Outline

1. Overview
2. Encoding Numbers
3. Text Encoding
4. Audio Encoding
5. Image Encoding
6. Video Encoding
7. Conclusion
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What is Encoding?

- Computers are great at numbers.
- Computers are terrible at everything else.
- We need to turn everything else into numbers for computers to deal with them.
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Numbers themselves can be encoded many ways:

roman: XLV
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**roman:** $\text{XLV} = 50 - 10 + 5$
Encoding Numbers

Numbers themselves can be encoded many ways:

- **roman**: $XLV = 50 - 10 + 5$
- **binary**: $101101_2$

For computers, we want a way that works well with digital logic circuits (i.e., using only 0 or 1).
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- **roman**: \( XLV = 50 - 10 + 5 \)
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Numbers themselves can be encoded many ways:

- **roman**: XLV = 50 - 10 + 5
- **binary**: 101101₂ = 1 * 2⁵ + 0 * 2⁴ + 1 * 2³ + 1 * 2² + 0 * 2¹ + 1 * 2²
- **octal**: 55₈ = 5 * 8¹ + 5
- **decimal**: 45
Encoding Numbers

Numbers themselves can be encoded many ways:

**roman:**  \[ XLV = 50 - 10 + 5 \]

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**Encoding Numbers**

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For computers, we want a way that works well with digital logic circuits (i.e., using only 0 or 1).
Instead of specifying the base every time we write a number, computer scientists often use different notations as shorthand:

- **binary**: 0b101101
- **octal**: 0o55 or 055
- **decimal**: 45
- **hex**: 0x2d
Binary looks great for computers (it's just zero or one), but there's a few problems:

- It's unwieldy for humans: `0b1010000001110` vs 5134.
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- It's unwieldy for humans: `0b101000001110` vs `5134`.
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- There's no “maximum” number, so there's no maximum number of bits to store “one number”.
- There's no easy way to represent negative numbers (like `-01100001`).
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• It's unwieldy for humans: 0b101000001110 vs 5134.
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• There's no “maximum” number, so there's no maximum number of bits to store “one number”.
• There's no easy way to represent negative numbers (like $-0110001_2$).
• It can't represent non-integer numbers (e.g., what's $\frac{01_2}{10_2}$?)
Sized Integers

The size problem is solved by defining different “sizes” of numbers, with different numbers of bits:

- **nibble** 4 bits
- **byte** 8 bits
- **short** 16 bits
- **int** 32 bits
- **long** 64 bits
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Different CPUs have different "default" sizes; this size is often called "word". For example, 64-bit machines (most computers today) have 64-bit words and 32-bit "halfwords".
The negative numbers problem is solved by using Two's Complement encoding, wherein a negative number is produced by:

1. Starting with the positive version of that number.
2. Inverting every bit (0 to 1, 1 to 0).
3. Add 1 to the number.
Signed Integers

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This means 31 (as a byte) becomes 0b00011111, but -31 becomes 0b11100001. The uppermost bit can be thought of as a “sign bit”.

0b11100001 could be -31 or 225.
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The negative numbers problem is solved by using **Two's Complement** encoding, wherein a negative number is produced by:

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3. Add 1 to the number.

This means 31 (as a byte) becomes 0b00011111, but -31 becomes 0b11100001. The uppermost bit can be thought of as a “sign bit”.

To interpret a number, you need to know if it is SIGNED or UNSIGNED; 0b11100001 could be -31 or 225.
The range of numbers we can represent depends on the encoding we use:

<table>
<thead>
<tr>
<th>Width</th>
<th>Unsigned</th>
<th>Signed</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>[0, 255]</td>
<td>[−128, 127]</td>
</tr>
<tr>
<td>16</td>
<td>[0, 65535]</td>
<td>[−32768, 32767]</td>
</tr>
<tr>
<td>32</td>
<td>[0, 4294967295]</td>
<td>[−2147483648, 2147483647]</td>
</tr>
<tr>
<td>64</td>
<td>[0, $2^{64} - 1$]</td>
<td>[−$2^{63}$, $2^{63} - 1$]</td>
</tr>
</tbody>
</table>
# Integer Ranges

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<table>
<thead>
<tr>
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</tr>
<tr>
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</tr>
</tbody>
</table>
Overflow and Underflow

Overflow/Underflow

A huge number of real-world bugs come from integer OVERFLOW and UNDERFLOW.
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// unsigned byte overflow:
(uint8_t)(255 + 1 == 0);
// unsigned byte underflow:
(uint8_t)(0 - 1 == 255);
// signed byte overflow:
(int8_t)(127 + 1 == -128);
// signed byte underflow:
(int8_t)(-128 - 1 == 127);
Endianness

When a single number is represented by multiple bytes, there are two valid ways to order those bytes: with the “big end” first or the “little end” first.

\[ \text{0xAABBCCDD} = \]

<table>
<thead>
<tr>
<th>Offset</th>
<th>Big Endian</th>
<th>Little Endian</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0xAA</td>
<td>0xDD</td>
</tr>
<tr>
<td>1</td>
<td>0xBB</td>
<td>0xCC</td>
</tr>
<tr>
<td>2</td>
<td>0xCC</td>
<td>0xBB</td>
</tr>
<tr>
<td>3</td>
<td>0xDD</td>
<td>0xAA</td>
</tr>
</tbody>
</table>

Most CPUs are little-endian, but most network protocols are big-endian. The way we write numbers (e.g., 0xAABBCCDD) is big-endian.
Real numbers (i.e., non-integers) are represented using “floating-point” arithmetic.
Floating Point

Real numbers (i.e., non-integers) are represented using “floating-point” arithmetic. A number like 1701.47 could be written as $170147 \times 10^{-2}$. Sometimes 32-bit floating point numbers are called float and 64-bit floating point numbers are called double.
Floating Point

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The IEEE 754 Standard specifies how computers would store $170147$ and $-2$ so they can do math easily.

Floating point numbers are inherently approximations, and prone to inaccuracies:

```
0.1 + 0.2 == 0.3 // false
0.1 + 0.2 // 0.30000000000000004
```
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```plaintext
0.1 + 0.2 == 0.3  // false
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Sometimes 32-bit floating point numbers are called `float` and 64-bit floating point numbers are called `double`. 
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3. Text Encoding
   3.1 English Text
   3.2 Text Around the World
   3.3 Unifying all the Codes

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Let's say we want to save this file:

Hi!
Let's say we want to save this file:

Hi!

One idea might be to do a simple substitution: A=1, B=2, C=3, etc. Problems:

• We need to handle both upper- and lower-case letters.
• We need to handle punctuation.
• We need to handle numbers.
• We need to handle special things like “space” and “enter”/“return”.
In the 1960s, Bell Labs created the American Standard Code for Information Interchange, which deals with all this:

```
Hi!
```

becomes

```
48 69 21
```

This is a 7-bit encoding (each letter/symbol takes 7 bits of data), but is often treated as an 8-bit encoding for convenience.

This encoding became super popular and is used everywhere.
<table>
<thead>
<tr>
<th>Decimal</th>
<th>Hex</th>
<th>Char</th>
<th>Decimal</th>
<th>Hex</th>
<th>Char</th>
<th>Decimal</th>
<th>Hex</th>
<th>Char</th>
<th>Decimal</th>
<th>Hex</th>
<th>Char</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>[NULL]</td>
<td>32</td>
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<td>64</td>
<td>40</td>
<td>@</td>
<td>96</td>
<td>6D</td>
<td>~</td>
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<tr>
<td>1</td>
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<td>95</td>
<td>5F</td>
<td>[DEL]</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Outline

1. Overview
2. Encoding Numbers
3. Text Encoding
   3.1 English Text
   3.2 Text Around the World
3.3 Unifying all the Codes
4. Audio Encoding
5. Image Encoding
6. Video Encoding
7. Conclusion
ASCII outside America

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• It only supports the “basic latin alphabet” (the 26 letters in English).
• Some other countries created slight modifications of ASCII for their use:
  • ISO 646-GB adds £ (UK English).
  • ISO 646-FR adds à, ç, é, ù, and è (French).
  • ISO 646-ES adds ñ, Ñ, ñ, ñ, and ç (Spanish).
• In some cases, people used the extra top bit to encode up to 256 extra characters in an 8-bit encoding, e.g., Code Page 1252.
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Alternatives to ASCII

Countries which use other alphabets came up with their own ASCII/ISO 646 variants. These generally encode all the ASCII characters for compatibility, but take advantage of the 8th bit to encode their own characters (or, often, a subset thereof).
JIS X 0201 (ISO 646-JP)

This was superseded by Shift JIS, which uses 2 bytes (16 bits).
Some companies also came up with custom encodings for their products.
Custom Encodings

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Generally these would only be usable on devices made by that company, so they tried to remain backwards-compatible with ASCII.
Over time, there grew to be thousands of incompatible character sets.
Custom Characters

In 1997, J-Phone (a Japanese phone company) released this character set:
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How standards proliferate:

**Situation:** There are 14 competing standards.

14?! Ridiculous! We need to develop one universal standard that covers everyone's use cases. Yeah!

**Soon:**

**Situation:** There are 15 competing standards.

Source: xkcd 927
Encoding Chaos

Mixing up encodings is problematic:

à®...à®•à¯¬à®·à®¯à¬
à®¶à¯¬à®°à¯¬€à®µà®®à¯¬à®¸à®©à¯

/ÉŒkÉj É-É¾ìÉÉ ÉŒdsÉŒn/

à®µà¯¬à®¶à¯¬à®žà®·à¯¬à®°à¯¬à®®à¯¬à®®à¯¬à®®à¯¬à®®à¯¬à®®à¯¬à®®à¯¬à®®à¯¬à®®à¯¬à®®à¯¬à®®à¯¬à®®à¯¬à®®à¯¬à®®à¯¬à®®à¯¬à®®à¯¬à®®à¯¬à®®à¯¬à®®à¯¬à®®à¯¬à®®à¯¬à®®à¯¬à®®à¯¬à®®à¯¬à®®à¯¬à®®à¯¬à®®à¯¬à®®à¯¬à®®à¯¬à®®à¯¬à®®à¯¬à®®à¯¬à®®à¯¬à®®à¯¬à®®à¯¬à®®à¯¬à®®à¯¬à®®à¯¬à®®à¯¬à®®à¯¬à®®à¯¬à®®à¯¬à®®à¯¬à®®à¯¬à®®à¯¬à®®à¯¬à®®à¯¬à®®à¯¬à®®à¯¬à®®à¯¬à®®à¯¬à®®à¯¬à®®à¯¬à®®à¯¬à®®à¯¬à®®à¯¬à®®à¯¬à®®à¯¬à®®à¯¬à®®à¯¬à®®à¯¬à®®à¯¬à®®à¯¬à®®à¯¬à®®à¯¬à®®à¯¬à®®à¯¬à®®à¯¬à®®à¯¬à®®à¯¬à®®à¯¬à®®à¯¬à®®à¯¬à®®à¯¬à®®à¯¬à®®à¯¬à®®à¯¬à®®à¯¬à®®à¯¬à®®à¯¬à®®à¯¬à®®à¯¬à®®à¯¬à®®à¯¬à®®&
In 1988, three engineers—Joe Becker, Lee Collins, and Mark Davis—proposed a unifying encoding that would supersede all the existing character sets. They wanted an encoding that was:

- universal (to every language)
- uniform (fixed-width), and
- unique (no ambiguity)

They called this encoding Unicode. In 1991, the Unicode Consortium was founded to develop this encoding further. In 1992, the Unicode 1.0 was released.
Unification

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- Related characters (e.g., letters in the same alphabet) are grouped together into "code planes".
- To uniquely represent all of these characters using a fixed-width encoding, each character would need a lot of bits... but this would be inefficient.
UTF-16 and UTF-32

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Under this encoding, more frequently used symbols (like the Latin alphabet) get represented by shorter sequences, while less frequently used ones (like hieroglyphics) get longer sequences.

Each character is now represented by both a code point and a UTF-8 byte sequence.

This encoding is the most popular encoding today, and used on all major operating systems.
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• This distinction exists to this day; some people standardized on “DOS line endings” (the web, email, etc.) and some on “UNIX line endings” (git, compilers, etc.).
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Audio

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• When these arrays are stored raw, they're called PULSE-CODE MODULATION files (or PCM) files. It's common to store these in files with a .wav file extension.
Audio Codecs

• PCM data takes up a lot of space, and audio is usually predictable, so there are a lot of encoders/decoders (codecs) to store audio more efficiently:

  • MPEG-1 Audio Layer III (MP3)
  • Free Lossless Audio Codec (FLAC)
  • Advanced Audio Coding (AAC)
  • Opus

• Some of these codecs are lossy, meaning they discard some data they consider unnecessary from the original audio.
• Some of these codecs are lossless, meaning they can be reversed 100% accurately to the original audio.
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The container may include multiple channels of audio.
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Image Formats

- Images are slightly simpler than audio, since each container format generally contains a specific codec.

- There are two kinds of images: raster and vector.
  - Raster images are essentially a grid of pixels, each of which has a specific color.
  - Vector images are a set of instructions to draw an image.
    - Drawings, Logos, Diagrams
    - Vector images can be rendered at any size on-demand, while raster images have a fixed size.
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• VECTOR images are a set of instructions to draw an image.
  • Drawings, Logos, Diagrams

• Vector images can be rendered at any size on-demand, while raster images have a fixed size.
Raster Formats

Common raster image formats include:

- Joint Photographic Experts Group (JPEG)
- Graphics Interchange Format (GIF)
- Portable Network Graphics (PNG)
- High Efficiency Image File Format (HEIF/AVIF)
  - High Efficiency Video Coding (HEVC)
  - AOMedia Video 1 (AV1)
- Tagged Image File Format (TIFF)
- Windows Bitmap (BMP)

Once again, there is a lossy vs. lossless distinction.
The great thing about digital data is that it never degrades.

Hard drives fail, of course, but their bits can be copied forever without loss.

Film degrades, paint cracks, but a copy of a century-old data file is identical to the original.

Source: xkcd 1683
Data Quality

Source: xkcd 2739
Common vector image formats include:

- Scalable Vector Graphics (SVG)
- Gerber (for printed circuit board designs)
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Vector formats are also common for 3D objects due to their relatively small size:

- Wavefront OBJ
- Blender
- various Autodesk formats
Raw Images

- High-end cameras can “shoot in raw”, which captures the raw pixel data coming from the image sensor.
- These images contain ridiculous amounts of data, most of which isn't useful.
- Photographers need to “develop” RAW images into a final image.
Color Spaces

- While light forms a continuous spectrum of colors, humans can usually only see the intensities of three wavelengths.
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• There are other ways to parametrize colors; for example, hue, saturation, and value/brightness (HSV).
As if different color spaces weren't bad enough, there are different representations of each color space.

- RGB (red, green, blue) is pretty common, but sometimes BGR (blue, green, red) or other permutations are also used.
- Sometimes you'll see RGBA or ARGB ("A" stands for "alpha", which is transparency).
- RGB888 uses 8 bits per color (24 bits total), RGB565 uses 5 or 6 per color (16 bits total), RGB332 uses 2 or 3 (8 total).
- 24-bit color is called "true color", 16-bit color is called "high color", and anything higher than 24 is called "deep color".
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- Only some codecs support HDR, including HEIC and AVIF.
Resolution

The “size” of an image in pixels is called its RESOLUTION.

Common resolutions include:

- **HD** 1280×780
- **Full HD** 1280×1080
- **Full HD** 1920×1080
- **4K Ultra HD** 3840×2160
- **8K Ultra HD** 7680×4320

Square power-of-two resolutions are also common (e.g., 16×16, 32×32, 2048×2048), especially for logos.
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Like audio, there are several different video codecs in use:

- High Efficiency Video Coding (H.265)
- Advanced Video Coding (H.264)
- VP8 and VP9
- Theora
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Uncompressed video is almost entirely useless outside of professional use, since the files are ridiculously large. Video is compressed using lossy algorithms.
Video Containers

There are also several container formats:

- Matroska (MKV)
- MPEG-4 (MP4)
- QuickTime (MOV)
- Audio Video Interleave (AVI)
- WebM
- Ogg

Video containers also double as audio containers, since most videos have associated audio.
In addition to all the parameters from both images and audio, video also has an additional parameter: the frame rate.
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High frame rates look smoother but require more data.

Typical frame rates are 24, 30, and 60 frames per second.
Reencoding Video

• In order to do almost any operation to a video, it needs to be reencoded.
• Reencoding a video is slow; usually it's about 1:1 with the length of the video.
• Reencoding a 90-minute lecture video takes about 90 minutes on my laptop.
• Reencoding also effectively recompresses a video, losing information every time if the encoding is lossy.
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Useful media tools

- **file**: identifies the format of many files
- **iconv**: converts between text encodings
- **FFmpeg**: converting (or identifying) audio and video
- **ImageMagick**: editing images
- **Pandoc**: converts documents between formats
• There are lots of ways to encode any given piece of media.
Review

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It's important to keep encoding in mind when working with media, and generally not mix together things with different encodings.