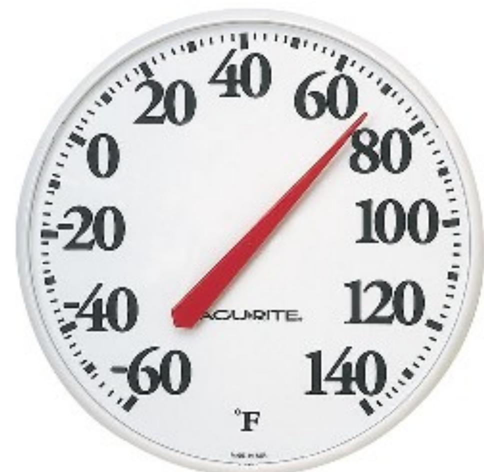
Bits, bytes, and representation of information

- **digital representation means that everything is represented by numbers only**
- **the usual sequence:**
  - something (sound, pictures, text, instructions, ...) is converted into numbers by some mechanism
  - the numbers can be stored, retrieved, processed, copied, transmitted
  - the numbers might be reconstituted into a version of the original
- **for sound, pictures, other real-world values**
  - make accurate measurements
  - convert them to numeric values

Analog versus Digital

- **analog: "analogous" or "the analog of"**
  - smoothly or continuously varying values
  - volume control, dimmer, faucet, steering wheel
  - value varies smoothly with something else
    - no discrete steps or changes in values
      - small change in one implies small change in another
      - infinite number of possible values
  - the world we perceive is largely analog
- **digital: discrete values**
  - only a finite number of different values
  - a change in something results in sudden change from one discrete value to another
    - digital speedometer, digital watch, push-button radio tuner, …
  - values are represented as <u>numbers</u>



Transducers

- **devices that convert from one representation to another**
  - microphone
  - loudspeaker / earphones
  - camera / scanner
  - printer / screen
  - keyboard
  - mouse
  - touch screen
  - etc.

- **something is usually lost by conversion (in each direction)**
  - the ultimate copy is not as good as the original

Encoding sound

- **need to measure intensity/loudness often enough and accurately enough that we can reconstruct it well enough**
- **higher frequency = higher pitch**
- **human ear can hear ~ 20 Hz to 20 KHz**
  - taking samples at twice the highest frequency is good enough (Nyquist)

- **CD audio usually uses**
  - 44,100 samples / second
  - accuracy of 1 in 65,536 (= 2^16) distinct levels
  - two samples at each time for stereo
  - data rate is 44,100 x 2 x 16 bits/sample
    = 1,411,200 bits/sec = 176,400 bytes/sec ~ 10.6 MB/minute

- **MP3 audio compresses by clever encoding and removal of sounds that won't really be heard**
  - data rate is ~ 1 MB/minute

ASCII: American Standard Code for Information Interchange

- **an arbitrary but agreed-upon representation for USA**
- **widely used everywhere**

000	001	002	003	004	005	006	007	008	009	010	011	012	013	014	015
NUL	SOH	STX	ETX	EOT	ENQ	ACK	BEL	BS	HT	LF	VT	FF	CR	SO	SI
016	017	018	019	020	021	022	023	024	025	026	027	028	029	030	031
DLE	DC1	DC2	DC3	DC4	NAK	SYN	ETB	CAN	EM	SUB	ESC	FS	GS	RS	US
032	033	034	035	036	037	038	039	040	041	042	043	044	045	046	047
SP	!	"	#	$	%	&	'	(	)	*	+	,	-	.	/
048	049	050	051	052	053	054	055	056	057	058	059	060	061	062	063
0	1	2	3	4	5	6	7	8	9	:	;	<	=	>	?
064	065	066	067	068	069	070	071	072	073	074	075	076	077	078	079
@	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
080	081	082	083	084	085	086	087	088	089	090	091	092	093	094	095
P	Q	R	S	T	U	V	W	X	Y	Z	[	\	]	^	x
096	097	098	099	100	101	102	103	104	105	106	107	108	109	110	111
`	a	b	c	d	e	f	g	h	i	j	k	l	m	n	o
112	113	114	115	116	117	118	119	120	121	122	123	124	125	126	127
p	q	r	s	t	u	v	w	x	y	z	{	|	}	~	DEL

Important ideas

- **number of items and number of digits are tightly related:**
  - one determines the other
  - maximum number of different items = base $^{\textbf{number of digits}}$
  - e.g., 9-digit SSN: 10^9 = 1 billion possible numbers

  - e.g., to represent up to 100 “characters”: 2 digits is enough
  - but for 1000 characters, we need 3 digits

- **interpretation depends on context**
  - without knowing that, we can only guess what things mean
  - what's 81615 ?

A review of how decimal numbers work

- **how many digits?**
  - we use 10 digits for counting: "decimal" numbers are natural for us
  - other schemes show up in some areas

    clocks use 12, 24, 60; calendars use 7, 12

    other cultures use other schemes (quatre-vingts)
- **what if we want to count to more than 10?**
  - 0 1 2 3 4 5 6 7 8 9

    1 decimal digit represents 1 choice from 10; counts 10 things; 10 distinct values
  - 00 01 02 … 10 11 12 … 20 21 22 … 98 99

    2 decimal digits represents 1 choice from 100; 100 distinct values

    we usually elide zeros at the front
  - 000 001 … 099 100 101 … 998 999

    3 decimal digits …
- **decimal numbers are shorthands for sums of powers of 10**
  - $1492 = 1 \times 1000 + 4 \times 100 + 9 \times 10 + 2 \times 1$
  - $= 1 \times 10^3 + 4 \times 10^2 + 9 \times 10^1 + 2 \times 10^0$
- **counting in "base 10", using powers of 10**

Binary numbers: using bits to represent numbers

- **just like decimal except there are only <u>two</u> digits: 0 and 1**
- **everything is based on powers of 2 (1, 2, 4, 8, 16, 32, …)**
  - instead of powers of 10 (1, 10, 100, 1000, …)
- **counting in binary or base 2:**

  0 1

  1 binary digit represents 1 choice from 2; counts 2 things; 2 distinct values

  00 01 10 11

  2 binary digits represents 1 choice from 4; 4 distinct values

  000 001 010 011 100 101 110 111

  3 binary digits …
- **binary numbers are shorthands for sums of powers of 2**

  $11011 = 1 \times 16 + 1 \times 8 + 0 \times 4 + 1 \times 2 + 1 \times 1$

  $= 1 \times 2^4 + 1 \times 2^3 + 0 \times 2^2 + 1 \times 2^1 + 1 \times 2^0$
- **counting in "base 2", using powers of 2**

Binary (base 2) arithmetic

- **works like decimal (base 10) arithmetic, but simpler**

- **addition:**

  0 + 0 = 0
  0 + 1 = 1
  1 + 0 = 1
  1 + 1 = 10

- **subtraction, multiplication, division are analogous**

Bytes

- **"byte" = group of 8 bits**
  - on modern machines, the fundamental unit of processing and memory addressing
  - can encode any of 2^8 = 256 different values, e.g., numbers 0 .. 255 or a single letter like A or digit like 7 or punctuation like $
    - ASCII character set defines values for letters, digits, punctuation, etc.
- **group 2 bytes together to hold larger entities**
  - two bytes (16 bits) holds 2^{16} = 65536 values
  - a bigger integer, a character in a larger character set
    - Unicode character set defines values for almost all characters anywhere
- **group 4 bytes together to hold even larger entities**
  - four bytes (32 bits) holds 2^{32} = 4,294,967,296 values
  - an even bigger integer, a number with a fractional part (floating point), a memory address
- **etc.**
  - recent machines use 64-bit integers and addresses (8 bytes)
    - 2^{64} = 18,446,744,073,709,551,616

Interpretation of bits depends on context

- **meaning of a group of bits depends on how they are interpreted**
- **1 byte could be**
  - 1 bit in use, 7 wasted bits (e.g., M/F in a database)
  - 8 bits storing a number between 0 and 255
  - an alphabetic character like W or + or 7
  - part of a character in another alphabet or writing system (2 bytes)
  - part of a larger number (2 or 4 or 8 bytes, usually)
  - part of a picture or sound
  - part of an instruction for a computer to execute
    - instructions are just bits, stored in the same memory as data
    - different kinds of computers use different bit patterns for their instructions
      - laptop, cellphone, game machine, etc., all potentially different
  - part of the location or address of something in memory
  - ...
- **one program's instructions are another program's data**
  - when you download a new program from the net, it's data
  - when you run it, it's instructions

Powers of two, powers of ten

1 bit = 2 possibilities

2 bits = 4 possibilities

3 bits = 8 possibilities

...

n bits = 2^n

2^{10} = 1,024 is about 1,000 or 1K or 10^3

2^{20} = 1,048,576 is about 1,000,000 or 1M or 10^6

2^{30} = 1,073,741,824 is about 1,000,000,000 or 1G or 10^9

the approximation is becoming less good

but it's still good enough for estimation

- **terminology is often imprecise:**
  - " 1K " might mean 1000 or 1024 (10^3 or 2^{10})
  - " 1M " might mean 1000000 or 1048576 (10^6 or 2^{20})

Converting binary to decimal

from right to left:

if bit is 1 add corresponding power of 2

i.e. 2^0, 2^1, 2^2, 2^3

(rightmost power is zero)

$$1101 = 1 \times 2^0 + 0 \times 2^1 + 1 \times 2^2 + 1 \times 2^3$$
$$= 1 \times 1 + 0 \times 2 + 1 \times 4 + 1 \times 8$$
$$= 13$$

Converting decimal to binary

repeat while the number is > 0:

    divide the number by 2
    write the remainder (0 or 1)
    use the quotient as the number and repeat

the answer is the resulting sequence

    in reverse (right to left) order

divide 13 by 2, write "1", number is 6

divide 6 by 2, write "0", number is 3

divide 3 by 2, write "1", number is 1

divide 1 by 2, write "1", number is 0

answer is 1101

Hexadecimal notation

- **binary numbers are bulky**
- **hexadecimal notation is a shorthand**
- **it combines 4 bits into a single digit, written in base 16**
  - a more compact representation of the same information
- **hex uses the symbols A B C D E F for the digits 10 .. 15**

  0 1 2 3 4 5 6 7 8 9 A B C D E F

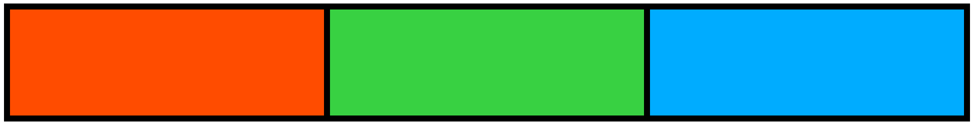
0	0000	1	0001	2	0010	3	0011
4	0100	5	0101	6	0110	7	0111
8	1000	9	1001	A	1010	B	1011
C	1100	D	1101	E	1110	F	1111

ASCII again

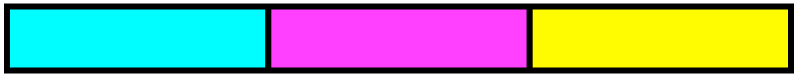
	0	1	2	3	4	5	6	7	8	9	A	B	C	D	E	F
0	NUL	SOH	STX	ETX	EOT	ENQ	ACK	BEL	BS	HT	LF	VT	FF	CR	SO	SI
1	DLE	DC1	DC2	DC3	DC4	NAK	SYN	ETB	CAN	EM	SUB	ESC	FS	GS	RS	US
2	SPC	!	"	#	$	%	&	'	(	)	*	+	,	-	.	/
3	0	1	2	3	4	5	6	7	8	9	:	;	<	=	>	?
4	@	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
5	P	Q	R	S	T	U	V	W	X	Y	Z	[	\	]	^	_
6	`	a	b	c	d	e	f	g	h	i	j	k	l	m	n	o
7	p	q	r	s	t	u	v	w	x	y	z	{	|	}	~	DEL

Color

- **TV & computer screens use Red-Green-Blue (RGB) model**



- **each color is a combination of red, green, blue components**
  - R+G = yellow, R+B = magenta, B+G = cyan, R+G+B = white
- **for computers, color of a pixel is usually specified by three numbers giving amount of each color, on a scale of 0 to 255**
- **this is often expressed in hexadecimal so the three components can be specified separately (in effect, as bit patterns)**
  - 000000 is black, FFFFFF is white
- **printers, etc., use cyan-magenta-yellow[-black] (CMY[K])**



Things to remember

- **digital devices represent everything as numbers**
  - discrete values, not continuous or infinitely precise
- **all modern digital devices use binary numbers (base 2)**
  - instead of decimal (base 10)
- **it's all bits at the bottom**
  - a bit is a "binary digit", that is, a number that is either 0 or 1
  - computers ultimately represent and process <u>everything</u> as bits
- **groups of bits represent larger things**
  - numbers, letters, words, names, pictures, sounds, instructions, ...
  - the interpretation of a group of bits depends on their context
  - the representation is arbitrary; standards (often) define what it is
- **the number of digits used in the representation determines how many different things can be represented**
  - number of values = base $^{\text{number of digits}}$
  - e.g., 10^2 , 2^{10}