Data Types & Structures

Physical Media, Abstractions, Programs & Performance

"[The files are] in the computer... it's so simple."

"[The files are] in the computer... it's so simple."

(Just Some) Motivations

- *Demystify foundations*
- *Gain insight & perspective*
- *Recognize solutions*
- *Write performant code*
- *Continue practicing OOP*
- *Interview well*

Coming Up

I. Information Theory & Hardware

II. Representations & Encodings

III. Abstractions & Languages

IV. Abstract Data Types & Data Structures

- IV.a. Queues
- IV.b. Linked Lists
- IV.c. Hash Tables
- IV.d. Trees

V. Extras

Part I:
Information Theory & Hardware

T

F

1

0

$\wedge$

$\vee$

$$\neg 0$$

$$\neg 1$$

My name is Boole AND I invented boolean algebra!

X AND Y

X	Y	XY
0	0	0
0	1	0
1	0	0
1	1	1

X OR Y

X	Y	X+Y
0	0	0
0	1	1
1	0	1
1	1	1

NOT X

X	$\overline{X}$
0	1
1	0

Law	Example	Example
Identity	$A \wedge 1 = A$	$A \vee 0 = A$
Idempotent	$A \wedge A = A$	$A \vee A = A$
Associative	$A \wedge (B \wedge C) = (A \wedge B) \wedge C$	$A \vee (B \vee C) = (A \vee B) \vee C$
Commutative	$A \wedge B = B \wedge A$	$A \vee B = B \vee A$
Absorption	$A \wedge (A \vee B) = A$	$A \vee (A \wedge B) = A$
Complementation	$A \wedge \neg A = 0$	$A \vee \neg A = 1$
Distributive	$A \wedge (B \vee C) = (A \wedge B) \vee (A \wedge C)$	$A \vee (B \wedge C) = (A \vee B) \wedge (A \vee C)$
De Morgan's	$\neg(A \wedge B) = \neg A \vee \neg B$	$\neg(A \vee B) = \neg A \wedge \neg B$
Common Identities	$A \wedge (\neg A \vee B) = A \wedge B$	$A \vee (\neg A \wedge B) = A \vee B$
Double Negation	$\neg(\neg A) = A$	

$\wedge$ means logical AND
$\vee$ means logical OR
$\neg$ means logical NOT

1 means true
0 means false

A/B/C are conditions (what goes inside the parentheses of an `if` statement)

1

0

ON

OFF

ON OFF

ON

OFF

Reducing Apparatus
Barrel
Carriage
Counting Apparatus
Rack
Plan 15 of August 1836
Number Cards
Feet

Carriage
Carriage
Carriage
Reducing Apparatus
Barrel
Counting Apparatus
Rack
Number Cards
Feet

Diagram for the computation by the Engine of the Numbers of Bernoulli. See Note G. (page 722 *et seq.*)

Number of Operation.	Nature of Operation.	Variables acted upon.	Variables receiving results.	Indication of change in the value on any Variable.	Statement of Results.	Data.			Working Variables.										Result Variables.			
						${}^1V_1$ ○ 0 0 1 [1]	${}^1V_2$ ○ 0 0 2 [2]	${}^1V_3$ ○ 0 0 4 [n]	${}^0V_4$ ○ 0 0 0 0 [ ]	${}^0V_5$ ○ 0 0 0 [ ]	${}^0V_6$ ○ 0 0 0 [ ]	${}^0V_7$ ○ 0 0 0 [ ]	${}^0V_8$ ○ 0 0 0 [ ]	${}^0V_9$ ○ 0 0 0 [ ]	${}^0V_{10}$ ○ 0 0 0 [ ]	${}^0V_{11}$ ○ 0 0 0 [ ]	${}^0V_{12}$ ○ 0 0 0 [ ]	${}^0V_{13}$ ○ 0 0 0 [ ]	${}^1V_{21}$ ○ B_1 in a decimal fraction. [B_1]	${}^1V_{22}$ ○ B_3 in a decimal fraction. [B_3]	${}^1V_{23}$ ○ B_5 in a decimal fraction. [B_5]	${}^0V_{21}$ ○ 0 0 0 [B_7]
1	×	${}^1V_2 \times {}^1V_3$	${}^1V_4, {}^1V_5, {}^1V_6$	$\left\{\begin{matrix} {}^1V_2 = {}^1V_2 \\ {}^1V_3 = {}^1V_3 \end{matrix}\right\}$	$= 2n$	...	2	n	$2n$	$2n$	$2n$											
2	−	${}^1V_4 - {}^1V_1$	${}^2V_4$	$\left\{\begin{matrix} {}^1V_4 = {}^2V_4 \\ {}^1V_1 = {}^1V_1 \end{matrix}\right\}$	$= 2n - 1$	1	...	...	$2n-1$													
3	+	${}^1V_5 + {}^1V_1$	${}^2V_5$	$\left\{\begin{matrix} {}^1V_5 = {}^2V_5 \\ {}^1V_1 = {}^1V_1 \end{matrix}\right\}$	$= 2n + 1$	1	...	...	...	$2n+1$												
4	÷	${}^2V_5 \div {}^2V_4$	${}^1V_{11}$	$\left\{\begin{matrix} {}^2V_5 = {}^0V_5 \\ {}^2V_4 = {}^0V_4 \end{matrix}\right\}$	$= \frac{2n-1}{2n+1}$	...	...	...	0	0	...	...	...	...	...	$\frac{2n-1}{2n+1}$						
5	÷	${}^1V_{11} \div {}^1V_2$	${}^2V_{11}$	$\left\{\begin{matrix} {}^1V_{11} = {}^2V_{11} \\ {}^1V_2 = {}^1V_2 \end{matrix}\right\}$	$= \frac{1}{2} \cdot \frac{2n-1}{2n+1}$	...	2	...	...	...	...	...	...	...	...	$\frac{1}{2} \cdot \frac{2n-1}{2n+1}$						
6	−	${}^0V_{13} - {}^2V_{11}$	${}^1V_{13}$	$\left\{\begin{matrix} {}^2V_{11} = {}^0V_{11} \\ {}^0V_{13} = {}^1V_{13} \end{matrix}\right\}$	$= -\frac{1}{2} \cdot \frac{2n-1}{2n+1} = A_0$	...	...	...	...	...	...	...	...	...	...	0	...	$-\frac{1}{2} \cdot \frac{2n-1}{2n+1} = A_0$				
7	−	${}^1V_3 - {}^1V_1$	${}^1V_{10}$	$\left\{\begin{matrix} {}^1V_3 = {}^1V_3 \\ {}^1V_1 = {}^1V_1 \end{matrix}\right\}$	$= n - 1 \ (= 3)$	1	...	n	...	...	...	...	...	...	$n-1$							
8	+	${}^1V_2 + {}^0V_7$	${}^1V_7$	$\left\{\begin{matrix} {}^1V_2 = {}^1V_2 \\ {}^0V_7 = {}^1V_7 \end{matrix}\right\}$	$= 2 + 0 = 2$	...	2	...	...	...	...	2										
9	÷	${}^1V_6 \div {}^1V_7$	${}^3V_{11}$	$\left\{\begin{matrix} {}^1V_6 = {}^1V_6 \\ {}^0V_{11} = {}^3V_{11} \end{matrix}\right\}$	$= \frac{2n}{2} = A_1$	...	...	...	...	...	$2n$	2	...	...	...	$\frac{2n}{2} = A_1$						
10	×	${}^1V_{21} \times {}^3V_{11}$	${}^1V_{12}$	$\left\{\begin{matrix} {}^1V_{21} = {}^1V_{21} \\ {}^3V_{11} = {}^3V_{11} \end{matrix}\right\}$	$= B_1 \cdot \frac{2n}{2} = B_1 A_1$	...	...	...	...	...	...	...	...	...	...	$\frac{2n}{2} = A_1$	$B_1 \cdot \frac{2n}{2} = B_1 A_1$	...	B_1			
11	+	${}^1V_{12} + {}^1V_{13}$	${}^2V_{13}$	$\left\{\begin{matrix} {}^1V_{12} = {}^0V_{12} \\ {}^1V_{13} = {}^2V_{13} \end{matrix}\right\}$	$= -\frac{1}{2} \cdot \frac{2n-1}{2n+1} + B_1 \cdot \frac{2n}{2}$	...	...	...	...	...	...	...	...	...	...	...	0	$\left\{-\frac{1}{2} \cdot \frac{2n-1}{2n+1} + B_1 \cdot \frac{2n}{2}\right\}$				
12	−	${}^1V_{10} - {}^1V_1$	${}^2V_{10}$	$\left\{\begin{matrix} {}^1V_{10} = {}^2V_{10} \\ {}^1V_1 = {}^1V_1 \end{matrix}\right\}$	$= n - 2 \ (= 2)$	1	...	...	...	...	...	...	...	...	$n-2$							
13	−	${}^1V_6 - {}^1V_1$	${}^2V_6$	$\left\{\begin{matrix} {}^1V_6 = {}^2V_6 \\ {}^1V_1 = {}^1V_1 \end{matrix}\right\}$	$= 2n - 1$	1	...	...	...	...	$2n-1$											
14	+	${}^1V_1 + {}^1V_7$	${}^2V_7$	$\left\{\begin{matrix} {}^1V_1 = {}^1V_1 \\ {}^1V_7 = {}^2V_7 \end{matrix}\right\}$	$= 2 + 1 = 3$	1	...	...	...	...	...	3										
15	÷	${}^2V_6 \div {}^2V_7$	${}^1V_8$	$\left\{\begin{matrix} {}^2V_6 = {}^2V_6 \\ {}^2V_7 = {}^2V_7 \end{matrix}\right\}$	$= \frac{2n-1}{3}$	...	...	...	...	...	$2n-1$	3	$\frac{2n-1}{3}$									
16	×	${}^1V_8 \times {}^3V_{11}$	${}^4V_{11}$	$\left\{\begin{matrix} {}^1V_8 = {}^0V_8 \\ {}^3V_{11} = {}^4V_{11} \end{matrix}\right\}$	$= \frac{2n}{2} \cdot \frac{2n-1}{3}$	...	...	...	...	...	...	...	0	...	...	$\frac{2n}{2} \cdot \frac{2n-1}{3}$						
17	−	${}^2V_6 - {}^1V_1$	${}^3V_6$	$\left\{\begin{matrix} {}^2V_6 = {}^3V_6 \\ {}^1V_1 = {}^1V_1 \end{matrix}\right\}$	$= 2n - 2$	1	...	...	...	...	$2n-2$											
18	+	${}^1V_1 + {}^2V_7$	${}^3V_7$	$\left\{\begin{matrix} {}^2V_7 = {}^3V_7 \\ {}^1V_1 = {}^1V_1 \end{matrix}\right\}$	$= 3 + 1 = 4$	1	...	...	...	...	...	4										
19	÷	${}^3V_6 \div {}^3V_7$	${}^1V_9$	$\left\{\begin{matrix} {}^3V_6 = {}^3V_6 \\ {}^3V_7 = {}^3V_7 \end{matrix}\right\}$	$= \frac{2n-2}{4}$	...	...	...	...	...	$2n-2$	4	...	$\frac{2n-2}{4}$	...	$\left\{\frac{2n}{2} \cdot \frac{2n-1}{3} \cdot \frac{2n-2}{3}\right\}$						

Diagram for the computation by the Engine of the Numbers of Bernoulli. See Note G. (page 722 *et seq.*)

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						${}^1V_1$ ○ 0 0 1 [1]	${}^1V_2$ ○ 0 0 2 [2]	${}^1V_3$ ○ 0 0 4 [n]	${}^0V_4$ ○ 0 0 0 [ ]	${}^0V_5$ ○ 0 0 0 [ ]	${}^0V_6$ ○ 0 0 0 [ ]	${}^0V_7$ ○ 0 0 0 [ ]	${}^0V_8$ ○ 0 0 0 [ ]	${}^0V_9$ ○ 0 0 0 [ ]	${}^0V_{10}$ ○ 0 0 0 [ ]	${}^0V_{11}$ ○ 0 0 0 [ ]	${}^0V_{12}$ ○ 0 0 0 [ ]	${}^0V_{13}$ ○ 0 0 0 [ ]	${}^1V_{21}$ ○ B_1 in a decimal fraction. [B_1]	${}^1V_{22}$ ○ B_3 in a decimal fraction. [B_3]	${}^1V_{23}$ ○ B_5 in a decimal fraction. [B_5]	${}^0V_{21}$ ○ 0 0 0 [B_7]
1	×	${}^1V_2 \times {}^1V_3$	${}^1V_4, {}^1V_5, {}^1V_6$	$\left\{ {}^1V_2 = {}^1V_2,\ {}^1V_3 = {}^1V_3 \right\}$	$= 2n$	...	2	n	$2n$	$2n$	$2n$											
2	−	${}^1V_4 - {}^1V_1$	${}^2V_4$	$\left\{ {}^1V_4 = {}^2V_4,\ {}^1V_1 = {}^1V_1 \right\}$	$= 2n - 1$	1	...															
3	+	${}^1V_5 + {}^1V_1$	${}^2V_5$	$\left\{ {}^1V_5 = {}^2V_5,\ {}^1V_1 = {}^1V_1 \right\}$	$= 2n + 1$	1	...															
4	÷	${}^2V_5 \div {}^2V_4$	${}^1V_{11}$	$\left\{ {}^2V_5 = {}^0V_5,\ {}^2V_4 = {}^0V_4 \right\}$	$= \frac{2n-1}{2n+1}$	...	...									$\frac{2n-1}{2n+1}$						
5	÷	${}^1V_{11} \div {}^1V_2$	${}^2V_{11}$	$\left\{ {}^1V_{11} = {}^2V_{11},\ {}^1V_2 = {}^1V_2 \right\}$	$= \frac{1}{2} \cdot \frac{2n-1}{2n+1}$	...	2									$\frac{1}{2} \cdot \frac{2n-1}{2n+1}$						
6	−	${}^0V_{13} - {}^2V_{11}$	${}^1V_{13}$	$\left\{ {}^2V_{11} = {}^0V_{11},\ {}^0V_{13} = {}^1V_{13} \right\}$	$= -\frac{1}{2} \cdot \frac{2n-1}{2n+1} = A_0$	...	...									0	...	$-\frac{1}{2} \cdot \frac{2n-1}{2n+1} = A_0$				
7	−	${}^1V_3 - {}^1V_1$	${}^1V_{10}$	$\left\{ {}^1V_3 = {}^1V_3,\ {}^1V_1 = {}^1V_1 \right\}$	$= n - 1\ (= 3)$	1	...															
8	+	${}^1V_2 + {}^0V_7$	${}^1V_7$	$\left\{ {}^1V_2 = {}^1V_2,\ {}^0V_7 = {}^1V_7 \right\}$	$= 2 + 0 = 2$	...	2															
9	÷	${}^1V_6 \div {}^1V_7$	${}^3V_{11}$	$\left\{ {}^1V_6 = {}^1V_6,\ {}^0V_{11} = {}^3V_{11} \right\}$	$= \frac{2n}{2} = A_1$	...	...									$\frac{2n}{2} = A_1$						
10	×	${}^1V_{21} \times {}^3V_{11}$	${}^1V_{12}$	$\left\{ {}^1V_{21} = {}^1V_{21},\ {}^3V_{11} = {}^3V_{11} \right\}$	$= B_1 \cdot \frac{2n}{2} = B_1 A_1$	...	...									$\frac{2n}{2} = A_1$	$B_1 \cdot \frac{2n}{2} = B_1 A_1$	...	B_1			
11	+	${}^1V_{12} + {}^1V_{13}$	${}^2V_{13}$	$\left\{ {}^1V_{12} = {}^0V_{12},\ {}^1V_{13} = {}^2V_{13} \right\}$	$= -\frac{1}{2} \cdot \frac{2n-1}{2n+1} + B_1 \cdot \frac{2n}{2}$	...	...									...	0	$\left\{ -\frac{1}{2} \cdot \frac{2n-1}{2n+1} + B_1 \cdot \frac{2n}{2} \right\}$				
12	−	${}^1V_{10} - {}^1V_1$	${}^2V_{10}$	$\left\{ {}^1V_{10} = {}^2V_{10},\ {}^1V_1 = {}^1V_1 \right\}$	$= n - 2\ (= 2)$	1	...															
13	−	${}^1V_6 - {}^1V_1$	${}^2V_6$	$\left\{ {}^1V_6 = {}^2V_6,\ {}^1V_1 = {}^1V_1 \right\}$	$= 2n - 1$	1	...	...	...	...	$2n-1$											
14	+	${}^1V_1 + {}^1V_7$	${}^2V_7$	$\left\{ {}^1V_1 = {}^1V_1,\ {}^1V_7 = {}^2V_7 \right\}$	$= 2 + 1 = 3$	1	...	...	...	...	...	3										
15	÷	${}^2V_6 \div {}^2V_7$	${}^1V_8$	$\left\{ {}^2V_6 = {}^2V_6,\ {}^2V_7 = {}^2V_7 \right\}$	$= \frac{2n-1}{3}$	...	...	...	...	...	$2n-1$	3	$\frac{2n-1}{3}$									
16	×	${}^1V_8 \times {}^3V_{11}$	${}^4V_{11}$	$\left\{ {}^1V_8 = {}^0V_8,\ {}^3V_{11} = {}^4V_{11} \right\}$	$= \frac{2n}{2} \cdot \frac{2n-1}{3}$	...	...	...	...	...	...	...	0	...	...	$\frac{2n}{2} \cdot \frac{2n-1}{3}$						
17	−	${}^2V_6 - {}^1V_1$	${}^3V_6$	$\left\{ {}^2V_6 = {}^3V_6,\ {}^1V_1 = {}^1V_1 \right\}$	$= 2n - 2$	1	...	...	...	...	$2n-2$											
18	+	${}^1V_1 + {}^2V_7$	${}^3V_7$	$\left\{ {}^2V_7 = {}^3V_7,\ {}^1V_1 = {}^1V_1 \right\}$	$= 3 + 1 = 4$	1	...	...	...	...	...	4										
19	÷	${}^3V_6 \div {}^3V_7$	${}^1V_9$	$\left\{ {}^3V_6 = {}^3V_6,\ {}^3V_7 = {}^3V_7 \right\}$	$= \frac{2n-2}{4}$	...	...	...	...	...	$2n-2$	4	...	$\frac{2n-2}{4}$	...	$\left\{ \frac{2n}{2} \cdot \frac{2n-1}{3} \cdot \frac{2n-2}{3} \right\}$						

Difference Engine

Analytical Engine

Glass tube
Anode
Heated
cathode
Heater

Glass tube
Anode
Grid
Heated cathode
Heater

microelectronics group
A replica of the first transistor,
invented at Bell Labs,
December 23, 1947
Lucent Technologies
Bell Labs Innovations
50 Years and Counting...

microelectronics group
A replica of the first transistor, invented at Bell Labs, December 23, 1947
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G
S
D
B

S

S
D

S
G
D

AND gate

OR gate

AND gate

OR gate

Full Adder

Cin
a0
b0
a1
b1
a2
b2
a3
b3
a4
b4
a5
b5
a6
b6
a7
b7
y0
y1
y2
y3
y4
y5
y6
y7
Cout

Give me an infinite piece of tape and I'll compute the universe

Add 1

- Move HEAD Right/Left
- Read value 0/1/blank
- Write value 0/1/blank

I built the first computer!

STORAGE

1	1	3	0	2	4	10	On	S	A	C	E	a	c	e	g			EB	SB	Ch	Sy	U	Sh	Hk	Br	Rm
2	2	4	1	3	E	15	Off	IS	B	D	F	b	d	f	h			SY	X	Fp	Cn	R	X	Al	Cg	Kg
3	0	0	0	0	W	20		0	0	0	0	0	0	0	0	0	0		0	0	0	0	0	0	0	0
A	1	1	1	1	0	25	A	1	1	1	1	1	1	1	1	1	1	1		1	1	1	1	1	1	1
B	2	2	2	2	5	30	B	2	2		2	2	2	2	2	2	2	2	2		2	2	2	2	2	2
C	3	3	3	3	0	3	C	3	3	3		3	3	3	3	3	3	3	3	3		3	3	3	3	3
D	4	4	4	4	1	4	D	4	4	4	4		4	4	4	4	4	4	4	4	4		4	4	4	4
E	5	5	5	5	2	C	E	5	5	5	5	5		5	5	5	5	5	5	5	5	5		5	5	5
F	6	6	6	6	A	D	F	6	6	6	6	6	6		6	6	6	6	6	6	6	6	6		6	6
G	7	7	7	7	B	E	G	7	7	7	7	7	7	7		7	7	7	7	7	7	7	7	7		7
H	8	8	8	8	a	F	H	8	8	8	8	8	8	8	8		8	8	8	8	8	8	8	8	8	
I	9	9	9	9	b	c	I	9	9	9	9	9	9	9	9	9		9	9	9	9	9	9	9	9	9

IBM

IBM

STORAGETEK

"...buy these ones, which parchment confines within small pages;
give your scroll-cases to the great authors, one hand can hold me." —Martial, -85 CE

VIDEO LINK

SS/SD
ЗОМ
ДО В БОЛГАРИИ
boedem
FLOPPY DISK
5,25" HD,DS
BASF
HD
WRITE ENABLE
WRITE PROTECT
INDEX

SAMSUNG
Solid State Drive

Control Gate
Oxide
= e
Floating Gate
N+ Source
N+ Drain
Channel
(Substrate)

STORAGE

STORAGE
MEMORY

PSC
A3R12E3GEF
620ALAOJ
TAIWAN-G5C
SEC941-L93G
A3R12E3GEF
623BCA54
TAIWAN-G5C
TAV747-C93G
NIKOS
FI7038DC
QEP10338
NIKOS
PD0030DC
GMV0977
6.3V

INTEL® CORE™ i7 PROCESSOR
Memory Controller
Misc IO
Core
Core
Queue
Core
Core
Misc IO
QPI
Intel® Smart Cache
QPI

Shared L3 Cache

L2
L2
L2
L2
Shared L3 Cache

L1
L1
L1
L1
L2
L2
L2
L2
Shared L3 Cache

Size vs. Speed vs. Cost

"Must Go Faster"

Medium	Typical Size (bytes)	Approx. Access Time
CPU Register	64 bits = 8	one cycle < 1 ns
L1 Cache	64 000	4–5 cycles ≈ 2 ns
L2 Cache	256 000	~12 cycles ≈ 5 ns
RAM	8 000 000 000	70 ns
Solid State Drive	256 000 000 000	100 000 ns
Hard Disk Drive	1 000 000 000 000	12 000 000 ns
Optical Drive	650 000 000	150 000 000 ns
Tape Drive	8 000 000 000 000	60 000 000 000 ns
Network	a big truck?	6e7 – inf∞ ns

"Memory"

primary storage

("non-blocking")

volatile
(goes away if power off)

"Storage"

secondary storage

("blocking")

non-volatile
(persists even without power)

If 1 byte = 1 mL and 1 clock cycle = 1s

Medium	Typical Size (bytes)	Approx. Access Time
CPU Register	8 mL (1.5 tsp)	1 s (on page)
L1 Cache	64 L (17 gallons)	2 s (on desk)
L2 Cache	256 L (2 barrels)	5 s (in a pile)
RAM	8k m^3 (3 pools)	1 min (downstairs)
Solid State Drive	256k m^3 (Hindenburg	1 day (other city)
Hard Disk Drive	2m m^3 (Pyramid)	4 months (Mars)
Optical Drive	650 L (5 barrels)	4.8 yrs (Pluto)
Tape Drive	8 m^3 (Chagan Lake)	2 millennia (stars)
Network	planet?	maybe Alpha C., never?

"Memory"

primary storage

("non-blocking")

volatile
(goes away if power off)

"Storage"

secondary storage

("blocking")

non-volatile
(persists even without power)

Part II:
Representations & Encodings

11101000 00011110 11010100 10010110 01000010
10101111 11000100 10001010 11011101 10011111
11101111 11011111
01101101 There are only 10 types of 00000100
00100000 people in the world: those 10001111
00110010 who understand binary, and 11111111
01110010 those who do not. 01011100
00110111 00110001
11000110 10100011 01101010 10010110 11000111
00001000 10010001 00101011 11011101 11100101
01101110 00101011 00011100 10011111 01101001
01010111 00100111 11111010 11111000 10111011
01111000 11000010 01000110 00100000 01111101

Using {0, 1} to Represent [0, 255]

Physical State	OFF	ON	ON	OFF	OFF	ON	ON	OFF
Binary Notation	0	1	1	0	0	1	1	0
Order of Magnitude	2^7	2^6	2^5	2^4	2^3	2^2	2^1	2^0
Decimal Value	128	64	32	16	8	4	2	1
Applicable Value	0	64	32	0	0	4	2	0
Total Decimal Value	102 = 64 + 32 + 4 + 2							

$-\frac{1}{2}$

IEEE 754: Floating-Point Signed Double

- **64 bits total — "*double*" the previous 32-bit word size**
- **52 bits for the *fraction* of the *significand* (with an implicit "1" bit)**
  - Decimal example: in 1.5204 x 10^4, the *fraction* is 5204
- **11 bits for the *exponent* — where the *bicimal point* should *float* to (order of mag.)**
  - Many special rules – encoding patterns for ± 0, ± infinity, NaN, etc.
- **1 bit for *sign* (0 positive, 1 negative)**

Hexadecimal Notation

Hex. digit	0	1	2	3	4	5	6	7	8	9	a	b	c	d	e	f
Dec. notation	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Bin. notation	0000	0001	0010	0011	0100	0101	0110	0111	1000	1001	1010	1011	1100	1101	1110	1111

- **Base-16: uses sixteen different digits per "place" (order)**
- **To avoid ambiguity: prefaced `0x` or `U+` or #, or subscript$_{16}$**
- **Much easier to convert b2 to/from b16 than to/from b10**
- **Example: what is `0x2a` (i.e. $2a_{16}$, `U+2a`) in b2? 10111001 in hex?**

of Shōchū, and the center of that
as being Shōwa. In regard to it
signed Kunimitsu, there prob-
rs. In the Shōwa Hon (Book
e the son of Bizen Saburō
riod, he is made out to be
en he was 88 years old,
rom Kunimune, there
time of Kunitsuna,
iro Den seems to
ōwa and Genkō
of suguba, and
ths. If Kuni-
smith as a
that was
or son.
nt in
lare

nakura, they were probably dis-
the family of Rai Kunitoshi of Kyoto.
mitsu and Kunihiro were also both called
sebe, and Hasebe Kunishige of Yamashiro was probably
someone who came after this.

PLATE I: KUNIMITSU

PAGE K337

Kunimitsu and Kunihiro cast a large shadow in the Kama-
kura period. In ancient times, the eldest son of an extended
family was made the center and all worked together, and
at the same time, in the pupil system, obtaining influence
by changing to the name of even a famous person was not
considered under ordinary circumstances. Also, as for the
father-son, teacher-pupil relationship, the continuation of
the one kanji of the name was the usual. I can think of the
MITSU since Osafune Mitsutada and Nagamitsu, the KUNI
of the Rai Mon, and the KUNI in the Sōshū smiths passed
on to Kunihiro, the son of Kunimitsu. After Hiromitsu, the
names of Hiromasa, Sukehiro, Hirotsugu etc. extended on
into the Muromachi period.

The names in the columns, top to bottom, starting with the
right hand column, are as follows.

KUNIMUNE, KUNIMITSU, KUNIHIRO, KUNISHI
(YAMASHIRO HASEBE)
UNITSUNA, YUKIMITSU, HIROMITSU
SAMUNE, SADAMUNE, AKIHIRO

line is a conjectural

of the bōshi.

PAGE K338

PLATE I: BUNPŌ SANNEN SANGATSU HI
PLATE II: KUNIMITSU

According to the writings of the Unchimyō Collection, the Bunpō Sannen Kunimitsu at the right became the third generation.

KUNIMITSU UDA

[ŌJI 1362 ETCHŪ] CHŪKOTŌ JŌSAKU 國光

The early Kunimitsu that moved his residence from Yamato no Kuni Uda to Etchū and entered the priesthood was said to be of around Bunpō, but the existing Kunimitsu works are of around the Yoshinochō period. This smith is probably the father of Ōei Kunifusa and Kunimune nado. He signed with a small signature, hamon is sugu.

MEI: UDA KUNIMITSU

KUNIMITSU TANSHŪ JŪ

[ŌJI 1362 TAJIMA] 國光

He is the founder of the Hōjō-ji Ha, and is said to be one of the three disciples of Sōshū Sadamune, but along with the two disciples of Masamune, this is a story that [illegible] *within the scope of the actual*

MEI:

.... . .– .. .– .. ––– .–– ––– .–. .– .. –..

HELLO WORLD

5
XYZABCDEFGH

ASCII

- American Standard Code for Information Interchange (1960s)
- 7-bit unsigned integers (stored in 8 bits) = 128 chars… +?

Binary	Decimal	Glyph	Binary	Decimal	Glyph
0010 1110	46	.	0011 1010	58	:
0010 1111	47	/	0011 1011	59	;
0011 0000	48	0	0011 1100	60	<
0011 0001	49	1	0011 1101	61	=
0011 0010	50	2	0011 1110	62	>
0011 0011	51	3	0011 1111	63	?
0011 0100	52	4	0100 0000	64	@
0011 0101	53	5	0100 0001	65	A
0011 0110	54	6	0100 0010	66	B
0011 0111	55	7	0100 0011	67	C
0011 1000	56	8	0100 0100	68	D
0011 1001	57	9	0100 0101	69	E

UTF-8

- *Universal Coded Character Set* + *Transformation Format* – 8-*bit*
- Handles every *code point* of **Unicode** (1.1M+; ~260K assigned)
- *Variable-width*: one to four 8-bit unsigned integers (*code units*)
- Superset of ASCII — backwards-compatible (best for web)

Glyph	Unicode Code Point	Code Unit 1: *singleton* or *lead*	Code Unit 2: *trail 1*	Code Unit 3: *trail 2*	Code Unit 4: *trail 3*

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❤	U+2764	1110 0010	1001 1101	1010 0100	

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❤	U+2764	1110 0010	1001 1101	1010 0100	
J	U+004A	0100 1010			
S	U+0053	0101 0011			

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I	U+0049	0100 1001			
❤	U+2764	1110 0010	1001 1101	1010 0100	
J	U+004A	0100 1010			
S	U+0053	0101 0011			
😄	U+1F604	1111 0000	1001 1111	1001 1000	1000 0100

UTF-16

- Variable-width: one or two 16-bit unsigned integers
- Incompatible with ASCII (no 8-bit blocks)
- byte vs. word stream issues
- byte order ambiguity
- space inefficiency for most languages, even C/J html
- (Sort of) predated UTF-8, which is why stuff inherits it

Image Encoding

- **Simple *bitmaps* are triads of 8-bit unsigned ints for RGB values**
- **8 bits makes 256 possible brightnesses per *channel***
- **"24-bit" (8 + 8 + 8) monitors have 256^3 = ~16.8M RGB distinct channel combinations ("colors").**
  - Since grayscale means RGB channels have to be the same, that's still only 256 possible B&W values.

[The Analytical Engine] might act upon ***other things besides number***, were objects found whose ***mutual fundamental relations*** could be expressed by those of the abstract science of operations, and which should be also susceptible of adaptations to the action of the operating notation and mechanism of the engine... Supposing, for instance, that the ***fundamental relations of pitched sounds*** in the science of ***harmony*** and of musical composition were susceptible of such expression and adaptations, the engine might compose elaborate and scientific pieces of music of any degree of complexity or extent.

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~ Ada Lovelace

Audio Encoding

- Simplest is raw PCM (pulse-code modulation)
- 44,100 *samples* per second; each sample 16-bit *amplitude*
- Different amplitudes over time models an audio wave
- DAC converts values to speaker cone analog signal

Part III:
Abstractions & Languages

Machine Code & Assembly

- Every CPU has its own *instruction set* — binary codes that trigger the CPU to perform operations on registers.

	op. code	source register	target reg.	destination reg.	shift amount	function type
instruction	000000	00001	00010	00110	00000	100000
hex	0x0	0x1	0x2	0x6	0x0	0x20
decimal	0	1	2	6	0	32
meaning	arithmetic	register 1	register 2	register 6	no offset	addition
English	*"take the value in register 1, add the value in register 2, place the result in register 6"*					
assembly	`add $t6, $t1, $t2`					

Compilers & Interpreters

- **First compiler written in 1952 by Grace Hopper, for A-0.**
- *"[She] helped teach the machines a language, stopped them from speaking in undecipherable numbers."* — 60 minutes
- **Followed by Mark 1, FORTRAN, COBOL, etc.**

C → machine code

CoffeeScript → JavaScript

Operating Systems & System Calls

More nuanced / complex...

based on *Advanced Linux Programming*

Languages & Memory Management

- Languages are a *specification*
- Compilers generate the real instructions to alter registers
- Some languages let you instruct the compiler to attempt to alter memory (C)
- Others only provide high-level *data types*, and it is up to the compiler/interpreter to figure out what to do (JS)

```
char ch = 'c';
char t;
char *chptr = &ch;
t = *chptr;
```

```
var ch = 'c';
var t = ch;
```

Part IV:
Abstract Data Types
& Data Structures

MEMORY

The Array Data Structure (non-JS*)

Pseudocode	Compiler/Intepreter	Memory
vals = int8 Array(5)	`vals` is 5 bytes at 0x3A6	_ _ _ X X X X X _ _ _ _
vals[0] = 9	put `9` at 0x3A6 + 0 = 0x3A6	_ _ _ 9 X X X X _ _ _ _
vals[3] = 4	put `4` at 0x3A6 + 3 = 0x3A9	_ _ _ 9 X X 4 X _ _ _ _
vals[2] // undef.	what is at 0x3A6 + 2 = 0x3A8	_ _ _ 9 X X 4 X _ _ _ _
vals[3] // 4	what is at 0x3A6 + 3 = 0x3A9	_ _ _ 9 X X 4 X _ _ _ _

The Stack ADT

- **Collection of elements**
- **Ordered**
- **Elements can repeat (not a set)**
- **Some example operations:**
  - Make a new stack
  - Add an element to the stack ("push")
  - Retrieve an element from the list ("pop") - *must be LIFO (Last In, First Out)*
  - Check if stack is empty
  - Look at the top element without removing it ("peek")
  - Clear the stack

The Stack ADT & Array DS

Stack Feature / Operation	Array Implementation with `top`
Collection of elements	Store values at memory addresses
Ordered	Sequential addresses maintain ordering
Create new stack	Initialize a new array
Push onto stack	Insert value at `top` var (next index to use)
Pop off of stack (LIFO)	Use `top` index to return latest value
Check if stack is empty	Return whether `top` variable is 0

ADTs vs DSs

Common Abstract Data Types	(Some) Data Structures
Set	List, Linked Tree, Trie, Hash Table, etc.
List	Linked List, Array
Stack	Array, Linked List
Queue	Linked List, Deque
Map (Associative Array / Dictionary / etc.)	Hash Table, Association List, Red-Black Tree
Graph	Adjacency List, Adjacency Matrix
Tree	Linked Tree, Heap

WHAT ABOUT JS?

Sorta-new concept: Built-In Types

- *ADT* or Abstract Data Type: describes the behavior we want
- *DS* or Data Structure: how to actually implement an ADT
- **Built-In Type: the building blocks provided by a given language**
  - language *might* specify an ADT: compiler authors decide what DS to use
  - language *might* specify a particular DS: compiler should (in theory) use it
  - or even something in between, like "the foo ADT but operation X must be constant time" (which strongly hints at a particular DS)

JavaScript Primitive (Immutable) Data Types

- `Undefined` · default for unassigned vars / nonexistent props
- `Null` · `typeof` is wrong; Null is a primitive, not "object"
- `Boolean` · could be 1 bit, but may not be *
- `String` · ES: engines use UTF-16 †
- `Number` · ES: 64-bit signed double float ‡
- `Symbol` · ES6: a unique token, can be key for objects

The JavaScript Non-Primitive Data Type

- `Object`
  - Mutable (can change)
  - Collection of *properties* – key-value pairs ("map")
  - Variable assignment copies reference, not value; it "points to" the object
  - Many other types are actually objects. Examples:
    - **Function**
    - **Array**
    - **Typed Array** (ES6-only)
    - **Regular Expression**, **Date**, others
    - Constructed primitives (**String**, **Number**, **Boolean**, etc.)

pass by value (primitives)

pass by value (primitives)

```
let x = 5
```

pass by value (primitives)

```
let x = 5
```

x → 5

pass by value (primitives)

```
let x = 5
let y = x
```

x → 5

pass by value (primitives)

```
let x = 5
let y = x
```

```
x → 5
y → 5
```

pass by value (primitives)

```
let x = 5
let y = x
x = 8
```

```
x → 5
y → 5
```

pass by value (primitives)

```
let x = 5
let y = x
x = 8
```

```
x → 8
y → 5
```

pass by value (primitives)

```
let x = 5
let y = x
x = 8
y // 5
```

```
x → 8
y → 5
```

pass by reference (Objects)

pass by reference (Objects)

```
let x = { age: 5 }
```

pass by reference (Objects)

```
let x = { age: 5 }
```

```
x → { age: 5 }
```

pass by reference (Objects)

```
let x = { age: 5 }
let y = x
```

```
x → { age: 5 }
```

pass by reference (Objects)

```
let x = { age: 5 }
let y = x
```

```
x → { age: 5 }
y ↗
```

pass by reference (Objects)

```
let x = { age: 5 }
let y = x
x.age = 8
```

```
x → { age: 5 }
y ↗
```

pass by reference (Objects)

```
let x = { age: 5 }
let y = x
x.age = 8
```

```
x → { age: 8 }
y ↗
```

pass by reference (Objects)

```
let x = { age: 5 }
let y = x
x.age = 8
y.age // 8
```

```
x → { age: 8 }
y ↗
```

Live Demo:
Pass by Ref. vs. Pass by Value

QUEUES & LINKED LISTS

The Queue ADT

- Like Stack, except FIFO (First In, First Out)
- Collection of elements
- Ordered / sequential
- Operations:
  - Enqueue (add)
  - Dequeue (remove)
  - Peek
  - Clear
  - IsEmpty… etc.

The Linked List DS

- Data structure used for *list, stack, queue, deque* ADTs etc.
- Uses *nodes* which encapsulate a value and pointer(s)
- Main entity holds reference(s) to just a head and/or tail node
  - the "handle(s)"
- Each node then *points* to the next and/or previous node
  - "singly-linked" (unidirectional) vs. "doubly-linked" (bidirectional)

Linked List

Head:

Linked List

Linked List

Linked List

Linked List

Linked List

Linked List

Linked List

Linked List

(some) pros/cons: Linked Lists vs Arrays

Operation	Linked List	Typed Array
Reach element in middle	Must crawl though nodes	Constant time
Insert in middle or start	Constant time (if we have ref).	Must move all following elements
Add element to end	With handle, constant time	Constant time
Space per element	Container + element + pointer(s)	Just element!
Total space	Grows as needed	Pre-reserved & limited*
Physical locality	Not likely	Best possible

WORKSHOP