Zeroth: Attribution

The inspiration for this lecture is:
There's No Such Thing As Plain Text by Dylan Beattie

Firstly: Some Revision

- Positive integers are represented in raw binary
  - eg 10010 = $1100100_2$
  - eg 364$_{10}$ = $101101100_2$
- Positive and Negative integers are represented in 2’s complement
  - eg 100$_{10}$ = $00000000000000000001100100_2$
  - eg -745$_{10}$ = $11111111111111110100010111_2$
- Floating point numbers are represented in IEEE 754
  - eg 3.14159$_{10}$ = $0100000001001001000011101111110100000_2$
Arguably, text is the most important data type in computing as text can be used to represent all other data types. This process is called serialization. JSON, XML, YAML, etc.

Strings are just a sequence of characters. So what we need is a way to encode characters. Once we can encode characters, we can create an array of characters to represent a string.

- This is how we represent text in C.
- Other languages might have more complex wrappers around this, but share the same core idea.
- Modern computers use UNICODE to represent text (the goal).

Secondly: The Timeline

- 1828: First electronic Telegraph system (Pavel Schilling)
- 1837: Cooke and Wheatstone Telegraph
- 1844: Morse Code
- 1897: First radio transmission
- Many other encoding schemes that we won’t cover
- 1943: First (modern) computer (Colossus)
- 1963: ASCII
- 1970s: Extended ASCII
- 1963: EBCDIC
- 1987: Unicode

Secondly: The Timeline (disclaimer)

Note, this timeline (and lecture) is every western-centric. There are many many other encoding schemes that we won’t cover. East Asian languages specifically have very interesting encoding schemes as they have a very different way of representing language as text resulting in huge alphabet sizes.
Cooke and Wheatstone Telegraph: The Good and The Bad

- Only has 20 possible characters
  - The letters C, J, Q, U, X and Z are omitted
- Five needles were used to represent the 20 characters
  - One needle was deflected left and one right, the intersection of the two needles represented the character
- Technical limitations required this representation
  - The entire system formed a single circuit
  - One needle represented the positive voltage the other the negative
- Each needle needed its own wire
  - So connecting two telegraphs 1Km apart required 5Km of wire
- Later on a sixth needle was added as a common ground allowing only one needle (plus the ground) to be deflected
  - This was used to encode digits 0-9
- As wires were expensive, when a wire was broken, instead of replacing the wire, a new encoding was used that needed less wires

Cooke and Wheatstone Telegraph: An Example

The Cooke and Wheatstone Telegraph can be represented as a 5-trit ternary encoding:

"Hello" would be:

<table>
<thead>
<tr>
<th>Letter</th>
<th>Nedles</th>
<th>Ternary</th>
<th>Decimal</th>
</tr>
</thead>
<tbody>
<tr>
<td>H</td>
<td>+-...</td>
<td>12000&lt;sub&gt;3&lt;/sub&gt;</td>
<td>135&lt;sub&gt;10&lt;/sub&gt;</td>
</tr>
<tr>
<td>E</td>
<td>+--...</td>
<td>10200&lt;sub&gt;3&lt;/sub&gt;</td>
<td>99&lt;sub&gt;10&lt;/sub&gt;</td>
</tr>
<tr>
<td>L</td>
<td>...+-</td>
<td>00012&lt;sub&gt;3&lt;/sub&gt;</td>
<td>5&lt;sub&gt;10&lt;/sub&gt;</td>
</tr>
<tr>
<td>L</td>
<td>...+-</td>
<td>00012&lt;sub&gt;3&lt;/sub&gt;</td>
<td>5&lt;sub&gt;10&lt;/sub&gt;</td>
</tr>
<tr>
<td>O</td>
<td>..-+</td>
<td>00210&lt;sub&gt;3&lt;/sub&gt;</td>
<td>21&lt;sub&gt;10&lt;/sub&gt;</td>
</tr>
</tbody>
</table>

A 5-trit ternary encoding has a maximum of $3^5 = 243$ possible values
But only 20 are used, giving a 8.23% efficiency
Character encoding is done by a lookup table

- Not a mathematical expression (like 2's complement or IEEE 754)

Morse Code: 1844

**International Morse Code**
1. The length of a dot is one unit.
2. A dash is three units.
3. The space between parts of the same letter is one unit.
4. The space between letters is three units.
5. The space between words is seven units.

<table>
<thead>
<tr>
<th>Letter</th>
<th>Morse Code</th>
<th>Binary</th>
<th>Decimal</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>.</td>
<td>0001</td>
<td>1</td>
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<td>B</td>
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<td>0010</td>
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<td>C</td>
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<td>0011</td>
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<tr>
<td>D</td>
<td>...</td>
<td>0100</td>
<td>4</td>
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<tr>
<td>E</td>
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<td>0101</td>
<td>5</td>
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<tr>
<td>F</td>
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<td>0110</td>
<td>6</td>
</tr>
<tr>
<td>G</td>
<td>-.</td>
<td>0111</td>
<td>7</td>
</tr>
<tr>
<td>H</td>
<td>....</td>
<td>1000</td>
<td>8</td>
</tr>
<tr>
<td>I</td>
<td>.</td>
<td>1001</td>
<td>9</td>
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<tr>
<td>J</td>
<td>-.</td>
<td>1010</td>
<td>10</td>
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<td>K</td>
<td>..</td>
<td>1011</td>
<td>11</td>
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<tr>
<td>L</td>
<td>.-</td>
<td>1100</td>
<td>12</td>
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<td>M</td>
<td>...</td>
<td>1101</td>
<td>13</td>
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<td>N</td>
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<td>1110</td>
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<td>O</td>
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<td>1111</td>
<td>15</td>
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<tr>
<td>P</td>
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<td>0000</td>
<td>0</td>
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<td>-.</td>
<td>0010</td>
<td>2</td>
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<td>..</td>
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<td>3</td>
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<td>...</td>
<td>0100</td>
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<td>T</td>
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<td>0101</td>
<td>5</td>
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<td>U</td>
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<tr>
<td>V</td>
<td>.-</td>
<td>0111</td>
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<td>W</td>
<td>..</td>
<td>1000</td>
<td>8</td>
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<tr>
<td>X</td>
<td>...</td>
<td>1001</td>
<td>9</td>
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<tr>
<td>Y</td>
<td>-.</td>
<td>1010</td>
<td>10</td>
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<tr>
<td>Z</td>
<td>..</td>
<td>1011</td>
<td>11</td>
</tr>
</tbody>
</table>

Morse Code: An Example

Can be represented as binary encoding:

"Hello" would be:

<table>
<thead>
<tr>
<th>Letter</th>
<th>Morse Code</th>
<th>Binary</th>
<th>Decimal</th>
</tr>
</thead>
<tbody>
<tr>
<td>H</td>
<td>....</td>
<td>0000</td>
<td>0</td>
</tr>
<tr>
<td>E</td>
<td>.</td>
<td>0010</td>
<td>2</td>
</tr>
<tr>
<td>L</td>
<td>-.</td>
<td>0100</td>
<td>4</td>
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<tr>
<td>L</td>
<td>-.</td>
<td>0100</td>
<td>4</td>
</tr>
<tr>
<td>O</td>
<td>-</td>
<td>1111</td>
<td>7</td>
</tr>
</tbody>
</table>

But both H and E are represented by the same decimal value 0?

Morse Code is a variable length encoding
So one 0 and four 0s are different values
This makes it difficult to represent in anything other binary
Morse Code: The Good and The Bad

- Morse Code isn’t actually binary because it has a time component
  - Unlike Cooke and Wheatstone Telegraph where all 5 trits were sent at the same time
  - Morse Code sends each dot and dash sequentially
  - A dot and a dash are both 1 values, but they are different lengths
  - This means that Morse Code can’t be represented as a binary encoding

- Morse Code has many versions
  - International Morse Code was standardized in 1848
  - Hasn’t changed since it was standardized
  - Allows for memorization of the encoding
    - Makes it easy to learn
    - Makes it very fast to use by a trained operator
    - But makes it very hard to change and/or improve

- Morse Code is a variable length encoding
  - More length of each letter’s encoding is proportional to the frequency of the letter
    - E is the most common letter in English, so it has the shortest encoding
    - Q is the least common letter in English, so it has the longest encoding

Morse Code: Other Encodings

- Standardization is good
  - It allows for communication between different people in different places

- Variable length encodings are very efficient
  - Both in terms of the amount of data needed to represent a character and the amount of time needed to send the data
  - Variable length encoding allowed (allows) for experts to send messages at very higher speeds
  - But they are more complex
### ASCII: 1963

American Standard Code for Information Interchange (ASCII) was created by the American Standards Association (ASA) and later became the American National Standards Institute (ANSI), who standardized the C programming language.

- **7-bit (fixed-size) encoding**
  - 128 possible values
  - All of the values are used

One of the most common encodings in computing.

- One of the most influential encodings in computing

### ASCII: Layout

ASCII is split into "sticks" which were blocks of 16 characters:

- The first 2 sticks are control characters
- The space character is the first character in the 3rd stick
  - As it is both a control character and a printable character
  - Plus this made sorting strings by ASCII value much more intuitive
- For similar reasons, the next several characters are commonly used as "word separators"
- The 2-5 sticks are a usable alphabet by themselves
• The digits per placed in such a way that the value is $0b011$
  followed by the digits value in binary
• This allows for very fast conversion between ASCII characters and binary numbers
• The Uppercase and Lowercase letters are placed in such a way that
  the only difference between them is the 6th bit
• This allows for very fast case conversion and case insensitive string comparison

• < and > 60 and 62, so < + 2 = >
• [ and ] 91 and 93, so [ + 2 = ]
• { and } 123 and 125, so { + 2 = }
• ( and ) 40 and 41, so ( + 2 = *)

WHY!?!?

When ASCII was created, computers didn’t have a keyboard and monitors.

Computers had teletype machines, which was a typewriter like device
that could be controlled by a human (for input) or a computer (for output)

Because they were physical devices, they had to be physically controlled
thus the control characters.
Punch cards were used to store data on computers (a very long time ago)

The problem was that storing data on punch cards made a physical change to the card

So deleting data from a punch card was not possible

Instead, the data was replaced with a special character called **DEL**

**DEL** is encoded as $0b0111111$ (127) (all bits set)

So on a punch card, **DEL** would be represented as a hole in all 7 columns

Thus making what was previously stored on the card unrecognizable
ASCII: ^C

On a modern computer, ^C is used to send a SIGINT signal to the current process. This effectively stops the current process (if it is well behaved).

But why is it ^C?

Because on a teletype machine, ^C is how you would input the 4th control character ^a, ^A, ^B, ^C (this makes sense on a typewriter where the keys are in alphabetical order)

What is the 4th control character?

ETX (End of Text)

This tells the teletype machine to stop receiving data

Thus ending the current process.

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Extended ASCII (Code Pages)

ASCII works well for English (American English)
And is fairly decent for British English.
Unless you use the pound sign (£)

But it doesn’t work well for other European languages and doesn’t work at all for other languages (like Asian languages).

The solution (for other European languages at least) was to use the 8th bit to extend the encoding.

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Extended ASCII

The issue with EASCII is that it is not standardized, there are many different encodings that are all in the category of “Extended ASCII”

KOI-8: Russian encoding ISO 8859-1 (aka Latin-1): Western European encoding Code page 899: DOS mathematical symbols etc...

(wikipedia lists 100s of different Code Pages)
EBCDIC

<table>
<thead>
<tr>
<th>0x</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>A</th>
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<tbody>
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<td>&quot;ETX&quot;</td>
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UNICODE

UNICODE is maintained by the Unicode Consortium
The goal of UNICODE is to create a single encoding that can represent all of the characters in all of the languages in the world.

There are currently 149,251 characters in UNICODE.
Because UNICODE is so large, it has a very structured layout to try and make it more intuitive.

The Unicode Standard defines a codespace, (ie "The encoding")

The Unicode codespace ranges from \texttt{0x0000} to \texttt{0x10FFFF}

Where each hex value represents a code point (ie a character)

giving a total of 1,114,112 code points, (293,168 are currently assigned)

approximately 25%

These 1.1 million code points are split into 17 planes

The zeroth plane \texttt{0x0000} - \texttt{0xFFFF} is the Basic Multilingual Plane (BMP) which contains the vast majority of characters for almost all modern languages

The first plane \texttt{0x10000} - \texttt{0x1FFFF} is the Supplementary Multilingual Plane (SMP)

The second plane \texttt{0x20000} - \texttt{0x2FFFF} is the Supplementary Ideographic Plane (SIP)

The third plane \texttt{0x30000} - \texttt{0x3FFFF} is the Tertiary Ideographic Plane (TIP)

The fourth through 13th planes \texttt{0x40000} - \texttt{0xDFFFF} are Unassigned Planes

The 14th plane \texttt{0xE0000} - \texttt{0xEFFFF} is the Supplementary Special-purpose Plane (SSP)

And the last two planes \texttt{0xF0000} - \texttt{0x10FFFF} are the Private Use Planes (SPUA-A/B) which are used for private use thus they are assigned but not to any specific character

Within each plane, the code points are split into blocks

Blocks are not a standard size, but are always multiples of 16 and usually multiples of 128

Blocks are used to roughly group characters by their purpose

The first plane contains the following blocks:

- Basic Latin (\texttt{0x0000} - \texttt{0x007F})
- Latin-1 Supplement (\texttt{0x0080} - \texttt{0x00FF})
- Latin Extended-A (\texttt{0x0100} - \texttt{0x017F})
- Latin Extended-B (\texttt{0x0180} - \texttt{0x024F})
- ... 
- Greek and Coptic (\texttt{0x0370} - \texttt{0x03FF})
- ... 
- Mongolian (\texttt{0x1800} - \texttt{0x18AF})
- ... 
- Symbols and Punctuation (\texttt{0x2000} - \texttt{0x206F})
The second plane mostly contains historical characters as well as notational symbols

- Hieroglyphs
- Musical symbols
- Emoji

The third plane is almost entirely used by the CJK characters

The fourth plane is mostly unused but contains additional CJK characters

The 14th plane contains a few misc characters

Every UNICODE character also has a major and minor category

The major category is one of the following:

- Letter
- Mark
- Number
- Punctuation
- Symbol
- Separator
- Other

And the minor category depending on the major category.

The largest category is **Letter - other** which contains 131,612 out of 149,251 characters almost 90%

- This is because essentially all of the CJK characters are in this category and there are just so many of them compared to any other category

**UTF-32**

How do we store UNICODE characters?

The easiest way is to use the smallest power of 2 that can represent all of the code points in UNICODE.

As the code points range from `0x0000` to `0x10FFFF` we need at least 21 bits to represent them.

So we can use 32 bits to represent a single character.

UTF-32 is a fixed width encoding that uses 32 bits to represent each character.

Simply take the UNICODE code point and store it in 32 bits.
UTF-32: Example

A -> U+0041 -> 0b00000000000000000000000001000001
€ -> U+20AC -> 0b00000000000000000010000010101100
\n -> U+5B57 -> 0b00000000000000000101101101010111
\n -> U+1F600 -> 0b00000000000000000000000000111100

U+XXXX is the representation of a raw UNICODE code point
code points are always at least 4 hex digits.

The 5th digit is the plane number
or the 0th plane (BMP) if there is no 5th digit

UTF-32: is very very inefficient

even if we are representing the character U+10FFFF (the largest code point)
there would still be 11 wasted bits

And the vast majority of characters used are in the 0th plane (BMP)
only using 16 bits to represent them, giving 16 wasted bits per character

And the vast majority of characters used in the BMP are in the first block (ASCII)
using only 7 bits to represent them giving 25 wasted bits per character

UTF-8

Taking a lesson from morse code, we can use a variable width encoding
the more common the character, the less bits we need to represent it.

Unicode already puts the most common characters near the beginning
so the goal of UTF-8 is to store the fewest number of leading 0s
UTF-8 (cont.)

This is the layout of UTF-8

<table>
<thead>
<tr>
<th>#bytes</th>
<th>#bits</th>
<th>Byte 1</th>
<th>Byte 2</th>
<th>Byte 3</th>
<th>Byte 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>7</td>
<td>0xxxxxxx</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>2</td>
<td>11</td>
<td>110xxxxx</td>
<td>10xxxxxx</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>3</td>
<td>16</td>
<td>1110xxxxx</td>
<td>10xxxxxx</td>
<td>10xxxxxx</td>
<td>-</td>
</tr>
<tr>
<td>4</td>
<td>21</td>
<td>11110xxxxx</td>
<td>10xxxxxx</td>
<td>10xxxxxx</td>
<td>10xxxxxx</td>
</tr>
</tbody>
</table>

A single UTF-8 character can be anywhere from 1 to 4 bytes long

The entire ASCII character set can be represented in 1 byte with zero wasted bits

The entire BMP can be represented in 3 bytes, being 8 bits more efficient than UTF-32

and the entire UNICODE character set can be represented in 4 bytes/ using exactly the same number of bits as UTF-32 in the worst case

UTF-8: Example

A -> U+0041 -> 0b01000001 -> 0x41

€ -> U+20AC -> 0b10000010101100 -> 0b10 000010 101100 -> 0b11100010 10000010 10101100 -> 0xE282AC

Firestore: $U+E0032$
to

UTF-32

UTF-32 is just a raw 32 bit representation of the code point

0xE0032

0b000000000011100000000001100010
UTF-8: Example (cont.)

- Example (cont.) to UTF-8
- Remove leading 0s from the UTF-32 encoding
  - 0b 11100000000000110010
- Split into 6 bit chunks from right to left
  - 0b 11 100000 000000 110010
- Match with the appropriate multi-byte encoding (in this case there are 4 chunks)
  - 0b 11110xxx 10xxxxxx 10xxxxxx 10xxxxxx
  - 0b 11 100000 000000 110010
  - Replace the x with the appropriate bits
  - 0b 11110011 10100000 10000000 10110010
  - Replace with appropriate bits
  - 0b 1111 0011 1010 0000 1000 0000 1011 0010
  - Translate to hex
  - 0xF3A080B2

UTF-16

- UTF-16 is a variable width encoding that uses 16 bits to represent each character.
- It's a strange hybrid of UTF-8 and UTF-32
- Part of the BMP is reserved for "Surrogates"
- Surrogates are used by UTF-16 to represent characters outside of the BMP
- UTF-16 is mainly used by Windows and Java and Javascript
- UTF-16 also requires a "BOM" (Byte Order Mark) to determine the endianness

UTF-1, UTF-7, UTF-EBCDIC

- Lesser used encodings
Writing C Code that uses UNICODE

DEMO