

System Programming

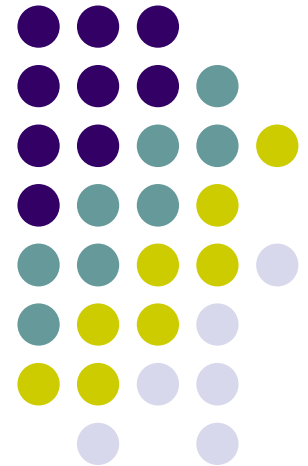
03. A. Binary Numbers (2.1)

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Lecture Outline



- **Decimal, Binary, and Hexadecimal**
- Base Conversion
- Binary Encoding
- IEC Prefixes

Decimal Numbering System



- Ten **symbols**: 0, 1, 2, 3, 4, 5, 6, 7, 8, 9
- Represent larger numbers as a sequence of **digits**
 - Each digit is one of the available symbols
- Example: 7061 in decimal (base 10)
 - $7061_{10} = (7 \times 10^3) + (0 \times 10^2) + (6 \times 10^1) + (1 \times 10^0)$

Octal Numbering System



- Eight symbols: 0, 1, 2, 3, 4, 5, 6, 7
 - Notice that we no longer use 8 or 9
- Base comparison:
 - Base 10: 0, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12...
 - Base 8: 0, 1, 2, 3, 4, 5, 6, 7, 10, 11, 12, 13, 14...
- Example: What is 7061_8 in base 10?
 - $7061_8 = (7 \times 8^3) + (0 \times 8^2) + (6 \times 8^1) + (1 \times 8^0) = 3633_{10}$

Question



- What is 34_8 in base 10?
 - A. 32_{10}
 - B. 34_{10}
 - C. 7_{10}
 - D. 28_{10}
 - E. 35_{10}

Binary and Hexadecimal



- Binary is base 2
 - Symbols: 0, 1
 - Convention: $2_{10} = 10_2 = \text{0b}10$
- Example: What is 0b110 in base 10?
 - $0\text{b}110 = 110_2 = (1 \times 2^2) + (1 \times 2^1) + (0 \times 2^0) = 6_{10}$
- Hexadecimal (**hex**, for short) is base 16
 - Symbols? 0, 1, 2, 3, 4, 5, 6, 7, 8, 9, ...?
 - Convention: $16_{10} = 10_{16} = \text{0x}10$
- Example: What is 0xA5 in base 10?
 - $0\text{x}A5 = A5_{16} = (10 \times 16^1) + (5 \times 16^0) = 165_{10}$

Question



- Which of the following orderings is correct?

A. $0xC < 0b1010 < 11$

B. $0xC < 11 < 0b1010$

C. $11 < 0b1010 < 0xC$

D. $0b1010 < 11 < 0xC$

E. $0b1010 < 0xC < 11$

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Converting to Base 10



- Can convert from any base *to* base 10
 - $0b110 = 110_2 = (1 \times 2^2) + (1 \times 2^1) + (0 \times 2^0) = 6_{10}$
 - $0xA5 = A5_{16} = (10 \times 16^1) + (5 \times 16^0) = 165_{10}$
- We learned to think in base 10, so this is fairly natural for us
- **Challenge:** Convert into other bases (e.g. 2, 16)

Challenge Question



- Convert 13_{10} into binary
- Hints:
 - $2^3 = 8$
 - $2^2 = 4$
 - $2^1 = 2$
 - $2^0 = 1$

Converting from Decimal to Binary



- Given a decimal number N:
 - List increasing powers of 2 from *right to left* until $\geq N$
 - Then from *left to right*, ask is that (power of 2) $\leq N$?
 - If **YES**, put a 1 below and subtract that power from N
 - If **NO**, put a 0 below and keep going
- Example: 13 to binary

$2^4=16$	$2^3=8$	$2^2=4$	$2^1=2$	$2^0=1$

Converting from Decimal to Base B



- Given a decimal number N:
 - List increasing powers of **B** from *right to left* until $\geq N$
 - Then from *left to right*, ask is that (power of **B**) $\leq N$?
 - If **YES**, put *how many of that power go into N* and subtract from N
 - If **NO**, put a 0 below and keep going
- Example: 165 to hex

$16^2=256$	$16^1=16$	$16^0=1$

Converting Binary ↔ Hexadecimal



- Hex → Binary

- Substitute hex digits, then drop any **leading zeros**
- Example: 0x2D to binary
 - 0x2 is 0b0010, 0xD is 0b1101
 - Drop two leading zeros, answer is 0b101101

- Binary → Hex

- Pad with **leading zeros** until multiple of 4, then substitute each group of 4
- Example: 0b101101
 - Pad to 0b 0010 1101
 - Substitute to get 0x2D

Base 10	Base 2	Base 16
0	0000	0
1	0001	1
2	0010	2
3	0011	3
4	0100	4
5	0101	5
6	0110	6
7	0111	7
8	1000	8
9	1001	9
10	1010	A
11	1011	B
12	1100	C
13	1101	D
14	1110	E
15	1111	F ¹³

Binary → Hex Practice



- Convert 0b100110110101101
 - How many digits?
 - Pad:
 - Substitute:

Base 10	Base 2	Base 16
0	0000	0
1	0001	1
2	0010	2
3	0011	3
4	0100	4
5	0101	5
6	0110	6
7	0111	7
8	1000	8
9	1001	9
10	1010	A
11	1011	B
12	1100	C
13	1101	D
14	1110	E
15	1111	F ¹⁴

Base Comparison



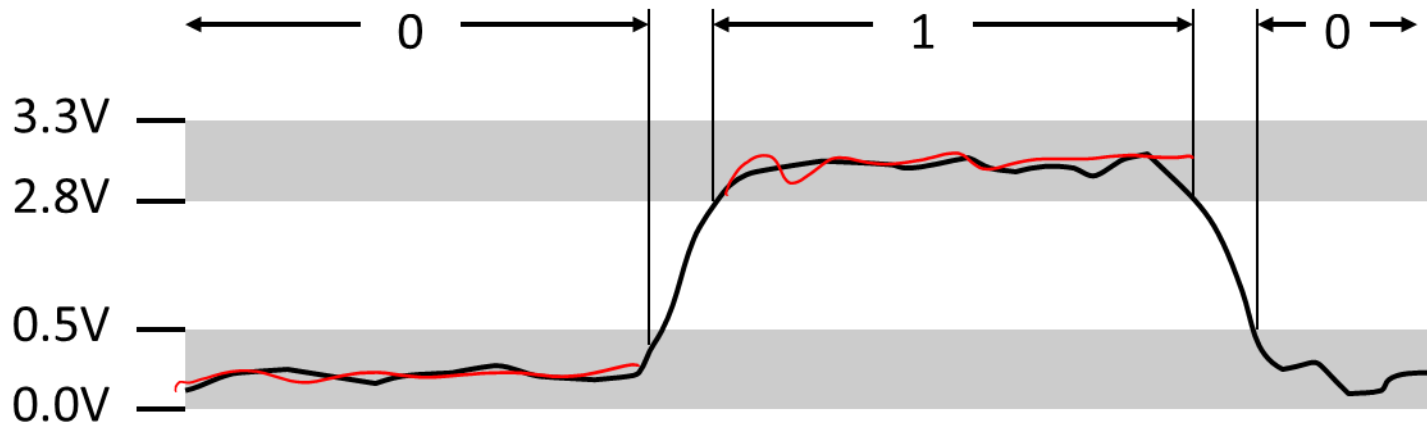
- Why does all of this matter?
 - *Humans* think about numbers in **base 10**, but *computers* “think” about numbers in **base 2**
 - **Binary encoding** is what allows computers to do all of the amazing things that they do!
- You should have this table memorized by the end of the class
 - Might as well start now

Base 10	Base 2	Base 16
0	0000	0
1	0001	1
2	0010	2
3	0011	3
4	0100	4
5	0101	5
6	0110	6
7	0111	7
8	1000	8
9	1001	9
10	1010	A
11	1011	B
12	1100	C
13	1101	D
14	1110	E
15	1111	F ¹⁵

Aside: Why Base 2?



- Electronic implementation
 - Easy to store with bi-stable elements
 - Reliably transmitted on noisy and inaccurate wires



- Other bases possible, but not yet viable:
 - DNA data storage (base 4: A, C, G, T) is a hot topic
 - Quantum computing

Lecture Outline



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Numerical Encoding



- **AMAZING FACT: You can represent *anything* countable using numbers!**
 - Need to agree on an **encoding**
 - Kind of like learning a new language
- Examples:
 - Decimal Integers: $0 \rightarrow 0b0$, $1 \rightarrow 0b1$, $2 \rightarrow 0b10$, etc.
 - English Letters: CSE $\rightarrow 0x435345$, yay $\rightarrow 0x796179$
 - Emoticons: 😊 0x0, 😞 0x1, 😎 0x2, 😊 0x3, 😈 0x4, 🙋 0x5

Binary Encoding



- With N binary digits, how many “things” can you represent?
 - Need N binary digits to represent n things, where $2^N \geq n$
 - Example: 5 binary digits for alphabet because $2^5 = 32 > 26$
- A binary digit is known as a **bit**
- A group of 4 bits (1 hex digit) is called a **nibble**
- A group of 8 bits (2 hex digits) is called a **byte**
 - 1 bit \rightarrow 2 things, 1 nibble \rightarrow 16 things, 1 byte \rightarrow 256 things

So What's It Mean?

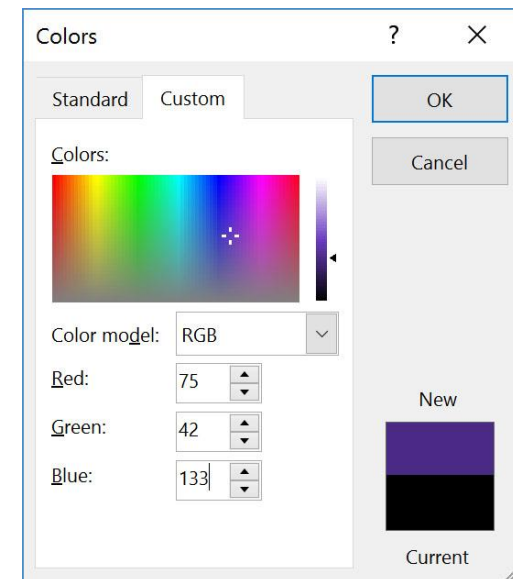
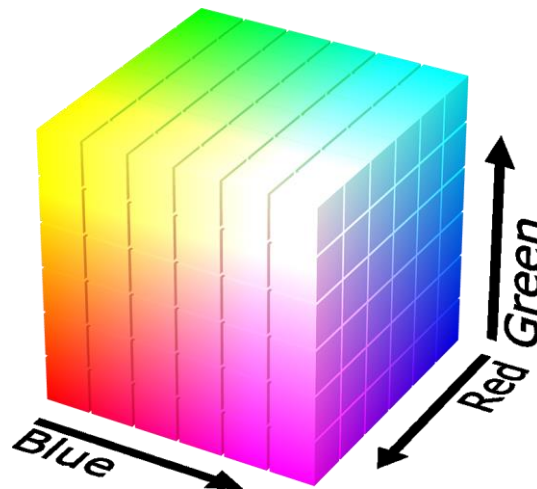


- A sequence of bits can have many meanings!
- Consider the hex sequence 0x4E6F21
 - Common interpretations include:
 - The decimal number 5140257
 - The characters “No!”
 - The background color of this slide
 - The real number 7.203034×10^{-39}
- It is up to the program/programmer to decide how to **interpret** the sequence of bits

Binary Encoding – Colors



- RGB – Red, Green, Blue
 - Additive color model (light): byte (8 bits) for each color
 - Commonly seen in hex (in HTML, photo editing, etc.)
 - Examples: **Blue**→0x0000FF, **Gold**→0xFFD700,
White→0xFFFFFF, **Deep Pink**→0xFF1493



Binary Encoding – Characters/Text



- ASCII Encoding (www.asciitable.com)
- American Standard Code for Information Interchange

Dec	Hx	Oct	Char	Dec	Hx	Oct	Html	Chr	Dec	Hx	Oct	Html	Chr	Dec	Hx	Oct	Html	Chr
0	0	000	NUL (null)	32	20	040	 	Space	64	40	100	@	@	96	60	140	`	`
1	1	001	SOH (start of heading)	33	21	041	!	!	65	41	101	A	A	97	61	141	a	a
2	2	002	STX (start of text)	34	22	042	"	"	66	42	102	B	B	98	62	142	b	b
3	3	003	ETX (end of text)	35	23	043	#	#	67	43	103	C	C	99	63	143	c	c
4	4	004	EOT (end of transmission)	36	24	044	$	\$	68	44	104	D	D	100	64	144	d	d
5	5	005	ENQ (enquiry)	37	25	045	%	%	69	45	105	E	E	101	65	145	e	e
6	6	006	ACK (acknowledge)	38	26	046	&	&	70	46	106	F	F	102	66	146	f	f
7	7	007	BEL (bell)	39	27	047	'	'	71	47	107	G	G	103	67	147	g	g
8	8	010	BS (backspace)	40	28	050	((72	48	110	H	H	104	68	150	h	h
9	9	011	TAB (horizontal tab)	41	29	051))	73	49	111	I	I	105	69	151	i	i
10	A	012	LF (NL line feed, new line)	42	2A	052	*	*	74	4A	112	J	J	106	6A	152	j	j
11	B	013	VT (vertical tab)	43	2B	053	+	+	75	4B	113	K	K	107	6B	153	k	k
12	C	014	FF (NP form feed, new page)	44	2C	054	,	,	76	4C	114	L	L	108	6C	154	l	l
13	D	015	CR (carriage return)	45	2D	055	-	-	77	4D	115	M	M	109	6D	155	m	m
14	E	016	SO (shift out)	46	2E	056	.	.	78	4E	116	N	N	110	6E	156	n	n
15	F	017	SI (shift in)	47	2F	057	/	/	79	4F	117	O	O	111	6F	157	o	o
16	10	020	DLE (data link escape)	48	30	060	0	0	80	50	120	P	P	112	70	160	p	p
17	11	021	DC1 (device control 1)	49	31	061	1	1	81	51	121	Q	Q	113	71	161	q	q
18	12	022	DC2 (device control 2)	50	32	062	2	2	82	52	122	R	R	114	72	162	r	r
19	13	023	DC3 (device control 3)	51	33	063	3	3	83	53	123	S	S	115	73	163	s	s
20	14	024	DC4 (device control 4)	52	34	064	4	4	84	54	124	T	T	116	74	164	t	t
21	15	025	NAK (negative acknowledge)	53	35	065	5	5	85	55	125	U	U	117	75	165	u	u
22	16	026	SYN (synchronous idle)	54	36	066	6	6	86	56	126	V	V	118	76	166	v	v
23	17	027	ETB (end of trans. block)	55	37	067	7	7	87	57	127	W	W	119	77	167	w	w
24	18	030	CAN (cancel)	56	38	070	8	8	88	58	130	X	X	120	78	170	x	x
25	19	031	EM (end of medium)	57	39	071	9	9	89	59	131	Y	Y	121	79	171	y	y
26	1A	032	SUB (substitute)	58	3A	072	:	:	90	5A	132	Z	Z	122	7A	172	z	z
27	1B	033	ESC (escape)	59	3B	073	;	;	91	5B	133	[[123	7B	173	{	{
28	1C	034	FS (file separator)	60	3C	074	<	<	92	5C	134	\	\	124	7C	174	|	
29	1D	035	GS (group separator)	61	3D	075	=	=	93	5D	135]]	125	7D	175	}	}
30	1E	036	RS (record separator)	62	3E	076	>	>	94	5E	136	^	^	126	7E	176	~	~
31	1F	037	US (unit separator)	63	3F	077	?	?	95	5F	137	_	_	127	7F	177		DEL

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Units and Prefixes



- Here focusing on large numbers (exponents > 0)
- Note that $10^3 \approx 2^{10}$
- SI prefixes are *ambiguous* if base 10 or 2
- IEC prefixes are *unambiguously* base 2

SIZE PREFIXES (10^x for Disk, Communication; 2^x for Memory)

SI Size	Prefix	Symbol	IEC Size	Prefix	Symbol
10^3	Kilo-	K	2^{10}	Kibi-	Ki
10^6	Mega-	M	2^{20}	Mebi-	Mi
10^9	Giga-	G	2^{30}	Gibi-	Gi
10^{12}	Tera-	T	2^{40}	Tebi-	Ti
10^{15}	Peta-	P	2^{50}	Pebi-	Pi
10^{18}	Exa-	E	2^{60}	Exbi-	Ei
10^{21}	Zetta-	Z	2^{70}	Zebi-	Zi
10^{24}	Yotta-	Y	2^{80}	Yobi-	Yi

How to Remember?



- Will be given to you on exam reference sheets
- Mnemonics
 - There unfortunately isn't one well-accepted mnemonic
 - But that shouldn't stop you from trying to come with one!
 - **K**iller **M**echanical **G**iraffe **T**eaches **P**et, **E**xting **Z**ebra to **Y**odel
 - **K**irby **M**issed **G**anondorf **T**erribly, **P**otentially **E**xterminating **Z**elda and **Y**oshi
 - xkcd: **K**arl **M**arx **G**ave **T**he **P**roletariat **E**leven **Z**eppelins, **Y**o
 - <https://xkcd.com/992/>
 - Post your best on Piazza!

Summary



- Humans think about numbers in decimal; computers think about numbers in binary
 - Base conversion to go between them
 - Hexadecimal is more human-readable than binary
- All information on a computer is binary
- Binary encoding can represent *anything!*
 - Computer/program needs to know how to interpret the bits

Q&A

