

BOOLEAN ALGEBRA AND LOGIC

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Bernhard Kainz (with thanks to **A. Gopalan**, **N. Dulay** and **E. Edwards**)

b.kainz@imperial.ac.uk

Learning Objectives

- At the end of this lecture you should:
 - Understand how logic relates to computing problems
 - Be able to represent Boolean logic problems as:
 - Truth tables
 - Logic circuits
 - Boolean algebra

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What is Logic?

- Dictionary definitions (dictionary.com - reduced!)
 - reason or sound judgement
 - a system of principles of reasoning
 - the science that investigates the principles governing correct or reliable inference
- Branch of philosophy
 - Principles of inference
- You use logic all the time in your everyday life

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Propositional Logic

- The Ancient Greek philosophers created a system to formalise arguments called propositional logic

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- A proposition is a statement that can be TRUE or FALSE

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- Propositions can be compounded by means of the operators AND, OR and NOT

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Propositional Logic Example

- Propositions may be TRUE or FALSE, for example:
 - It is raining
 - The weather forecast is bad
- A combined proposition example is:
 - It is raining OR the weather forecast is bad

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Propositional Logic Example

- Can assign values to propositions, for example: I will take an umbrella if it is raining OR the weather forecast is bad

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- Means that the proposition “I will take an umbrella” is the result of the Boolean combination (OR) between raining and weather forecast being bad. In fact we could write:

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- I will take an umbrella = it is raining OR the weather forecast is bad

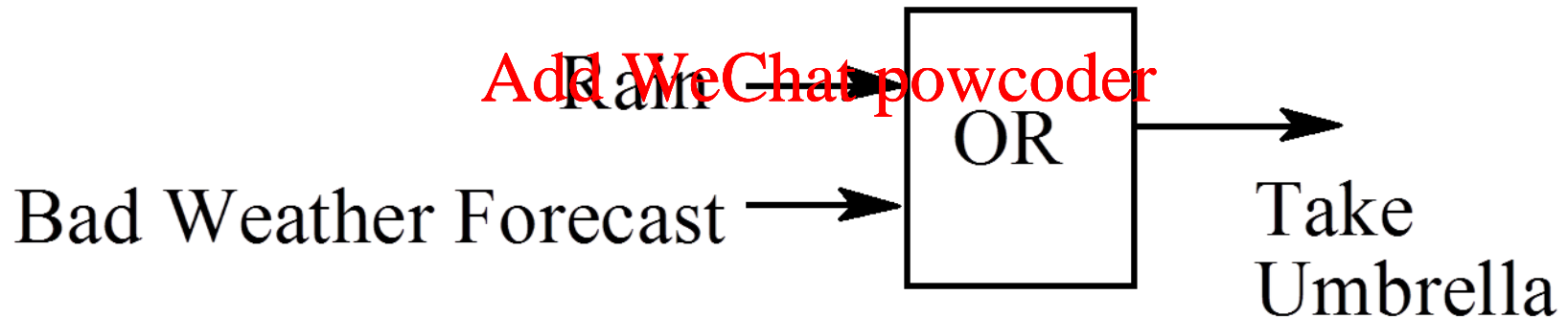
Diagrammatic Representation

- Can think of the umbrella proposition as a result that we calculate from the weather forecast and the fact that it is raining by means of a logical OR

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Truth Tables

- Since propositions can only take two values, we can express all possible outcomes of the umbrella proposition by a table

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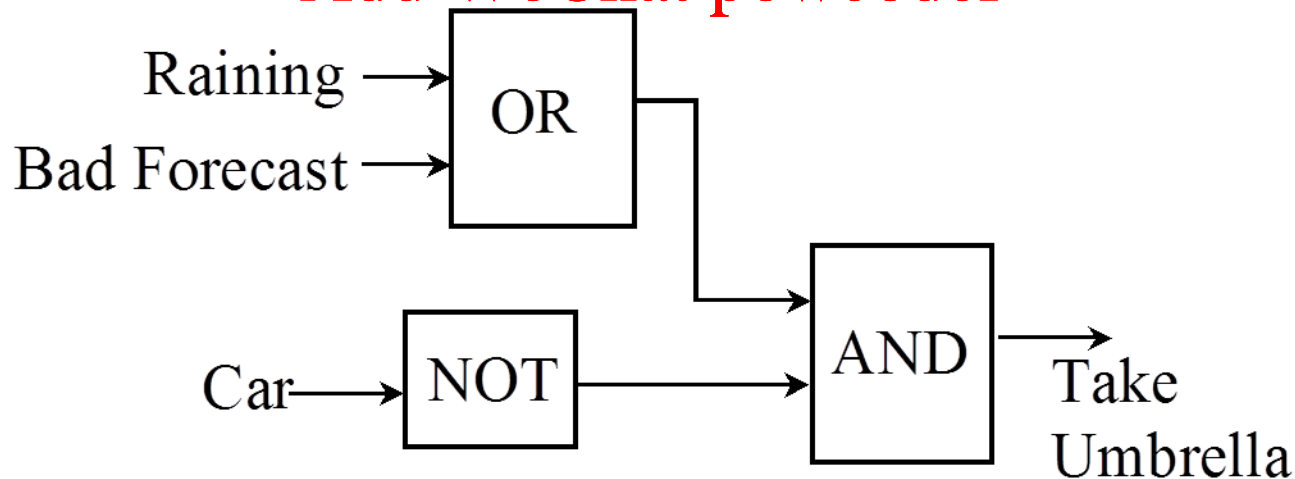
Raining	Bad Forecast	Umbrella
FALSE	FALSE	FALSE
FALSE	TRUE	TRUE
TRUE	FALSE	TRUE
TRUE	TRUE	TRUE

Complex Propositions

- Can make our propositions more complex, for example:
 - $(\text{Take Umbrella}) = (\text{NOT}(\text{Take Car}) \text{ AND } (\text{Bad Forecast}) \text{ OR } (\text{Raining}))$

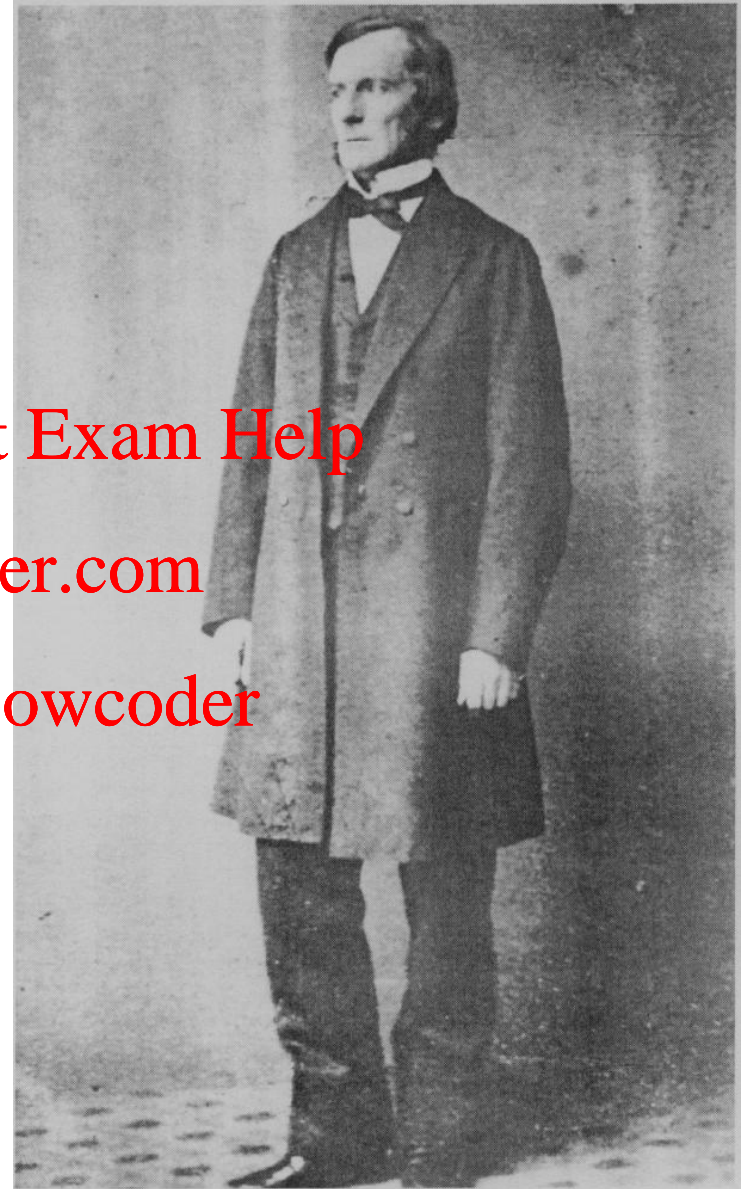
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- Diagrammatical representation



Boolean Logic

- To perform calculations quickly and efficiently we need a more succinct notation than propositional logic
- Need to have well-defined semantics for all the “operators”, or connectives that we intend to use
- Boolean Algebra satisfies the criterion above
- Named after George Boole
- Provides a system of logical operations
- Rules for combining operations
- Describes their application to binary numbers



George Boole: 1815-1864

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Boolean Algebra – Fundamentals

- The truth values are replaced by 1 and 0
 - 1 = TRUE 0 = FALSE

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- Propositions are replaced by variables
 - R = it is raining W = The weather forecast is bad
- Operators are replaced by symbols
 - ' = NOT + = OR • = AND

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Boolean Algebra – Simplify Propositions

- Recall:

- (Take Umbrella) = (NOT (Take Car) AND (Head Forecast) OR (Raining))

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- Using notations notations, we get:

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- $U = (C') \cdot (W + R)$

Boolean Algebra – Precedence

- Operator Precedence
 - Highest precedence operator is evaluated first

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OPERATOR	SYMBOL	PRECEDENCE
NOT	' (\neg)	Highest
AND	• (\wedge)	Middle
OR	+ (\vee)	Lowest

math (logic) symbol

- Note that: $(C') \cdot (W + R)$ is not the same as $C' \cdot W + R$
- Logic operators in, e.g., C:
 - Logical: AND: $\&\&$ OR: $\|$ NOT: $!$
 - (Binary: AND: $\&$ OR: $|$ NOT: \sim)

Boolean Algebra – Truth Tables

- All possible outcomes of the operators can be written as truth tables

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AND •			OR v			NOT '	
A	B	R	A	B	R	A	R
0	0	0	0	0	0	0	1
0	1	0	0	1	1	1	0
1	0	0	1	0	1		
1	1	1	1	1	1		

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Boolean Algebra – Truth Tables

- Given any Boolean expression e.g.: $U = C' \cdot (W + R)$
- We can calculate a truth table for every possible value of the variables on the right hand side
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- For n variables there are 2^n possibilities
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Boolean Algebra – Truth Tables

- Truth table for “Umbrella”

- $U = C' \cdot (W + R)$

R	W	C	$X1=R+W$	$X2=C'$	$U=X1 \cdot X2$
0	0	0	0	1	0
0	0	1	0	0	0
0	1	0	1	1	1
0	1	1	1	0	0
1	0	0	1	1	1
1	0	1	1	0	0
1	1	0	1	1	1
1	1	1	1	0	0
Inputs			Partial Results		Outputs

Boolean Algebra – Rules

- **Note: A and B can be any Boolean Expression**

Negation:

$$(A')' = A$$

$$A \cdot A' = 0$$

$$A + A' = 1$$

Associative:

$$(A \cdot B) \cdot C = A \cdot (B \cdot C)$$

$$(A + B) + C = A + (B + C)$$

Commutative:

$$A \cdot B = B \cdot A$$

$$A + B = B + A$$

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Distributive:

$$A \cdot (B + C) = A \cdot B + A \cdot C$$

$$A + (B \cdot C) = (A + B) \cdot (A + C)$$

Note the precedence

Boolean Algebra – Rules

Single variables (Idempotent law):

$$A \cdot A = A$$

$$A + A = A$$

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Simplification rules with 1 and 0:

$$A \cdot 0 = 0$$

$$A \cdot 1 = A$$

$$A + 0 = A$$

$$A + 1 = 1$$

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Boolean Algebra – de Morgan's Rule

$$(A + B)' = A' \cdot B'$$

$$(A \cdot B)' = A' + B'$$

as before, A and B can be any Boolean expression

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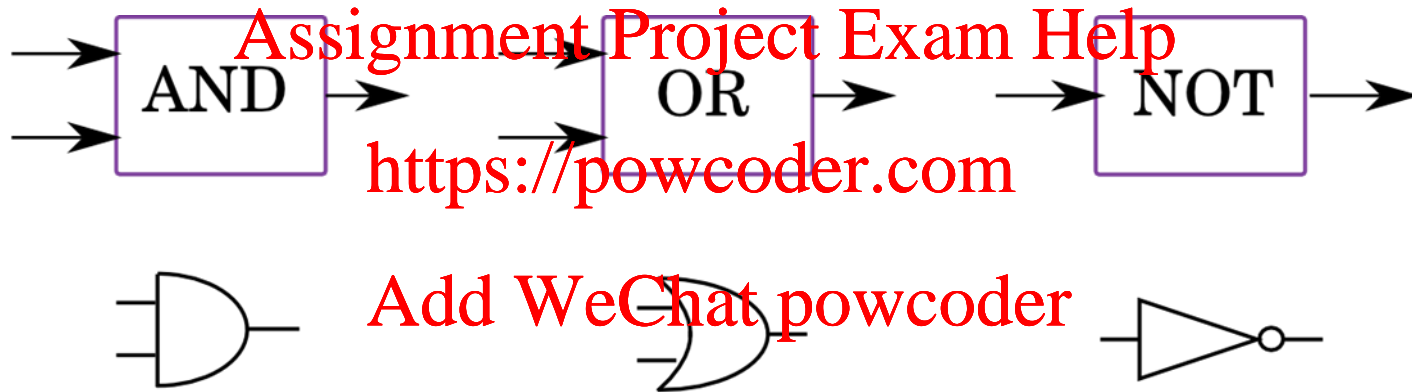
Can generalise to n Boolean variables:

$$(A + B + C + D + \dots)' = A' \cdot B' \cdot C' \cdot D' \cdot \dots$$

$$(A \cdot B \cdot C \cdot D \cdot \dots \cdot X)' = A' + B' + C' + D' + \dots + X'$$

Boolean Functions – Schematic Representation

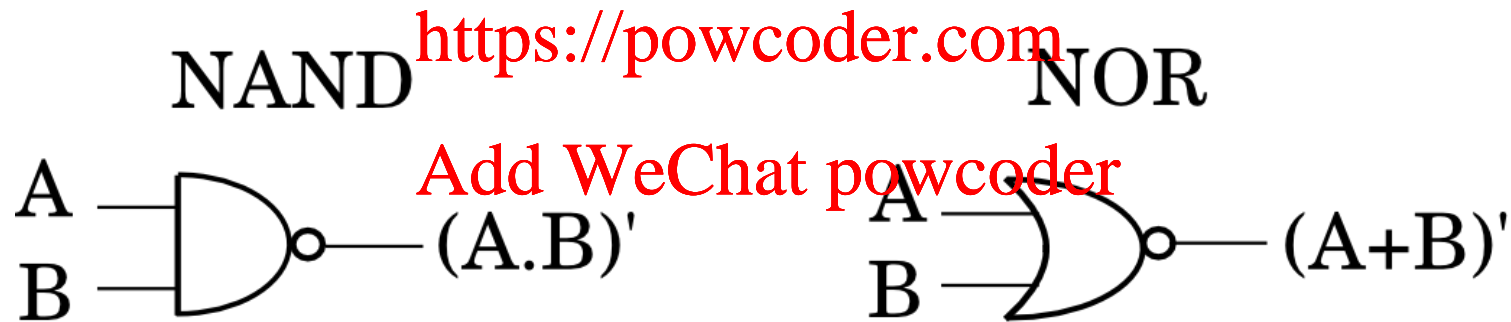
- A standard set of easy-to-recognise symbols is used to represent Boolean functions



- A circle is all that is required to indicate NOT. The triangle is just to indicate Input/Output direction

Inverting Functions

- A circle can be added to the AND and OR symbol outputs to create their inverted functions – NotAnd (NAND) and NotOr (NOR) gates



Building Blocks for Circuits

- NAND/NOR are the commonly used building blocks for most circuits

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- NAND / NOR can easily be constructed from transistors

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- NAND is complete

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- A set of Boolean functions f_1, f_2, \dots is “complete” if and only if any Boolean function can be generated by a combination these functions
- Also called “universal gate”

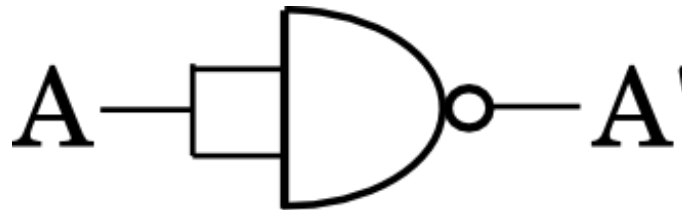
NAND Gate – NOT

- It is possible to build all other gates out of NAND gates

- Create a NOT gate using the idempotent law:

- $A \cdot A = A$ therefore $(A \cdot A)' = A'$

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NAND Gate – AND

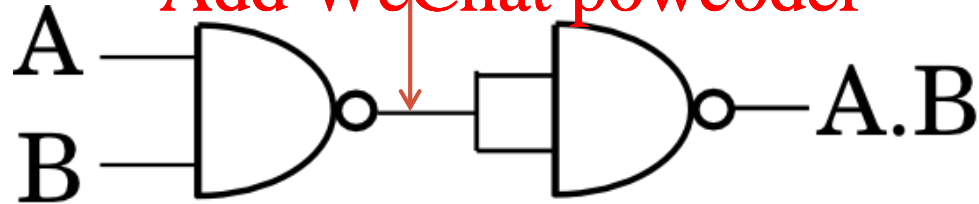
- Create an AND gate using the Involution law:

- $(A')' = A$

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NAND Gate – OR / NOR

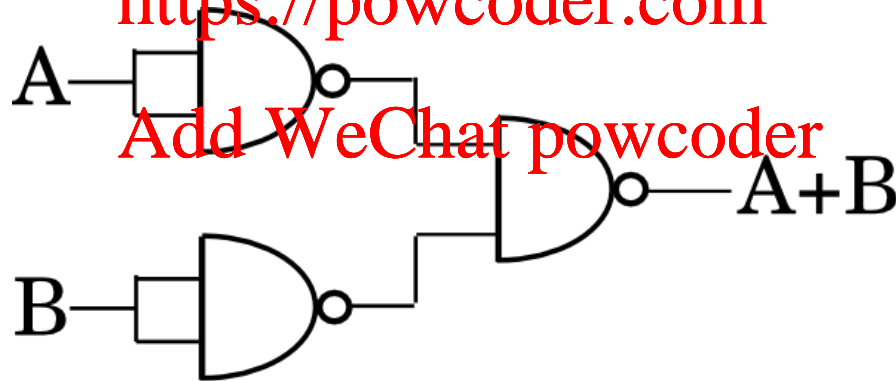
- To make an OR gate we need to apply de Morgan's theorem:

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- $A + B = (A' \cdot B')'$

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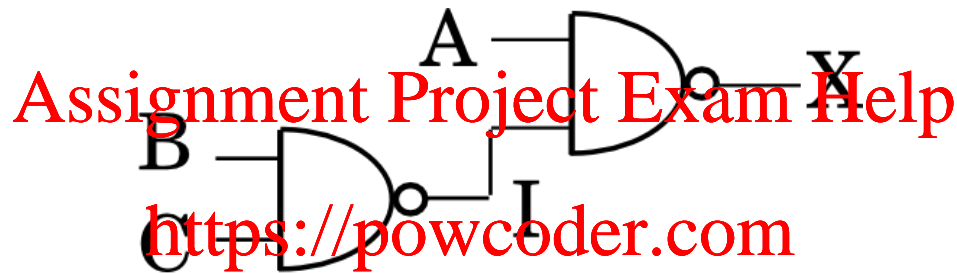
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- Just invert output to get a **NOR** gate 😊

NAND – Complex Circuits

- Consider two cascading NAND Gates



- What circuit have we created?
 - Use Boolean Algebra to find out
 - $I = (B \cdot C)'$
 - $X = (A \cdot I)' = (A \cdot (B \cdot C)')'$
 - Apply de Morgan's law, we get
 - $X = A' + ((B \cdot C)')' = A' + (B \cdot C)$

NAND – Complex Circuits

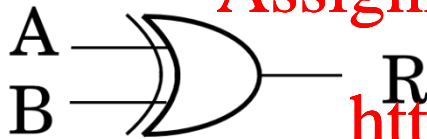
- Truth table for $X = A' + (B \cdot C)$

A	B	C	$B \cdot C$	$X = A' + (B \cdot C)$
0	0	0	0	1
0	0	1	0	1
0	1	0	0	1
0	1	1	1	1
1	0	0	0	0
1	0	1	0	0
1	1	0	0	0
1	1	1	1	1

XOR and XNOR Gates

- Very useful gates

Exclusive Or (XOR)



Exclusive Nor (XNOR)



$$R = A.B' + A'.B$$

$$R = A'.B' + A.B$$

A	B	XOR
0	0	0
0	1	1
1	0	1
1	1	0

A	B	XNOR
0	0	1
0	1	0
1	0	0
1	1	1

Behind the scenes

- Instantaneous on IC?

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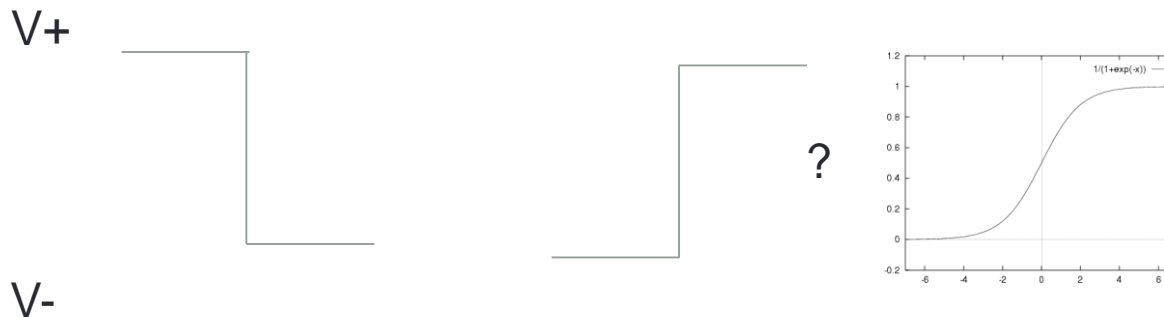


Behind the scenes

- Instantaneous on IC?

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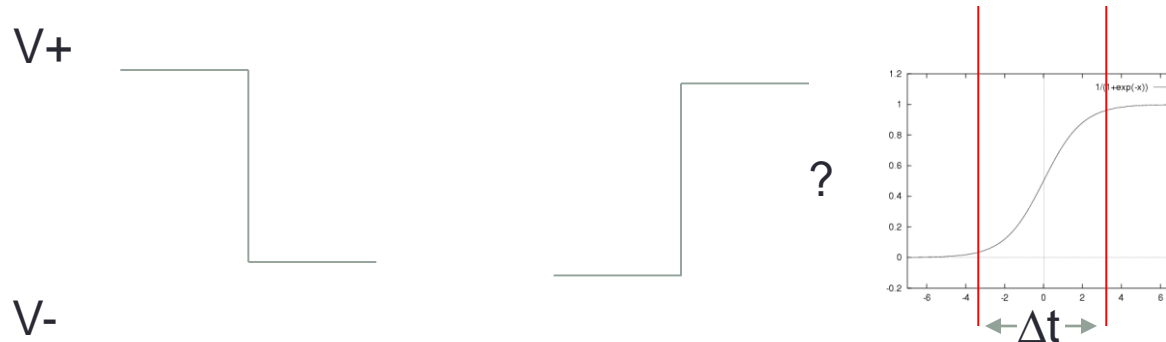


Behind the scenes

- Time delay and saturation limit state 'switching' speed of real in-silico circuits

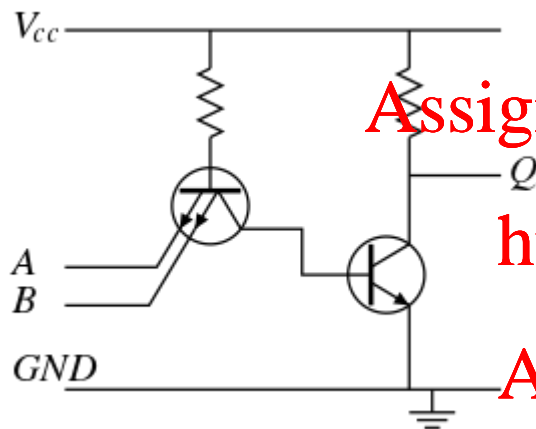
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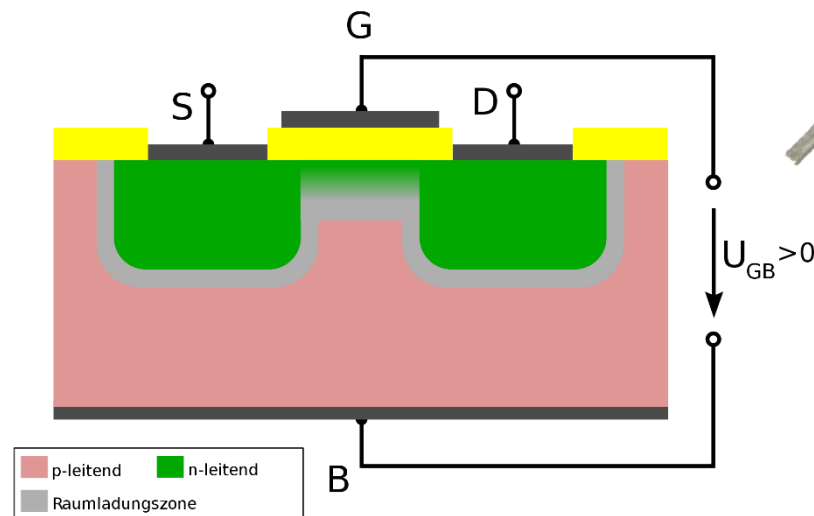
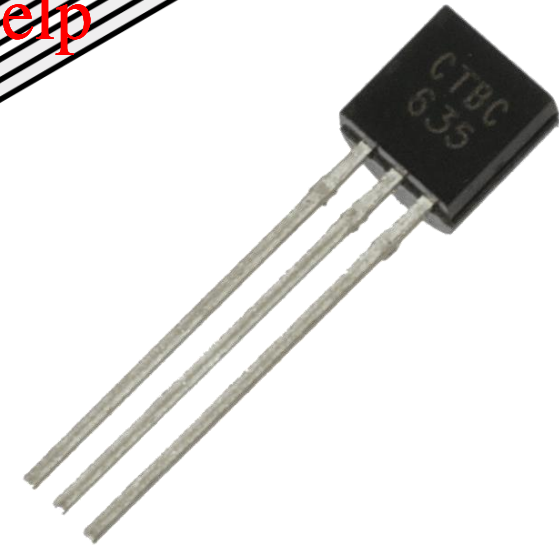
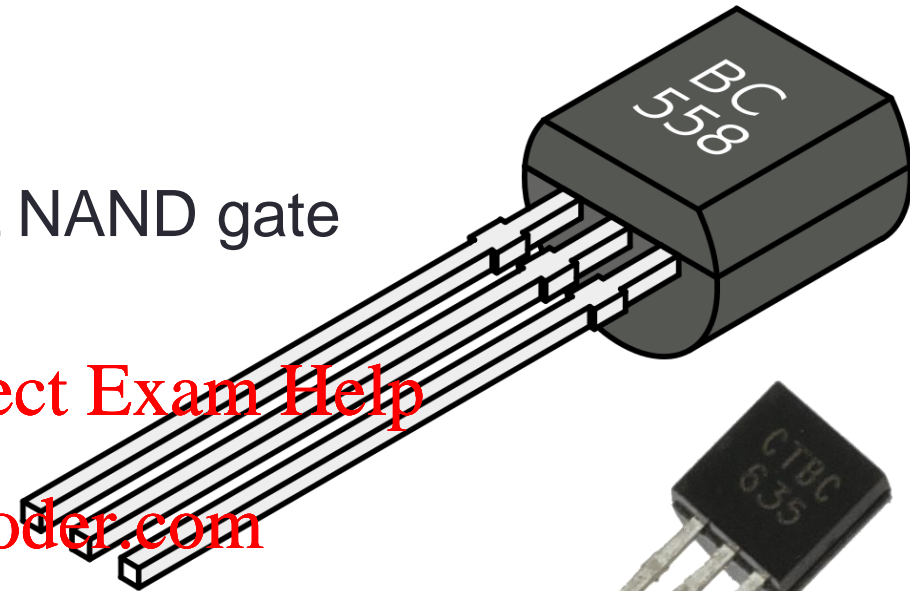
- Transistor-transistor logic TTL NAND gate



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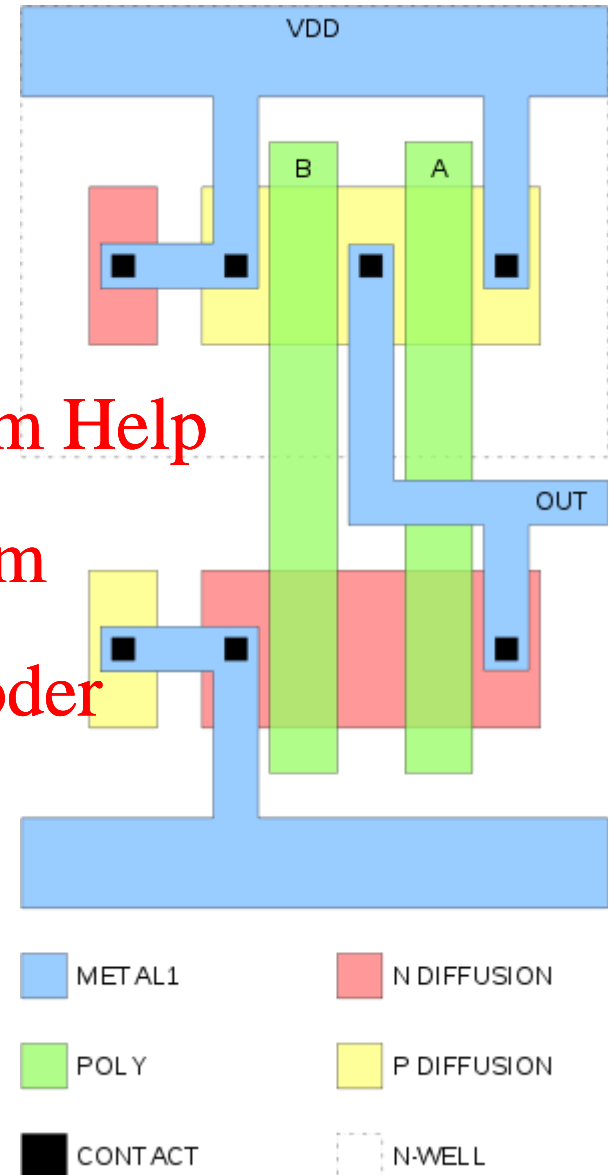
Behind the scenes

- CMOS NAND in silico

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Behind the scenes

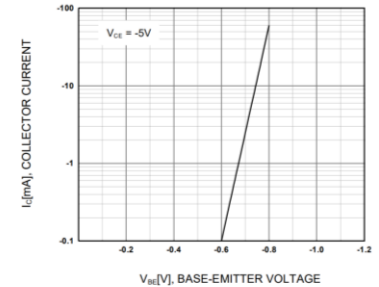


Figure 4. Base-Emitter On Voltage

