COMP110: Principles of Computing

3: Data Types

FALMOUTH
UNIVERSITY

Binary notation

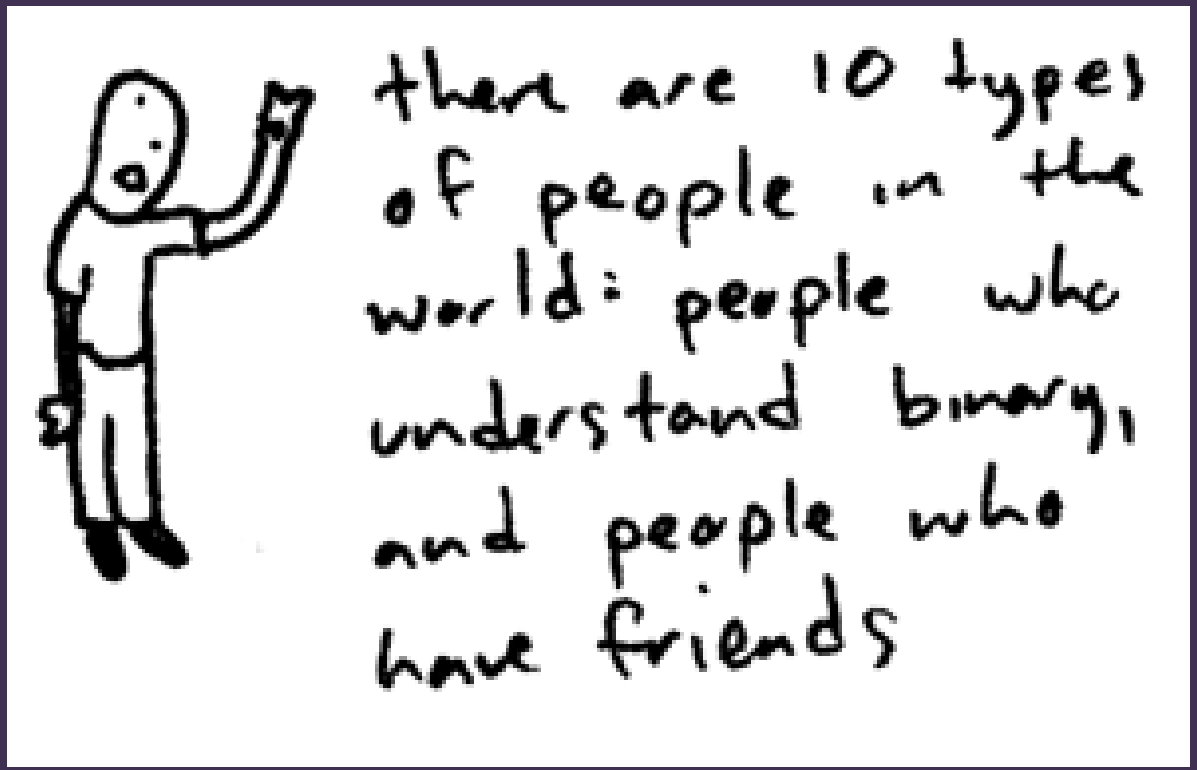


Image credit: `http://www.toothpastefordinner.com`

How we write numbers

How we write numbers

- We write numbers in **base 10**

How we write numbers

- We write numbers in **base 10**
- We have 10 **digits**: $0, 1, 2, \ldots, 8, 9$

How we write numbers

- We write numbers in **base 10**
- We have 10 **digits**: $0, 1, 2, \ldots, 8, 9$
- When we write 6397, we mean:

How we write numbers

- We write numbers in **base 10**
- We have 10 **digits**: $0, 1, 2, \ldots, 8, 9$
- When we write 6397, we mean:
  - Six thousand, three hundred and ninety seven

How we write numbers

- We write numbers in **base 10**
- We have 10 **digits**: $0, 1, 2, \ldots, 8, 9$
- When we write 6397, we mean:
  - Six thousand, three hundred and ninety seven
  - (Six thousands) and (three hundreds) and (nine tens) and (seven)

How we write numbers

- We write numbers in **base 10**
- We have 10 **digits**: $0, 1, 2, \ldots, 8, 9$
- When we write 6397, we mean:
  - Six thousand, three hundred and ninety seven
  - (Six thousands) and (three hundreds) and (nine tens) and (seven)
  - $(6 \times 1000) + (3 \times 100) + (9 \times 10) + (7)$

How we write numbers

- We write numbers in **base 10**
- We have 10 **digits**: $0, 1, 2, \ldots, 8, 9$
- When we write 6397, we mean:
  - Six thousand, three hundred and ninety seven
  - (Six thousands) and (three hundreds) and (nine tens) and (seven)
  - $(6 \times 1000) + (3 \times 100) + (9 \times 10) + (7)$
  - $(6 \times 10^3) + (3 \times 10^2) + (9 \times 10^1) + (7 \times 10^0)$

How we write numbers

- We write numbers in **base 10**
- We have 10 **digits**: $0, 1, 2, \ldots, 8, 9$
- When we write 6397, we mean:
  - Six thousand, three hundred and ninety seven
  - (Six thousands) and (three hundreds) and (nine tens) and (seven)
  - $(6 \times 1000) + (3 \times 100) + (9 \times 10) + (7)$
  - $(6 \times 10^3) + (3 \times 10^2) + (9 \times 10^1) + (7 \times 10^0)$
  -

Thousands	Hundreds	Tens	Units
6	3	9	7

Binary

Binary

- Binary notation works the same, but is **base 2** instead of **base 10**

Binary

- Binary notation works the same, but is **base 2** instead of **base 10**
- We have 2 **digits**: 0, 1

Binary

- Binary notation works the same, but is **base 2** instead of **base 10**
- We have 2 **digits**: 0, 1
- When we write 10001011 in binary, we mean:

Binary

- Binary notation works the same, but is **base 2** instead of **base 10**
- We have 2 **digits**: 0, 1
- When we write 10001011 in binary, we mean:

$$(1 \times 2^7) + (0 \times 2^6) + (0 \times 2^5) + (0 \times 2^4) + (1 \times 2^3) + (0 \times 2^2) + (1 \times 2^1) + (1 \times 2^0)$$

Binary

- Binary notation works the same, but is **base 2** instead of **base 10**
- We have 2 **digits**: 0, 1
- When we write 10001011 in binary, we mean:

$$\begin{aligned}&(1 \times 2^7) + (0 \times 2^6) + (0 \times 2^5) + (0 \times 2^4) \\ &+ (1 \times 2^3) + (0 \times 2^2) + (1 \times 2^1) + (1 \times 2^0) \\ &= 2^7 + 2^3 + 2^1 + 2^0\end{aligned}$$

Binary

- Binary notation works the same, but is **base 2** instead of **base 10**
- We have 2 **digits**: 0, 1
- When we write 10001011 in binary, we mean:

$$\begin{aligned}
&(1 \times 2^7) + (0 \times 2^6) + (0 \times 2^5) + (0 \times 2^4) \\
&+ (1 \times 2^3) + (0 \times 2^2) + (1 \times 2^1) + (1 \times 2^0) \\
&= 2^7 + 2^3 + 2^1 + 2^0 \\
&= 128 + 8 + 2 + 1 \text{ (base 10)}
\end{aligned}$$

Binary

- Binary notation works the same, but is **base 2** instead of **base 10**
- We have 2 **digits**: 0, 1
- When we write 10001011 in binary, we mean:

$$\begin{aligned}
&(1 \times 2^7) + (0 \times 2^6) + (0 \times 2^5) + (0 \times 2^4) \\
&+ (1 \times 2^3) + (0 \times 2^2) + (1 \times 2^1) + (1 \times 2^0) \\
&= 2^7 + 2^3 + 2^1 + 2^0 \\
&= 128 + 8 + 2 + 1 \text{ (base 10)} \\
&= 139 \text{ (base 10)}
\end{aligned}$$

Why binary?

Why binary?

- Modern computers are **digital**

Why binary?

- Modern computers are **digital**
- Based on the flow of current in a circuit being either **on** or **off**

Why binary?

- Modern computers are **digital**
- Based on the flow of current in a circuit being either **on** or **off**
- Hence it is natural to store and operate on numbers in base 2

Why binary?

- Modern computers are **digital**
- Based on the flow of current in a circuit being either **on** or **off**
- Hence it is natural to store and operate on numbers in base 2
- The binary digits 0 and 1 correspond to **off** and **on** respectively

Converting to binary

https://www.youtube.com/watch?v=OezK_zTyvAQ

Bits, bytes and words

Bits, bytes and words

- A **bit** is a binary digit

Bits, bytes and words

- A **bit** is a binary digit
  - Can store a 0 or 1 (i.e. a boolean value)

Bits, bytes and words

- A **bit** is a binary digit
  - Can store a 0 or 1 (i.e. a boolean value)
  - The smallest possible unit of information

Bits, bytes and words

- A **bit** is a binary digit
  - Can store a 0 or 1 (i.e. a boolean value)
  - The smallest possible unit of information
- A **byte** is 8 **bits**

Bits, bytes and words

- A **bit** is a binary digit
  - Can store a 0 or 1 (i.e. a boolean value)
  - The smallest possible unit of information
- A **byte** is 8 **bits**
  - Can store a number between 0 and 255 in binary

Bits, bytes and words

- A **bit** is a binary digit
  - Can store a 0 or 1 (i.e. a boolean value)
  - The smallest possible unit of information
- A **byte** is 8 **bits**
  - Can store a number between 0 and 255 in binary
- A **word** is the number of bits that the CPU works with at once

Bits, bytes and words

- A **bit** is a binary digit
  - Can store a 0 or 1 (i.e. a boolean value)
  - The smallest possible unit of information
- A **byte** is 8 **bits**
  - Can store a number between 0 and 255 in binary
- A **word** is the number of bits that the CPU works with at once
  - 32-bit CPU: 32 bits = 1 word

Bits, bytes and words

- A **bit** is a binary digit
  - Can store a 0 or 1 (i.e. a boolean value)
  - The smallest possible unit of information
- A **byte** is 8 **bits**
  - Can store a number between 0 and 255 in binary
- A **word** is the number of bits that the CPU works with at once
  - 32-bit CPU: 32 bits = 1 word
  - 64-bit CPU: 64 bits = 1 word

Bits, bytes and words

- A **bit** is a binary digit
  - Can store a 0 or 1 (i.e. a boolean value)
  - The smallest possible unit of information
- A **byte** is 8 **bits**
  - Can store a number between 0 and 255 in binary
- A **word** is the number of bits that the CPU works with at once
  - 32-bit CPU: 32 bits = 1 word
  - 64-bit CPU: 64 bits = 1 word
- An n-bit word can store a number between 0 and $2^n - 1$

Bits, bytes and words

- A **bit** is a binary digit
  - Can store a 0 or 1 (i.e. a boolean value)
  - The smallest possible unit of information
- A **byte** is 8 **bits**
  - Can store a number between 0 and 255 in binary
- A **word** is the number of bits that the CPU works with at once
  - 32-bit CPU: 32 bits = 1 word
  - 64-bit CPU: 64 bits = 1 word
- An n-bit word can store a number between 0 and $2^n - 1$
  - $2^{16} - 1 = 65,535$

Bits, bytes and words

- A **bit** is a binary digit
  - Can store a 0 or 1 (i.e. a boolean value)
  - The smallest possible unit of information
- A **byte** is 8 **bits**
  - Can store a number between 0 and 255 in binary
- A **word** is the number of bits that the CPU works with at once
  - 32-bit CPU: 32 bits = 1 word
  - 64-bit CPU: 64 bits = 1 word
- An n-bit word can store a number between 0 and $2^n - 1$
  - $2^{16} - 1 = 65,535$
  - $2^{32} - 1 = 4,294,967,295$

Bits, bytes and words

- A **bit** is a binary digit
  - Can store a 0 or 1 (i.e. a boolean value)
  - The smallest possible unit of information
- A **byte** is 8 **bits**
  - Can store a number between 0 and 255 in binary
- A **word** is the number of bits that the CPU works with at once
  - 32-bit CPU: 32 bits = 1 word
  - 64-bit CPU: 64 bits = 1 word
- An n-bit word can store a number between 0 and $2^n - 1$
  - $2^{16} - 1 = 65,535$
  - $2^{32} - 1 = 4,294,967,295$
  - $2^{64} - 1 = 18,446,744,073,709,551,615$

Other units

Other units

- A **nibble** is 4 **bits**

Other units

- A **nibble** is 4 **bits**
- A **kilobyte** is 1000 or 1024 **bytes**

Other units

- A **nibble** is 4 **bits**
- A **kilobyte** is 1000 or 1024 **bytes**
  - $10^3 = 1000 \approx 1024 = 2^{10}$

Other units

- A **nibble** is 4 **bits**
- A **kilobyte** is 1000 or 1024 **bytes**
  - $10^3 = 1000 \approx 1024 = 2^{10}$
- A **megabyte** is 1000 or 1024 **kilobytes**

Other units

- A **nibble** is 4 **bits**
- A **kilobyte** is 1000 or 1024 **bytes**
  - $10^3 = 1000 \approx 1024 = 2^{10}$
- A **megabyte** is 1000 or 1024 **kilobytes**
- A **gigabyte** is 1000 or 1024 **megabytes**

Other units

- A **nibble** is 4 **bits**
- A **kilobyte** is 1000 or 1024 **bytes**
  - $10^3 = 1000 \approx 1024 = 2^{10}$
- A **megabyte** is 1000 or 1024 **kilobytes**
- A **gigabyte** is 1000 or 1024 **megabytes**
- A **terabyte** is 1000 or 1024 **gigabytes**

Other units

- A **nibble** is 4 **bits**
- A **kilobyte** is 1000 or 1024 **bytes**
  - $10^3 = 1000 \approx 1024 = 2^{10}$
- A **megabyte** is 1000 or 1024 **kilobytes**
- A **gigabyte** is 1000 or 1024 **megabytes**
- A **terabyte** is 1000 or 1024 **gigabytes**
- A **petabyte** is 1000 or 1024 **terabytes**

Other units

- A **nibble** is 4 **bits**
- A **kilobyte** is 1000 or 1024 **bytes**
  - $10^3 = 1000 \approx 1024 = 2^{10}$
- A **megabyte** is 1000 or 1024 **kilobytes**
- A **gigabyte** is 1000 or 1024 **megabytes**
- A **terabyte** is 1000 or 1024 **gigabytes**
- A **petabyte** is 1000 or 1024 **terabytes**
- An **exabyte** is 1000 or 1024 **petabytes**

Other units

- A **nibble** is 4 **bits**
- A **kilobyte** is 1000 or 1024 **bytes**
  - $10^3 = 1000 \approx 1024 = 2^{10}$
- A **megabyte** is 1000 or 1024 **kilobytes**
- A **gigabyte** is 1000 or 1024 **megabytes**
- A **terabyte** is 1000 or 1024 **gigabytes**
- A **petabyte** is 1000 or 1024 **terabytes**
- An **exabyte** is 1000 or 1024 **petabytes**
- A **zettabyte** is 1000 or 1024 **exabytes**

Other units

- A **nibble** is 4 **bits**
- A **kilobyte** is 1000 or 1024 **bytes**
  - $10^3 = 1000 \approx 1024 = 2^{10}$
- A **megabyte** is 1000 or 1024 **kilobytes**
- A **gigabyte** is 1000 or 1024 **megabytes**
- A **terabyte** is 1000 or 1024 **gigabytes**
- A **petabyte** is 1000 or 1024 **terabytes**
- An **exabyte** is 1000 or 1024 **petabytes**
- A **zettabyte** is 1000 or 1024 **exabytes**
- ...

Addition with carry

In base 10:

$$\begin{array}{rcccc} & 1 & 2 & 3 & 4 \\ + & 5 & 6 & 7 & 8 \\ \hline \end{array}$$

Addition with carry

In base 10:

$$\begin{array}{cccccc} & 1 & 2 & 3 & 4 \\ + & 5 & 6 & 7_1 & 8 \\ \hline & & & & 2 \end{array}$$

Addition with carry

In base 10:

$$\begin{array}{rcccc} & 1 & 2 & 3 & 4 \\ + & 5 & 6_1 & 7_1 & 8 \\ \hline & & & 1 & 2 \end{array}$$

Addition with carry

In base 10:

$$\begin{array}{rcccc} & 1 & 2 & 3 & 4 \\ + & 5 & 6_1 & 7_1 & 8 \\ \hline & & 9 & 1 & 2 \end{array}$$

Addition with carry

In base 10:

$$\begin{array}{rcccc} & 1 & 2 & 3 & 4 \\ + & 5 & 6_1 & 7_1 & 8 \\ \hline & 6 & 9 & 1 & 2 \end{array}$$

Addition with carry

In base 2:

$$\boxed{1+1=10 \qquad 1+1+1=11}$$

$$\begin{array}{rcccccccc} & 0 & 1 & 1 & 0 & 1 & 1 & 1 & 0 \\ + & 0 & 0 & 1 & 0 & 0 & 1 & 1 & 1 \\ \hline \end{array}$$

Addition with carry

In base 2:

$$\boxed{1+1=10 \qquad 1+1+1=11}$$

$$\begin{array}{rcccccccc} & 0 & 1 & 1 & 0 & 1 & 1 & 1 & 0 \\ + & 0 & 0 & 1 & 0 & 0 & 1 & 1 & 1 \\ \hline & & & & & & & & 1 \end{array}$$

Addition with carry

In base 2:

$$\boxed{1+1=10 \qquad 1+1+1=11}$$

$$\begin{array}{rcccccccc} & 0 & 1 & 1 & 0 & 1 & 1 & 1 & 0 \\ + & 0 & 0 & 1 & 0 & 0 & 1_1 & 1 & 1 \\ \hline & & & & & & & 0 & 1 \end{array}$$

Addition with carry

In base 2:

$$\boxed{1+1=10 \qquad 1+1+1=11}$$

$$\begin{array}{rcccccccc} & 0 & 1 & 1 & 0 & 1 & 1 & 1 & 0 \\ + & 0 & 0 & 1 & 0 & 0_1 & 1_1 & 1 & 1 \\ \hline & & & & & & 1 & 0 & 1 \end{array}$$

Addition with carry

In base 2:

$$\boxed{1+1=10 \qquad 1+1+1=11}$$

$$\begin{array}{rcccccccc} & 0 & 1 & 1 & 0 & 1 & 1 & 1 & 0 \\ + & 0 & 0 & 1 & 0_1 & 0_1 & 1_1 & 1 & 1 \\ \hline & & & & & 0 & 1 & 0 & 1 \end{array}$$

Addition with carry

In base 2:

$$\boxed{1+1=10 \qquad 1+1+1=11}$$

$$\begin{array}{rcccccccc} & 0 & 1 & 1 & 0 & 1 & 1 & 1 & 0 \\ + & 0 & 0 & 1 & 0_1 & 0_1 & 1_1 & 1 & 1 \\ \hline & & & & 1 & 0 & 1 & 0 & 1 \end{array}$$

Addition with carry

In base 2:

$$\boxed{1+1=10 \qquad 1+1+1=11}$$

$$\begin{array}{rcccccccc} & 0 & 1 & 1 & 0 & 1 & 1 & 1 & 0 \\ + & 0 & 0_1 & 1 & 0_1 & 0_1 & 1_1 & 1 & 1 \\ \hline & & & 0 & 1 & 0 & 1 & 0 & 1 \end{array}$$

Addition with carry

In base 2:

$$\boxed{1+1=10 \qquad 1+1+1=11}$$

$$\begin{array}{cccccccc} & 0 & 1 & 1 & 0 & 1 & 1 & 1 & 0 \\ + & 0_1 & 0_1 & 1 & 0_1 & 0_1 & 1_1 & 1 & 1 \\ \hline & & 0 & 0 & 1 & 0 & 1 & 0 & 1 \end{array}$$

Addition with carry

In base 2:

$$\boxed{1+1=10 \qquad 1+1+1=11}$$

$$\begin{array}{cccccccc} & 0 & 1 & 1 & 0 & 1 & 1 & 1 & 0 \\ + & 0_1 & 0_1 & 1 & 0_1 & 0_1 & 1_1 & 1 & 1 \\ \hline & 1 & 0 & 0 & 1 & 0 & 1 & 0 & 1 \end{array}$$

Hexadecimal notation

Hexadecimal notation

- Other number bases than 2 and 10 are also useful

Hexadecimal notation

- Other number bases than 2 and 10 are also useful
- Hexadecimal is **base 16**

Hexadecimal notation

- Other number bases than 2 and 10 are also useful
- Hexadecimal is **base 16**
- Uses extra digits:
  - `A`=10, `B`=11, ..., `F`=15

Hexadecimal notation

- Other number bases than 2 and 10 are also useful
- Hexadecimal is **base 16**
- Uses extra digits:
  - A=10, B=11, ..., F=15

Hex	Dec	Hex	Dec	Hex	Dec
00	0	10	16	F0	240
01	1	11	17	F1	241
⋮	⋮	⋮	⋮	⋮	⋮
09	9	19	25	F9	249
0A	10	1A	26	FA	250
0B	11	1B	27	FB	251
0C	12	1C	28	FC	252
0D	13	1D	29	FD	253
0E	14	1E	30	FE	254
0F	15	1F	31	FF	255

FALMOUTH
UNIVERSITY

Numeric types

Integers

Integers

- An **integer** is a whole number — positive, negative or zero

Integers

- An **integer** is a whole number — positive, negative or zero
- Stored in memory using binary notation, with 2's complement for negative values

Integers

- An **integer** is a whole number — positive, negative or zero
- Stored in memory using binary notation, with 2's complement for negative values
- In C#: `int` is a 32-bit integer, `long` is a 64-bit integer

Integers

- An **integer** is a whole number — positive, negative or zero
- Stored in memory using binary notation, with 2's complement for negative values
- In C#: `int` is a 32-bit integer, `long` is a 64-bit integer
- In Python: `int` is a "big integer" — expands number of bits automatically to fit the value to be stored

Floating point numbers

Floating point numbers

- What about storing non-integer numbers?

Floating point numbers

- What about storing non-integer numbers?
- Usually we use **floating point** numbers

Floating point numbers

- What about storing non-integer numbers?
- Usually we use **floating point** numbers
- Details on in-memory representation later in the module

Floating point numbers

- What about storing non-integer numbers?
- Usually we use **floating point** numbers
- Details on in-memory representation later in the module
- In C#: `float` or `double`

Floating point numbers

- What about storing non-integer numbers?
- Usually we use **floating point** numbers
- Details on in-memory representation later in the module
- In C#: `float` or `double`
- `double` is more precise, but uses twice as much memory (8 bytes vs 4 bytes)

Floating point numbers

- What about storing non-integer numbers?
- Usually we use **floating point** numbers
- Details on in-memory representation later in the module
- In C#: `float` or `double`
- `double` is more precise, but uses twice as much memory (8 bytes vs 4 bytes)
- Python type: `float`, which has the same precision as C# `double`!

Integers vs floating point numbers

Integers vs floating point numbers

- Integers and floating point numbers are **different types**!

Integers vs floating point numbers

- Integers and floating point numbers are **different types**!
- `42` and `42.0` are technically different values

Integers vs floating point numbers

- Integers and floating point numbers are **different types**!
- `42` and `42.0` are technically different values
  - One is an `int`, the other is a `double`

Integers vs floating point numbers

- Integers and floating point numbers are **different types**!
- `42` and `42.0` are technically different values
  - One is an `int`, the other is a `double`
  - They are stored differently in memory (completely different sequences of bytes)

Integers vs floating point numbers

- Integers and floating point numbers are **different types**!
- `42` and `42.0` are technically different values
  - One is an `int`, the other is a `double`
  - They are stored differently in memory (completely different sequences of bytes)
  - However, `==` etc still know how to compare them sensibly

FALMOUTH
UNIVERSITY

String types

Strings

Strings

- A **string** represents a sequence of textual characters

Strings

- A **string** represents a sequence of textual characters
- E.g. `"Hello world!"`

Strings

- A **string** represents a sequence of textual characters
- E.g. `"Hello world!"`
- C# type: `string`

Strings

- A **string** represents a sequence of textual characters
- E.g. `"Hello world!"`
- C# type: `string`
- Python type: `str`

String representation

String representation

- Stored as sequences of **characters** encoded as **integers**

String representation

- Stored as sequences of **characters** encoded as **integers**
- Often **null-terminated**

String representation

- Stored as sequences of **characters** encoded as **integers**
- Often **null-terminated**
  - Character number 0 signifies the end of the string

What is a character?

What is a character?

- Broadly speaking, a single **printable symbol** or **glyph**

What is a character?

- Broadly speaking, a single **printable symbol** or **glyph**
- (Actually a lot more complicated than this, but this will do for today)

What is a character?

- Broadly speaking, a single **printable symbol** or **glyph**
- (Actually a lot more complicated than this, but this will do for today)
- There are also some special **non-printable characters** e.g. line break

ASCII

ASCII

- American Standard Code for Information Interchange

ASCII

- American Standard Code for Information Interchange
- Defines a standard set of 128 characters (7 bits per character)

ASCII

- American Standard Code for Information Interchange
- Defines a standard set of 128 characters (7 bits per character)
- Originally developed in the 1960s for teletype machines, but survives in computing to this day

ASCII

- American Standard Code for Information Interchange
- Defines a standard set of 128 characters (7 bits per character)
- Originally developed in the 1960s for teletype machines, but survives in computing to this day
- 95 printable characters: upper and lower case English alphabet, digits, punctuation

ASCII

- American Standard Code for Information Interchange
- Defines a standard set of 128 characters (7 bits per character)
- Originally developed in the 1960s for teletype machines, but survives in computing to this day
- 95 printable characters: upper and lower case English alphabet, digits, punctuation
- 33 non-printable characters

Hex	Value	Hex	Value	Hex	Value	Hex	Value	Hex	Value	Hex	Value	Hex	Value	Hex	Value
00	NUL	10	DLE	20	SP	30	0	40	@	50	P	60	`	70	p
01	SOH	11	DC1	21	!	31	1	41	A	51	Q	61	a	71	q
02	STX	12	DC2	22	"	32	2	42	B	52	R	62	b	72	r
03	ETX	13	DC3	23	#	33	3	43	C	53	S	63	c	73	s
04	EOT	14	DC4	24	$	34	4	44	D	54	T	64	d	74	t
05	ENQ	15	NAK	25	%	35	5	45	E	55	U	65	e	75	u
06	ACK	16	SYN	26	&	36	6	46	F	56	V	66	f	76	v
07	BEL	17	ETB	27	'	37	7	47	G	57	W	67	g	77	w
08	BS	18	CAN	28	(	38	8	48	H	58	X	68	h	78	x
09	HT	19	EM	29	)	39	9	49	I	59	Y	69	i	79	y
0A	LF	1A	SUB	2A	*	3A	:	4A	J	5A	Z	6A	j	7A	z
0B	VT	1B	ESC	2B	+	3B	;	4B	K	5B	[	6B	k	7B	{
0C	FF	1C	FS	2C	,	3C	<	4C	L	5C	\	6C	l	7C	|
0D	CR	1D	GS	2D	-	3D	=	4D	M	5D	]	6D	m	7D	}
0E	SO	1E	RS	2E	.	3E	>	4E	N	5E	^	6E	n	7E	~
0F	SI	1F	US	2F	/	3F	?	4F	O	5F	_	6F	o	7F	DEL

ASCII

ASCII

- ASCII works OK for English

ASCII

- ASCII works OK for English
- Standards exist to add another 128 characters (taking us to 8 bits per character)

ASCII

- ASCII works OK for English
- Standards exist to add another 128 characters (taking us to 8 bits per character)
- E.g. accented characters for European languages, other Western alphabets e.g. Greek, Cyrillic, mathematical symbols

ASCII

- ASCII works OK for English
- Standards exist to add another 128 characters (taking us to 8 bits per character)
- E.g. accented characters for European languages, other Western alphabets e.g. Greek, Cyrillic, mathematical symbols
- However 256 characters isn't enough...

Unicode

Unicode

- Standard character set developed from 1987 to present day

Unicode

- Standard character set developed from 1987 to present day
- Currently defines 144697 characters (Unicode 14.0)

Unicode

- Standard character set developed from 1987 to present day
- Currently defines 144697 characters (Unicode 14.0)
- First 128 characters are the same as ASCII

Unicode

- Standard character set developed from 1987 to present day
- Currently defines 144697 characters (Unicode 14.0)
- First 128 characters are the same as ASCII
- Covers most of the world's writing systems

Unicode

- Standard character set developed from 1987 to present day
- Currently defines 144697 characters (Unicode 14.0)
- First 128 characters are the same as ASCII
- Covers most of the world's writing systems
- Also covers mathematical symbols and emoji

Encoding Unicode

Encoding Unicode

- **UTF-32** encodes characters as 32-bit integers

Encoding Unicode

- **UTF-32** encodes characters as 32-bit integers
- **UTF-8** encodes characters as 8, 16, 24 or 32-bit integers

Encoding Unicode

- **UTF-32** encodes characters as 32-bit integers
- **UTF-8** encodes characters as 8, 16, 24 or 32-bit integers
  - 8-bit characters correspond to the first 128 ASCII characters $\implies$ backwards compatible

Encoding Unicode

- **UTF-32** encodes characters as 32-bit integers
- **UTF-8** encodes characters as 8, 16, 24 or 32-bit integers
  - 8-bit characters correspond to the first 128 ASCII characters $\implies$ backwards compatible
  - More common Unicode characters are smaller $\implies$ more efficient than UTF-32

UTF-8 representation

UTF-8 representation

- For characters in ASCII, UTF-8 is the same:

UTF-8 representation

- For characters in ASCII, UTF-8 is the same:
  - a $\rightarrow$ [97]

UTF-8 representation

- For characters in ASCII, UTF-8 is the same:
  - a $\rightarrow$ [97]
- Other characters are encoded as multi-byte sequences:

UTF-8 representation

- For characters in ASCII, UTF-8 is the same:
  - a $\rightarrow$ [97]
- Other characters are encoded as multi-byte sequences:
  - ü $\rightarrow$ [195, 188]

UTF-8 representation

- For characters in ASCII, UTF-8 is the same:
  - a $\rightarrow$ [97]
- Other characters are encoded as multi-byte sequences:
  - ü $\rightarrow$ [195, 188]
  - 喂 $\rightarrow$ [229, 150, 130]

UTF-8 representation

- For characters in ASCII, UTF-8 is the same:
  - a $\rightarrow$ [97]
- Other characters are encoded as multi-byte sequences:
  - ü $\rightarrow$ [195, 188]
  - 喂 $\rightarrow$ [229, 150, 130]
  - 😂 $\rightarrow$ [240, 159, 152, 130]

UTF-8 representation

- For characters in ASCII, UTF-8 is the same:
  - a $\rightarrow$ [97]
- Other characters are encoded as multi-byte sequences:
  - ü $\rightarrow$ [195, 188]
  - 喂 $\rightarrow$ [229, 150, 130]
  - 😂 $\rightarrow$ [240, 159, 152, 130]
- `"Haha 😂"` encoded in UTF-8:

UTF-8 representation

- For characters in ASCII, UTF-8 is the same:
  - a $\rightarrow$ [97]
- Other characters are encoded as multi-byte sequences:
  - ü $\rightarrow$ [195, 188]
  - 喂 $\rightarrow$ [229, 150, 130]
  - 😂 $\rightarrow$ [240, 159, 152, 130]
- `"Haha 😂"` encoded in UTF-8:

H	a	h	a	space	😂				null
72	97	104	97	32	240	159	152	130	0

Escape sequences

Escape sequences

- Backslash \ has a special meaning in string literals — it denotes the start of an **escape sequence**

Escape sequences

- Backslash \ has a special meaning in string literals — it denotes the start of an **escape sequence**
- Typically used to write **non-printable characters**

Escape sequences

- Backslash \ has a special meaning in string literals — it denotes the start of an **escape sequence**
- Typically used to write **non-printable characters**
- Most useful: `"\n"` is a new line

Escape sequences

- Backslash \ has a special meaning in string literals — it denotes the start of an **escape sequence**
- Typically used to write **non-printable characters**
- Most useful: `"\n"` is a new line
- How to type a backslash character? Use `"\\"`

Text files

Text files

- Stored on disk as essentially one long string

Text files

- Stored on disk as essentially one long string
- Line endings are denoted by non-printable characters

Text files

- Stored on disk as essentially one long string
- Line endings are denoted by non-printable characters
  - Unix format: line feed character (ASCII/UTF-8 character 10, `"\n"`)

Text files

- Stored on disk as essentially one long string
- Line endings are denoted by non-printable characters
  - Unix format: line feed character (ASCII/UTF-8 character 10, `"\n"`)
  - Windows format: carriage return character (ASCII/UTF-8 character 13) followed by line feed, `"\r\n"`

Text files

- Stored on disk as essentially one long string
- Line endings are denoted by non-printable characters
  - Unix format: line feed character (ASCII/UTF-8 character 10, `"\n"`)
  - Windows format: carriage return character (ASCII/UTF-8 character 13) followed by line feed, `"\r\n"`
  - Most text editors can handle and convert both formats

Text files

- Stored on disk as essentially one long string
- Line endings are denoted by non-printable characters
  - Unix format: line feed character (ASCII/UTF-8 character 10, `"\n"`)
  - Windows format: carriage return character (ASCII/UTF-8 character 13) followed by line feed, `"\r\n"`
  - Most text editors can handle and convert both formats
  - Most languages allow files to be opened in "text mode" which automatically converts

FALMOUTH
UNIVERSITY

Booleans

Booleans

Booleans

- A **boolean** can have one of two values: **true** or **false**

Booleans

- A **boolean** can have one of two values: **true** or **false**
- Named after George Boole (1815–1864), British mathematician

Booleans

- A **boolean** can have one of two values: **true** or **false**
- Named after George Boole (1815–1864), British mathematician
- Type in both C# and Python: `bool`

Booleans

- A **boolean** can have one of two values: **true** or **false**
- Named after George Boole (1815–1864), British mathematician
- Type in both C# and Python: `bool`
- In Python, we have the keywords `True` and `False`

Booleans

- A **boolean** can have one of two values: **true** or **false**
- Named after George Boole (1815–1864), British mathematician
- Type in both C# and Python: `bool`
- In Python, we have the keywords `True` and `False`
- In C#, we have `true` and `false`

Booleans

- A **boolean** can have one of two values: **true** or **false**
- Named after George Boole (1815–1864), British mathematician
- Type in both C# and Python: `bool`
- In Python, we have the keywords `True` and `False`
- In C#, we have `true` and `false`
- Could be represented by a single bit in memory...

Booleans

- A **boolean** can have one of two values: **true** or **false**
- Named after George Boole (1815–1864), British mathematician
- Type in both C# and Python: `bool`
- In Python, we have the keywords `True` and `False`
- In C#, we have `true` and `false`
- Could be represented by a single bit in memory...
- ... but since memory is addressed in bytes (or words of multiple bytes), usually represented as an `int` with 0 meaning `false` and any non-zero (e.g. 1) meaning `true`

Boolean values

Boolean values

- The `if` statement takes a boolean value as its condition:

```
if (x > 10)
{
    Debug.Log(x);
}
```

Boolean values

- The `if` statement takes a boolean value as its condition:

```
if (x > 10)
{
    Debug.Log(x);
}
```

- Variables can also store boolean values:

```
bool result = x > 10;    # result now stores True or False
if (result)
{
    Debug.Log(x);
}
```

FALMOUTH
UNIVERSITY

Boolean Logic

Boolean logic

Boolean logic

- Works with two values: TRUE and FALSE

Boolean logic

- Works with two values: TRUE and FALSE
- Foundation of the **digital computer**: represented in circuits as **on** and **off**

Boolean logic

- Works with two values: TRUE and FALSE
- Foundation of the **digital computer**: represented in circuits as **on** and **off**
- Representing as 1 and 0 leads to **binary notation**

Boolean logic

- Works with two values: TRUE and FALSE
- Foundation of the **digital computer**: represented in circuits as **on** and **off**
- Representing as 1 and 0 leads to **binary notation**
- One boolean value = one **bit** of information

Boolean logic

- Works with two values: TRUE and FALSE
- Foundation of the **digital computer**: represented in circuits as **on** and **off**
- Representing as 1 and 0 leads to **binary notation**
- One boolean value = one **bit** of information
- Programmers use boolean logic for conditions in `if` and `while` statements

Not

Not

NOT *A* is TRUE
if and only if
A is FALSE

Not

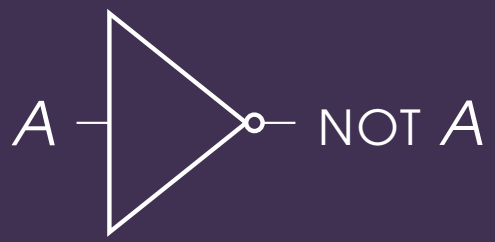
NOT *A* is TRUE
if and only if
A is FALSE

A	NOT *A*
FALSE	TRUE
TRUE	FALSE

Not

NOT *A* is TRUE
if and only if
A is FALSE

A	NOT *A*
FALSE	TRUE
TRUE	FALSE



And

And

A AND *B* is TRUE
if and only if
both *A* **and** *B* are TRUE

And

A AND *B* is TRUE
if and only if
both *A* **and** *B* are TRUE

A	*B*	*A* AND *B*
FALSE	FALSE	FALSE
FALSE	TRUE	FALSE
TRUE	FALSE	FALSE
TRUE	TRUE	TRUE

And

A AND *B* is TRUE
if and only if
both *A* **and** *B* are TRUE

A	*B*	*A* AND *B*
FALSE	FALSE	FALSE
FALSE	TRUE	FALSE
TRUE	FALSE	FALSE
TRUE	TRUE	TRUE

Or

Or

A OR *B* is TRUE
if and only if
either *A* **or** *B*, **or both,** are TRUE

Or

A OR *B* is TRUE
if and only if
either *A* **or** *B*, **or both,** are TRUE

A	*B*	*A* OR *B*
FALSE	FALSE	FALSE
FALSE	TRUE	TRUE
TRUE	FALSE	TRUE
TRUE	TRUE	TRUE

Or

A OR *B* is TRUE
if and only if
either *A* **or** *B*, **or both,** are TRUE

A	*B*	*A* OR *B*
FALSE	FALSE	FALSE
FALSE	TRUE	TRUE
TRUE	FALSE	TRUE
TRUE	TRUE	TRUE

Socrative FALCOMPED

What is the value of

$$A \text{ AND } (B \text{ OR } C)$$

when

$$A = \text{TRUE}$$
$$B = \text{FALSE}$$
$$C = \text{TRUE}$$

?

Socrative FALCOMPED

What is the value of

$$(\text{NOT } A) \text{ AND } (B \text{ OR } C)$$

when

$$A = \text{TRUE}$$
$$B = \text{FALSE}$$
$$C = \text{TRUE}$$

?

Socrative FALCOMPED

For what values of A, B, C, D is

$$A \text{ AND NOT } B \text{ AND NOT } (C \text{ OR } D) = \text{TRUE}$$

?

Socrative FALCOMPED

What is the value of

A OR NOT *A*

?

Socrative FALCOMPED

What is the value of

$$A \text{ AND NOT } A$$

?

Socrative FALCOMPED

What is the value of

$$A \text{ OR } A$$

?

Socrative FALCOMPED

What is the value of

$$A \text{ AND } A$$

?

Writing logical operations

Writing logical operations

Operation	Python	C#	Mathematics
NOT A	`not a`	`!a`	$\neg A$ or $\overline{A}$

Writing logical operations

Operation	Python	C#	Mathematics
NOT A	`not a`	`!a`	$\neg A$ or $\overline{A}$
A AND B	`a and b`	`a && b`	$A \wedge B$

Writing logical operations

Operation	Python	C#	Mathematics
NOT A	`not a`	`!a`	$\neg A$ or $\overline{A}$
A AND B	`a and b`	`a && b`	$A \wedge B$
A OR B	`a or b`	`a || b`	$A \vee B$

Writing logical operations

Operation	Python	C#	Mathematics
NOT A	`not a`	`!a`	$\neg A$ or $\overline{A}$
A AND B	`a and b`	`a && b`	$A \wedge B$
A OR B	`a or b`	`a || b`	$A \vee B$

Other operators can be expressed by combining these

De Morgan's Laws

De Morgan's Laws

$$\text{NOT } (A \text{ OR } B) = (\text{NOT } A) \text{ AND } (\text{NOT } B)$$

De Morgan's Laws

$$\text{NOT } (A \text{ OR } B) = (\text{NOT } A) \text{ AND } (\text{NOT } B)$$

$$\text{NOT } (A \text{ AND } B) = (\text{NOT } A) \text{ OR } (\text{NOT } B)$$

De Morgan's Laws

$$\text{NOT } (A \text{ OR } B) = (\text{NOT } A) \text{ AND } (\text{NOT } B)$$

$$\text{NOT } (A \text{ AND } B) = (\text{NOT } A) \text{ OR } (\text{NOT } B)$$

Proof: see this week's worksheet

FALMOUTH
UNIVERSITY

Truth tables

Enumeration

Enumeration

- Since booleans have only two possible values, we can often **enumerate** all possible values of a set of boolean variables

Enumeration

- Since booleans have only two possible values, we can often **enumerate** all possible values of a set of boolean variables
- For n variables there are 2^n possible combinations

Enumeration

- Since booleans have only two possible values, we can often **enumerate** all possible values of a set of boolean variables
- For n variables there are 2^n possible combinations
- Essentially, all the n-bit binary numbers

Enumeration

- Since booleans have only two possible values, we can often **enumerate** all possible values of a set of boolean variables
- For n variables there are 2^n possible combinations
- Essentially, all the n-bit binary numbers
- A **truth table** enumerates all the possible values of a boolean expression

Enumeration

- Since booleans have only two possible values, we can often **enumerate** all possible values of a set of boolean variables
- For n variables there are 2^n possible combinations
- Essentially, all the n-bit binary numbers
- A **truth table** enumerates all the possible values of a boolean expression
- Can be used to prove that two expressions are equivalent

Truth table example

(*A* OR NOT *B*) AND *C*

A	*B*	*C*	NOT *B*	*A* OR NOT *B*	(*A* OR NOT *B*) AND *C*

Truth table example

(*A* OR NOT *B*) AND *C*

A	*B*	*C*	NOT *B*	*A* OR NOT *B*	(*A* OR NOT *B*) AND *C*
FALSE	FALSE	FALSE	TRUE	TRUE	FALSE

Truth table example

$(A \text{ OR NOT } B) \text{ AND } C$

A	B	C	NOT B	A OR NOT B	(A OR NOT B) AND C
FALSE	FALSE	FALSE	TRUE	TRUE	FALSE
FALSE	FALSE	TRUE	TRUE	TRUE	TRUE

Truth table example

(*A* OR NOT *B*) AND *C*

A	*B*	*C*	NOT *B*	*A* OR NOT *B*	(*A* OR NOT *B*) AND *C*
FALSE	FALSE	FALSE	TRUE	TRUE	FALSE
FALSE	FALSE	TRUE	TRUE	TRUE	TRUE
FALSE	TRUE	FALSE	FALSE	FALSE	FALSE

Truth table example

(*A* OR NOT *B*) AND *C*

A	*B*	*C*	NOT *B*	*A* OR NOT *B*	(*A* OR NOT *B*) AND *C*
FALSE	FALSE	FALSE	TRUE	TRUE	FALSE
FALSE	FALSE	TRUE	TRUE	TRUE	TRUE
FALSE	TRUE	FALSE	FALSE	FALSE	FALSE
FALSE	TRUE	TRUE	FALSE	FALSE	FALSE

Truth table example

(*A* OR NOT *B*) AND *C*

A	*B*	*C*	NOT *B*	*A* OR NOT *B*	(*A* OR NOT *B*) AND *C*
FALSE	FALSE	FALSE	TRUE	TRUE	FALSE
FALSE	FALSE	TRUE	TRUE	TRUE	TRUE
FALSE	TRUE	FALSE	FALSE	FALSE	FALSE
FALSE	TRUE	TRUE	FALSE	FALSE	FALSE
TRUE	FALSE	FALSE	TRUE	TRUE	FALSE

Truth table example

(*A* OR NOT *B*) AND *C*

A	*B*	*C*	NOT *B*	*A* OR NOT *B*	(*A* OR NOT *B*) AND *C*
FALSE	FALSE	FALSE	TRUE	TRUE	FALSE
FALSE	FALSE	TRUE	TRUE	TRUE	TRUE
FALSE	TRUE	FALSE	FALSE	FALSE	FALSE
FALSE	TRUE	TRUE	FALSE	FALSE	FALSE
TRUE	FALSE	FALSE	TRUE	TRUE	FALSE
TRUE	FALSE	TRUE	TRUE	TRUE	TRUE

Truth table example

(*A* OR NOT *B*) AND *C*

A	*B*	*C*	NOT *B*	*A* OR NOT *B*	(*A* OR NOT *B*) AND *C*
FALSE	FALSE	FALSE	TRUE	TRUE	FALSE
FALSE	FALSE	TRUE	TRUE	TRUE	TRUE
FALSE	TRUE	FALSE	FALSE	FALSE	FALSE
FALSE	TRUE	TRUE	FALSE	FALSE	FALSE
TRUE	FALSE	FALSE	TRUE	TRUE	FALSE
TRUE	FALSE	TRUE	TRUE	TRUE	TRUE
TRUE	TRUE	FALSE	FALSE	TRUE	FALSE

Truth table example

(*A* OR NOT *B*) AND *C*

A	*B*	*C*	NOT *B*	*A* OR NOT *B*	(*A* OR NOT *B*) AND *C*
FALSE	FALSE	FALSE	TRUE	TRUE	FALSE
FALSE	FALSE	TRUE	TRUE	TRUE	TRUE
FALSE	TRUE	FALSE	FALSE	FALSE	FALSE
FALSE	TRUE	TRUE	FALSE	FALSE	FALSE
TRUE	FALSE	FALSE	TRUE	TRUE	FALSE
TRUE	FALSE	TRUE	TRUE	TRUE	TRUE
TRUE	TRUE	FALSE	FALSE	TRUE	FALSE
TRUE	TRUE	TRUE	FALSE	TRUE	TRUE

FALMOUTH
UNIVERSITY

Other logic gates

Exclusive Or

Exclusive Or

A XOR *B* is TRUE
if and only if
either *A* **or** *B*, **but not both,** are TRUE

Exclusive Or

A XOR *B* is TRUE
if and only if
either *A* **or** *B*, **but not both,** are TRUE

A	*B*	*A* XOR *B*
FALSE	FALSE	FALSE
FALSE	TRUE	TRUE
TRUE	FALSE	TRUE
TRUE	TRUE	FALSE

Exclusive Or

A XOR *B* is TRUE
if and only if
either *A* **or** *B*, **but not both,** are TRUE

A	*B*	*A* XOR *B*
FALSE	FALSE	FALSE
FALSE	TRUE	TRUE
TRUE	FALSE	TRUE
TRUE	TRUE	FALSE

Socrative FALCOMPED

How can *A* XOR *B* be written using the operations AND , OR , NOT ?

Negative gates

Negative gates

NAND , NOR , XNOR
are the **negations** of
AND , OR , XOR

Negative gates

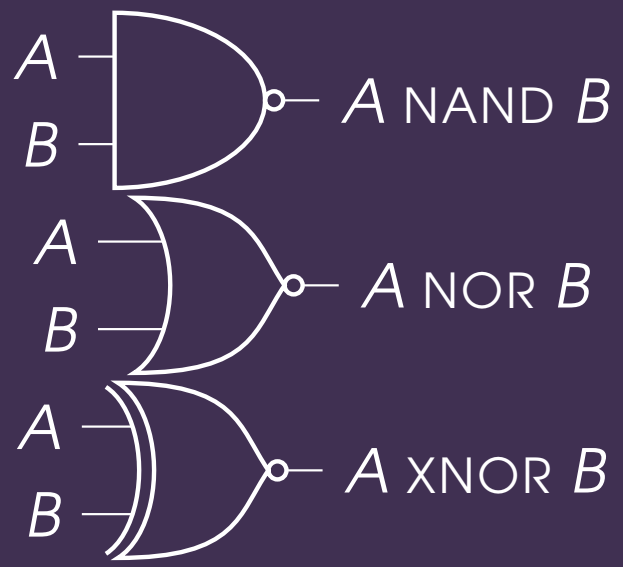
NAND , NOR , XNOR
are the **negations** of
AND , OR , XOR

$$A \text{ NAND } B = \text{NOT } (A \text{ AND } B)$$
$$A \text{ NOR } B = \text{NOT } (A \text{ OR } B)$$
$$A \text{ XNOR } B = \text{NOT } (A \text{ XOR } B)$$

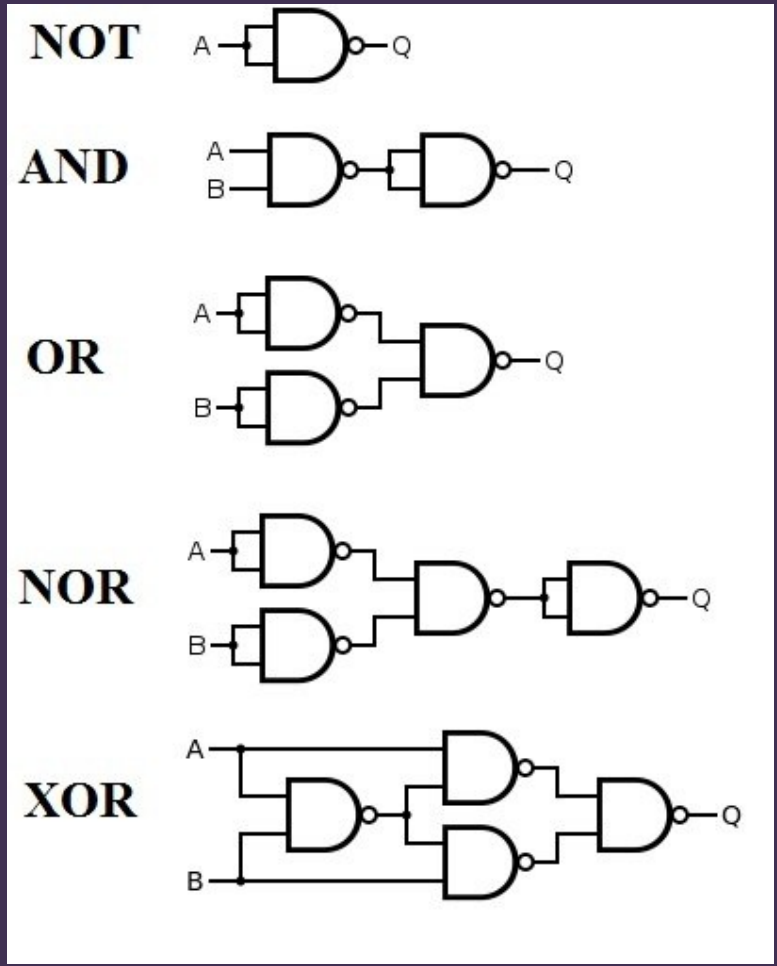
Negative gates

NAND , NOR , XNOR
are the **negations** of
AND , OR , XOR

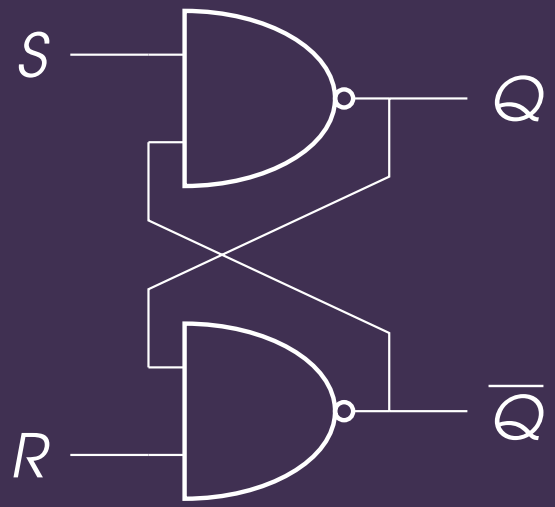
$$A \text{ NAND } B = \text{NOT } (A \text{ AND } B)$$
$$A \text{ NOR } B = \text{NOT } (A \text{ OR } B)$$
$$A \text{ XNOR } B = \text{NOT } (A \text{ XOR } B)$$



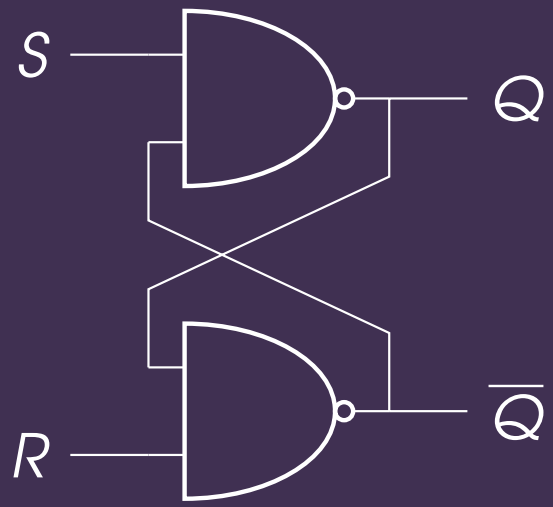
Any logic gate can be constructed from NAND gates



What does this circuit do?

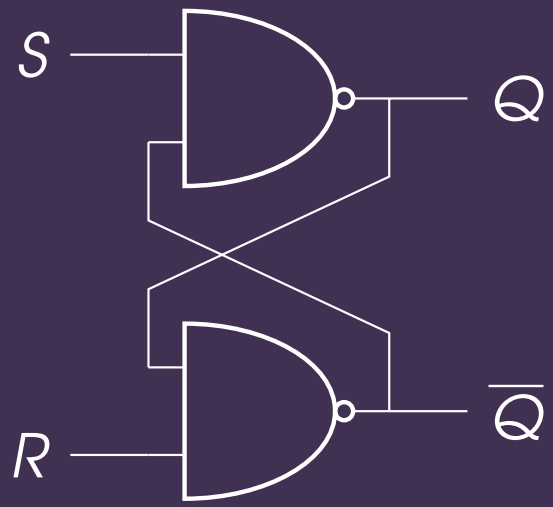


What does this circuit do?



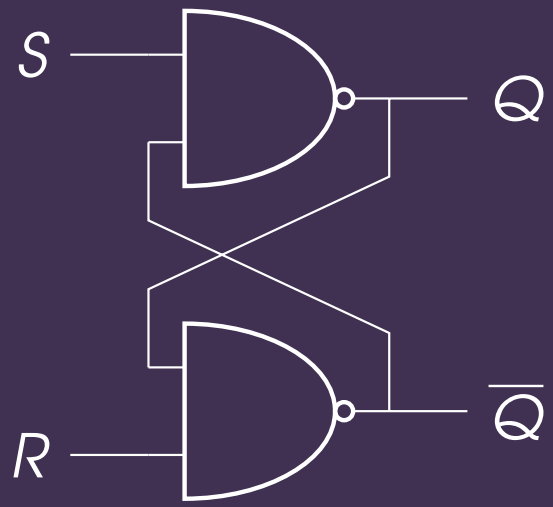
- This is called a **NAND latch**

What does this circuit do?



- This is called a **NAND latch**
- It "remembers" a single boolean value

What does this circuit do?



- This is called a **NAND latch**
- It "remembers" a single boolean value
- Put a few billion of these together (along with some control circuitry) and you've got **memory**!

NAND gates

NAND gates

- All arithmetic and logic operations, as well as memory, can be built from NAND gates

NAND gates

- All arithmetic and logic operations, as well as memory, can be built from NAND gates
- So an entire computer can be built just from NAND gates!

NAND gates

- All arithmetic and logic operations, as well as memory, can be built from NAND gates
- So an entire computer can be built just from NAND gates!
- NAND gate circuits are **Turing complete**

NAND gates

- All arithmetic and logic operations, as well as memory, can be built from NAND gates
- So an entire computer can be built just from NAND gates!
- NAND gate circuits are **Turing complete**
- The same is true of NOR gates

Workshop activity

- Split into **breakout groups**
- Play `http://nandgame.com`
- We'll reconvene and see how far everyone got!