CS152: Computer Systems Architecture
Circuits Recap – Digital Why And How

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Spring 2023

Large amount of material adapted from MIT 6.004, “Computation Structures”,
Morgan Kaufmann “Computer Organization and Design: The Hardware/Software Interface: RISC-V Edition”,
and CS 152 Slides by Isaac Scherson

Course outline

- ❑ Part 1: The Hardware-Software Interface
  - What makes a ‘good’ processor?
  - Assembly programming and conventions
- ❑ Part 2: Recap of digital design
  - Combinational and sequential circuits
  - How their restrictions influence processor design
- ❑ Part 3: Computer Architecture
  - Computer Arithmetic
  - Simple and pipelined processors
  - Caches and the memory hierarchy
- ❑ Part 4: Computer Systems
  - Operating systems, Virtual memory

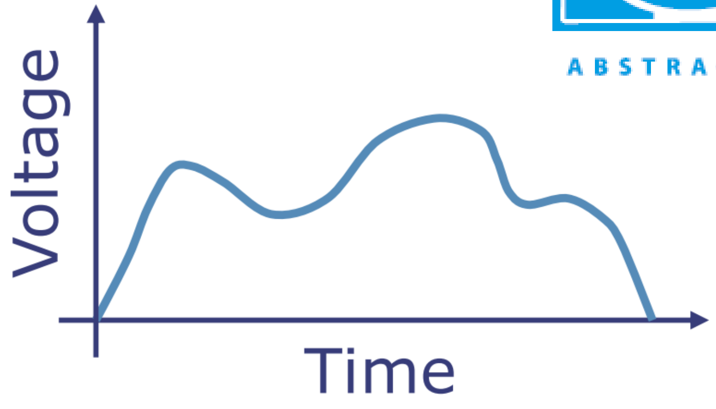
The digital abstraction

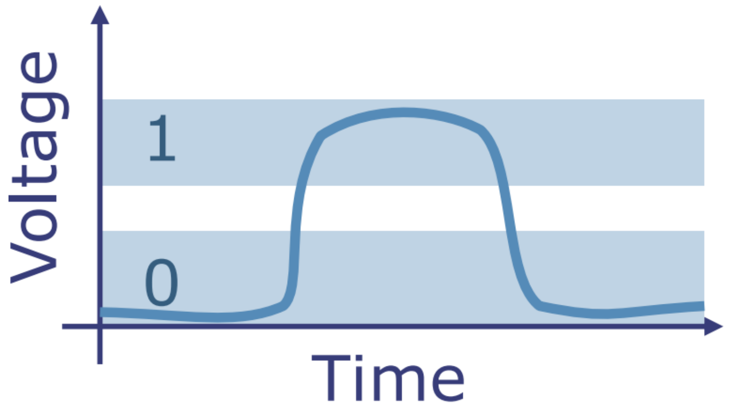
"Building Digital Systems in an Analog World"

The digital abstraction

- ❑ Electrical signals in the real world is analog
    - o Continuous signals in terms of voltage, current,

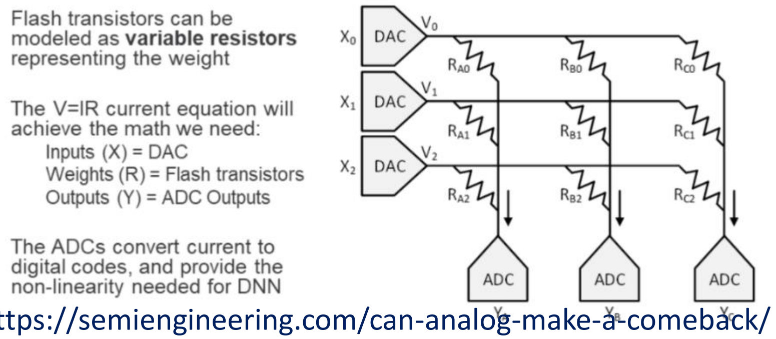
- ❑ Modern computers represent and process information using discrete representations
    - o Typically binary (bits)
    - o Encoded using ranges of physical quantities (typically voltage)





Aside: Historical analog computers

- Computers based on analog principles have existed
  - Uses analog characteristics of capacitors, inductors, resistors, etc to model complex mathematical formulas
    - Very fast differential equation solutions!
    - Example: Solving circuit simulation would be very easy if we had the circuit and was measuring it
- Some modern resurgence as well!
  - Research on sub-modules performing fast non-linear computation using analog circuitry


Flash transistors can be modeled as **variable resistors** representing the weight

The V=IR current equation will achieve the math we need:
Inputs (X) = DAC
Weights (R) = Flash transistors
Outputs (Y) = ADC Outputs

The ADCs convert current to digital codes, and provide the non-linearity needed for DNN

https://semiengineering.com/can-analog-make-a-comeback/

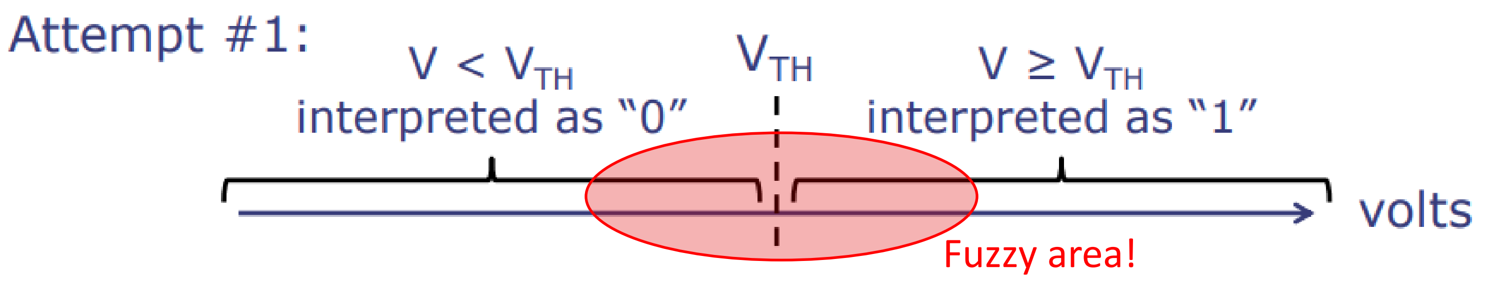
Why are digital systems desirable?

Hint: Noise

Polish analog computer AKAT-1 (1959)
Source: Topory

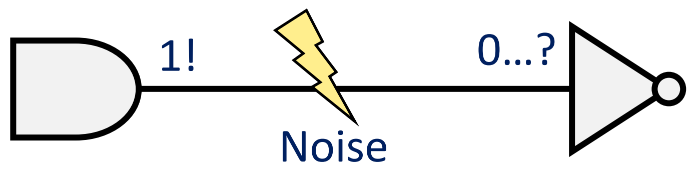
Using voltage digitally

- Key idea
  - Encode two symbols, “0” and “1” (1 bit) in an analog space
  - And use the same convention for every component and wire in system


Attempt #1:
$V < V_{TH}$ interpreted as “0”
V_{TH}
$V \geq V_{TH}$ interpreted as “1”
volts
Fuzzy area!

Problem: There is always noise between transmitter and receiver

Also, noise can accumulate as we pass through more gates



Source: MIT 6.004 2019 L05

Using voltage digitally

- ❑ Key idea
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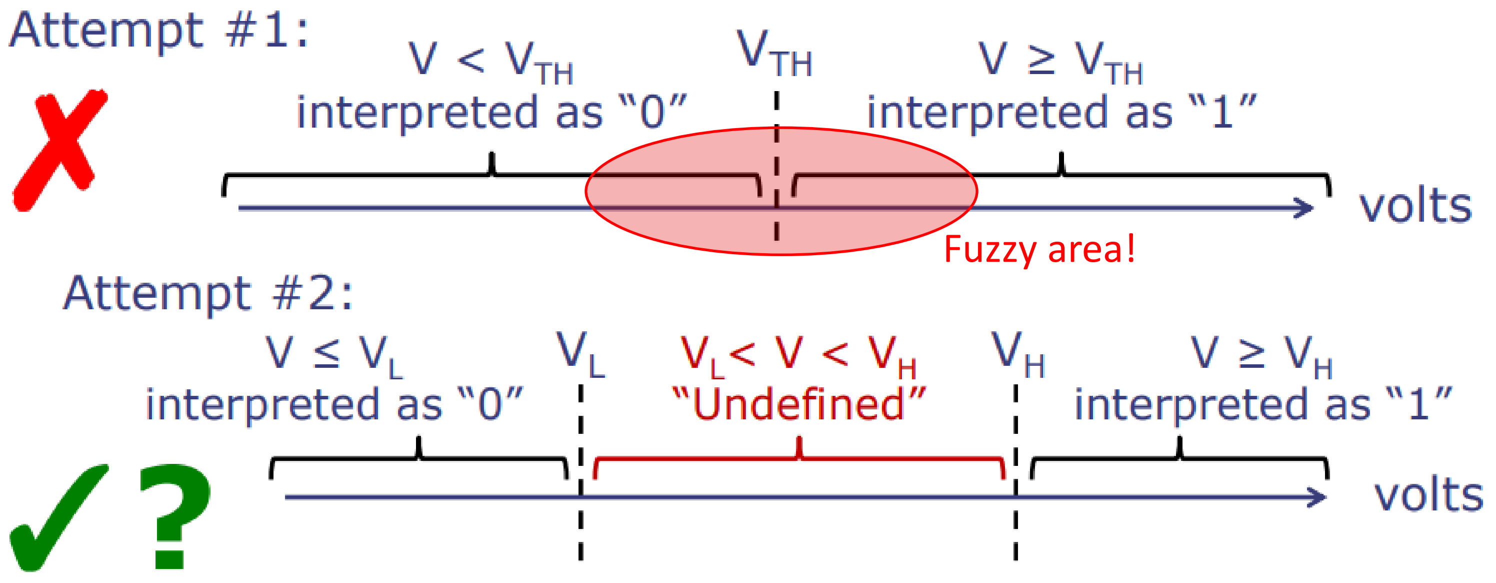
  - And use the same convention for every component and wire in system

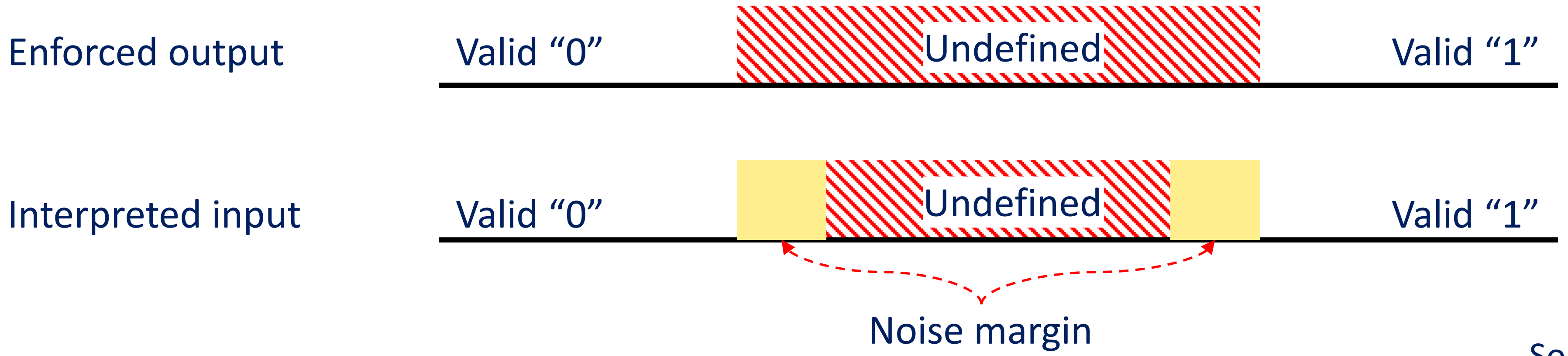


V_L and V_H of output are enforced during component design and manufacture

Source: MIT 6.004 2019 L05

Handling noise

- When a signal travels between two entities, **there will be noise**
  - Temperature, electromagnetic fields, interaction with surrounding modules, …
- What if V_{out} is barely lower than V_L, or barely higher than V_H?
  - Noise may push the signal into invalid range
  - Rest of the system runs into undefined state!
- Solution: Output signals use a stricter range than input

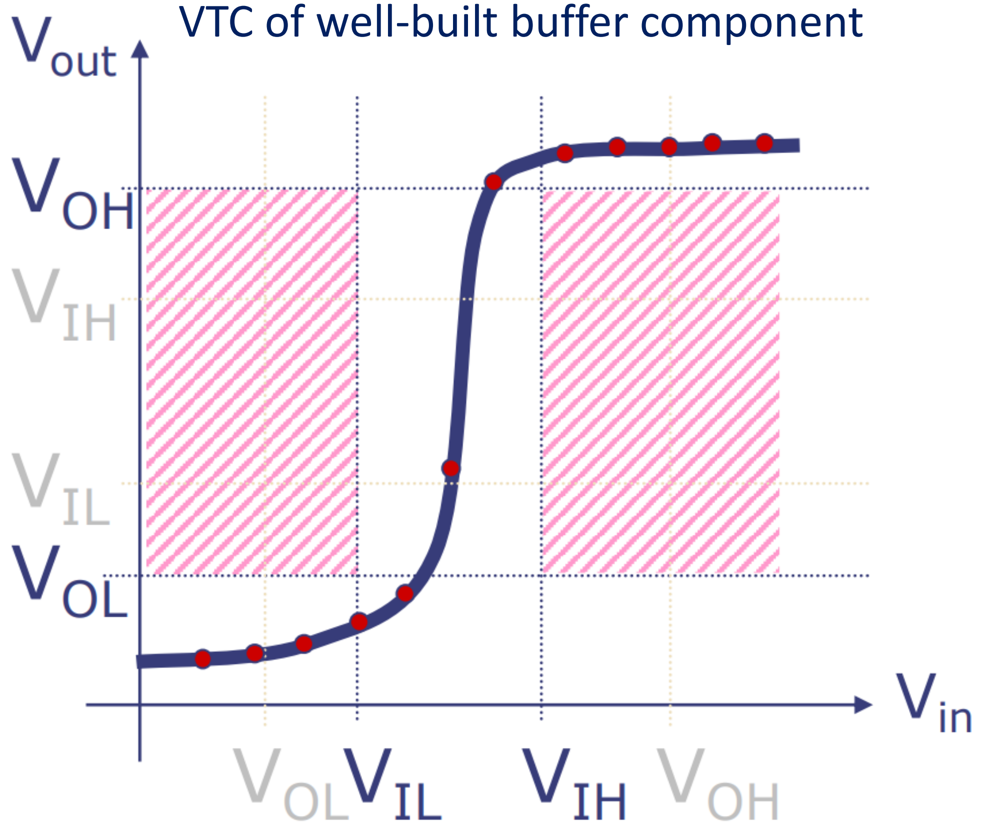


Source: MIT 6.004 2019 L05

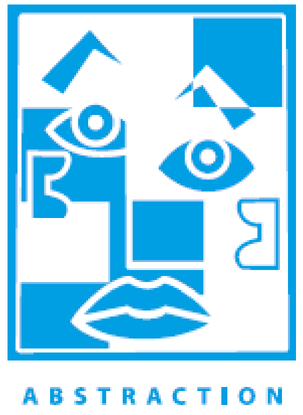
Voltage Transfer Characteristic

- Example component: Buffer
  - A simple digital device that copies its input value to its output
- Voltage Transfer Characteristic (VTC):
  - Plot of V_{out} vs. V_{in} where each measurement is taken after any transients have died out.
  - Not a measure of circuit speed!
    - Only determines behavior under static input
- Each component generates a new, "clean" signal!
  - Noise from previous component corrected

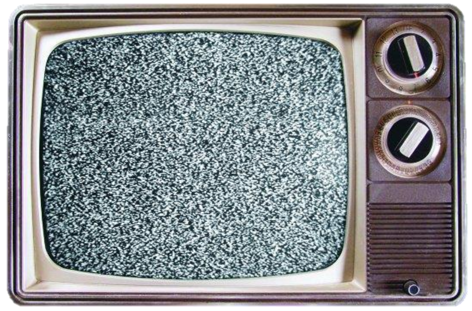
VTC of well-built buffer component



Benefits of digital systems

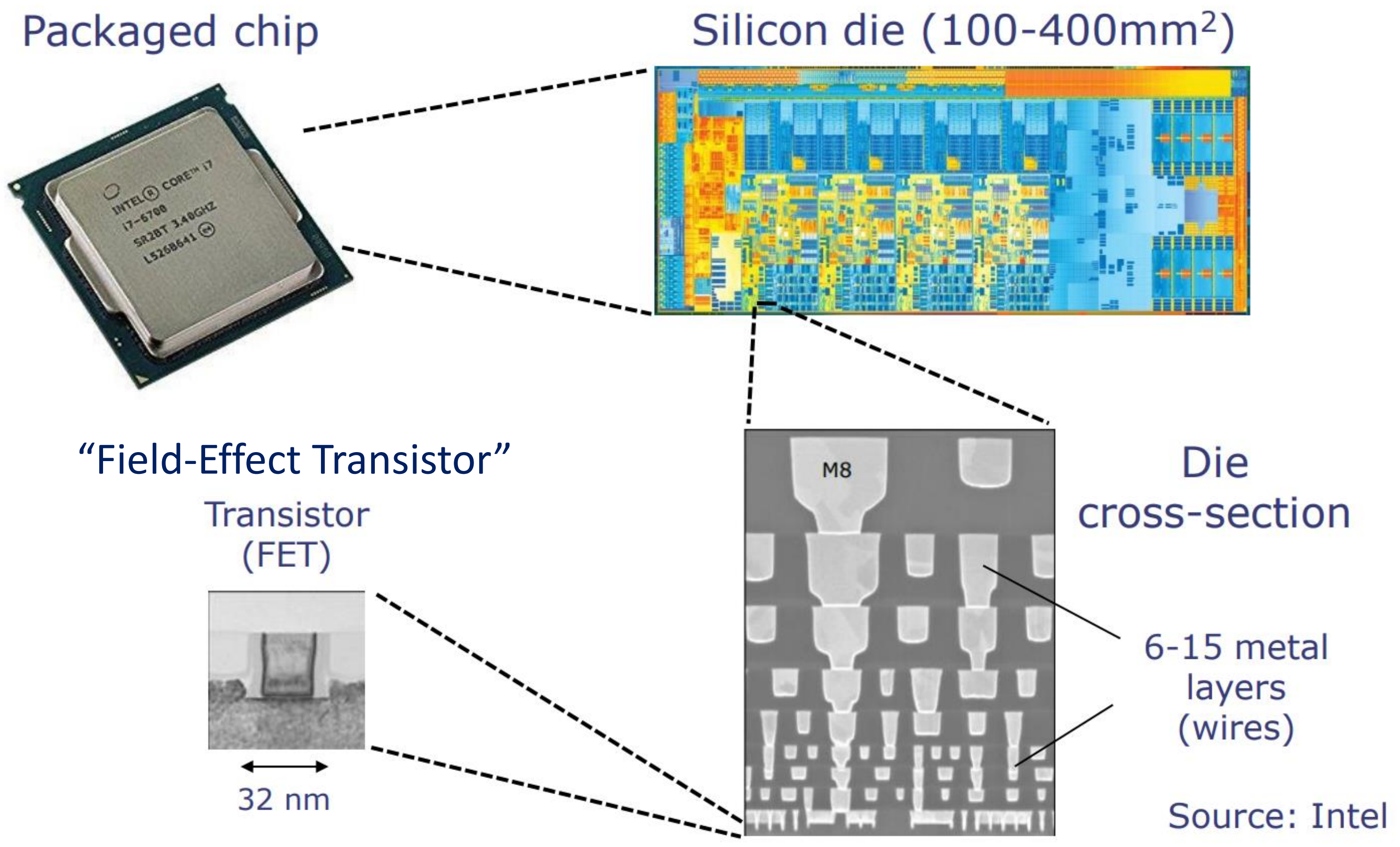


- Digital components are “restorative”
  - Noise is cancelled at each digital component
  - Very complex designs can be constructed on the abstraction of digital behavior
- Compare to analog components
  - Noise is accumulated at each component
  - Lay example: Analog television signals! (Before 2000s)
    - Limitation in range, resolution due to transmission noise and noise accumulation
    - Contrary: digital signals use repeaters and buffers to maintain clean signals



Source: “Does TV static have anything to do with the Big Bang?” How it works, 2012

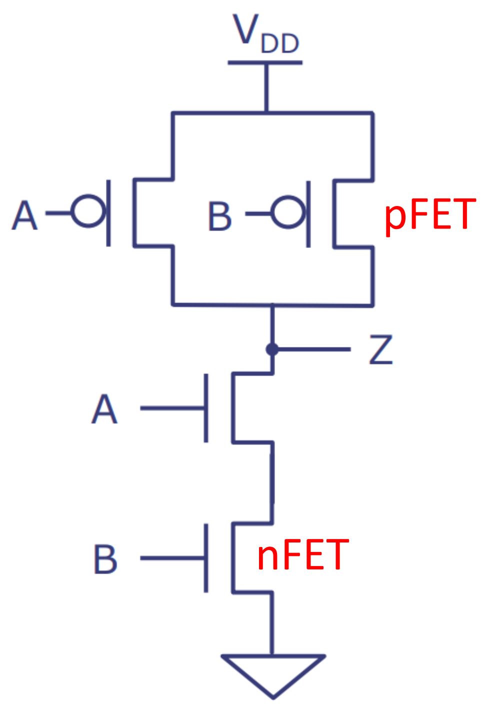
The basic building block: CMOS transistors (“Complementary Metal–Oxide–Semiconductor”)

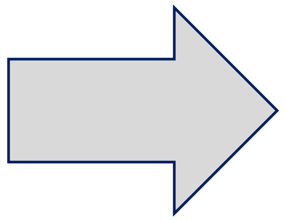


Everything is built as a network of transistors!

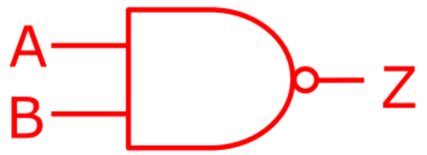
The basic building block: CMOS FETs

- Remember CS151 – FETs come in two varieties, and are composed to create Boolean logic





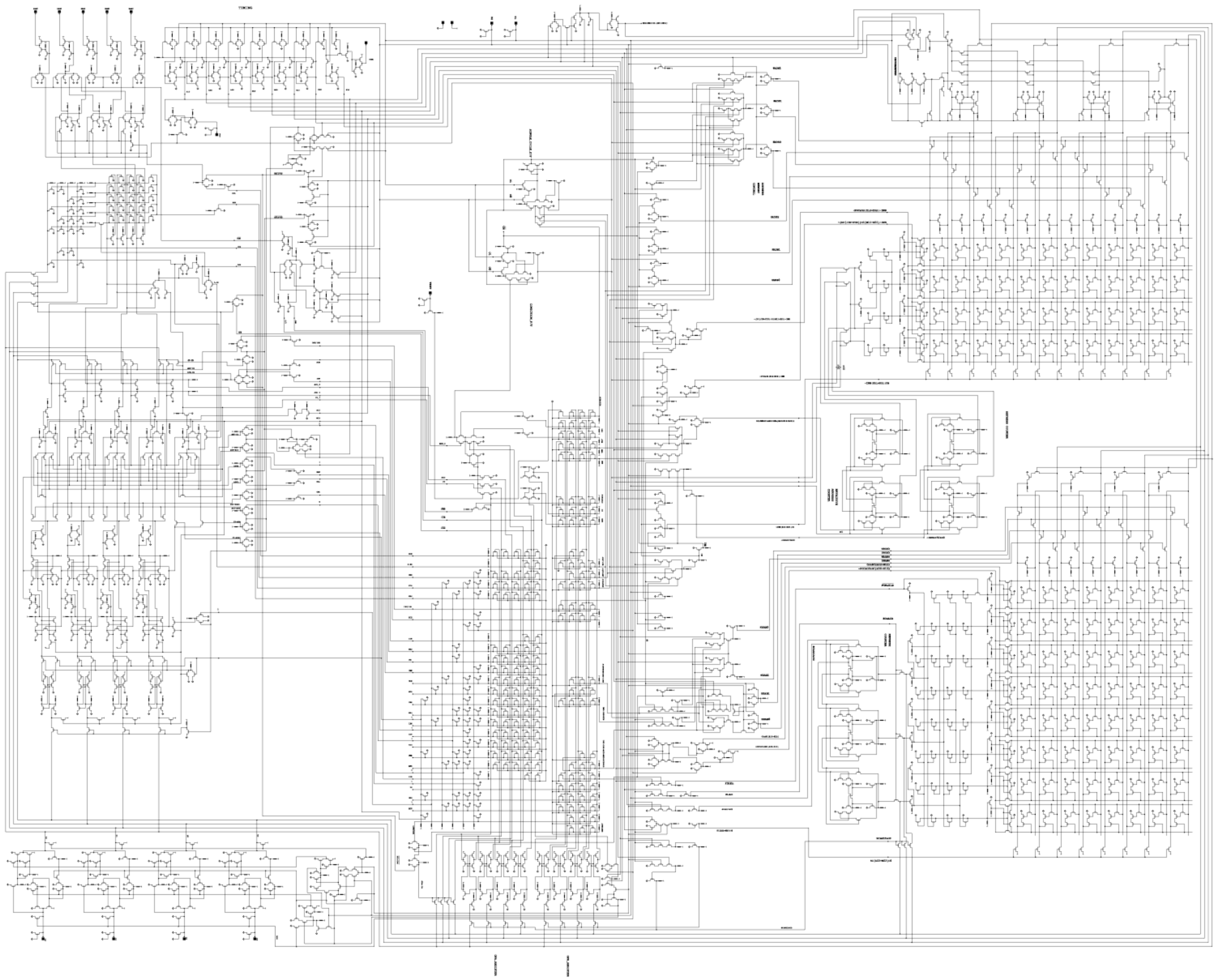
A	B	Z
0	0	1
0	1	1
1	0	1
1	1	0



CMOS NAND Gate

Source: MIT 6.004 2019 L09

Making chips out of transistors…?



Intel 4004 Schematics
drawn by Lajos Kintli and Fred Huettig
for the Intel 4004 50th anniversary project

The basic building block 2: Standard cell library

- ❑ Standard cell
  - ○ Group of transistor and interconnect structures that provides a boolean logic function
    - Inverter, buffer, AND, OR, XOR, …
  - ○ For a specific implementation technology/vendor/etc…
  - ○ Also includes physical characteristic information
- ❑ Eventually, chips designs are expressed as a group of standard cells networked via wires
  - ○ Among what is sent to a fab plant

Example:

Gate	Delay (ps)	Area (μ^2)
Inverter	20	10
Buffer	40	20
AND2	50	25
NAND2	30	15
OR2	55	26
NOR2	35	16
AND4	90	40
NAND4	70	30
OR4	100	42
NOR4	80	32

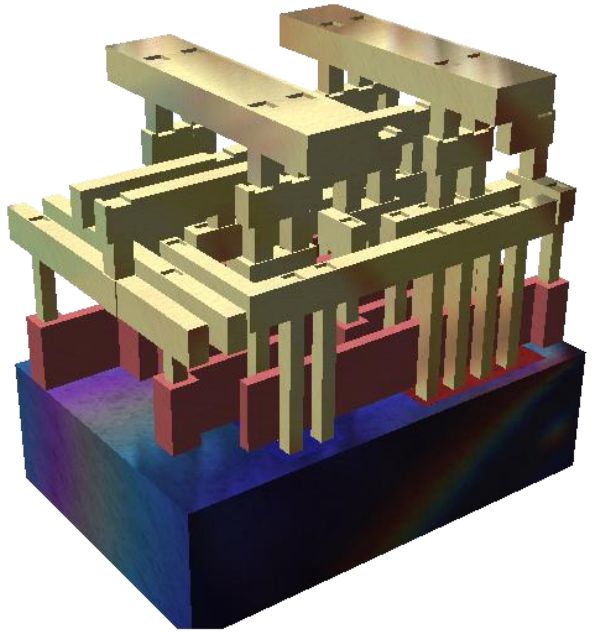
Various components have different delays and area!

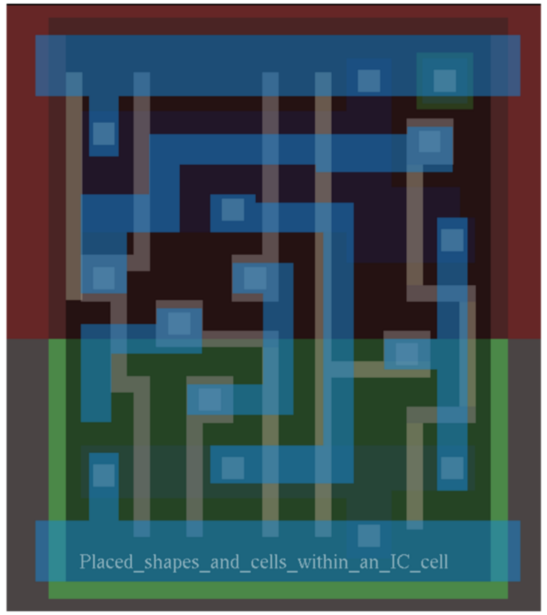
The actual numbers are not important right now

Source: MIT 6.004 2019 L06

Aside: Describing chips for foundries

- GDSII, OASIS file formats
- Depicts many standard cells connected via multiple wire layers





Source: File:Silicon_chip_3d.png, Tgrebinski, File:Wikipediaoasisimage 2.png (Wikipedia)

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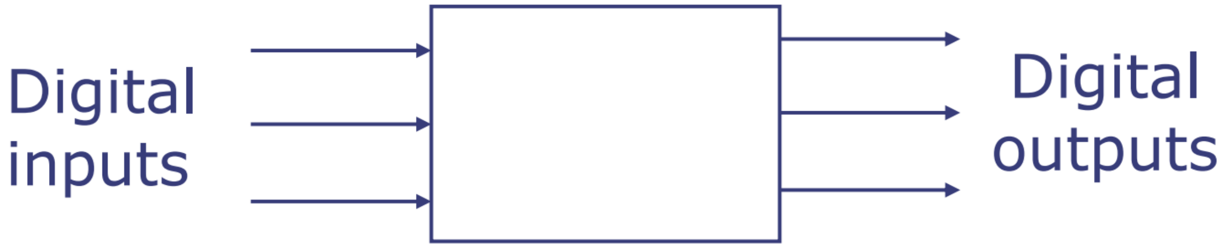
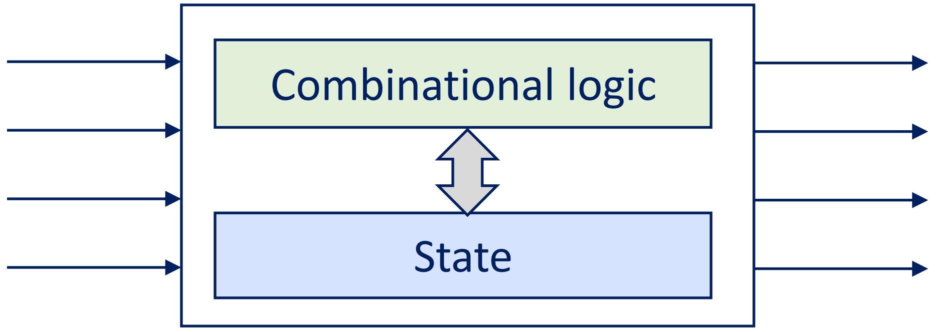
Combinational and sequential circuits

- Two types of digital circuits
- Combinational circuit
  - Output is a function of current input values
    - output = f(input)
    - Output depends exclusively on input
- Sequential circuit
  - Have memory ("state")
    - Output depends on the "sequence" of past inputs





What constitutes combinational circuits

1. Input
2. Output
3. Functional specifications
   - The value of the output depending on the input
   - Defined in many ways!
   - Boolean logic, truth tables, hardware description languages,

We've done this in CS51/CS151

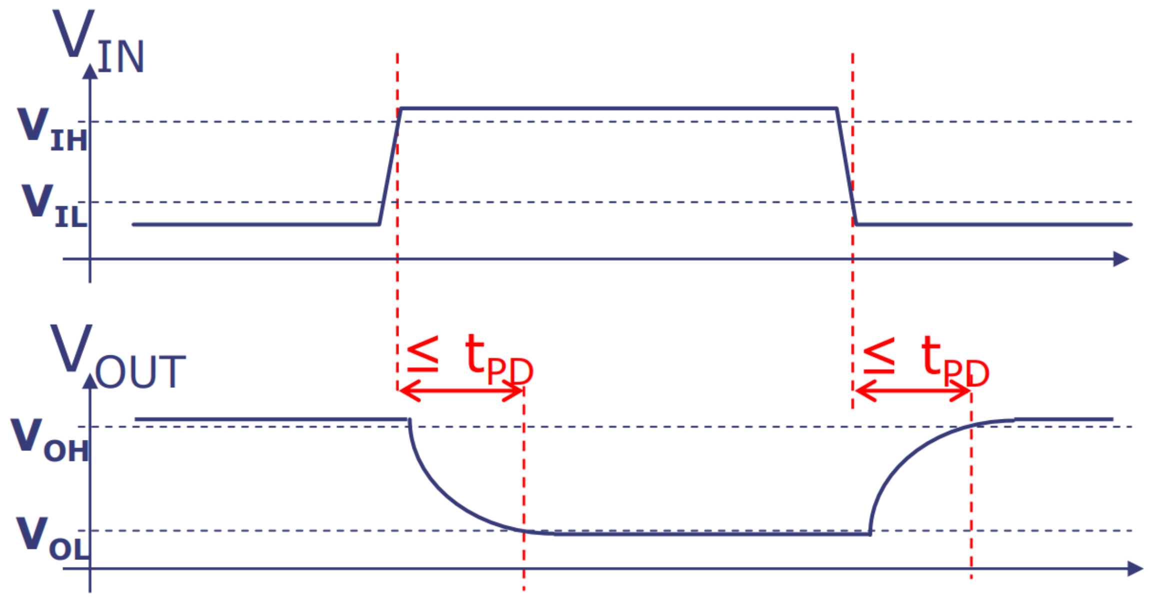
4. Timing specifications

Hinted at in CS51/CS151

   - Given dynamic input, how does the output change over time?

Timing specifications of combinational circuits

- Propagation delay (t_{PD})
  - An upper bound on the delay from valid inputs to valid outputs
  - Restricts how fast input can be consumed
    (Too fast input → output cannot change in time, or undefined output)



A good circuit has low t_{PD}
→ Faster input
→ Higher performance

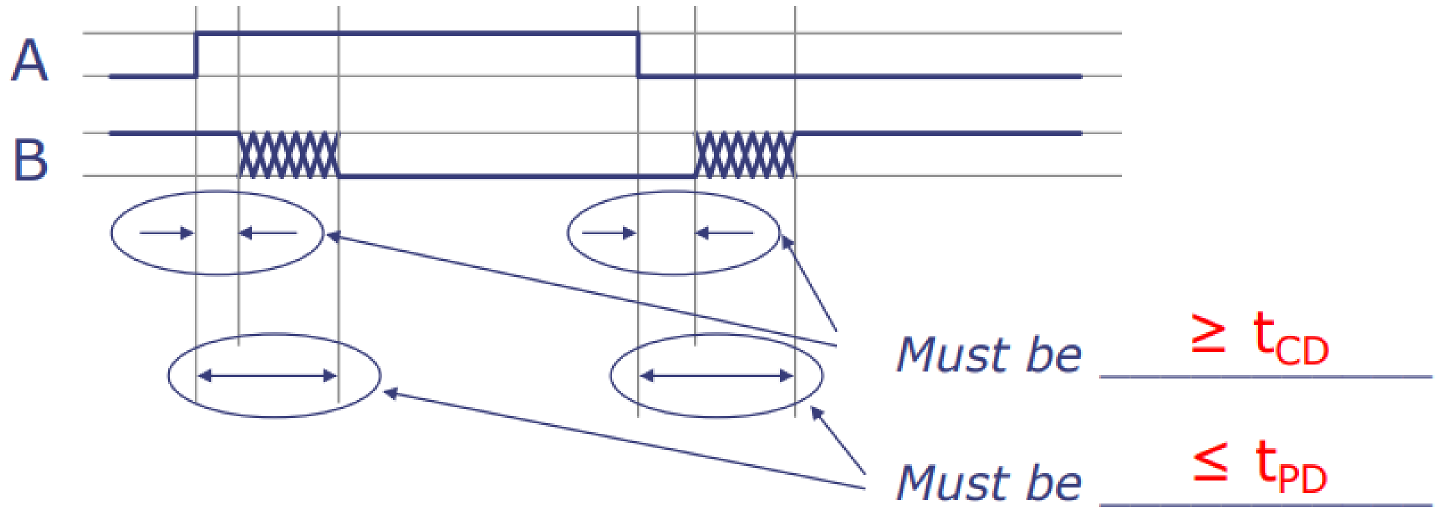
How do we get low t_{PD}?

Source: MIT 6.004 2019 L05

Timing specifications of combinational circuits

- Contamination delay (t_{CD})
  - A lower bound on the delay between input change to output starting to change
    - Does not mean output has stable value!
  - Guarantees that output will not change within this timeframe regardless of what happens to input

Example: Inverter

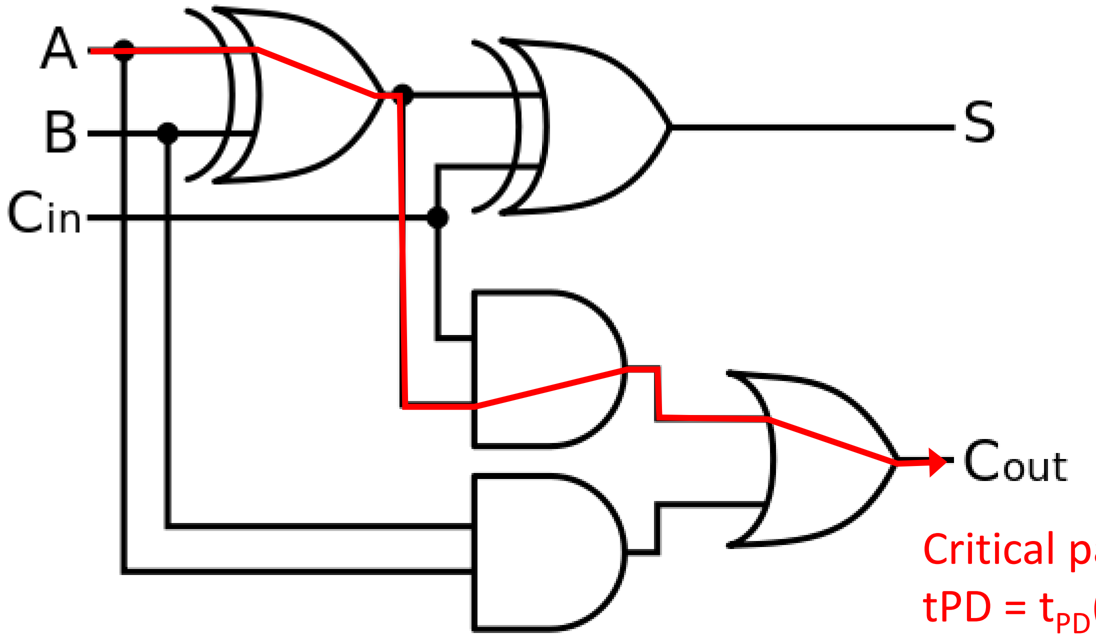


No promises during XXXXX

Source: MIT 6.004 2019 L05

Back to propagation delay of combinational circuits

- A chain of logic components has additive delay
  - The “depth” of combinational circuits is important
- The “critical path” defines the overall propagation delay of a circuit



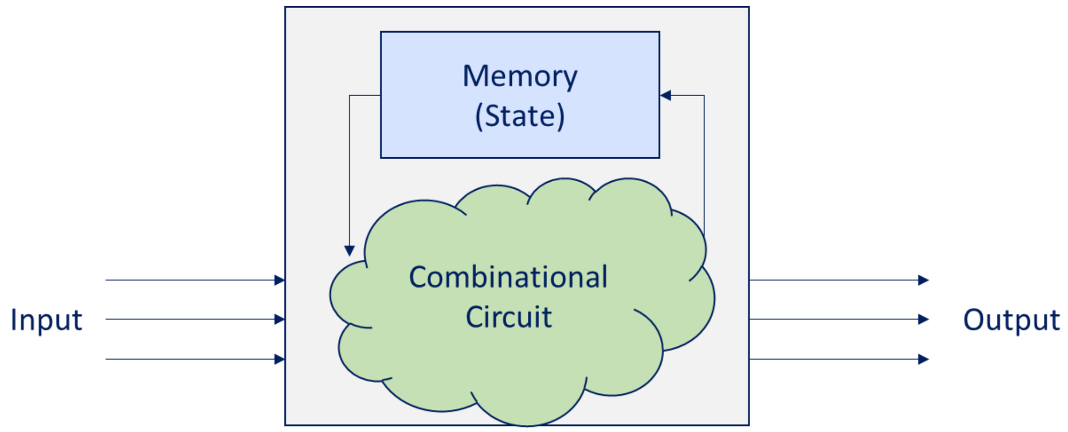
Critical path of three components
tPD = t_{PD}(xor2)+t_{PD} (and2)+t_{PD} (or2)

Source: en:User:Cburnett @ Wikimedia

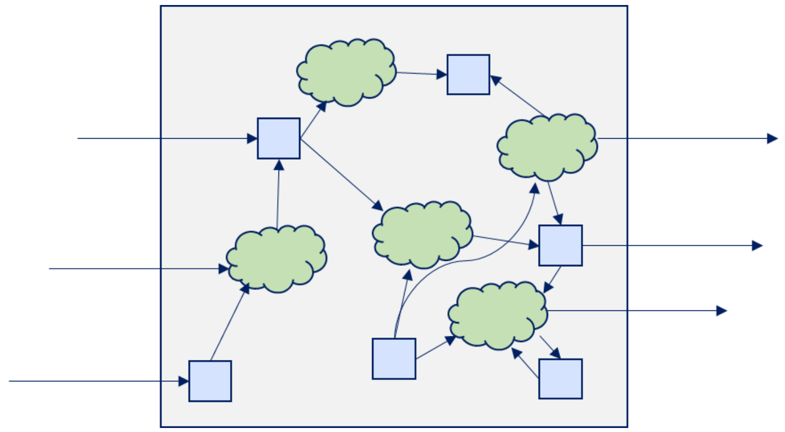
Example: A full adder

Sequential circuits

- ❑ Combinational circuits on their own are not very useful
- ❑ Sequential logic has memory (“state”)
  - State acts as input to internal combinational circuit
  - Subset of the combinational circuit output updates state



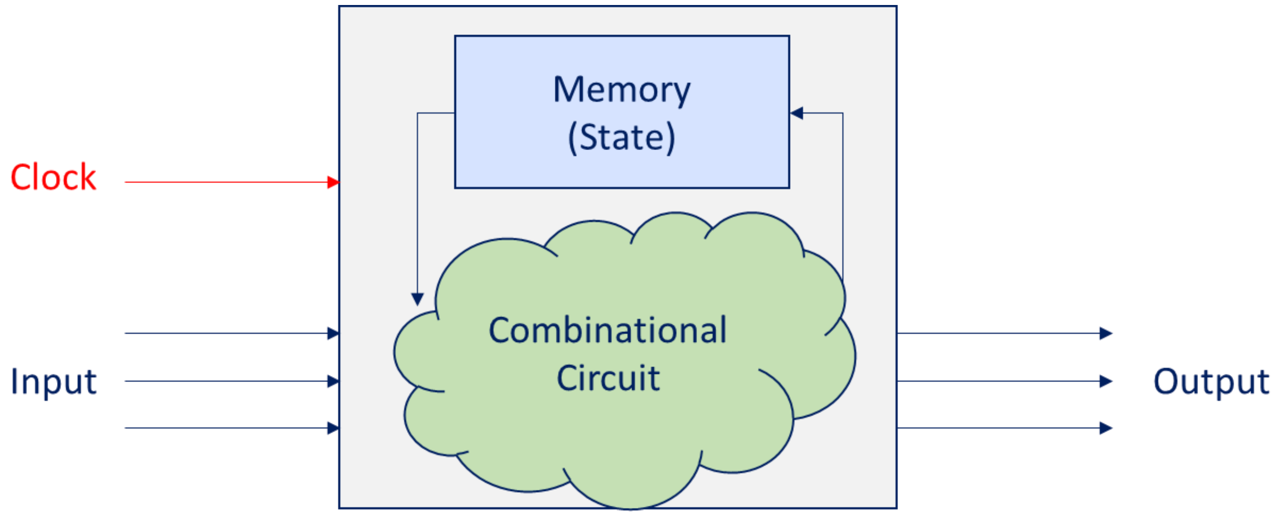
Abstract model of Sequential circuits



Slightly more realistic Sequential circuit

Synchronous sequential circuits

- "Synchronous": all operation are aligned to a shared clock signal
  - Speed of the circuit determined by the delay of its longest critical path
  - For correct operation, all paths must be shorter than clock speed
  - Either simplify logic, or reduce clock speed!



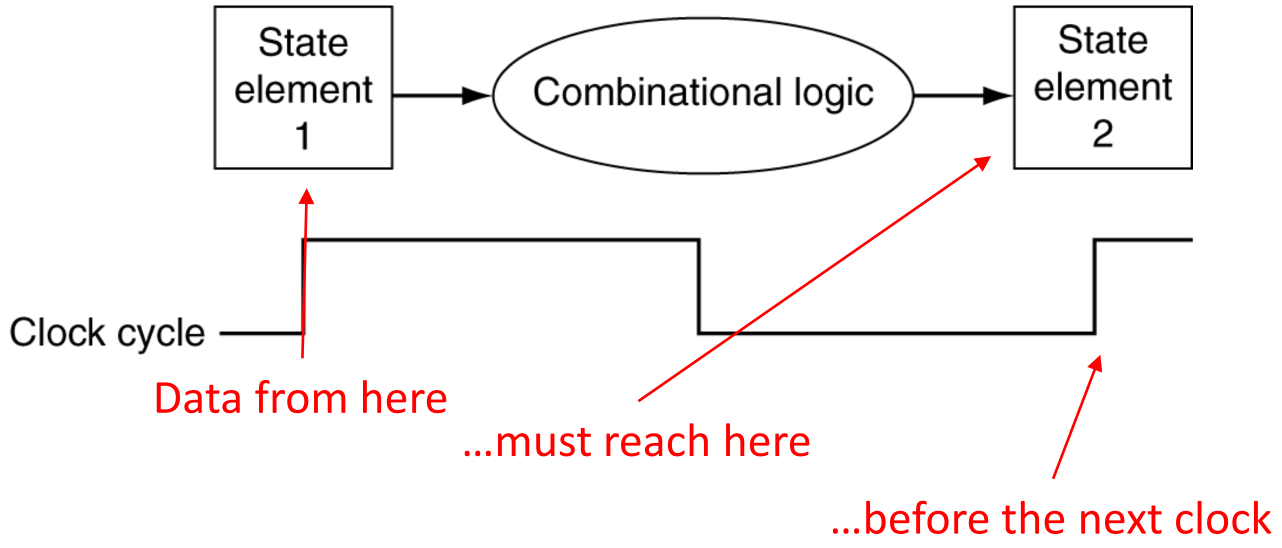
Timing constraints of state elements

- Synchronous state elements also add timing complexities
  - Beyond propagation delay and contamination delay
- Propagation delay (t_{PD}) of state elements
  - Rising edge of the clock to valid output from state element
- Contamination delay (t_{CD})
  - State element output should not change for t_{CD} after clock change

- Setup time (t_{SETUP})
  - State element should have held correct data for t_{SETUP} before clock edge
- Hold time (t_{HOLD})
  - Input to state element should hold correct data for t_{HOLD} after clock edge

Timing behavior of state elements

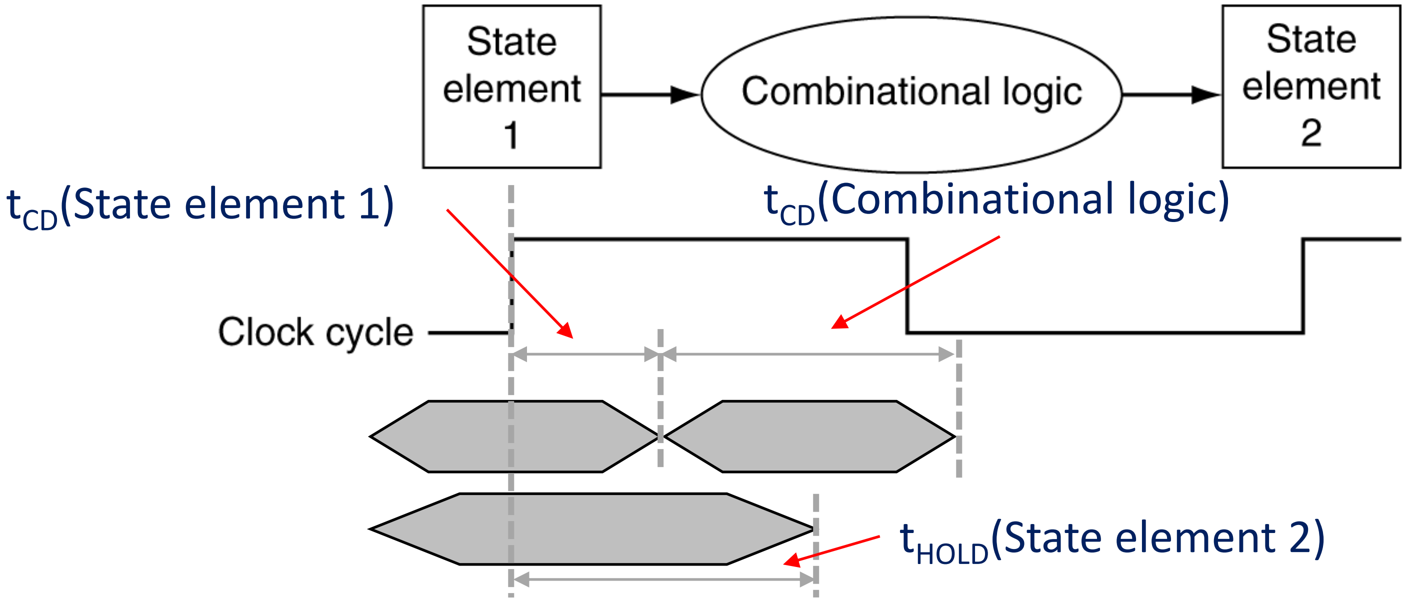
- Meeting the setup time constraint
  - "Processing must fit in clock cycle"
  - After rising clock edge,
  - t_{PD}(State element 1) + t_{PD}(Combinational logic) + t_{SETUP}(State element 2)
  - must be **smaller** than the clock period



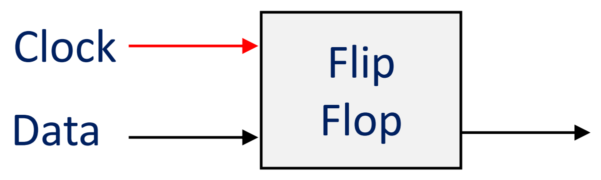
Otherwise, "timing violation"

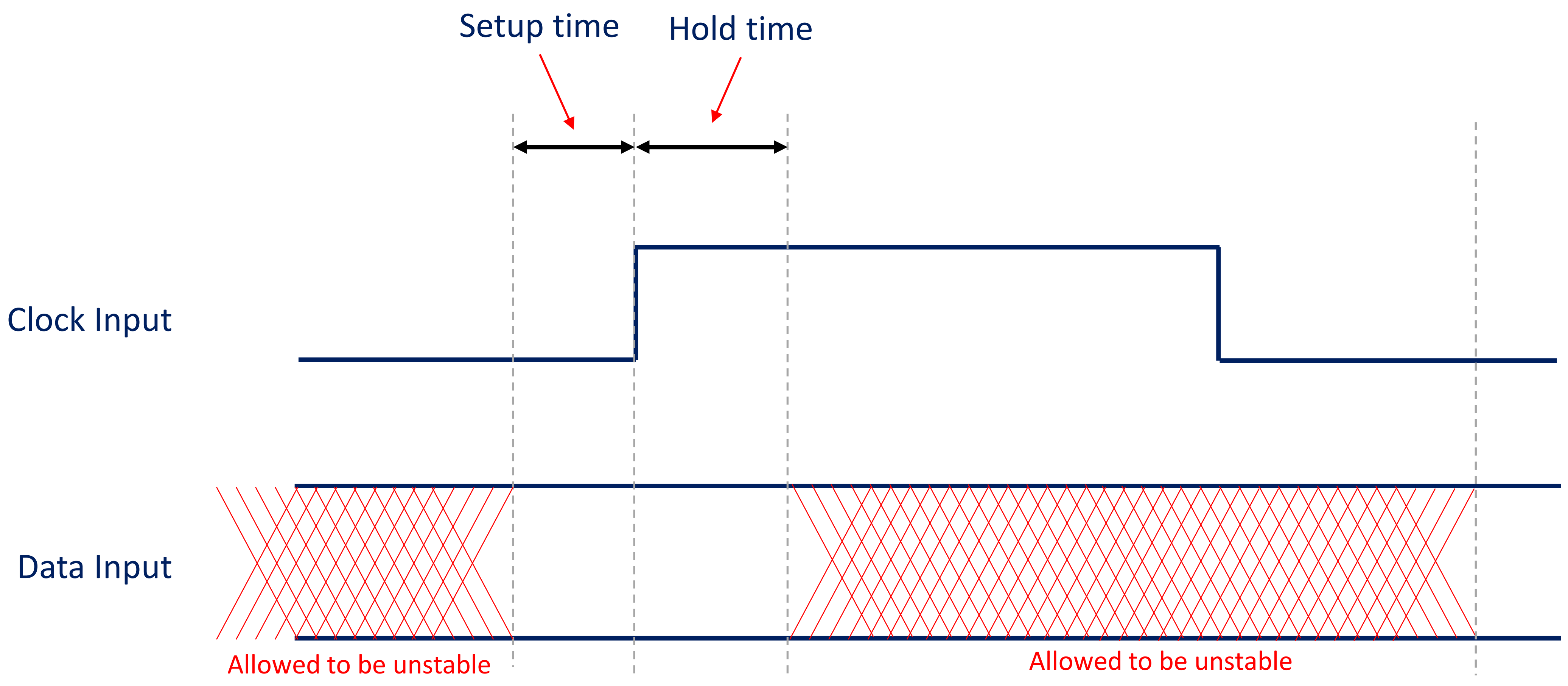
Timing behavior of state elements

- Meeting the hold time constraint
  - "Processing should not effect next state too early"
  - After rising clock edge,
  - t_{CD}(State element 1) + t_{CD}(Combinational logic) = Guaranteed time output will not change
  - must be **larger** than t_{HOLD}(State element 2)


State element 1
Combinational logic
State element 2
t_{CD}(State element 1)
t_{CD}(Combinational logic)
Clock cycle
t_{HOLD}(State element 2)

Setup and hold time window





If any constraint is violated, state may hold wrong data!

Real-world implications

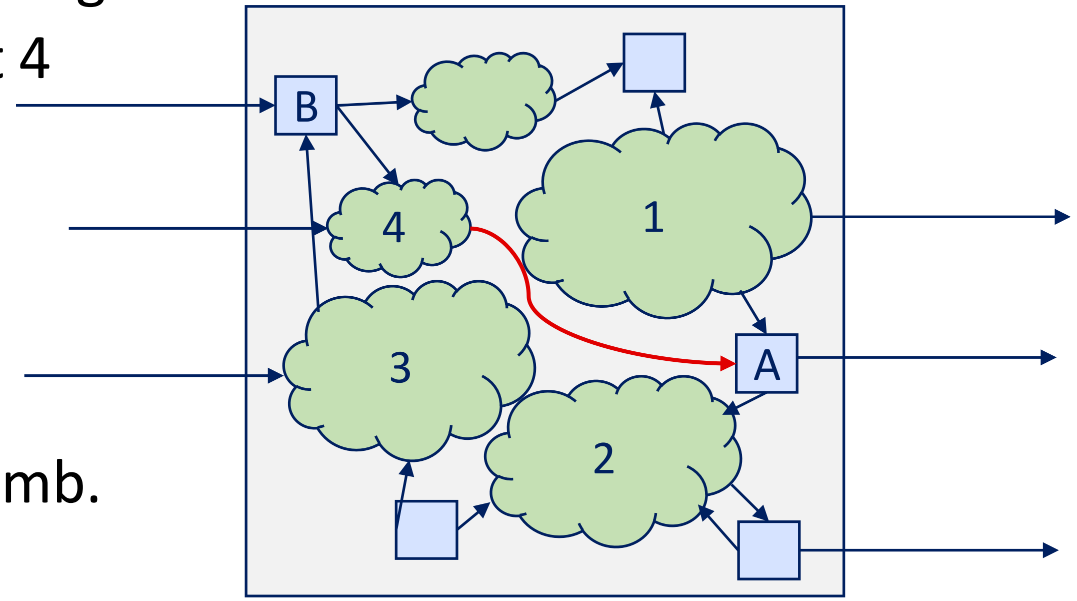
- Constraints are met via Computer-Aided Design (CAD) tools
  - Cannot do by hand!
  - Given a high-level representation of function, CAD tools will try to create a physical circuit representation that meets all constraints

- Rule of thumb: Meeting **hold time** is typically not difficult
  - e.g., Adding a bunch of buffers can add enough t_{CD}(Sequential Circuit)
- Rule of thumb: Meeting **setup time** is often difficult
  - Somehow construct shorter critical paths, or
  - reduce clock speed (We want to avoid this!)

How do we create shorter critical paths for the same function?

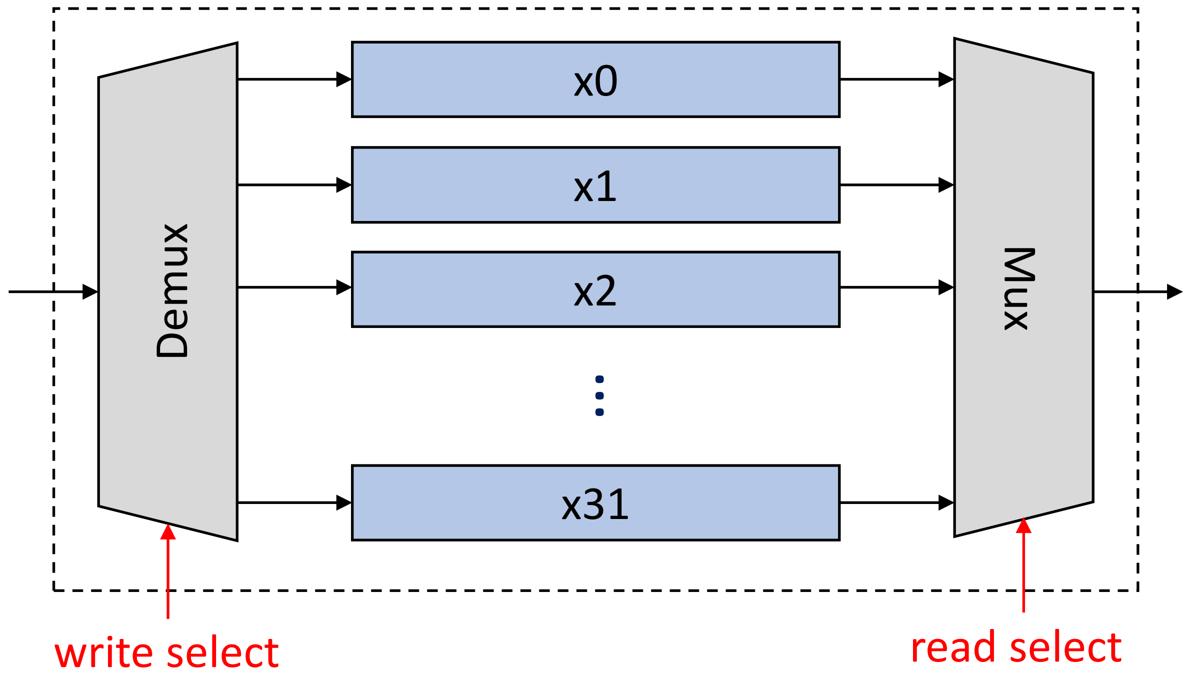
Simplified introduction to placement/routing

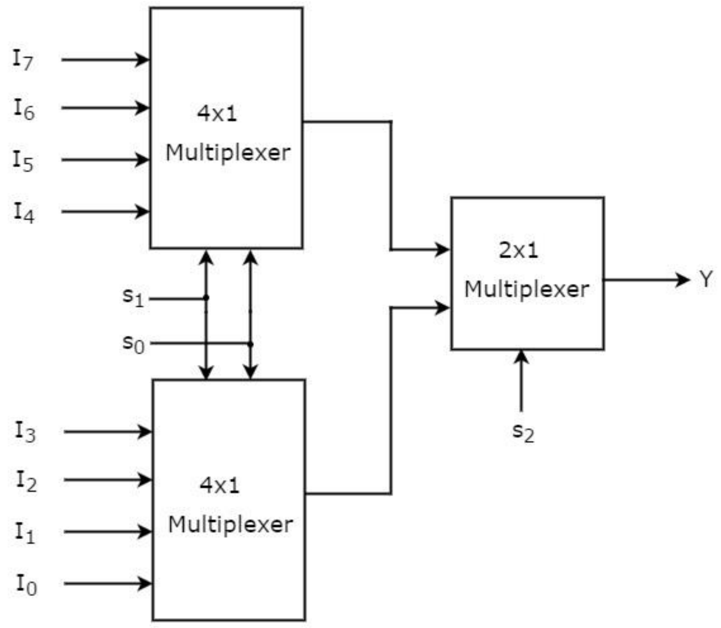
- ❑ Mapping state elements and combinational circuits to limited chip space
  - o Also done via CAD tools
  - o May add significant propagation delay to combinational circuits
- ❑ Example:
  - o Complex combinational circuits 1 and 2 accessing state A
  - o Spatial constraints push combinational circuit 4 far from state A
  - o Path from B to A via 4 is now very long!
- ❑ Rule of thumb:
  - o One comb. should not access too many state
  - o One state should not be used by too many comb.



Looking back:
Why are register files small?

- Why are register files 32-element? Why not 1024 or more?





Hierarchical design of a 8x1 multiplexer

Propagation delay increases with more registers!

Real-world example

- ❑ Back in 2002 (When frequency scaling was going strong, but larger FETs)
  - Very high frequency (multi-GHz) meant:
  - … setup time constraint could tolerate
  - … up to 8 inverters in its critical path
  - Such stringent restrictions!

Can we even fit a 32-bit adder there? No!