

Computer Arithmetic

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Optional Readings from Textbooks

- “Computer Organization and Design,” Chapter 3 “Arithmetic for Computers.”
- “Computer Architecture: A Quantitative Approach,” Appendix A “Instruction Set Principles.”

Road Map

- Binary and hexadecimal representations
- Binary Math
- Two's Complement Encoding
- Floating-point Numbers
- Basic ALU Design

Binary and hexadecimal representations

Numbering Systems

- We use a decimal numbering system
- Base is 10
- There are ten different digits, starting with zero (0 – 9).
- Expressing a decimal number, we write it with n digits as $i_n i_{n-1} i_{n-2} \dots i_1 i_0$. The actual value of this number is $i_n * 10^n + i_{n-1} * 10^{n-1} + i_{n-2} * 10^{n-2} + \dots + i_1 * 10^1 + i_0 * 10^0$
 - E.g. 256 express the value of $2 * 10^2 + 5 * 10^1 + 6 * 10^0 = 256_{\text{base}=10}$.

Binary Numbers

- Similar to decimals, we can express any number in binary with 2 as the base.
- In binary numbers, there are only two different digits, which are 0 and 1.
- For a binary number $i_n i_{n-1} i_{n-2} \dots i_1 i_0$,
 - it's value is $i_n * 2^n + i_{n-1} * 2^{n-1} + i_{n-2} * 2^{n-2} + \dots + i_1 * 2^1 + i_0 * 2^0$
 - Notice that 10s are replaced with 2s.
 - For example, binary number 1011 has a value of $1 * 2^3 + 0 * 2^2 + 1 * 2^1 + 1 * 2^0 = 11_{\text{base}=10}$

Hexadecimal Numbers

- We can also express any number in hexadecimal (hex) with 16 as the base.
- In hex numbers, there are 16 different digits,
 - 0–9 as in decimal
 - The letters A–F for numbers 10 to 16
 - A = 10, B = 11, C = 12, D = 13, E = 14, F = 15
- For a hex number $i_n i_{n-1} i_{n-2} \dots i_1 i_0$,
 - it's value is $i_n * 16^n + i_{n-1} * 16^{n-1} + i_{n-2} * 16^{n-2} + \dots + i_1 * 16^1 + i_0 * 16^0$
 - Notice that 10s are replaced with 16s.
 - For example, binary number A1B7 has a value of $A * 16^3 + 1 * 16^2 + B * 16^1 + 7 * 16^0 = (10 * 16^3 + 1 * 16^2 + 11 * 16^1 + 7 * 16^0)_{\text{base}=10} = 41399_{\text{base}=10}$

Some Conventions

- We can write a number with its base in subscript
 - E.g., 1001_{10} is a decimal number, 1001_2 is a binary number and 1001_{16} is a hexadecimal number.
- In most programming languages, you can write
 - `0bDDDD`, as binary numbers. E.g., `0b0001010`
 - `0xDDDD`, as hex numbers, E.g., `0x10AB`
- I may use any of these formats in the slides.

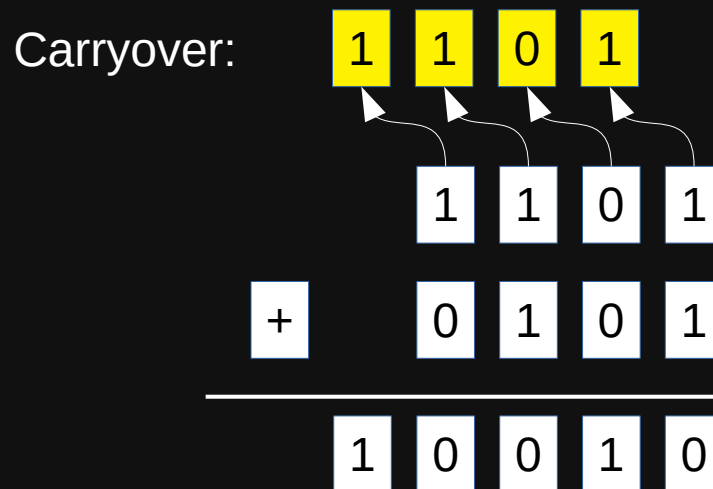
Binary Math

Single Digit Sums

- $0_2 + 1_2 = 1_2$
- $1_2 + 0_2 = 1_2$
- $0_2 + 0_2 = 0_2$
- $1_2 + 1_2 = 10_2$

Multiple Digits Sums

- Adding two binary numbers is the same as adding two decimal numbers
 - Add from the right-most digit
 - Keep track of carryovers



Adding 1101_2 (13_{10})
and 0101_2 (5_{10}).

Other Math Operations

- Subtractions, multiplications and divisions are carried out similarly to decimal numbers as well.
- Bit-wise logical operations are straightforward.

$$\begin{array}{r} 1101 \\ \& 0101 \\ \hline 0101 \end{array}$$

Bit-wise and
 1101_2 (13_{10}) and
 0101_2 (5_{10}).

Two's Complement Encoding

Numbers inside Computers

- Since we only have 0s and 1s (charged/uncharged transistors) in our computers, all numbers are represented in binary.
 - A charged bit represents 1, and an uncharged bit represents 0.
- For unsigned and positive integers, they are represented with bits corresponding to their binary representations.
- For negative integers, they are represented using a format slightly different from their absolute values, as there are no negative signs in transistors
 - This format is called **Two's complement** encoding.

Two's Complement

- Let's consider a simple case:
 - We want to express -2_{10} or -10_2 , with 3 binary bits.
 - With 3 bits, they can represent $2^3=8_{10}=1000_2$ numbers.
 - We then **define** the representation of -2_{10} or -10_2 as: $1000_2 - 10_2 = 110_2$
- In general, computers express a negative number $-x$ with N bits using the binary representation of its complement, $2^N - x$.
 - Note that 2^N must be larger than $| -x |$, otherwise you need more bits.

Generalizing Two's Complement Encoding

- In two's complement encoding with N bits,
 - For a positive number x , it is encoded with its binary representation.
 - For a negative number $-x$, it is encoded with the binary representation of its complement, $2^N - x$.
- Note that, for two's complement encoding, the highest bit for a negative number is always 1.

Example: 3-bit Two's Complement Encoding

Decimal Value	Two's Complement Binary Encoding
0	000
1	001
2	010
3	011
-4	100
-3	101
-2	110
-1	111

A Faster Algorithm of Two's Complement

- A faster algorithm to find the two's complement encoding for $-x$ is,
 - Get the encoding for x . For example, for -1 , we starts with the 3-bit encoding of 1 , which is 001
 - Invert the digits of x 's encoding, i.e., 0 becomes 1 , 1 becomes 0 . E.g., for 001 , inverting the digits gives 110 .
 - Add 1 to the inverted encoding gives the encoding of $-x$. E.g., add 1 to 110 gives 111 , which is the two's complement encoding for -1 .
- I am not going to discuss why this algorithm works, but you are welcome to formally prove its correctness.

Why Two's Complement?

- Two's complement encoding makes addition very easy.
 - No need to convert adding a negative number into subtracting.
 - For example, adding -1 with 3 . With two's complement, we are adding 111 with 011 .
 - Simply adding them as two positive binary integers, we have $111 + 011 = 1010$.
 - Removing the left-most bit, we have 010 , which is 2 , the correct result.
 - There are still corner cases to handle, but much easier in general.
- Subtraction is also fairly easy with two's complement.
- Multiplication and division are slightly more difficult than adds and subtractions, but no more difficult than multiplying and dividing in other encodings.

Floating-Point Numbers

Scientific Notation for Real Numbers

- Computers are also used to do computations on real numbers.
- Real numbers are written in the following form in scientific notation

$$m * 10^n$$

- For example,

Decimal Notation	Scientific Notation
2	$2.0 * 10^0$
300	$3.0 * 10^2$
42421.3232	$4.24213232 * 10^4$
-0.2	$-2.0 * 10^{-1}$

Reals in Binary Format with Scientific Notation

- Similarly, we can express reals in binary format with scientific notation:
 $1.xxxxxxx * 2^{eeee}$
- For example:
 - $1.001010 * 2^{10010}$
- The `xxxxxx` is the **fraction** of the real number, while `eeee` is the **exponent** in base 2.
- The dot before the fraction part is called **binary point** (analogous to decimal point).
- Note that there is only one digit before the binary point, and that digit is always 1.
 - Since the digits can only be 1 or 0, we can always remove leading 0s, leaving a 1 before the decimal point.

Floating Point Numbers

- Computer arithmetic that supports binary real numbers in their scientific format is called **floating point**, as the position of the binary point is moving depending on the value of the exponent.
 - An integer is fixed point, as the binary point is always at the end of the integer.
- In C language, real numbers are simply called **floats**.

Encoding Floats with Bits

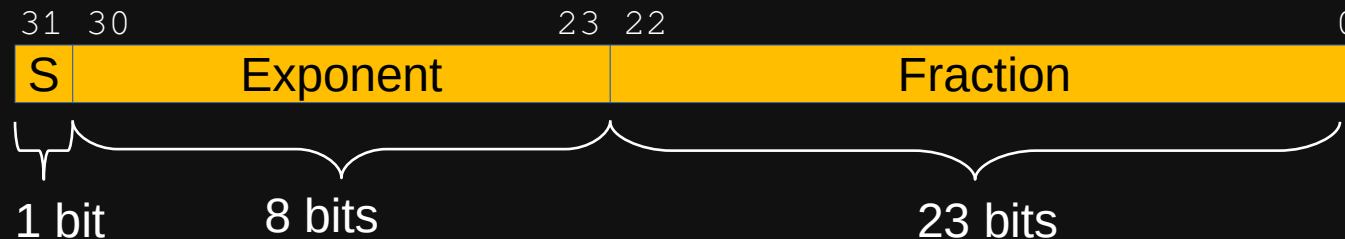
- Derived from the scientific notation, a binary floating point number is uniquely identified by its sign (s), fraction (F) and exponent (E).

$$(-1)^s * 1.F * 2^E$$

- Therefore, computers encode floats with only sign, fraction and exponent.
 - The fraction part is also called “mantissa.”

Encoding Floats with Bits cont'd

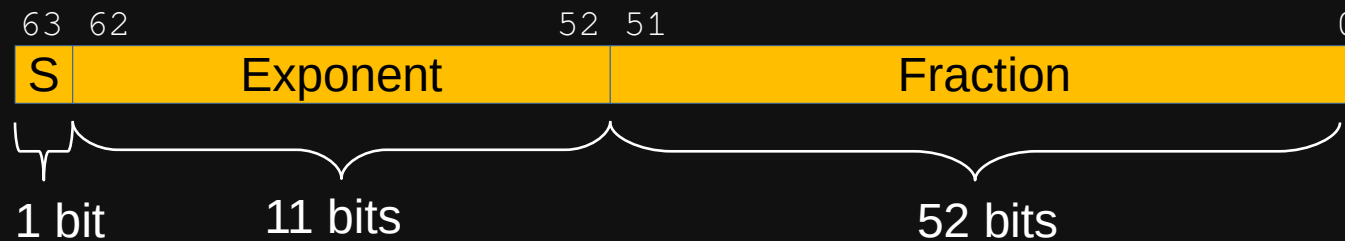
- For 32-bit floats



- 1 bit for the sign, 8 bits for exponent and 23 bits for fractions
- The maximum positive float with 32-bit encoding is $(1+2^{-23}) * 2^{127}$, roughly 10^{38}
- The minimum positive float with 32-bit encoding is $(2-2^{-32}) * 2^{-126}$, roughly 10^{-38}
- Any number larger than the maximum causes an **overflow**, while any number smaller than the minimum causes an **underflow**.

Encoding Floats with Bits cont'd

- For 64-bit doubles



- 1 bit for the sign, 11 bits for exponent and 32 bits for fractions

IEEE 754 Encoding

- IEEE 754 is a standard encoding for floating point numbers.
- The encoding is roughly the same as the 32-bit and 64-bit encoding we have seen.
- Exponent part is encoded with a bias, instead of two's complement
 - If the exponent is E (positive or negative), it is encoded as the binary number of $(E + \text{Bias})$.
 - For 32-bit single-precision floats, the bias is 127.
 - E.g., if the exponent is -5, it is encoded as $(-5+127=122)$ or `0b01111010`.
 - For 64-bit double-precision floats, the bias is 1023.

IEEE 754 Encoding cont'd

- Specially values of the exponent and fraction are reserved to represent special cases

Exponent	Fraction	Value
0	0	0
0b11111111	0	Infinity
0	Not 0	Denormalized (no leading 1 before binary point)
0b11111111	Not 0	Not a number (NaN)

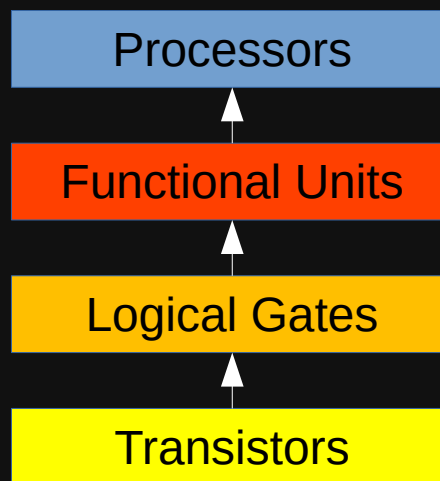
Floating Point Computation

- There are standard algorithms for
 - Converting between binary floats and decimal floats
 - Doing sum, subtraction, multiplication and division.
- I will not cover these algorithms, but you can easily find these algorithms online and in the text book.

Basic ALU Design

Logical Gates

- Processors are built from transistors.
- More accurately, transistors constitute logical gates, logical gates constitute functional units, and functional units constitute processors.

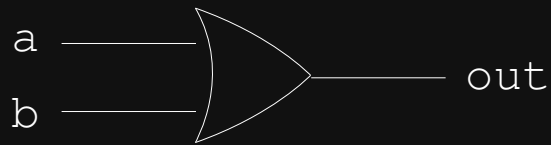


Basic Logic Gates: AND Gate



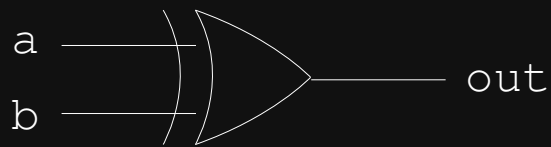
a	b	out
0	0	0
0	1	0
1	0	0
1	1	1

Basic Logic Gates: OR Gate



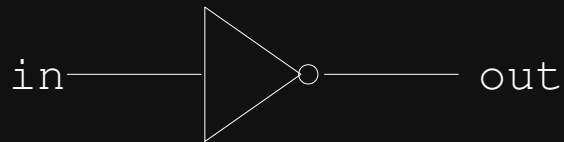
a	b	out
0	0	0
0	1	1
1	0	1
1	1	1

Basic Logic Gates: XOR Gate



a	b	out
0	0	0
0	1	1
1	0	1
1	1	0

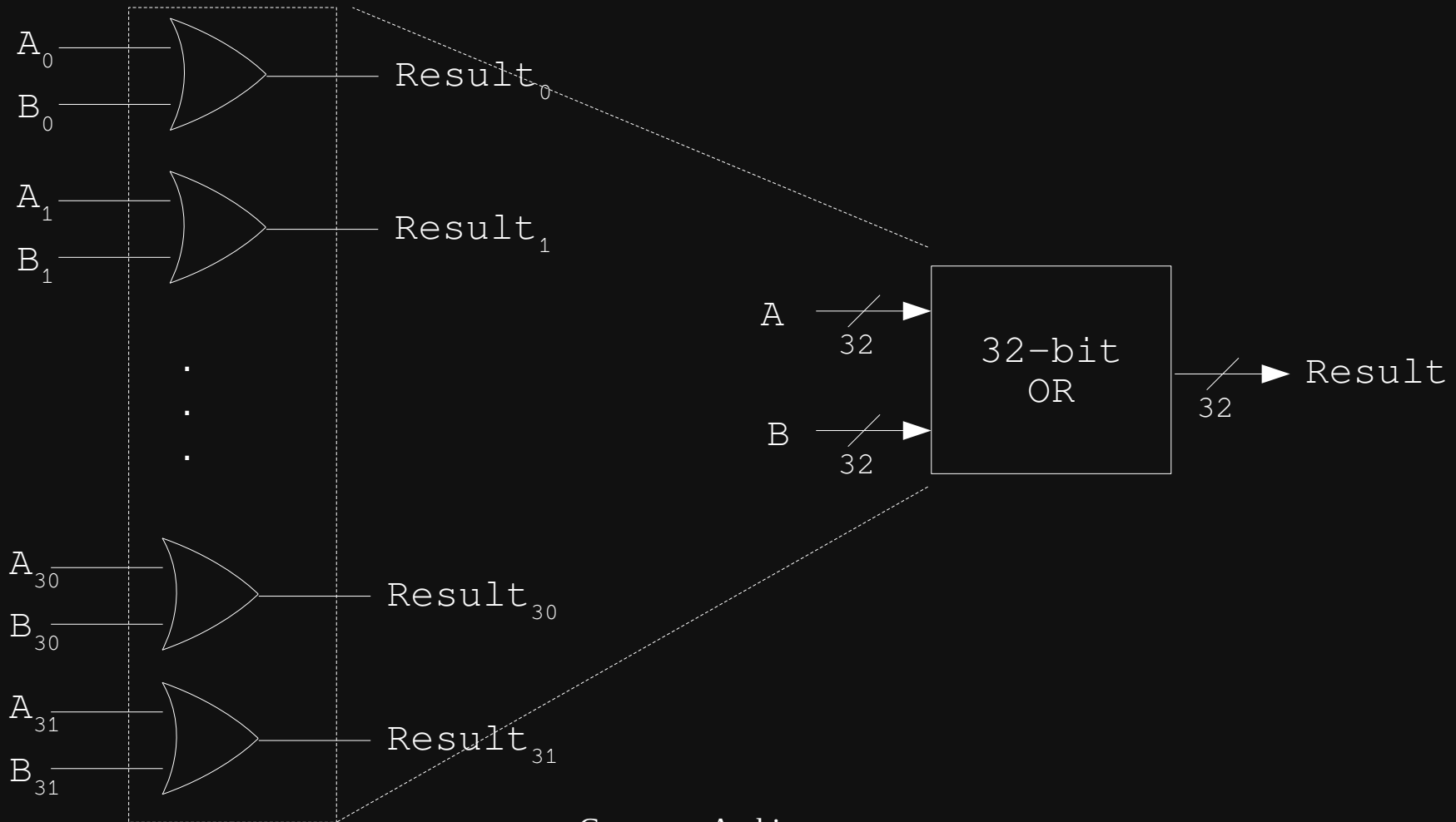
Basic Logic Gates: Not Gate



in	out
0	1
1	0

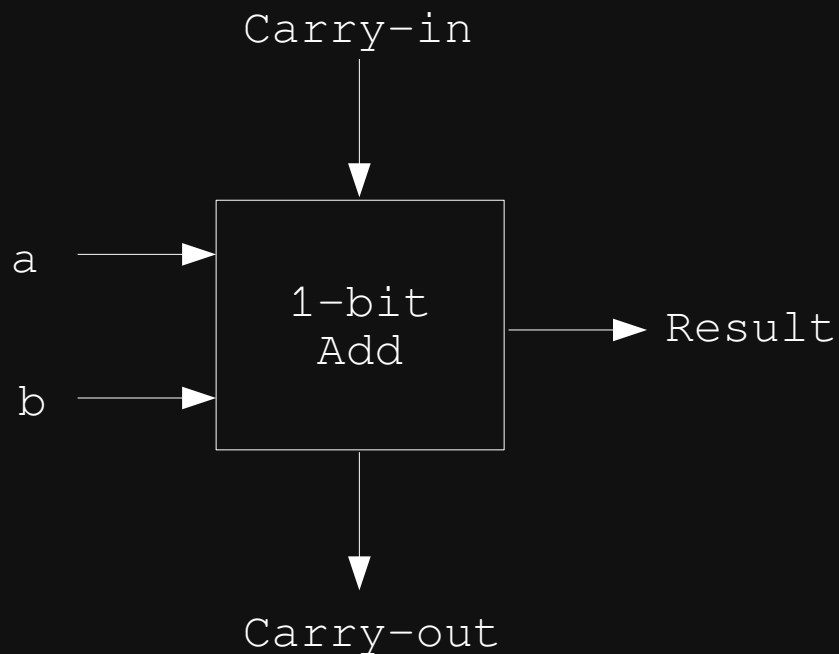
ALU: 32-Bit Bitwise OR

- Connect 32 OR gates in parallel.



ALU Unit: 1-Bit Adder

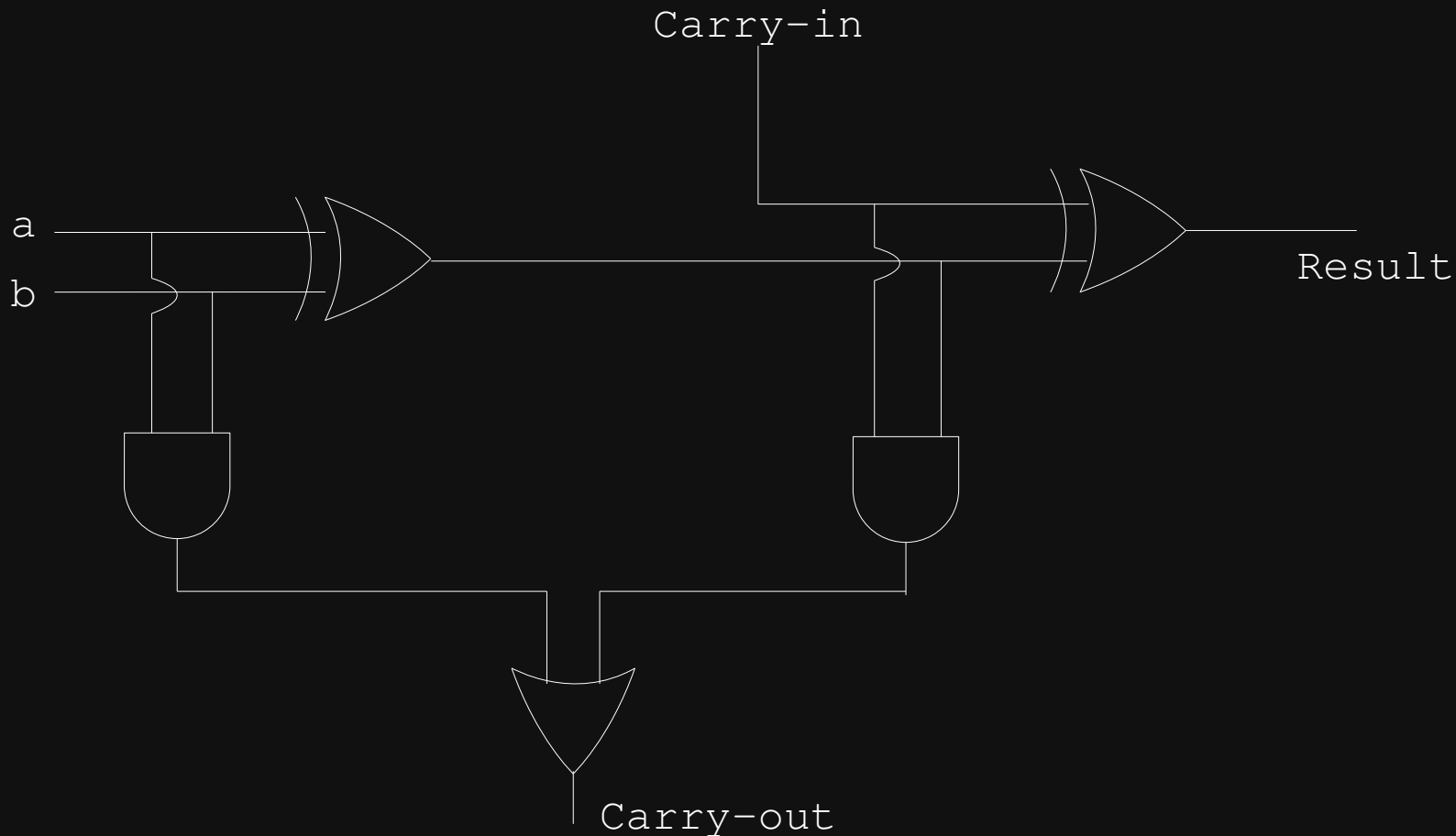
- 1-bit add has two 1-bit inputs and one carry-in.
- It returns one 1-bit results with a carry-out



C_{in}	a	b	Res.	C_{out}
0	0	0	0	0
0	0	1	1	0
0	1	0	1	0
0	1	1	0	1
1	0	0	1	0
1	0	1	0	1
1	1	0	0	1
1	1	1	1	1

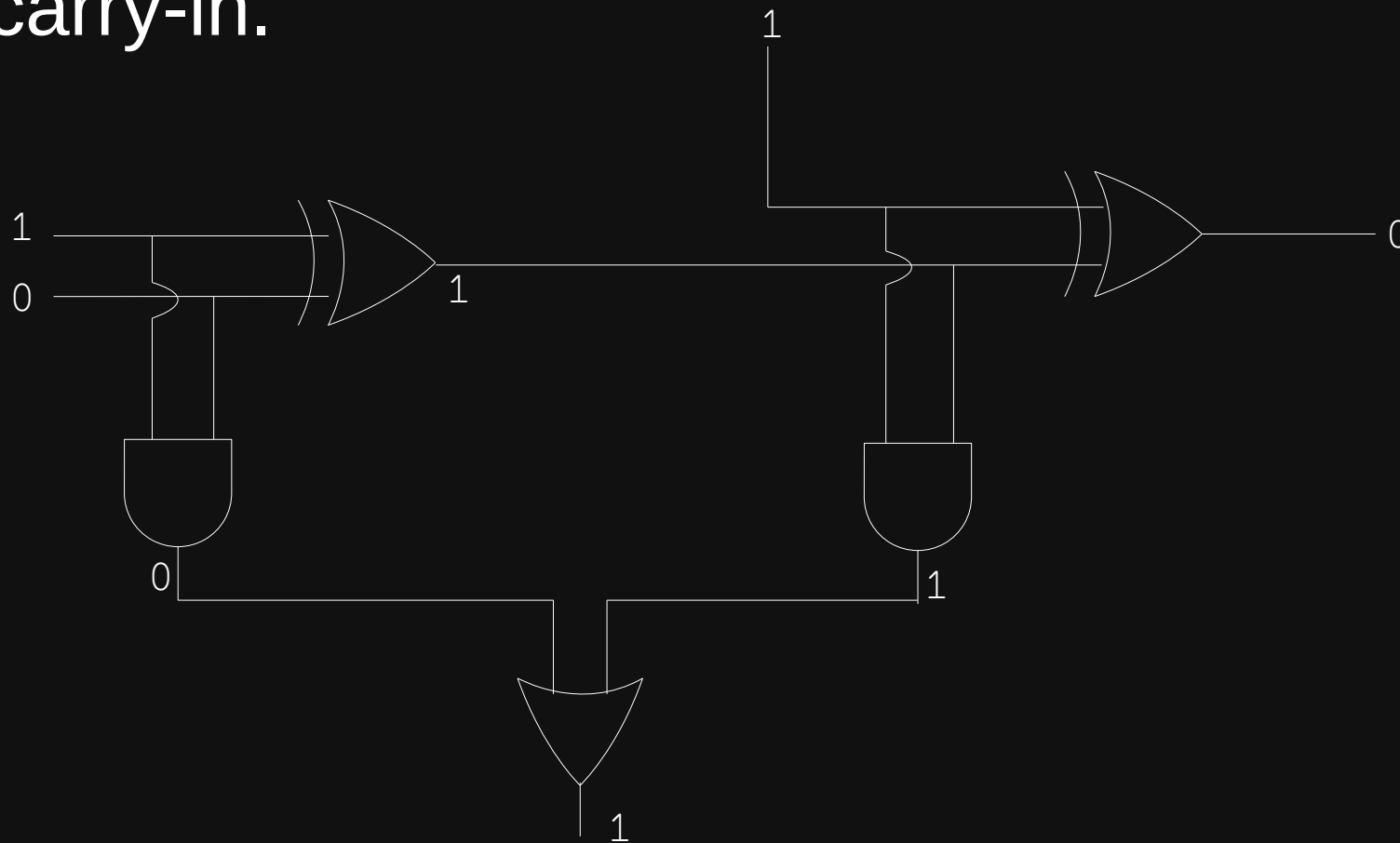
ALU Unit: 1-Bit Adder cont'd

- Internal of 1-Bit add with 5 logic gates



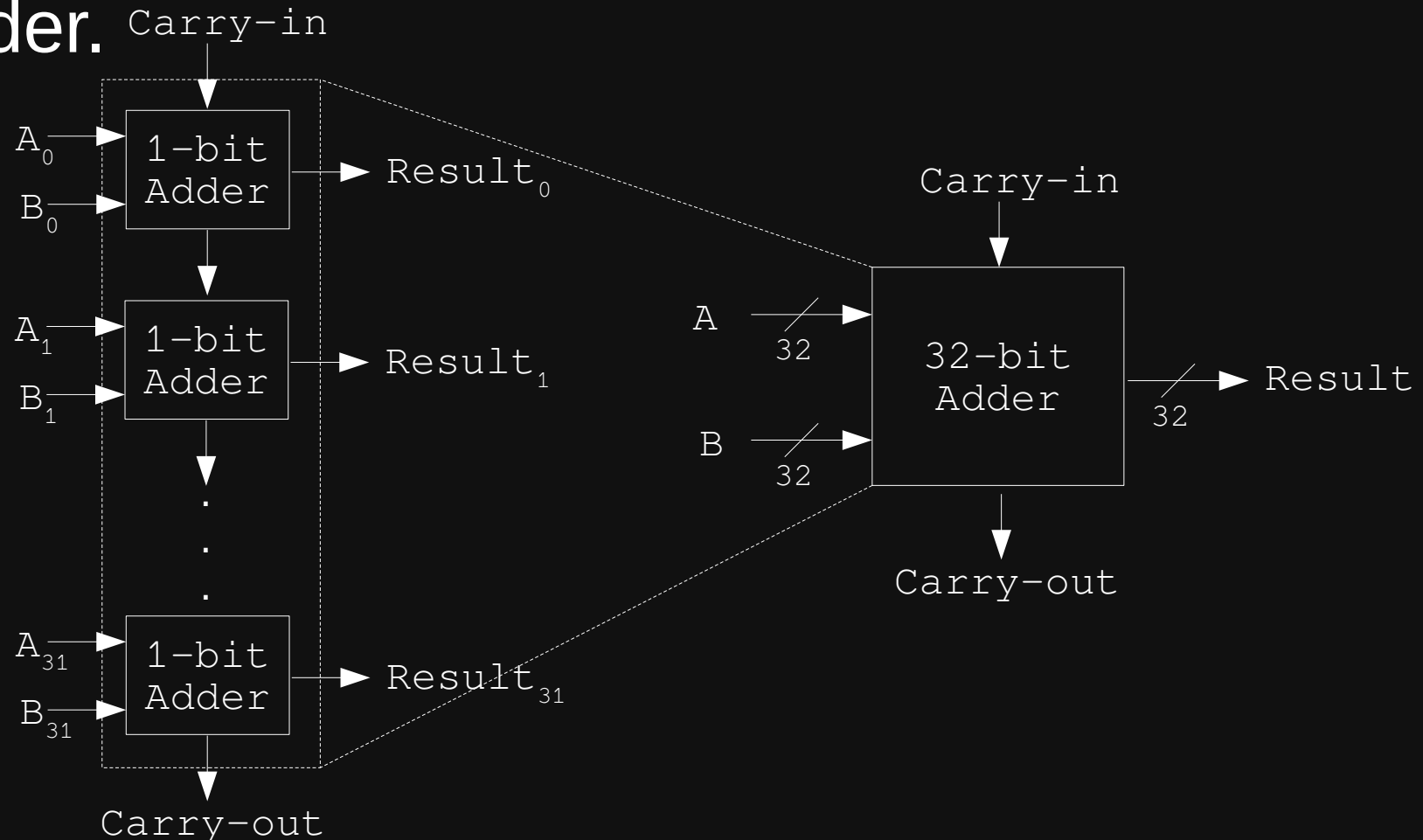
ALU Unit: 1-Bit Adder cont'd

- A simple example of adding 1 and 0, with 1 as carry-in.



ALU Unit: 32-Bit Adder

- Serially connecting 32 1-bit adder gives a 32-bit adder.

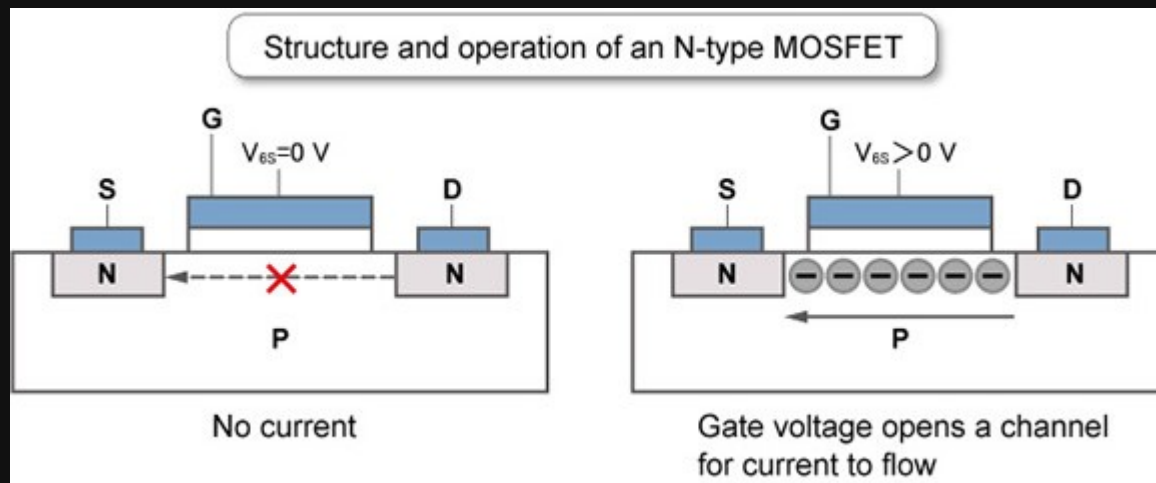


Other Function Units

- Most functional units can be built from logical gates.
 - E.g., subtracter, multiplier and multiplexer
- Some functional units can be very complex, such as branch predictors.

Transistor Basics

- Transistors used in processors are mostly Field-Effect Transistors (FETs).
 - Most common FET is MOSFET (metal-oxide-semiconductor FET).
 - For a MOSFET transistor, when it is given a gate voltage (V_{GS}) that is high enough, the transistor will be turned on and allows current to flow.

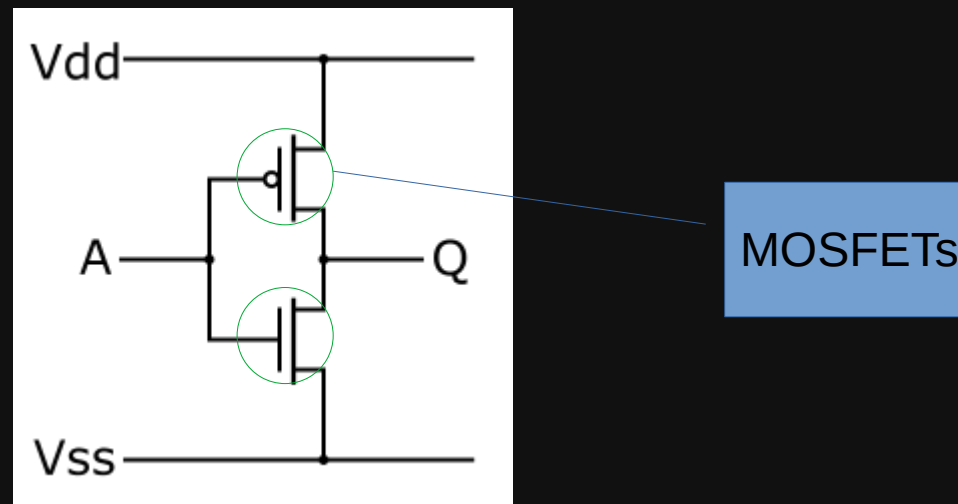


A N-Type MOSFET as an ON/OFF Switch

* figure from <https://www.renesas.com/us/en/support/technical-resources/engineer-school/electronic-circuits-02-diodes-transistors-fets.html>

Transistor Basics cont'd

- A NOT-gate (aka. CMOS inverter) can be built from P-type and N-Type MOSFETs:



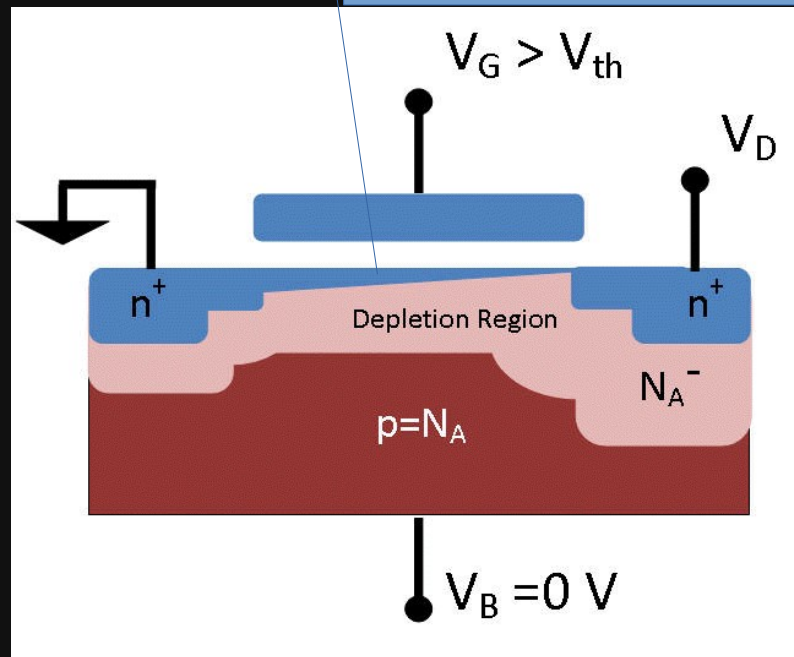
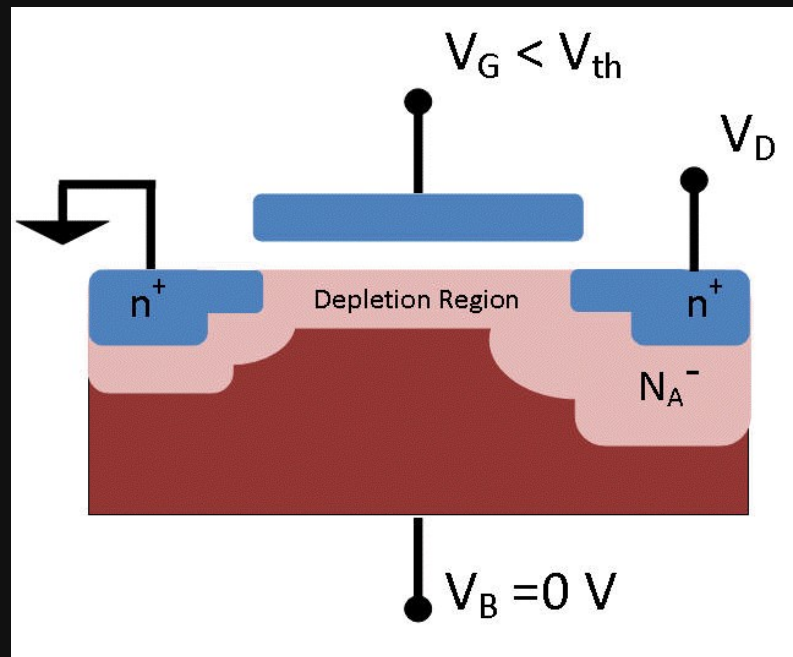
- Similarly, all other gates can be built from transistors

Transistor Basics cont'd

- Computer architects generally ignore MOSFET and the internal design of logic gates. They focus more on the management of functional units.
- But the decline of Dennard Scaling drew computer architects' attention back to MOSFET.
 - For a MOSFET transistor, there is a minimum voltage that is required to turn on the transistor, which is called threshold voltage, V_{th} .
 - As the gate voltage (V_{GS}) keeps reducing, it finally approaches V_{th} . Once V_{GS} is the same as V_{th} , we cannot reduce it anymore, and hence the failure of Dennard Scaling.

Another Illustration of Threshold Voltage

Note the blue materials are connected



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