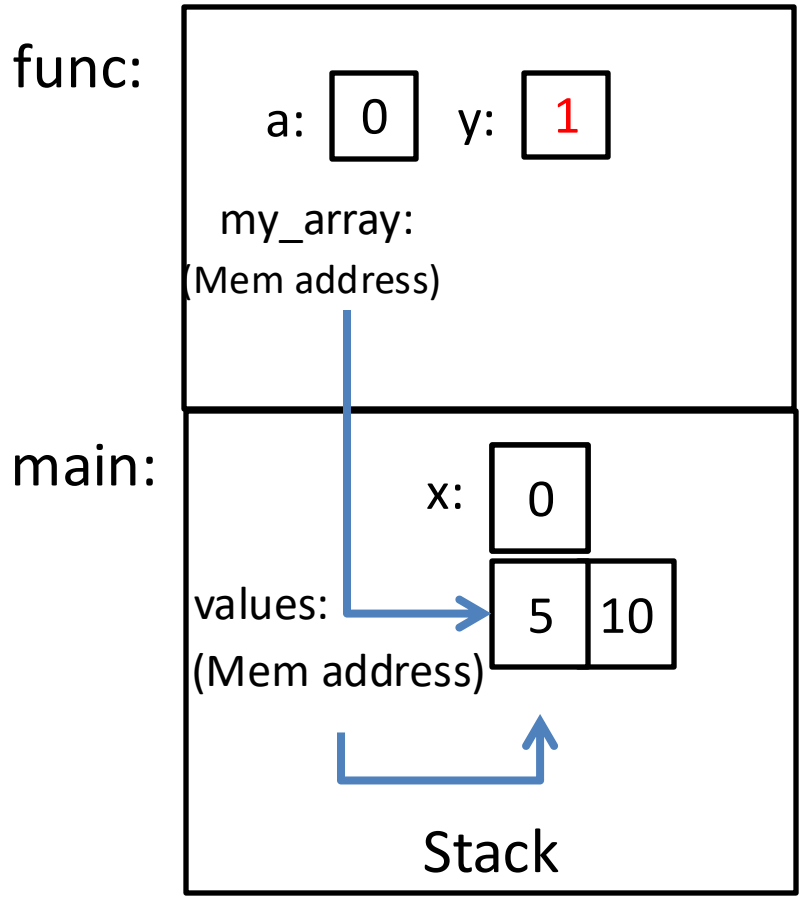
```
int func(int a, int y, int my_array[]) {
    y = 1;
    my_array[a] = 0;
    my_array[y] = 8;
    return y;
}

int main() {
    int x;
    int values[2];

    x = 0;
    values[0] = 5;
    values[1] = 10;

    x = func(x, x, values);

    printf("%d, %d, %d", x, values[0], values[1]);
}
```



What will this print?

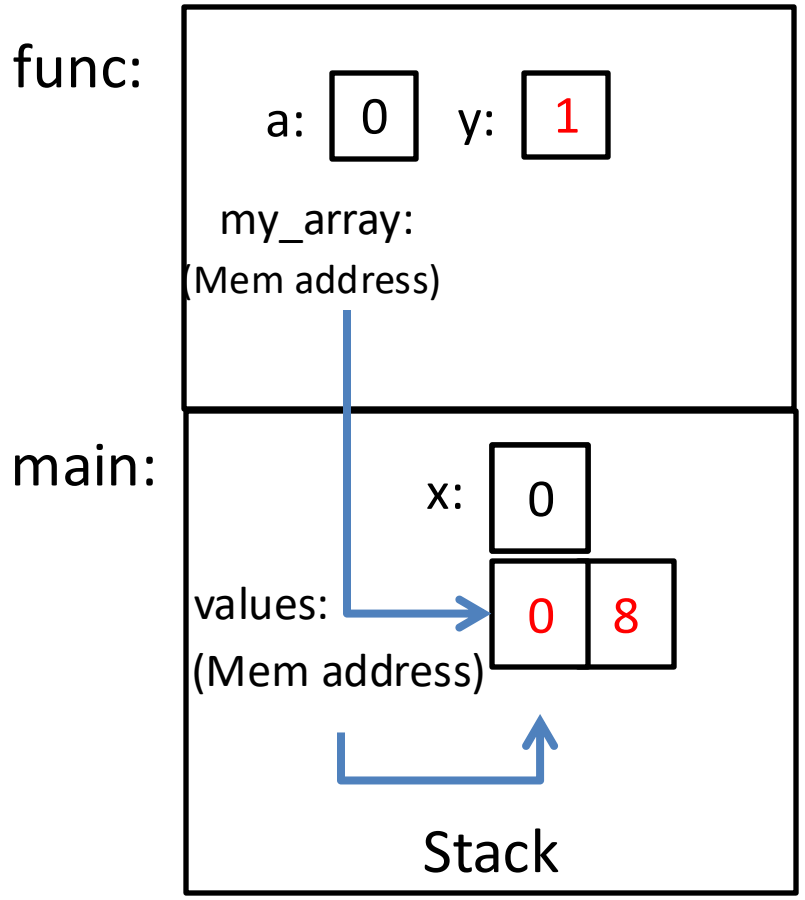
```
int func(int a, int y, int my_array[]) {
    y = 1;
    my_array[a] = 0;
    my_array[y] = 8;
    return y;
}

int main() {
    int x;
    int values[2];

    x = 0;
    values[0] = 5;
    values[1] = 10;

    x = func(x, x, values);

    printf("%d, %d, %d", x, values[0], values[1]);
}
```



What will this print?

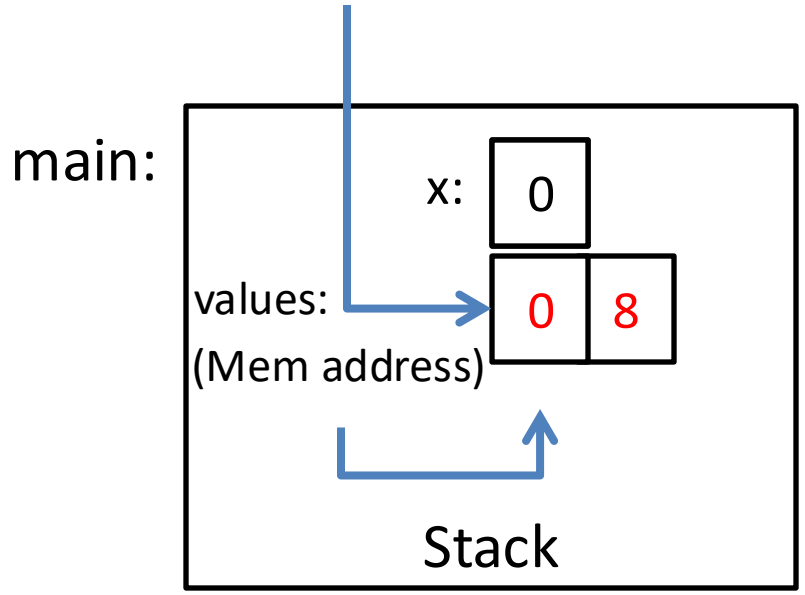
```
int func(int a, int y, int my_array[]) {
    y = 1;
    my_array[a] = 0;
    my_array[y] = 8;
    return y;
}

int main() {
    int x;
    int values[2];

    x = 0;
    values[0] = 5;
    values[1] = 10;

    x = func(x, x, values);

    printf("%d, %d, %d", x, values[0], values[1]);
}
```



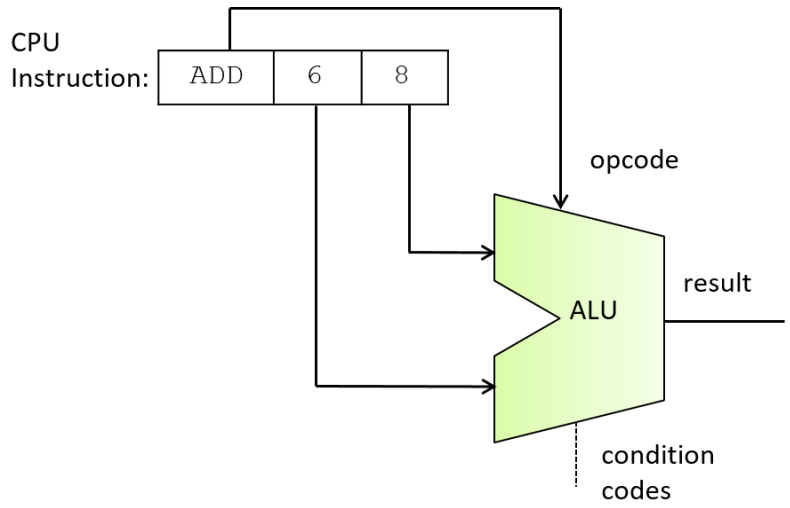
- You are not expected to master C.
- It’s a skill you’ll pick up as you go.
- We’ll revisit these topics when necessary.

- When in doubt: solve the problem in English, whiteboard pictures, whatever else!
  - Translate to C later.
  - Eventually, you’ll start to think in C.

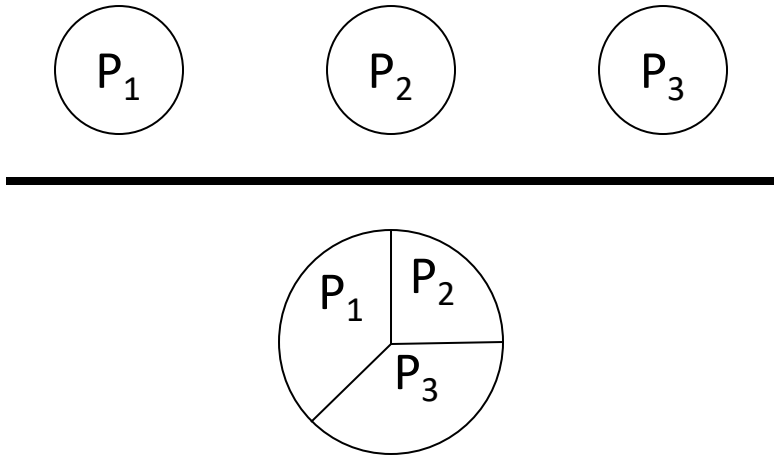
What is a computer system?

Hardware (HW) & Special Systems Software (OS) that work together to run application programs

- HW executes program instructions
- OS that manages the computer HW
- OS also provides abstractions to the programs/users



Computer Hardware



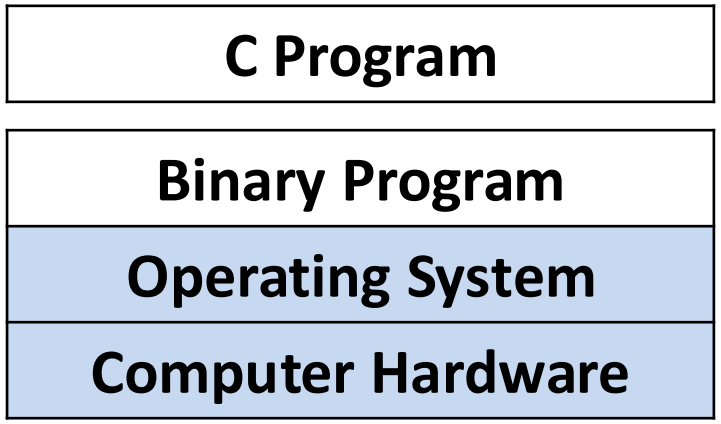
Operating System
CPU | Memory | Storage

C program:

```
// example C program
void main() {
  int authenticate;
  scanf("Enter your
  username and pwd:");
}
```

Program

How a Computer Runs a Program



How C program is run on System:

How instructions & data are encoded

OS Abstractions, Resource management

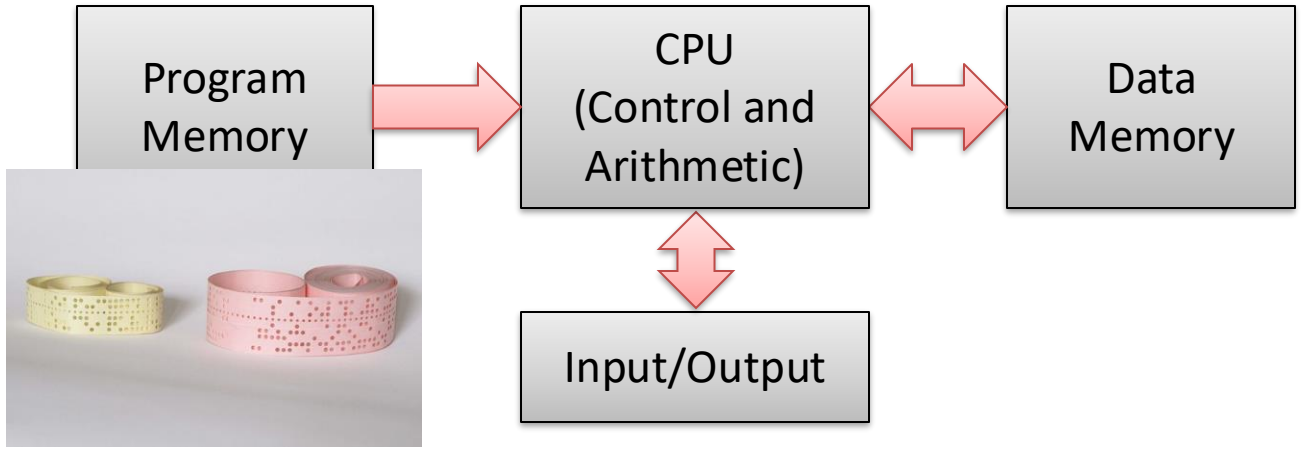
How underlying HW organized & works

What we know so far:

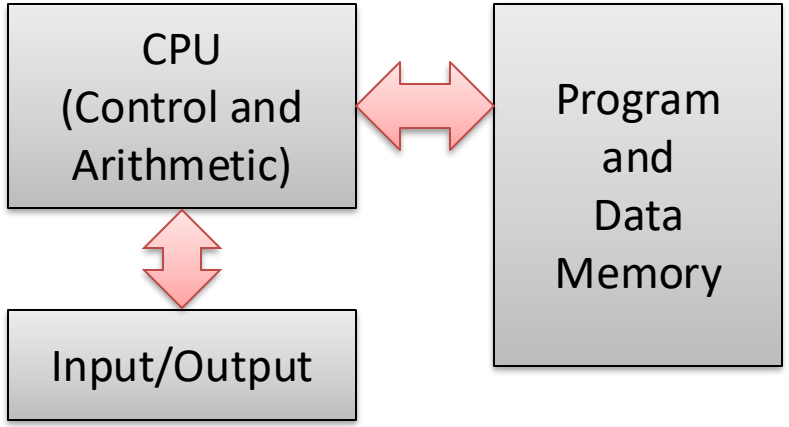
- Much of C programming language
  - types, operators, arrays, parameter passing, strings
- Binary encodings & sizes for different C types
  - `char`: signed (2's complement), 1 byte value
  - `unsigned int`: unsigned, 4 byte value
- How to perform binary operations (Add, Sub, Bit-wise)

Hardware Models (1940's)

- Harvard Architecture:



- Von Neumann Architecture:



Von Neumann Architecture 1945

Computer is a generic computing machine

- Can be used to compute anything that is computable
- Based on Alan Turing's Universal Turing Machine

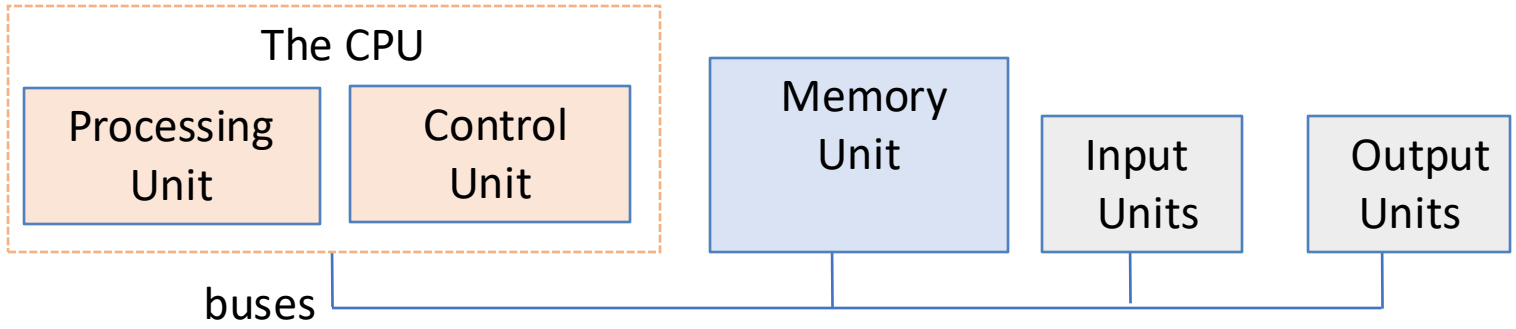
Uses a stored program model

- both program & data loaded into computer memory
- No distinction between data & instructions in memory
  - Earlier computers used fixed program encoded on machine, data loaded and run by fixed program

All modern computers based on the Von Neumann model

Von Neumann Model

5 units connected by buses (wires) to communicate



Processing & Control Units:

- implement CPU \execute program instructions on program data

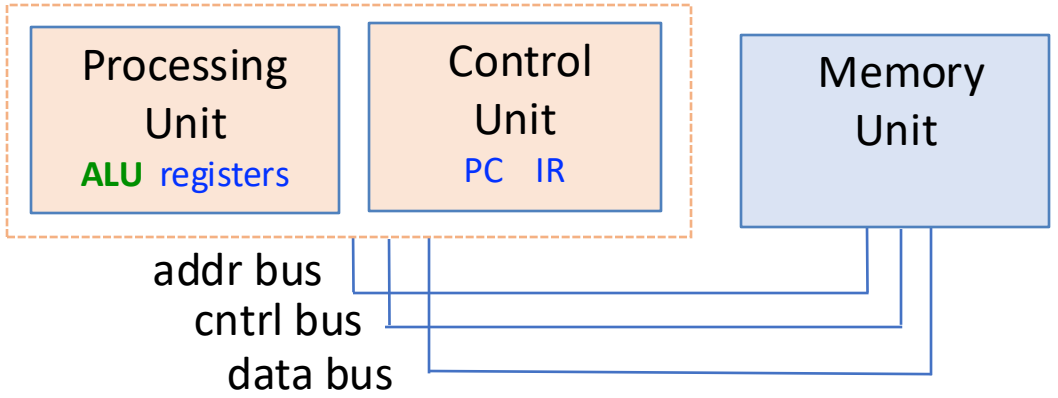
Memory: stores program instructions and data

- memory is addressable: addr 0, 1, 2, …

Input, Output: interface to compute

- trigger actions: load program, initiate execution, …
- display/store results: to terminal, save to disk, ...

CPU: Processing and Control Units

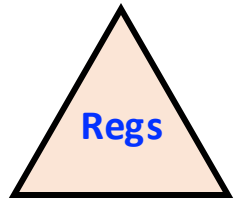


Processing Unit: executes instructions selected by Control unit

- **ALU** (arithmetic logic unit): simple functional units: ADD, SUB…
- Registers: temporary storage directly accessible by instructions

Control unit: determines instruction executed next

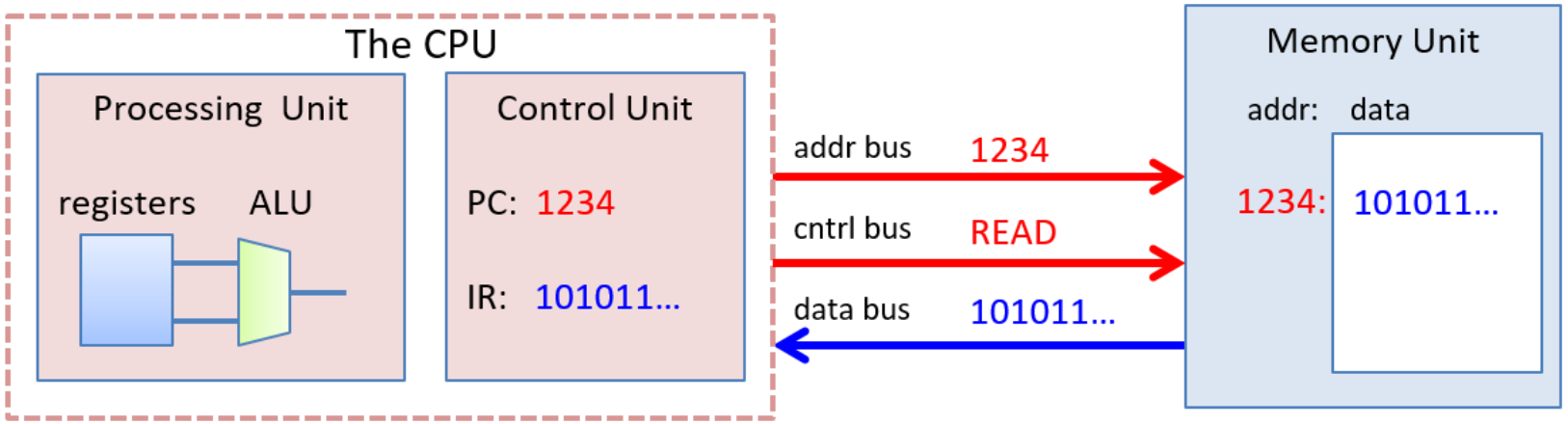
- PC: program counter: memory address of next instruction
- IR: holds current instruction bits



on-chip storage: fastest to access

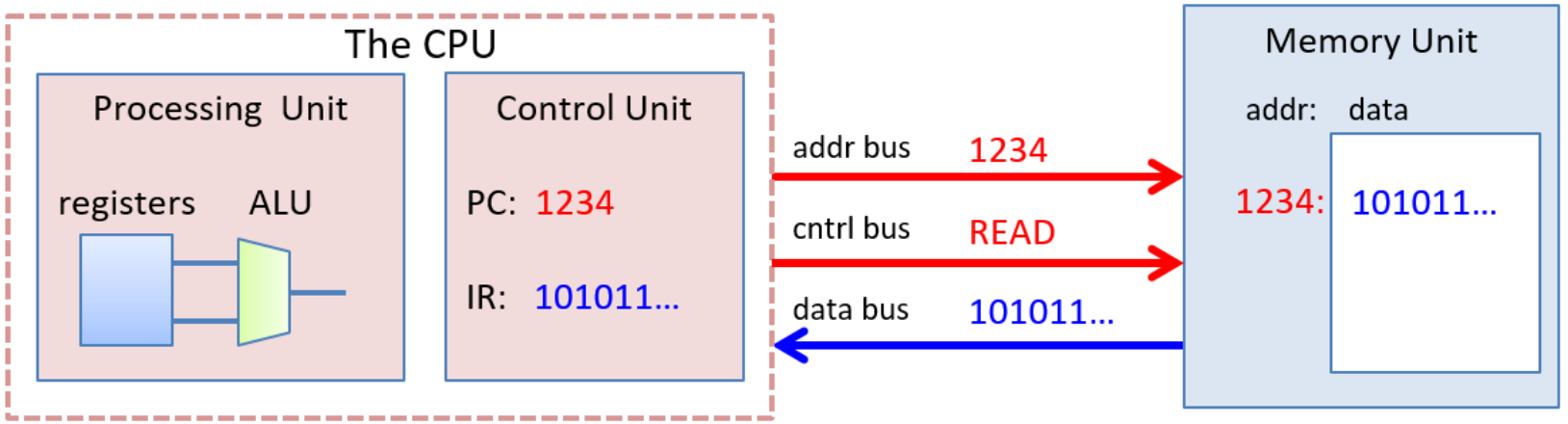
1. Fetch instruction from Memory (its addr in PC) into IR

   (and increment address in PC to next instruction address)

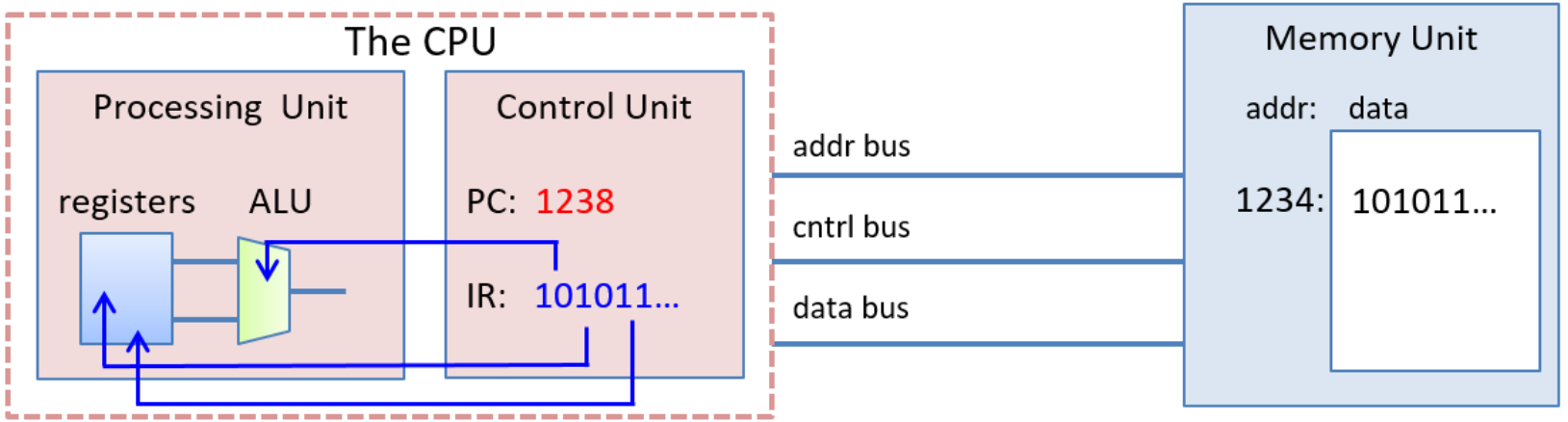


1. Fetch instruction from Memory (its addr in PC) into IR

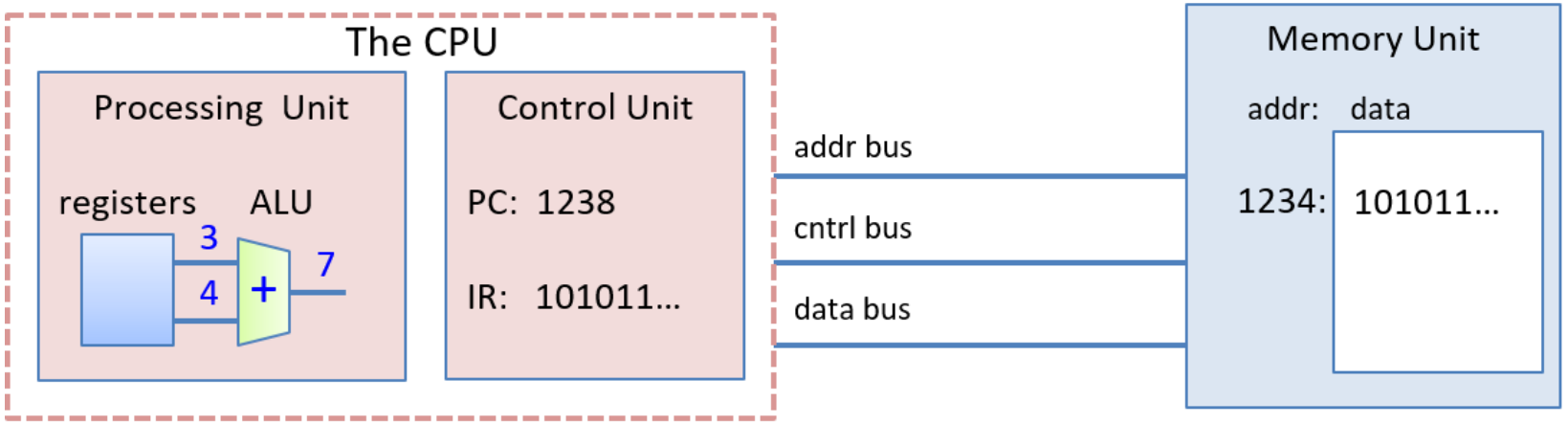
(and increment address in PC to next instruction address)



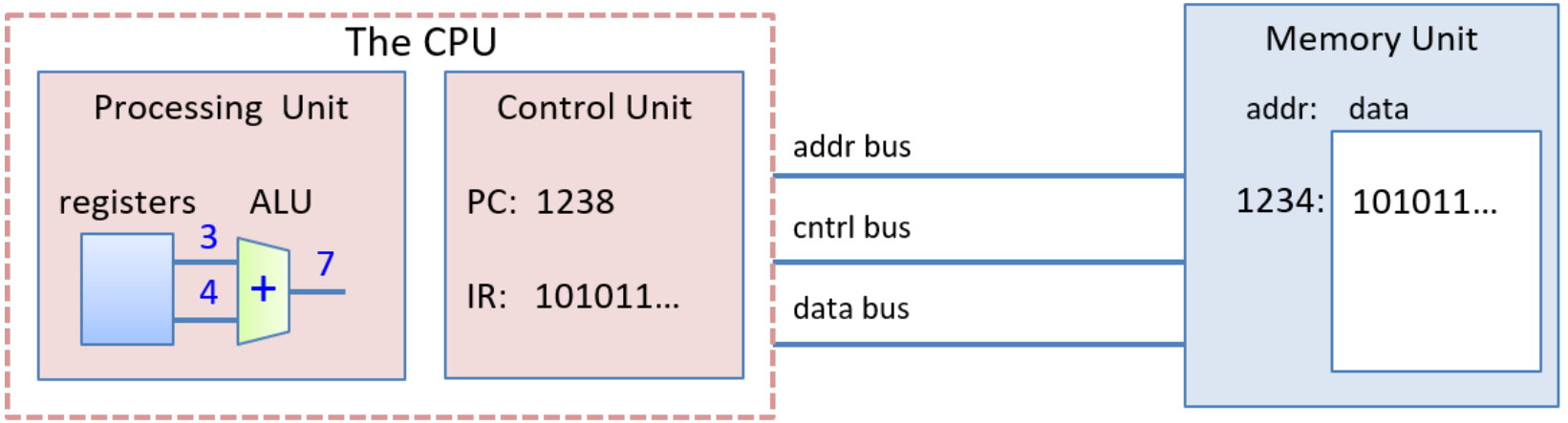
2. Decode instruction bits to determine operation & operands



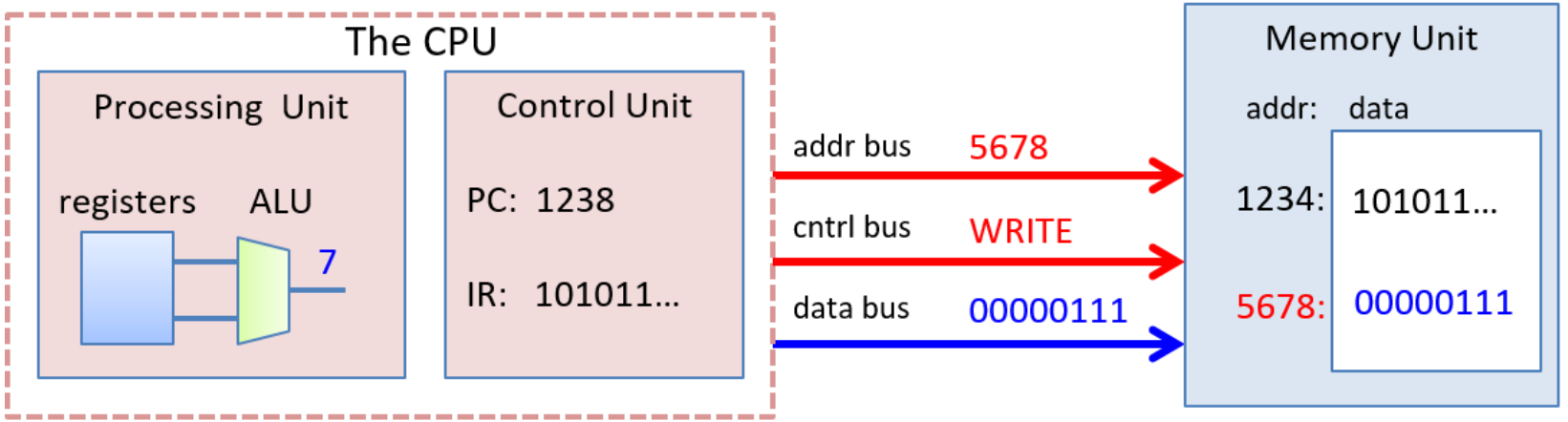
3. Execute instruction on ALU



3. Execute instruction on ALU



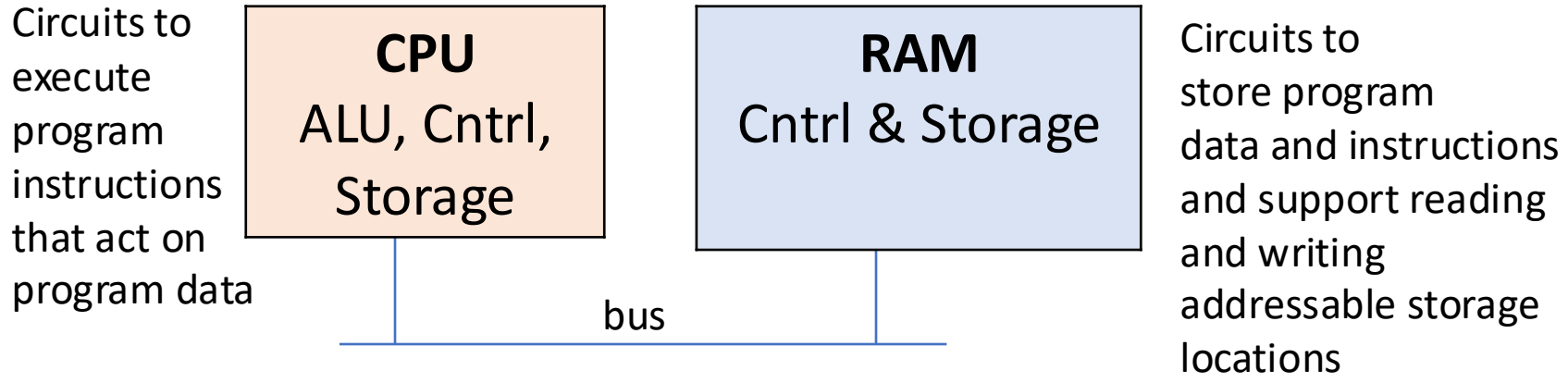
4. Store instruction results to Memory



Digital Computers

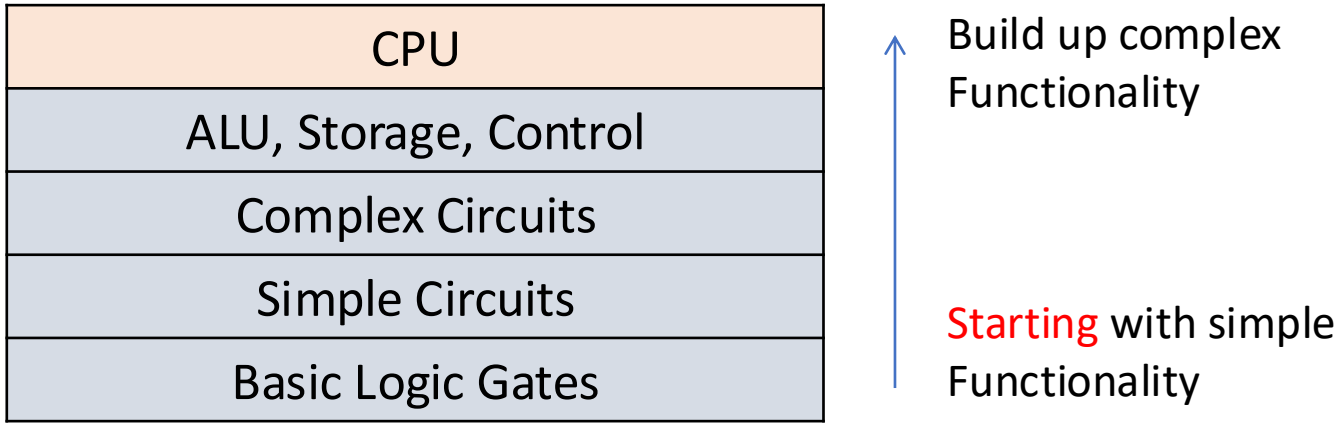
- All input & output are discrete and binary
  - data, instructions, control signals (0: no voltage, 1: voltage)
  - execution is driven by a clock (will discuss later)
  - time is discrete: time 1, time 2, time 3, ...

- To run program, need different types of circuits



Our Goal: Build a CPU (model)

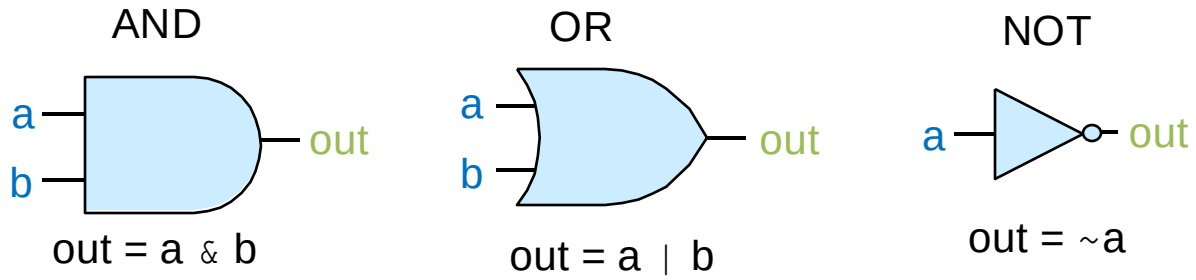
Start with very simple functionality, and add complexity



Logic Gates

Input: Boolean value(s) (high and low voltages for 1 and 0)

Output: Boolean value result of Boolean function
Always present, but may change when input changes



A	B	A & B	A | B	~A
0	0	0	0	1
0	1	0	1	1
1	0	0	1	0
1	1	1	1	0

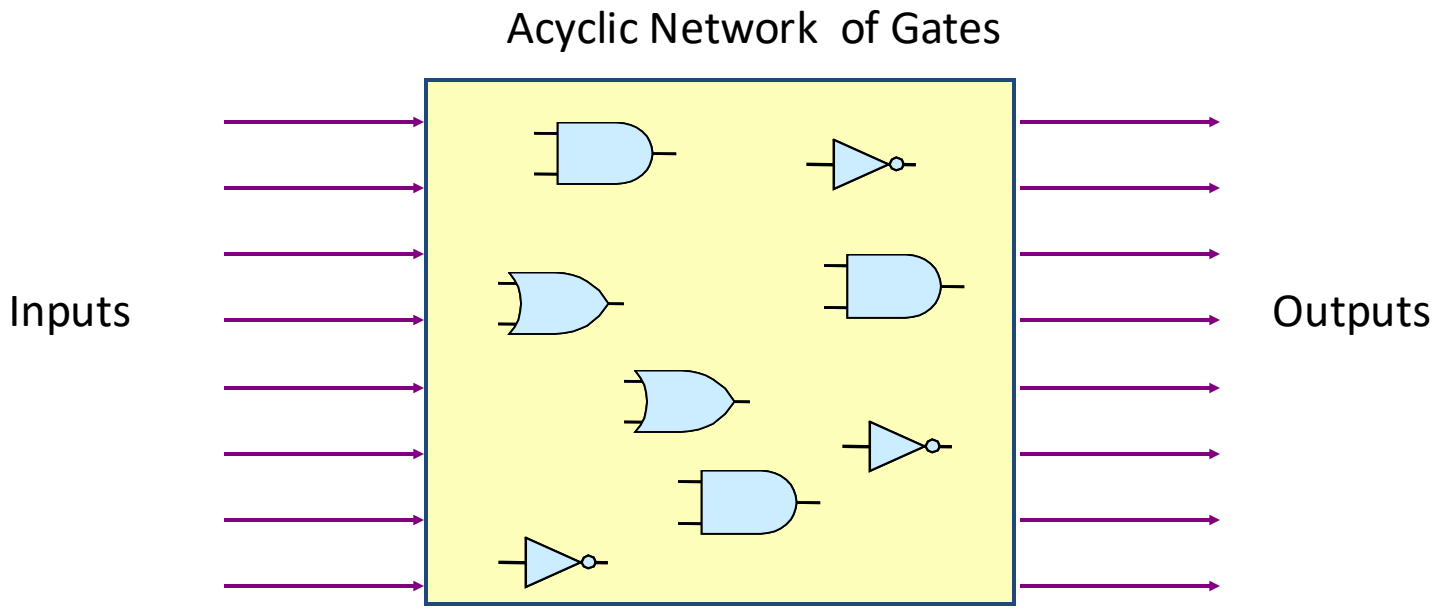
More Logic Gates

Note the circle on the output. This circle means bitwise "not" (flip bits).

A	B	A NAND B	A NOR B
0	0	1	1
0	1	1	0
1	0	1	0
1	1	0	0

Combinational Logic Circuits

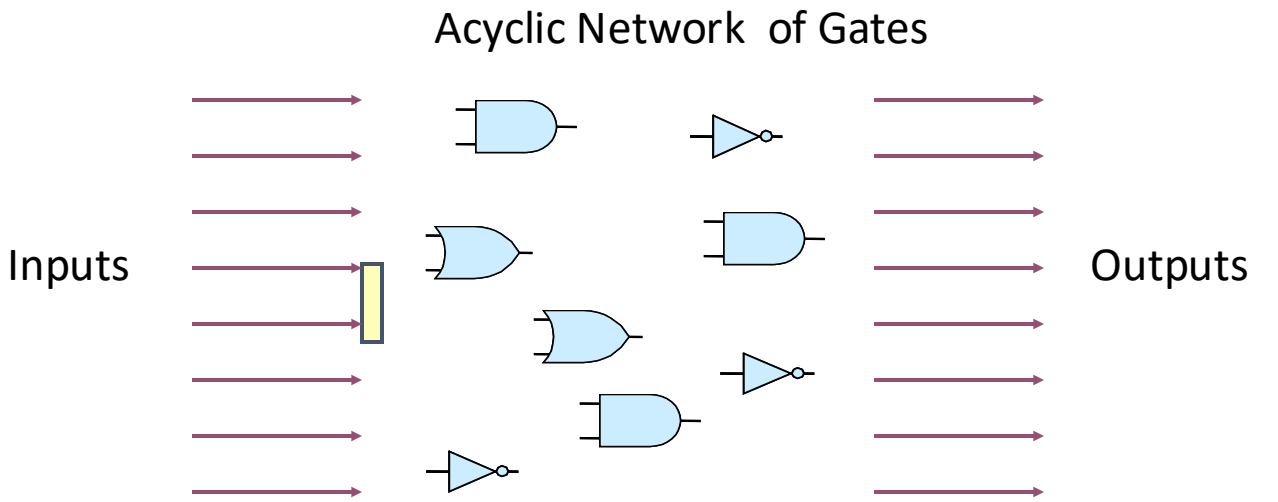
- Build up higher level processor functionality from basic gates



- Outputs are boolean functions of inputs
- Outputs continuously respond to changes to inputs

Combinatorial Logic Circuits

- Combine logic circuits together to implement higher-level functionality

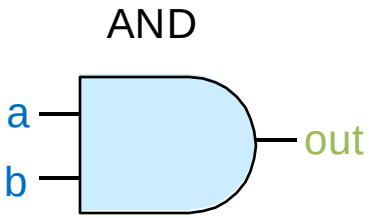


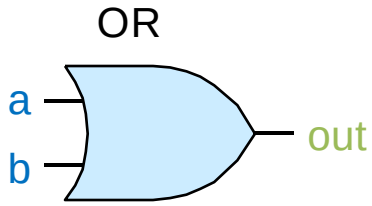
Outputs are boolean functions of inputs

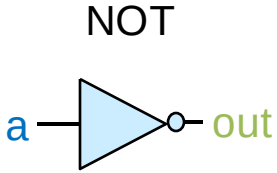
Outputs continuously respond to changes to inputs

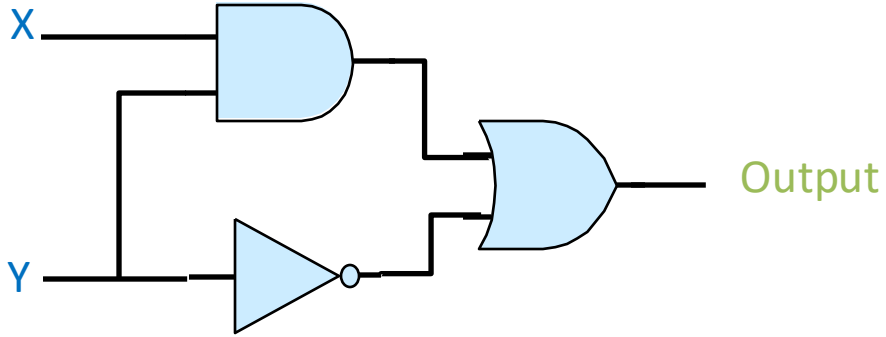
- Use this new functionality as a building block for even higher level functionality (Abstraction!)

What does this circuit output?





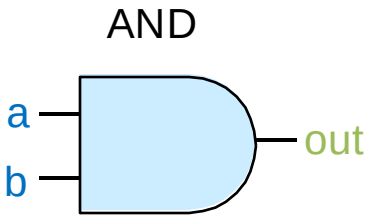


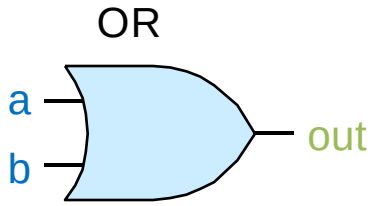


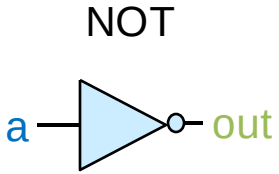
Clicker Choices

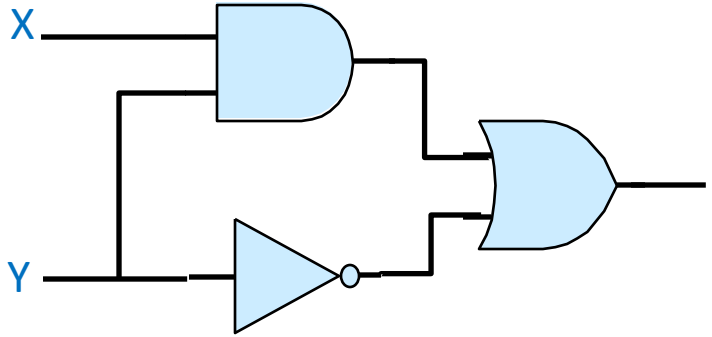
X	Y	Out_A	Out_B	Out_C	Out_D	Out_E
0	0	0	1	0	1	0
0	1	0	1	0	0	1
1	0	1	0	1	1	1
1	1	0	0	1	1	0

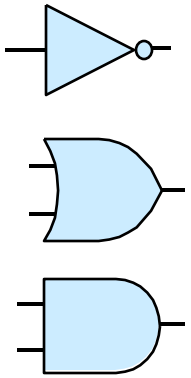
What does this circuit output?











Clicker Choices

X	Y	Out_A	Out_B	Out_C	Out_D	Out_E
0	0	0	1	0	1	0
0	1	0	1	0	0	1
1	0	1	0	1	1	1
1	1	0	0	1	1	0