

CSE 2600

Intro. To Digital Logic & Computer Design

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&
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Announcements

- Reminder: Prep quizzes are due Monday night with no makeup. Please plan ahead if you have a scheduled conflict; quizzes are always available.
- Prep 2B was due today at 11:00 am, but is still accepted until 11:59 pm (one-time due to the holiday).
- Homework 2B is posted / Due Sunday at 11:59pm
- Office hours: Posted but there may be updates. See “help” page in Canvas or [course site](#)

Studio 2A Highlights

- Unsigned number line
- Two's complement

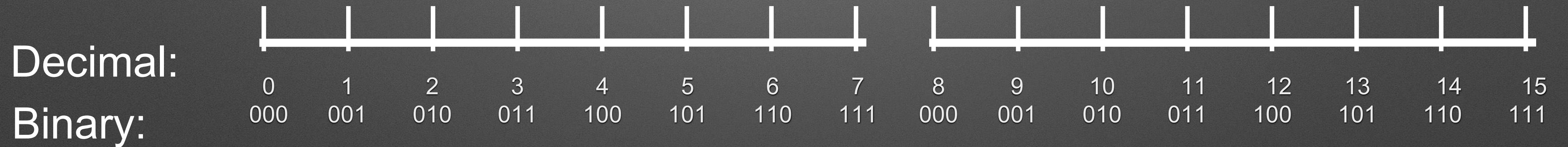
Last Time

- Studio: Binary Number Lines Extended



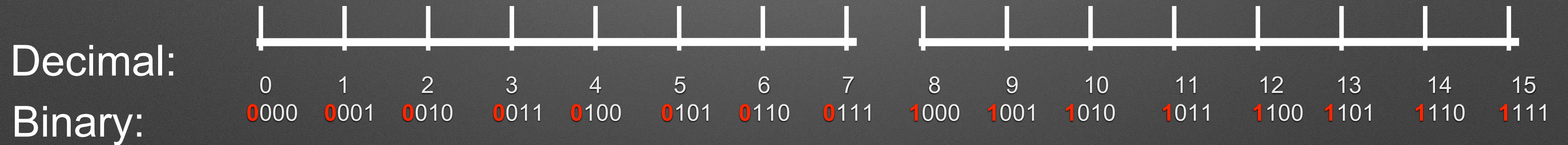
Last Time

- Studio: Binary Number Lines Extended



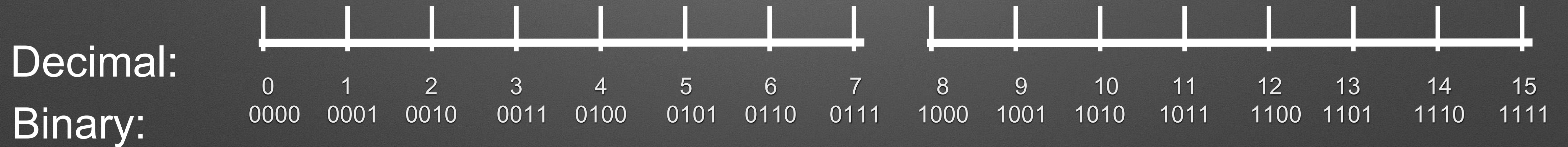
Last Time

- Studio: Binary Number Lines Extended



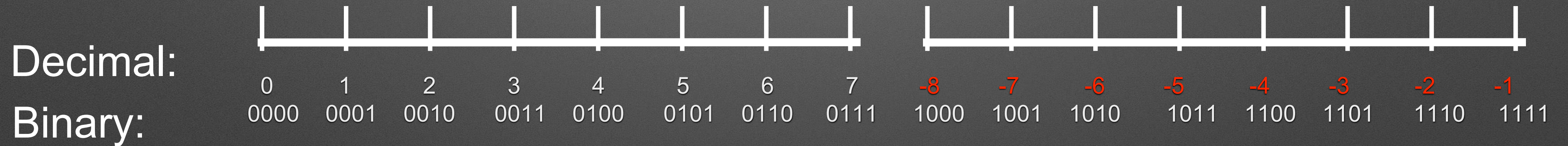
Last Time

- Studio: Binary Number Lines Extended



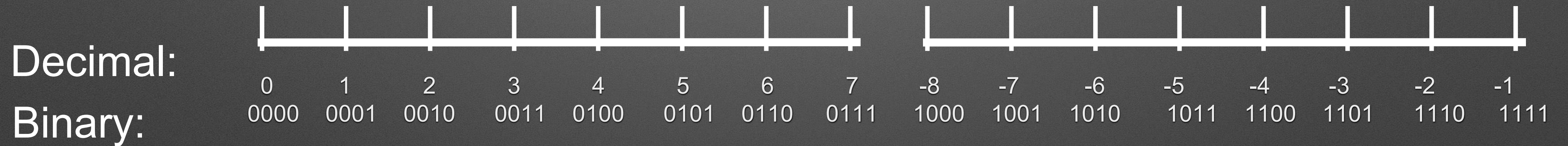
Last Time

- Studio: Two's Complement



Last Time

- Studio: Two's Complement

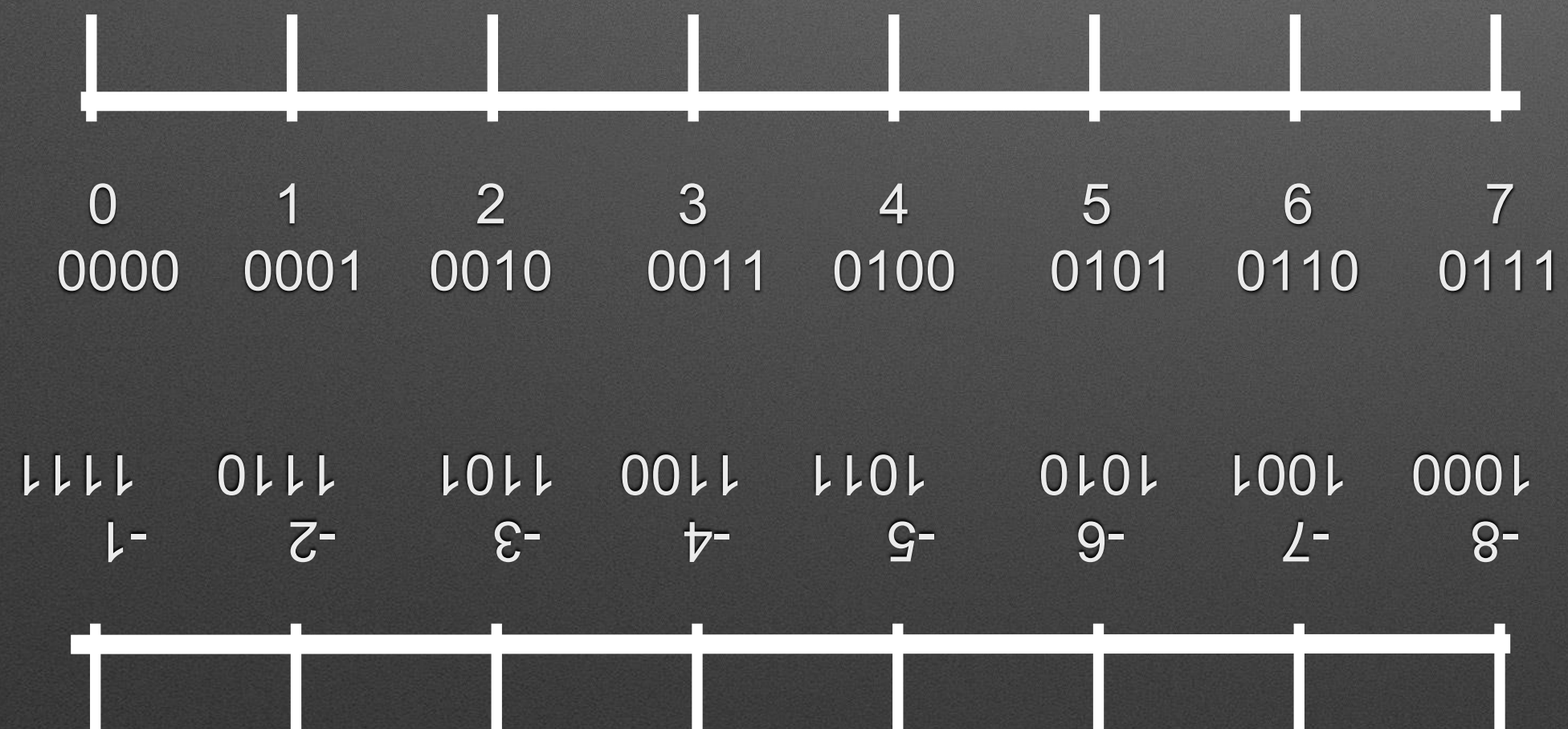


Last Time

- Studio: Two's Complement - Above/Below

Decimal:

Binary:



Last Time

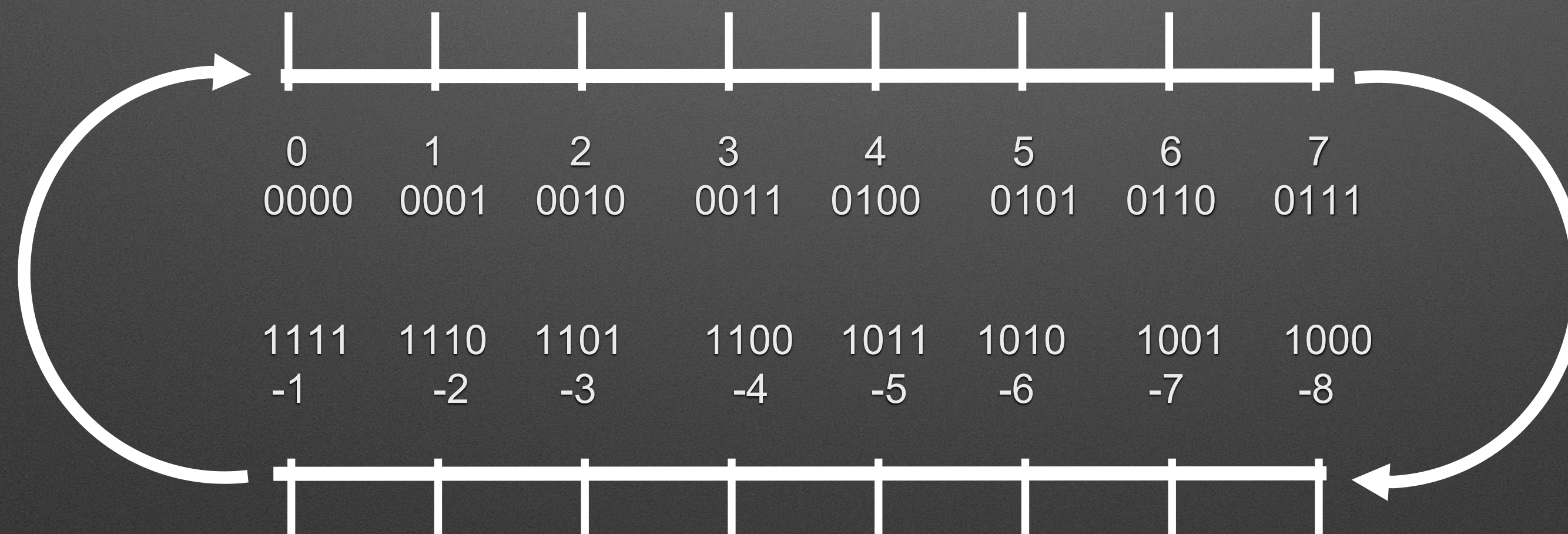
- Studio: Two's Complement - Above/Below & Bitwise Inversion

Decimal:

Binary:

Binary:

Decimal:



Last Time

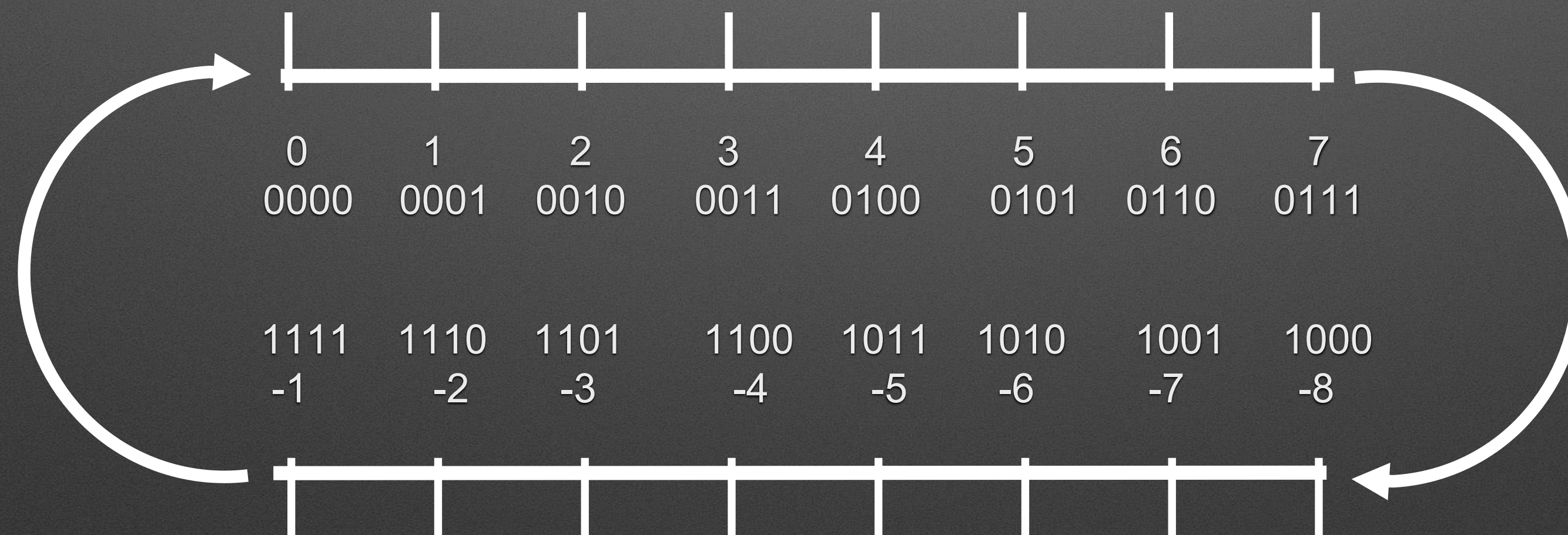
- Studio: Two's Complement - Mathematical Negation ($-1 \times$)

Decimal:

Binary:

Binary:

Decimal:



Last Time

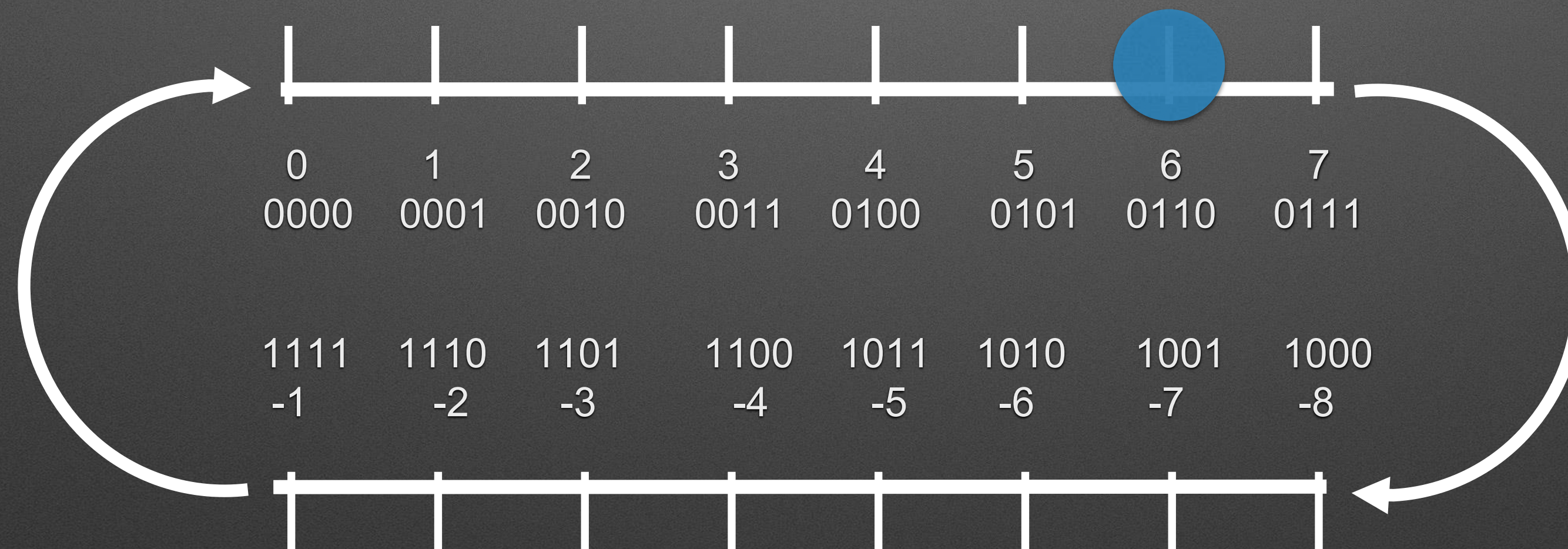
- Studio: Two's Complement - Mathematical Negation (-1×6)

Decimal:

Binary:

Binary:

Decimal:



Last Time

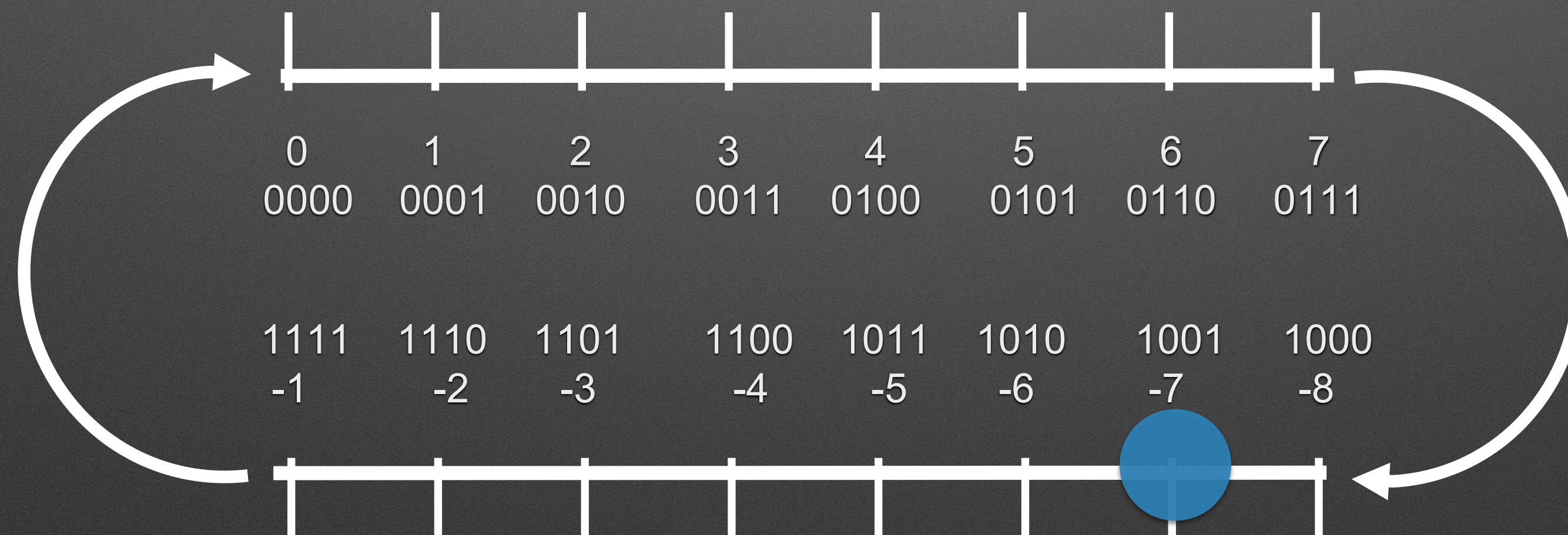
- Studio: Two's Complement - Mathematical Negation (-1×6)

Decimal:

Binary:

Binary:

Decimal:



Last Time

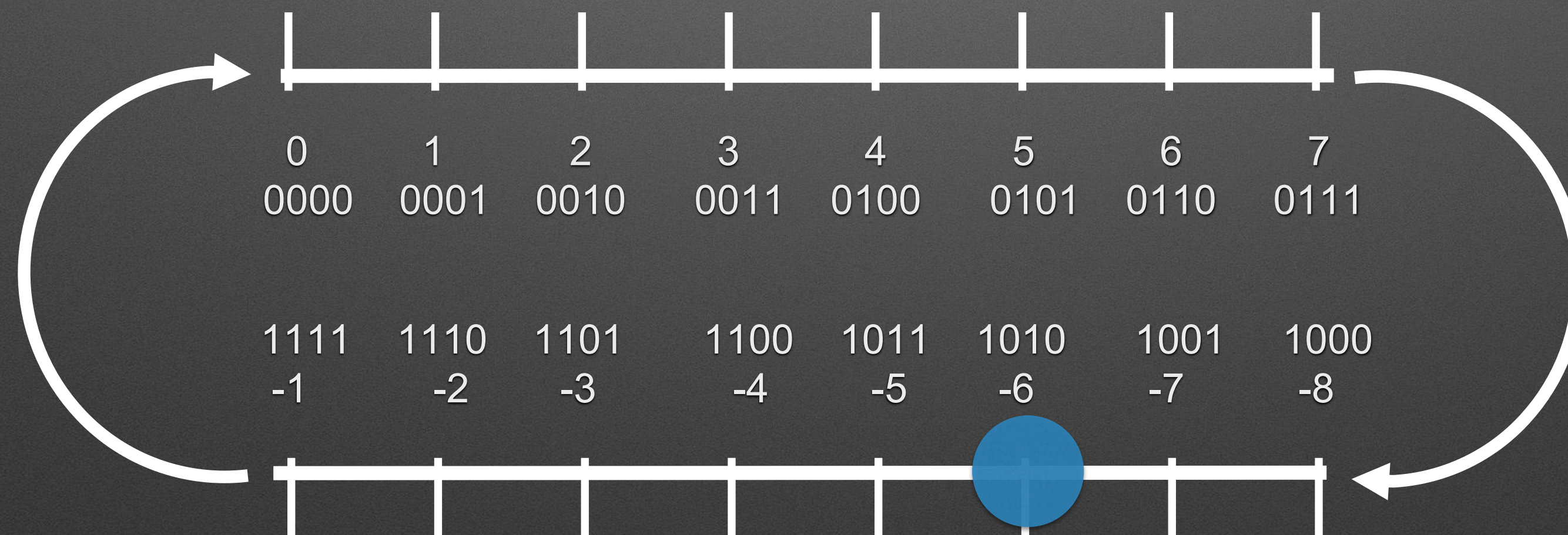
- Studio: Two's Complement - Mathematical Negation (-1×6)

Decimal:

Binary:

Binary:

Decimal:



Last Time

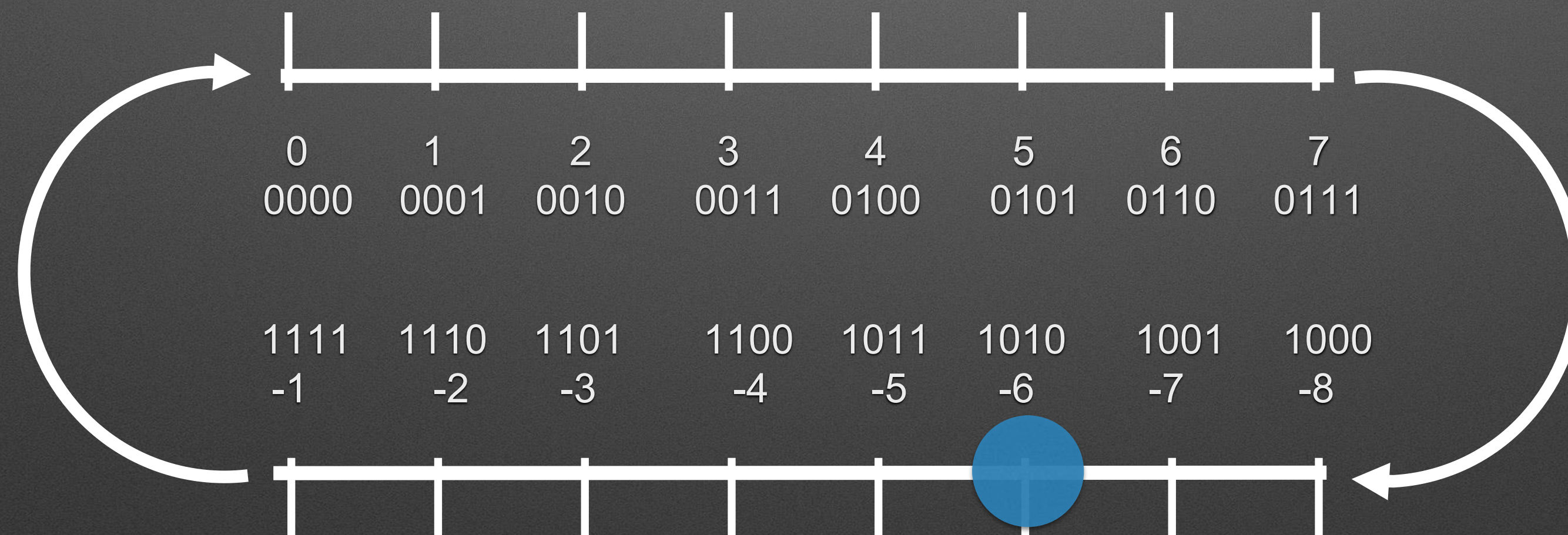
- Studio: Two's Complement - Mathematical Negation (-1×-6)

Decimal:

Binary:

Binary:

Decimal:



Last Time

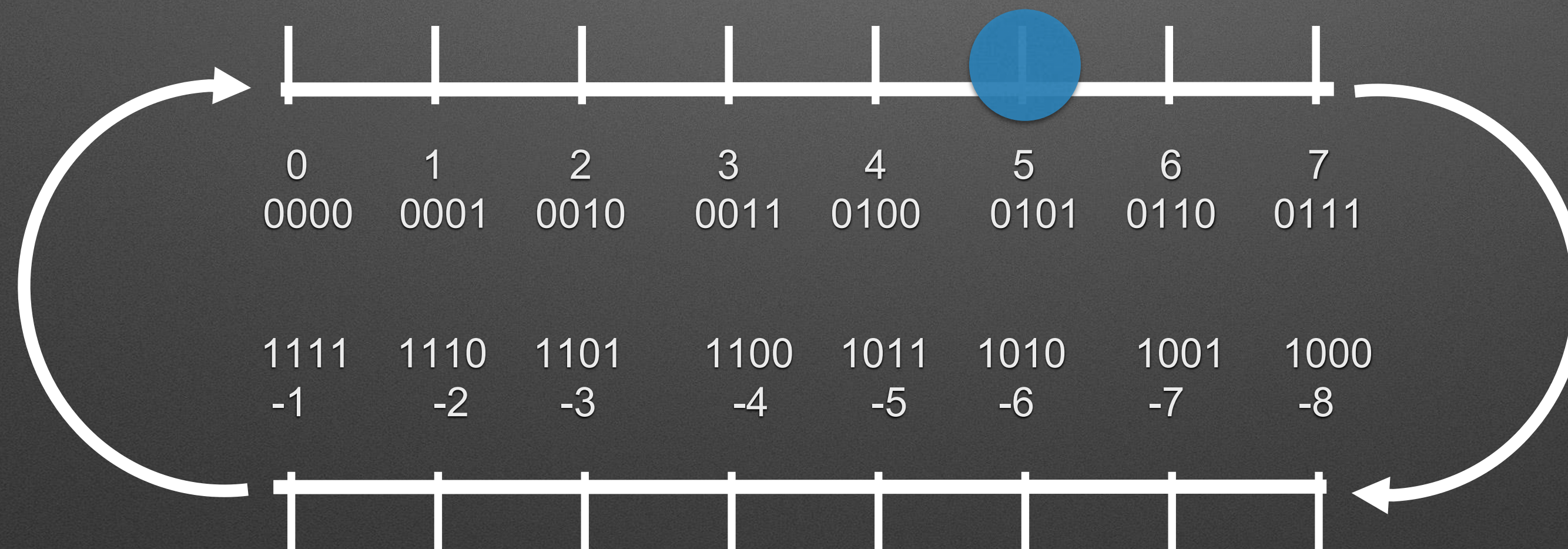
- Studio: Two's Complement - Mathematical Negation (-1×-6)

Decimal:

Binary:

Binary:

Decimal:



Last Time

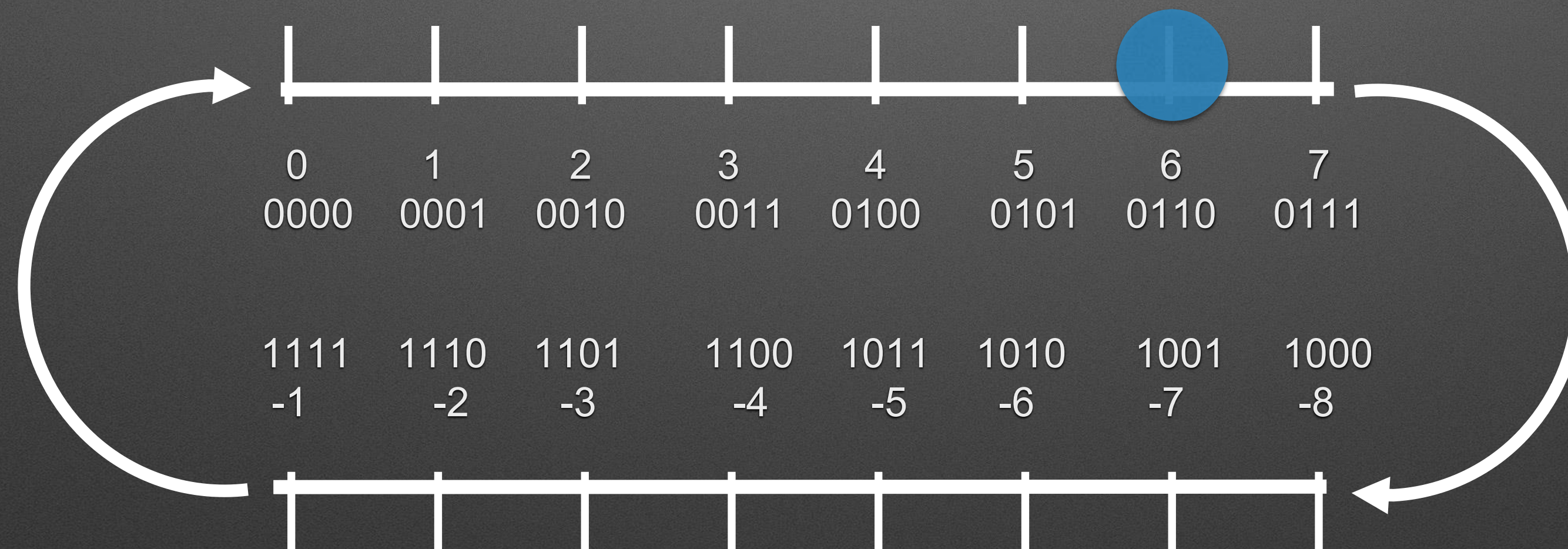
- Studio: Two's Complement - Mathematical Negation (-1×-6)

Decimal:

Binary:

Binary:

Decimal:



Last Time

- Studio: Two's Complement - Mathematical Negation ($-1 \times A$)
- Logic: $\overline{A} + 1$
- We are assumed to have “machines” for both;
 - Bitwise inversion (n invertors) and n -bit addition
(more to come on n -bit addition)

Last Time

- Assume an n bit adder, like:
- n bit subtractor can be built:

Last Time: Tee

- $t_b + \overline{t_b}$
- Theorem / Dual T5': $B + \overline{B} = 1$
- Therefore “1”
- *Eventually...* JLS



Last Time

- JLS Logic Types: Unsigned & Assumes values are 0 at $t = 0$

Chapter 2

- Tables & Sum-of-products
 - A “can’t go wrong” way to build logic that behaves a specified way
- Karnaugh Maps: A form of optimization
- Timing: Delay of circuits

Background: Minterms

- Minterms: Given n variables, a product (AND) containing all n exactly once, in either their original or negated form
- Consider: $\overline{A} \cdot B \cdot C \cdot \overline{D}$
Identify all possible combinations of inputs which make it true:

Chapter 2: Minterms

- Consider $n = 3$ and A, B, C ; Which are Minterms? Which are *not* and why?
 - ABC
 - $AB\bar{A}$
 - $CB\bar{A}$
 - $\bar{A}C$

Minterms & Truth Tables

CI	A	B		Carry Out	Sum
0+	0+	0	=	0	0
0+	0+	1	=	0	1
0+	1+	0	=	0	1
0+	1+	1	=	1	0
1+	0+	0	=	0	1
1+	0+	1	=	1	0
1+	1+	0	=	1	0
1+	1+	1	=	1	1

Minterms & Truth Tables

- Minterms are true for a *single* combination of inputs
 - This is essentially *selecting* a row of a truth table

Minterms & Truth Tables

CI	A	B		Sum
0+	0+	0	=	0
0+	0+	1	=	1
0+	1+	0	=	1
0+	1+	1	=	0
1+	0+	0	=	1
1+	0+	1	=	0
1+	1+	0	=	0
1+	1+	1	=	1

- $n = 3$: CI, A, B
- Where/when is Sum true (any place)?

Minterms & Truth Tables

CI	A	B		Sum
0+	0+	0	=	0
0+	0+	1	=	1
0+	1+	0	=	1
0+	1+	1	=	0
1+	0+	0	=	1
1+	0+	1	=	0
1+	1+	0	=	0
1+	1+	1	=	1

- $n = 3$: CI, A, B

- Where/when is any of these true?

$$\begin{aligned} Sum = & \overline{CI} \cdot \overline{A} \cdot B + \\ & \overline{CI} \cdot A \cdot \overline{B} + \\ & CI \cdot \overline{A} \cdot \overline{B} + \\ & CI \cdot A \cdot B \end{aligned}$$

Truth Table -> Sum of Minterms
Canonical Form

Important!

- Any simple function (mapping) can be represented as a truth table
 - n -bit binary numbers can be used to represent all the inputs
 - The table will need 2^n rows to represent all the possible combinations of inputs
 - m -bit binary numbers can represent the output(s)
 - *Each* of the m bits of output can be represent by a sum-of-products (sum of minterms) equation.
 - There's a minterm for each place the bit of m is a 1 (true)
 - Canonical form = The “sum” of these Minterms

Sum-of-Products

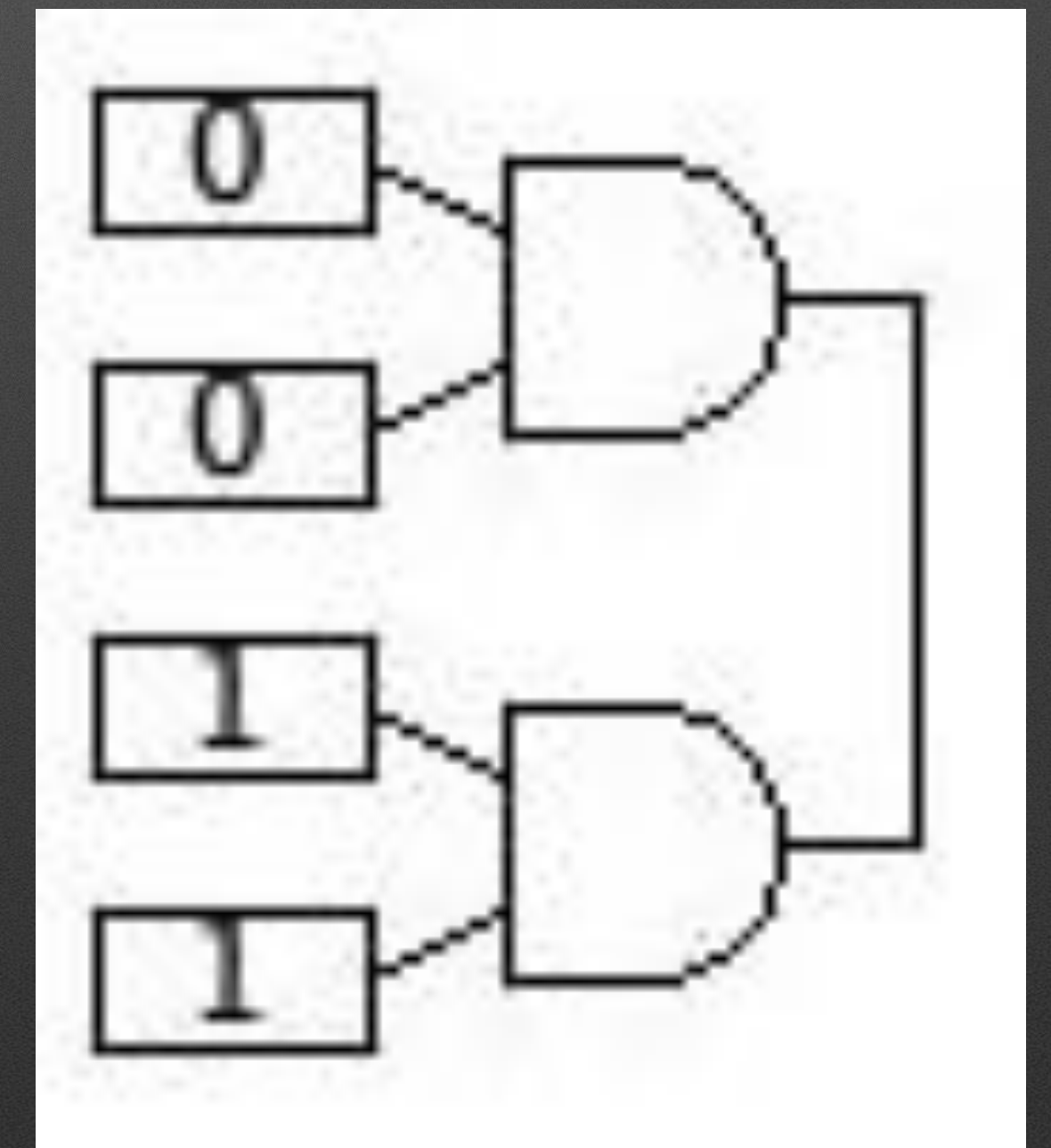
- All our combinational logic *could* be represented in a table
- All the outputs can be represented as equations
- Those equations can be realized with just the concept of AND, OR, & NOT
 - I.e., we can build computing machines for anything we can represent in a table if we have AND, OR, or NOT.
- The idea of Tables and “Look Up Tables” (LUTs) is really useful!

Product-Of-Sums

- Alternative to SOP: Uses maxterms (SUM of all input variables) in large product
- Form: $Y = (A + B + C) \cdot (A + \overline{B} + C) \dots$
- Can be constructed from table by focusing on:
 - 1) rows with zeros $\Rightarrow$ each a “sum” for a zero in only that row and
 - 2) products that will combine them
- Sum-of-Prod: Smaller when fewer 1s than 0s in table;
Otherwise Prod-of-Sums is smaller
- This class: slightly focused on Look-up Table (LUT) concept / usually favor SOP

Real Circuits: Xs and Zs

- 0s and 1s represent real-world, continuous values, like voltages
 - Ex: 0 = 0v (gnd); 1 = 5v
 - What's 2.3v?
 - What happens if a 0v wire is connected to 5v wire? ("Contention")
- X: That's illegal / don't know



Simulator / Language Types

- Bits & Types: 10101100 can have different interpretations
 - Programming languages use data types
- Verilog (Chapter 4)'s logic type:
 - 0, 1, X (unknown), Z (high-impedance)
- Other simulators often use X for initial value
(Helps catch errors and misunderstandings earlier vs. building on a bad assumption!)

Real Circuits: Xs and Zs

- 0s and 1s represent real-world, continuous values, like voltages
 - Ex: 0 = 0v (gnd); 1 = 5v (relative to that ground)
 - Voltage is a relative measure
(like water pressure: it's the difference between two points)
- Z: “Floating” value / disconnected
 - Sometimes useful to “disconnect” something to prevent contention
(to share wires with different things in control at different times)
 - Sometimes an error when nothing is connected
(Behavior depends on technology and conditions; Can be random or influenced by external things — like moving a hand near a circuit!)

Circuit “Optimization”

- Time or performance?
- Number of parts?
- Total cost?
- Combination: E.g., Cheapest way to achieve a specific level of performance

Circuit “Optimization”

- Logic Minimization
 - Canonical Form is seldom the minimum number of parts
 - Can “combine” overlapping terms ([implicants / product](#))
 - Prime Implicant: Can’t be further reduced
 - Ex: $A \cdot B \cdot C + A \cdot \overline{B} \cdot C$
 - True when $A \cdot C$. The B and $\overline{B}$ cancel

Karnaugh (K) Maps

- A visual way to do term optimization
- Rely on tables that allow easy identification of ways to combine implicants
 - Uses Gray code ordering, not counting order!!!
- Only useful for up to 4 variables. I.e., small problems

Karnaugh (K) Maps

- Goal: Cover all 1s with circles
 - As few circles as possible & as large as possible
 - Span rectangles with sides of 1, 2, 4, or 8
 - Top/bottom and left/right wrap!

Give an opt. equation for...

Inputs			Output
S	D1	D0	O
0	0	0	0
0	0	1	1
0	1	0	0
0	1	1	1
1	0	0	0
1	0	1	0
1	1	0	1
1	1	1	1

D1/D0			
00		??	??
S	0		
	1		

Give an opt. equation for...

Inputs			Output
S	D1	D0	O
0	0	0	0
0	0	1	1
0	1	0	0
0	1	1	1
1	0	0	0
1	0	1	0
1	1	0	1
1	1	1	1

D1/D0					
		00	01	11	10
S	0				
	1				

Give an opt. equation for...

Inputs			Output
S	D1	D0	O
0	0	0	0
0	0	1	1
0	1	0	0
0	1	1	1
1	0	0	0
1	0	1	0
1	1	0	1
1	1	1	1

D1 changes

D0 changes

Give an opt. equation for...

Inputs			Output
S	D1	D0	O
0	0	0	0
0	0	1	1
0	1	0	0
0	1	1	1
1	0	0	0
1	0	1	0
1	1	0	1
1	1	1	1

E2: Give an opt. equation for...

Inputs			Output
A	B	C	O
0	0	0	1
0	0	1	0
0	1	0	1
0	1	1	0
1	0	0	1
1	0	1	0
1	1	0	1
1	1	1	0

E3: Give an equation for...

Inputs			Output
X	Y	Z	O
0	0	0	1
0	0	1	1
0	1	0	0
0	1	1	1
1	0	0	0
1	0	1	1
1	1	0	0
1	1	1	0

Y/Z					
		00	01	11	10
X	0				
	1				

Don't cares in K-maps

- Sometimes there are input combinations that can never occur
- Rather than specify a default value, we can use “X” for Don't Care
- This often results in simpler Boolean equations

Inputs				Output
A	B	C	D	Y
0	0	0	0	1
0	0	0	1	0
0	0	1	0	1
0	0	1	1	1
0	1	0	0	0
0	1	0	1	X
0	1	1	0	1
0	1	1	1	1
1	0	0	0	1
1	0	0	1	1
1	0	1	0	X
1	0	1	1	X
1	1	0	0	X
1	1	0	1	X
1	1	1	0	X
1	1	1	1	X

C/D					
		00	01	11	10
A/B	00				
	01				
	11				
	10				

Don't cares in K-maps

- Sometimes there are input combinations that can never occur
- Rather than specify a default value, we can use "X" for Don't Care
- This often results in simpler Boolean equations

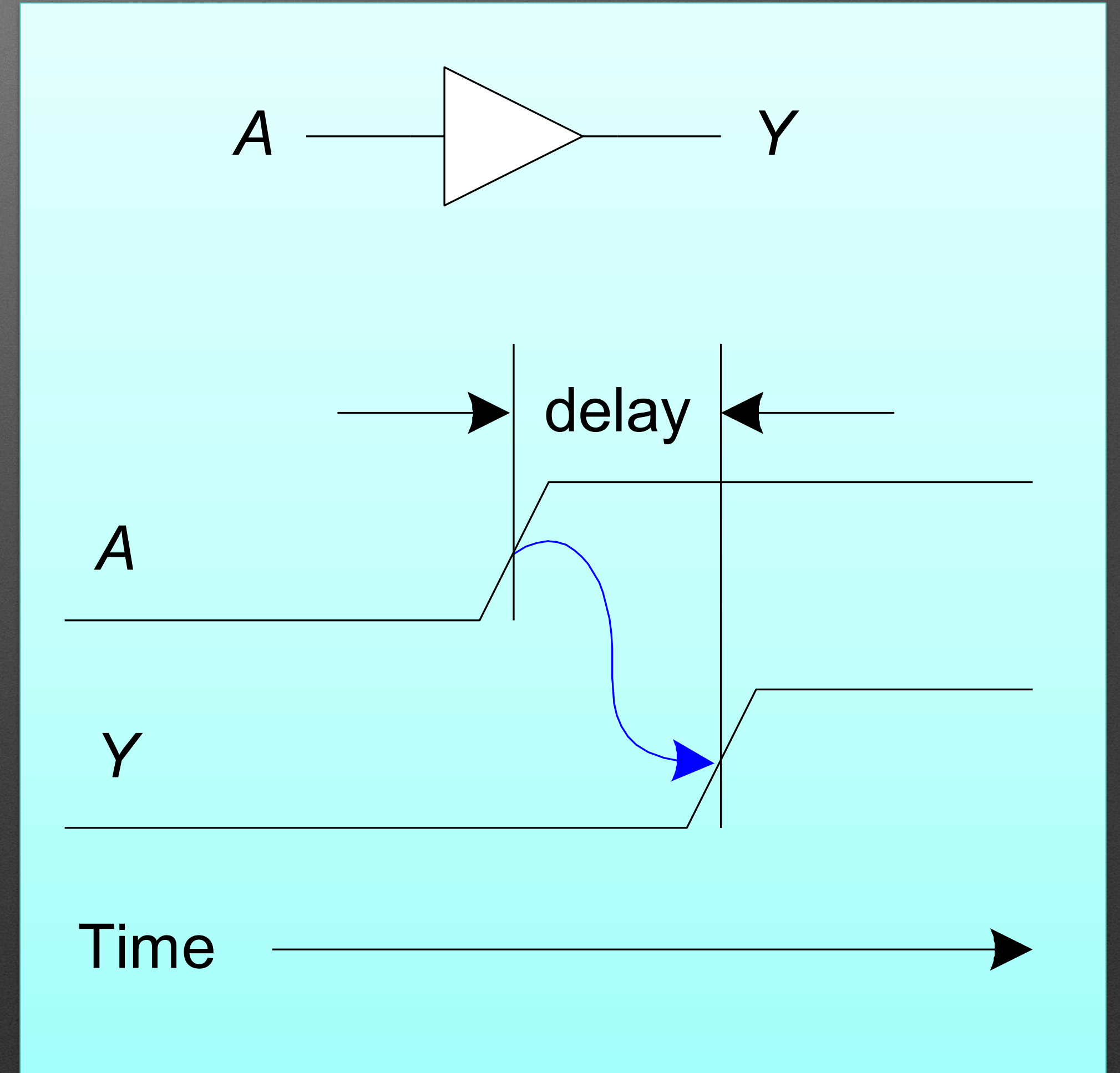
Inputs				Output
A	B	C	D	Y
0	0	0	0	1
0	0	0	1	0
0	0	1	0	1
0	0	1	1	1
0	1	0	0	0
0	1	0	1	X
0	1	1	0	1
0	1	1	1	1
1	0	0	0	1
1	0	0	1	1
1	0	1	0	X
1	0	1	1	X
1	1	0	0	X
1	1	0	1	X
1	1	1	0	X
1	1	1	1	X

		C/D			
		00	01	11	10
A/B	00	1	0	1	1
	01	0	X	1	1
	11	X	X	X	X
	10	1	1	X	X

$$Y = A + \overline{B} \overline{D} + C$$

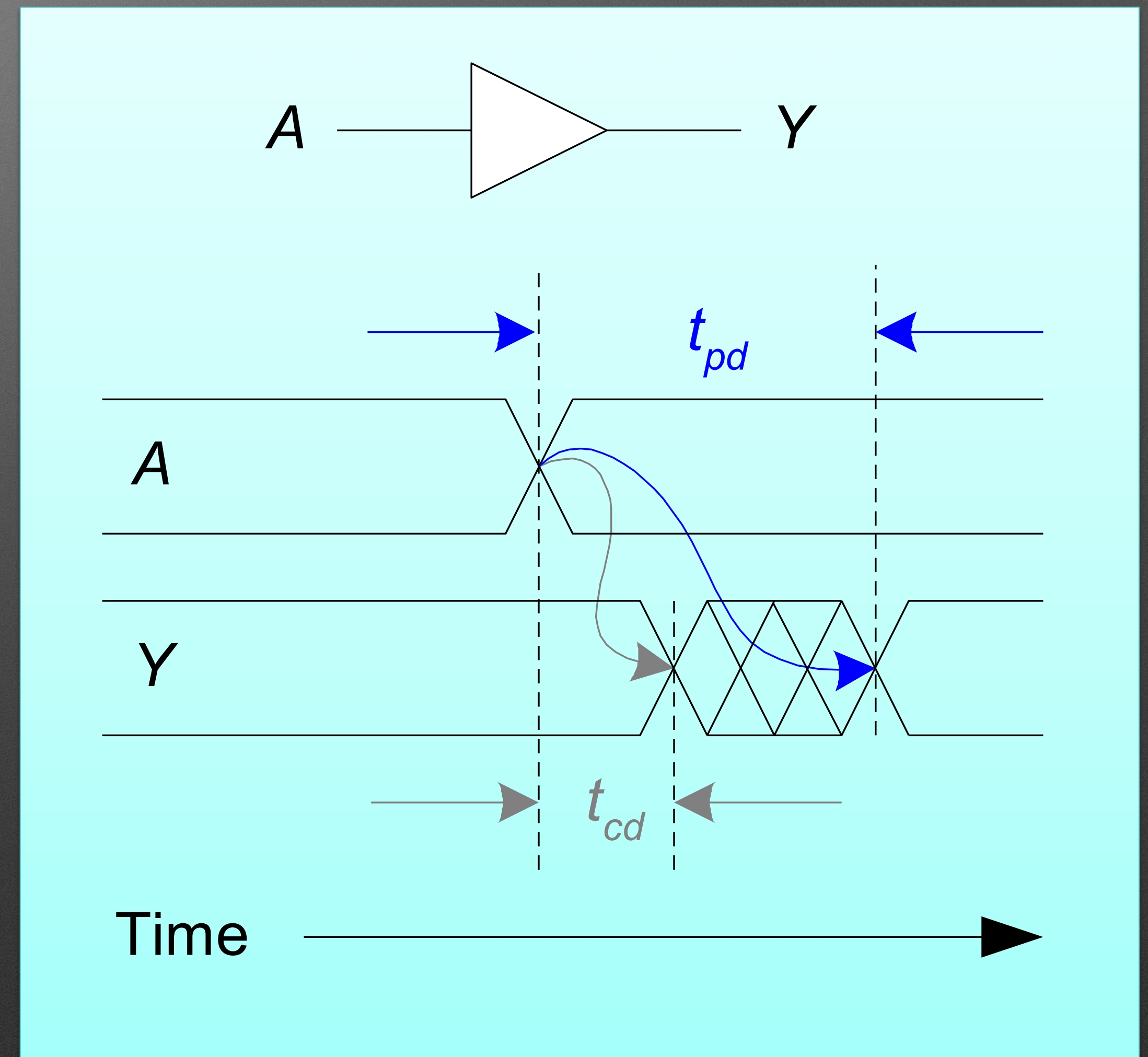
Timing

- Delay: time between input change and output changing
- Determines how fast we can build circuits
- Caused by
 - Capacitance and resistance in a circuit
 - Speed of light limitation



Propagation & Contamination Delay

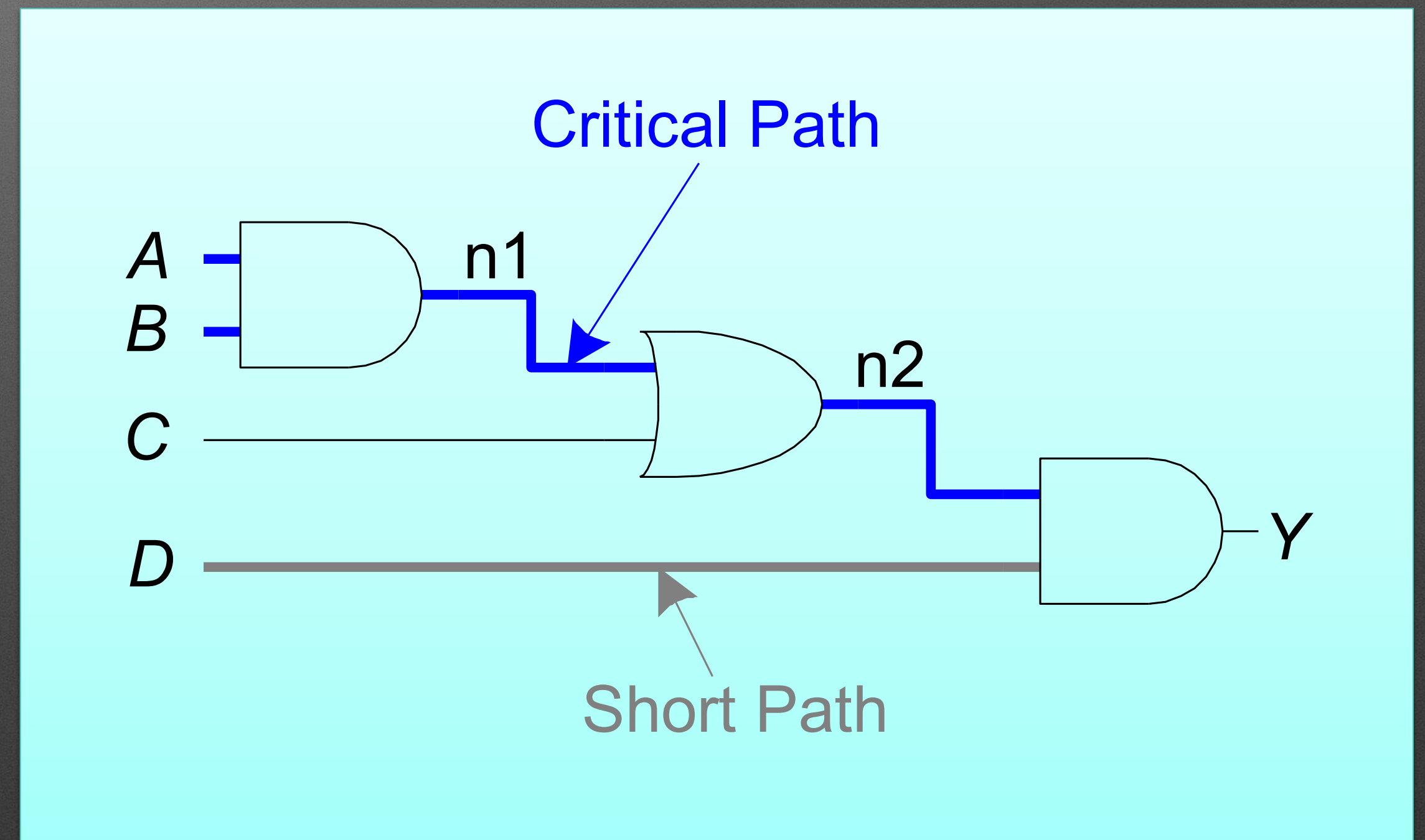
- Propagation delay: t_{pd} = **max** delay from input to output
- Contamination delay: t_{cd} = **min** delay from input to output
- Reasons why t_{pd} and t_{cd} may be different:
 - Different rising and falling delays (e.g., n- vs p-type transistors)
 - Multiple inputs and outputs, some of which are faster than others
 - Temperature of the circuit: Circuits slow down when hot and speed up when cold



Delay Calculation

Critical (Long) Path: $t_{pd} = 2t_{pd_AND} + t_{pd_OR}$
(max delay)

Short Path: $t_{cd} = t_{cd_AND}$
(min delay)



2.8: More Parts

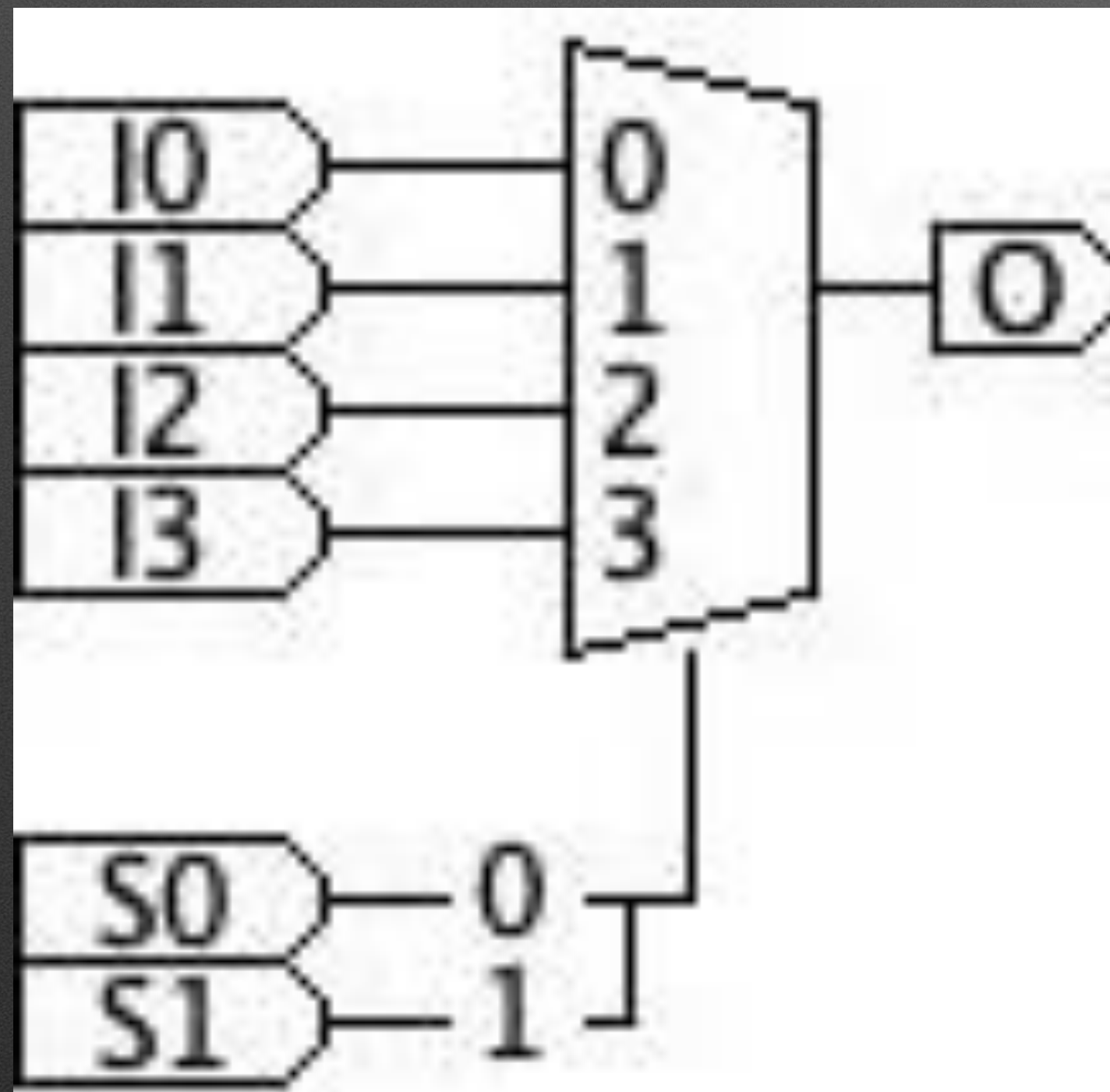
- Q: We want a 4-to-1 multiplexor. How big is the full truth table?
- Q: Our CPU may need a 32-to-1 multiplexor. How big is the truth table?
- We need a new approach
 - Hierarchical construction

Hierarchical Approach

- We've created a 2-to-1 MUX
 - Construct a 4-to-1 MUX using 2-to-1 MUXes
 - Focus on desired behavior using existing parts

4-to-1 MUX Behavior

- Behavioral Description as a Table



Inputs of Interest		Output (In terms of Inputs)
S1	S0	O
0	0	I0
0	1	I1
1	0	I2
1	1	I3

Hierarchical Construction of 4-input Mix

Questions

- “I'm still confused about how K-maps really work. How do we determine where the clusters are?”
- “I genuinely don't understand how we would apply K-maps directly to a circuit. I get that they simplify boolean expressions, but how would we use the truth table to change the physical circuit?”
- “Why would you use a multiplexer as a lookup table instead of implementing the logic?”
- “How can glitches caused by propagation delays be prevented or reduced in a real circuit?”
- “Are Karnaugh maps still used in practice nowadays, or is it mainly just logic synthesizers?”