CS 45, Lecture 17
Encoding

Spring 2023

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Outline

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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.

Outline

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

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).

Human Representation

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`

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- 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".

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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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To interpret a number, you need to know if it is SIGNED or UNSIGNED; `0b11100001` could be -31 or 225.

Integer Ranges

The range of numbers we can represent depends on the encoding we use:

Width	Unsigned	Signed
8	$[0, 255]$	$[-128, 127]$
16	$[0, 65535]$	$[-32768, 32767]$
32	$[0, 4294967295]$	$[-2147483648, 2147483647]$
64	$[0, 2^{64} - 1]$	$[-2^{63}, 2^{63} - 1]$

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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.

`0xAABBCCDD =`

Offset	Big Endian	Little Endian
0	0xAA	0xDD
1	0xBB	0xCC
2	0xCC	0xBB
3	0xDD	0xAA

Most CPUs are little-endian, but most network protocols are big-endian. The way we write numbers (e.g., `0xAABBCCDD`) is big-endian.

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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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Text

Let's say we want to save this file:

```
Hi!
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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”.

ASCII

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.

ASCII Table

ASCII TABLE

Decimal	Hex	Char	Decimal	Hex	Char	Decimal	Hex	Char	Decimal	Hex	Char
0	0	[NULL]	32	20	[SPACE]	64	40	@	96	60	`
1	1	[START OF HEADING]	33	21	!	65	41	A	97	61	a
2	2	[START OF TEXT]	34	22	"	66	42	B	98	62	b
3	3	[END OF TEXT]	35	23	#	67	43	C	99	63	c
4	4	[END OF TRANSMISSION]	36	24	$	68	44	D	100	64	d
5	5	[ENQUIRY]	37	25	%	69	45	E	101	65	e
6	6	[ACKNOWLEDGE]	38	26	&	70	46	F	102	66	f
7	7	[BELL]	39	27	'	71	47	G	103	67	g
8	8	[BACKSPACE]	40	28	(	72	48	H	104	68	h
9	9	[HORIZONTAL TAB]	41	29	)	73	49	I	105	69	i
10	A	[LINE FEED]	42	2A	*	74	4A	J	106	6A	j
11	B	[VERTICAL TAB]	43	2B	+	75	4B	K	107	6B	k
12	C	[FORM FEED]	44	2C	,	76	4C	L	108	6C	l
13	D	[CARRIAGE RETURN]	45	2D	-	77	4D	M	109	6D	m
14	E	[SHIFT OUT]	46	2E	.	78	4E	N	110	6E	n
15	F	[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	[NEGATIVE 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 OF 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	[SUBSTITUTE]	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	[DEL]

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- 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, ¡, ¿, 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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Code Page 1252 Table

NUL SOH STX ETX EOT ENQ ACK BEL BS HT LF VT FF CR SO SI DLE DC1 DC2 DC3 DC4 NAK SYN ETB CAN EM SUB ESC FS GS RS US

 !"#$%&'()*+,-./0123456789:;<=>?

@ABCDEFGHIJKLMNOPQRSTUVWXYZ[\]^_

`abcdefghijklmnopqrstuvwxyz{|}~ DEL

€·‚ƒ„…†‡ˆ‰Š‹Œ·Ž··‘’“”•–—˜™š›œ·žŸ

 ¡¢£¤¥¦§¨©ª«¬®¯°±²³´µ¶·¸¹º»¼½¾¿

ÀÁÂÃÄÅÆÇÈÉÊËÌÍÎÏÐÑÒÓÔÕÖ×ØÙÚÛÜÝÞß

àáâãäåæçèéêëìíîïðñòóôõö÷øùúûüýþÿ

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)

NUL SOH STX ETX EOT ENQ ACK BEL BS HT LF VT FF CR SO SI DLE DC1 DC2 DC3 DC4 NAK SYN ETB CAN EM SUB ESC FS GS RS US

 !"#$%&'()*+,-./0123456789:;<=>?

@ABCDEFGHIJKLMNOPQRSTUVWXYZ[¥]^_

`abcdefghijklmnopqrstuvwxyz{|}‾ DEL

｡｢｣､･ｦｧｨｩｪｫｬｭｮｯｰｱｲｳｴｵｶｷｸｹｺｻｼｽｾｿ

ﾀﾁﾂﾃﾄﾅﾆﾇﾈﾉﾊﾋﾌﾍﾎﾏﾐﾑﾒﾓﾔﾕﾖﾗﾘﾙﾚﾛﾜﾝﾞﾟ

Custom Encodings

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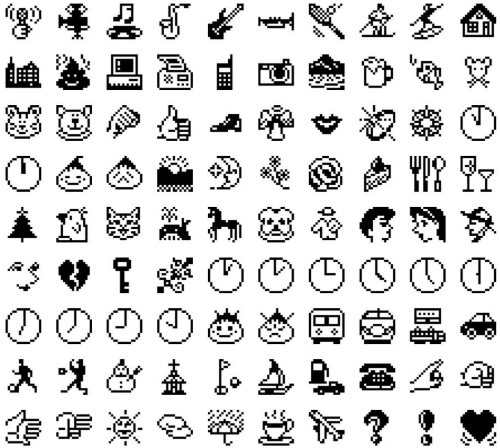
Over time, there grew to be thousands of incompatible character sets.

Custom Characters

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



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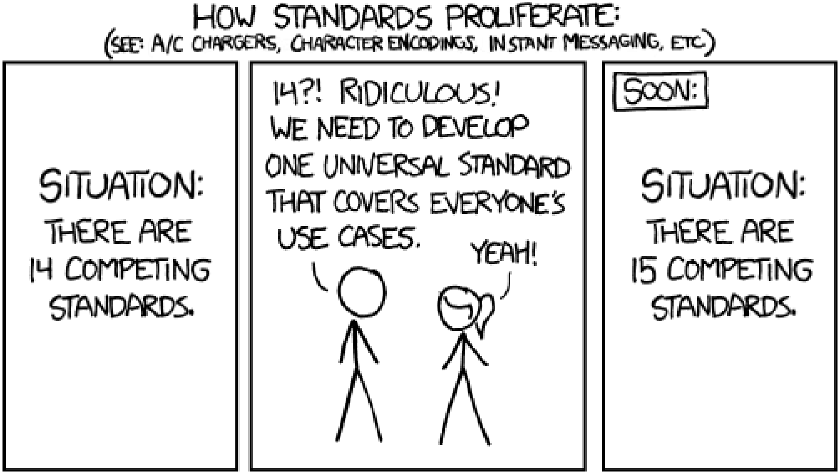
Standards



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¯

/ÊŒkÊ‚ÊŒj É·É¾iË‹ÊŒdsÊŒn/

à®µà¯‡à®±à¯ à®Žà®´à¯à®¤à¯à®¤à¯ à®®à¯à®±à¯ˆà®•à®³à®¿à®²à¯: Akshay Srivatsan
à®®à®±à¯à®±à¯à®®à¯ à¤…à¤•à¥à¤·à¤¯à¥ à¤¶à¥à¤°à¥€à¤µà¤¤à¥à¤¸à¤¨à¥
à®®à®±à¯à®±à¯à®®à¯ ð‘€…ð‘€“ð‘†ð‘€±ð‘€¬ð‘† ð‘€°ð‘†ð‘€ð‘€»ð‘€¯ð‘€¢ð‘†ð‘€²ð‘€¦ð‘†
à®®à®±à¯à®±à¯à®®à¯ akṣay srÄ«vatsan à®®à®±à¯à®±à¯à®®à¯ ð‘Œ…ð‘Œ•ð‘ð‘Œ·ð‘Œ¯ð‘
ð‘Œ¶ð‘ð‘Œ°ð‘€ð‘Œµð‘Œ¤ð‘ð‘Œ¸ð‘Œ¨ð‘

à®¤à®®à®¿à®´à¯ à®®à¯Šà®´à®¿à®¯à®¿à®²à¯ à®¤à®µà®¿à®°, à®‡à®¨à¯à®¤
à®‡à®£à¯ˆà®¯à®¤à¯à®¤à®³à®®à¯ à®†à®™à¯à®•à®¿à®²
à®®à¯Šà®´à®¿à®¯à®¿à®²à¯à®®à¯, à®²à®¤à¯à®¤à¯€à®©à¯
à®®à¯Šà®´à®¿à®¯à®¿à®²à¯à®®à¯, à®¹à®¿à®¨à¯à®¤à®¿
à®®à¯Šà®´à®¿à®¯à®¿à®²à¯à®®à¯ à®•à®¿à®Ÿà¯ˆà®•à¯à®•à¯à®®à¯.

à®Žà®©à¯à®©à¯ˆà®ªà¯ à®ªà®±à¯à®±à®¿

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.

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- Unix decided to save a byte: a newline was just `0x0A`.
- 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.).

Outline

Audio

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- As most humans have two ears, we tend to prefer STEREO audio, where there are left and right CHANNELS; each channel is a separate array.
- 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

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

Image Formats

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- RASTER images are essentially a grid of pixels, each of which has a specific color.
  - Photographs
- 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.

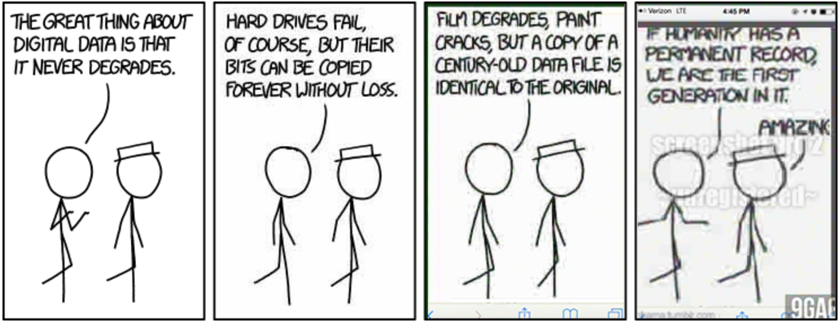
Raster Formats

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)

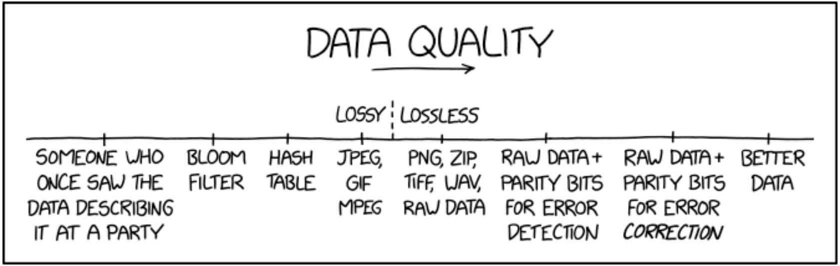
Once again, there is a lossy vs. lossless distinction.

Lossy Compression



Source: xkcd 1683

Data Quality



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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.

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- The exact way human brains reconstruct colors from these three wavelengths is complicated, so there are various COLOR SPACES which attempt to approximate it.
- There are other ways to parametrize colors; for example, hue, saturation, and value/brightness (HSV).

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- 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".

High Dynamic Range

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- Cameras don't have this, so they fake it by taking photos with different exposure settings and merging them together.
- 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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Video Codecs

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.

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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.

Outline

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

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- The appropriate encoding for a specific purpose depends on a lot of factors.
- Different people/software/systems may expect different encodings, and run into problems when given data in the wrong encoding.
- It's important to keep encoding in mind when working with media, and generally not mix together things with different encodings.