ECE/CS 250
Computer Architecture

Fall 2023

Basics of Logic Design:
Storage Elements and the Register File
(Sequential Logic)

John Board

Duke University

Slides are derived from work by
Daniel J. Sorin (Duke), Alvy Lebeck (Duke), Tyler Bletsch (Duke), John Board (Duke), and Drew Hilton (Duke)

So far…

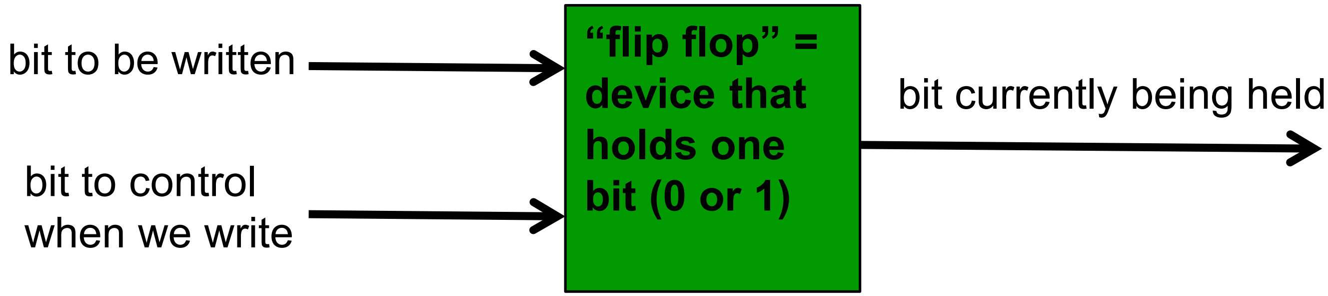
- We can make logic to compute "math"
  - Add, subtract … and you can do mul/div in 350
    - Assume for now that mul/div can be built
  - Bitwise: AND, OR, NOT,…
  - Shifts (left or right)
  - Selection (MUX)
  - …pretty much anything
- But processors need state (hold value)
  - Registers
  - …

Storage

- All the circuits we looked at so far are combinational circuits: the output is a Boolean function of the inputs.
- We need circuits that can remember values (registers, memory)
- The output of the circuit is a function of the input and a function of a stored value (state)
- Circuits with storage are called sequential circuits
- Key to storage: feedback loops from outputs to inputs

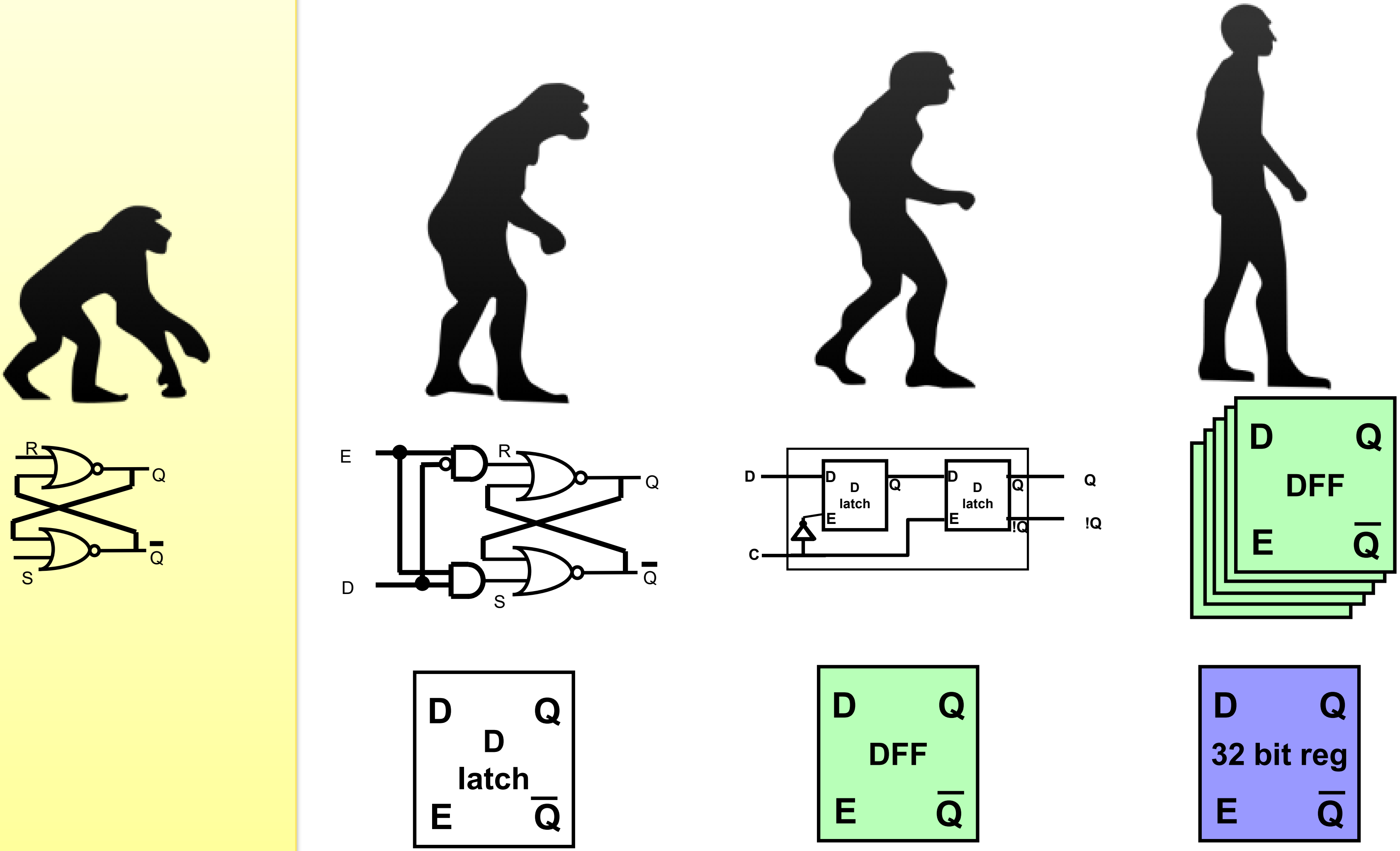
Ideal Storage – Where We're Headed

- Ultimately, we want something that can hold 1 bit and we want to control when it is re-written



- However, instead of just giving it to you as a magic black box, we're going to first dig a bit into the box
  - I will not test you on the insides of the "flip flop"
  - But in CS/ECE350 we will probe their very souls in excruciating detail!

Building up to the D Flip-Flop and beyond



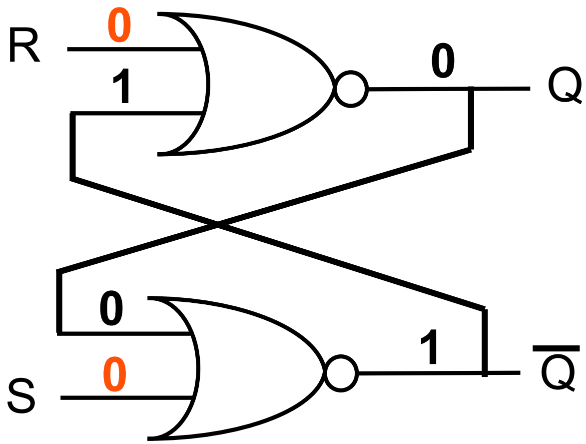
SR Latch
(too awkward)

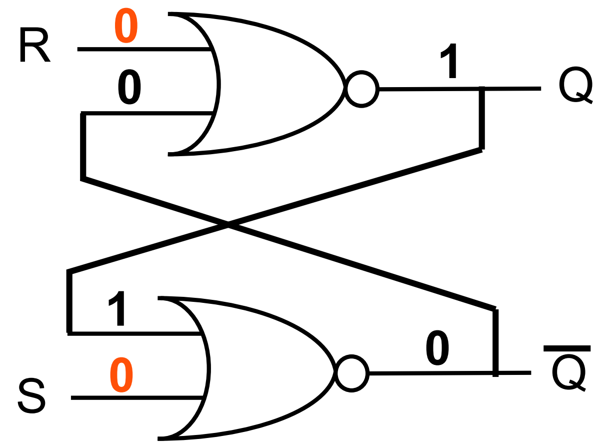
D Latch
(bad timing)

D Flip-Flop
(okay but only one bit)

Register
(*nice!*)

FF Step #1: NOR-based Set-Reset (SR) Latch

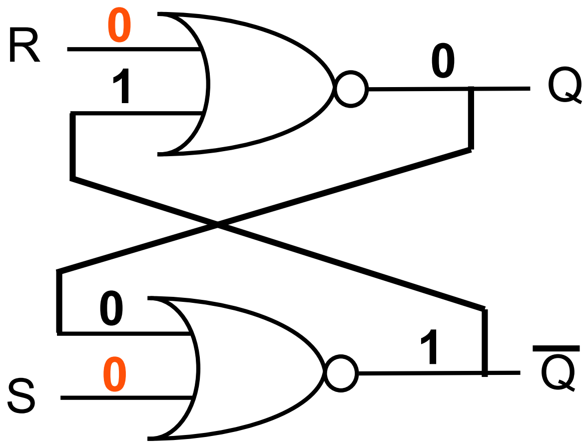


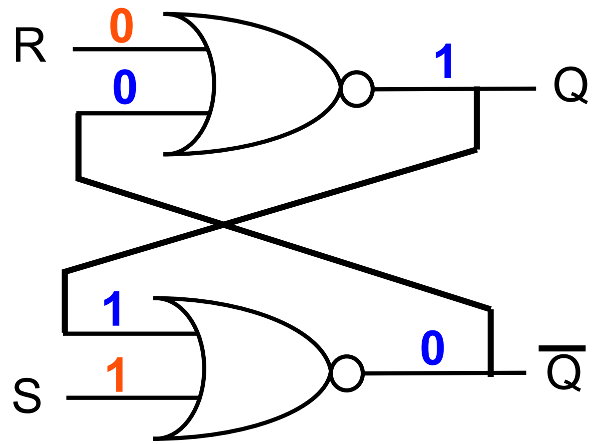


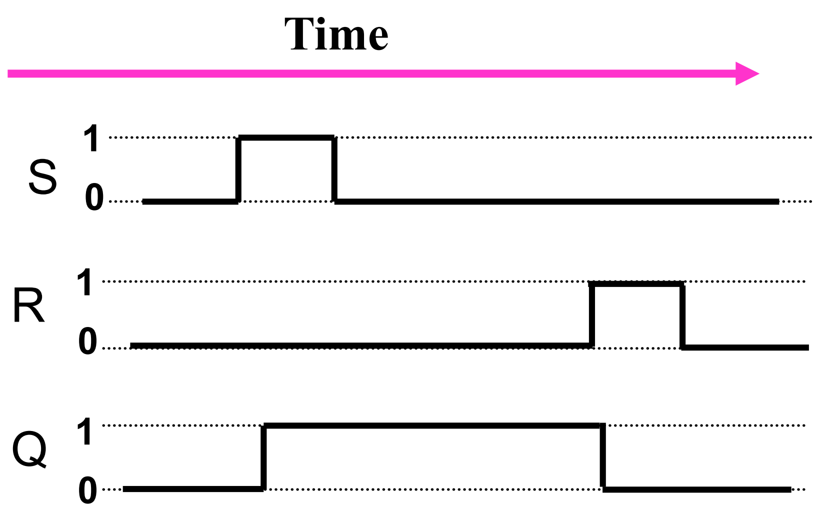
R	S	Q
0	0	Q
0	1	1
1	0	0
1	1	–

Don't set both S & R to 1. Seriously, don't do it. Half an entire lecture in 350 on this.

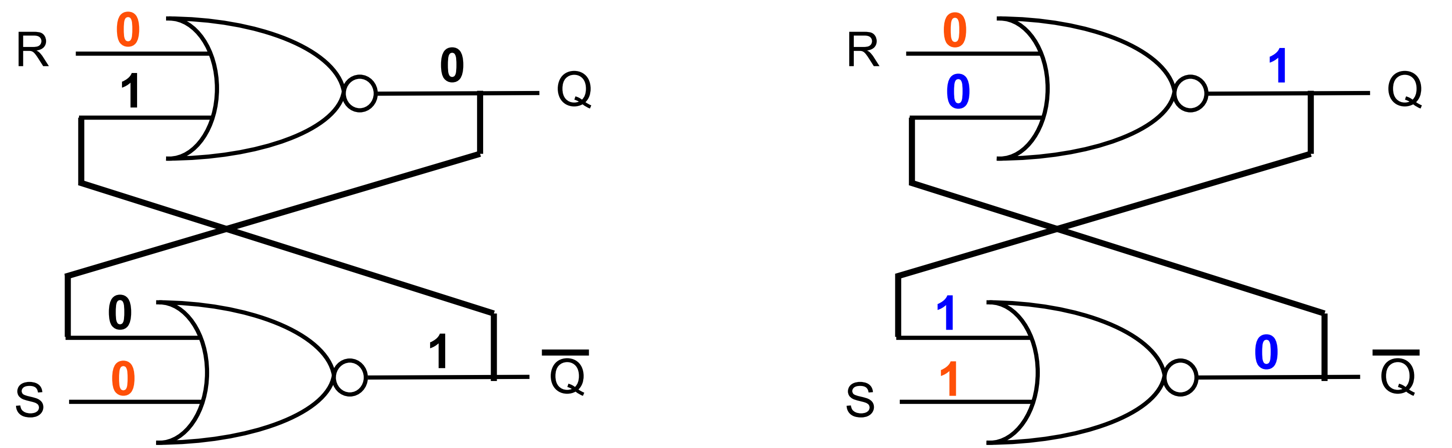
Set-Reset Latch (Continued)

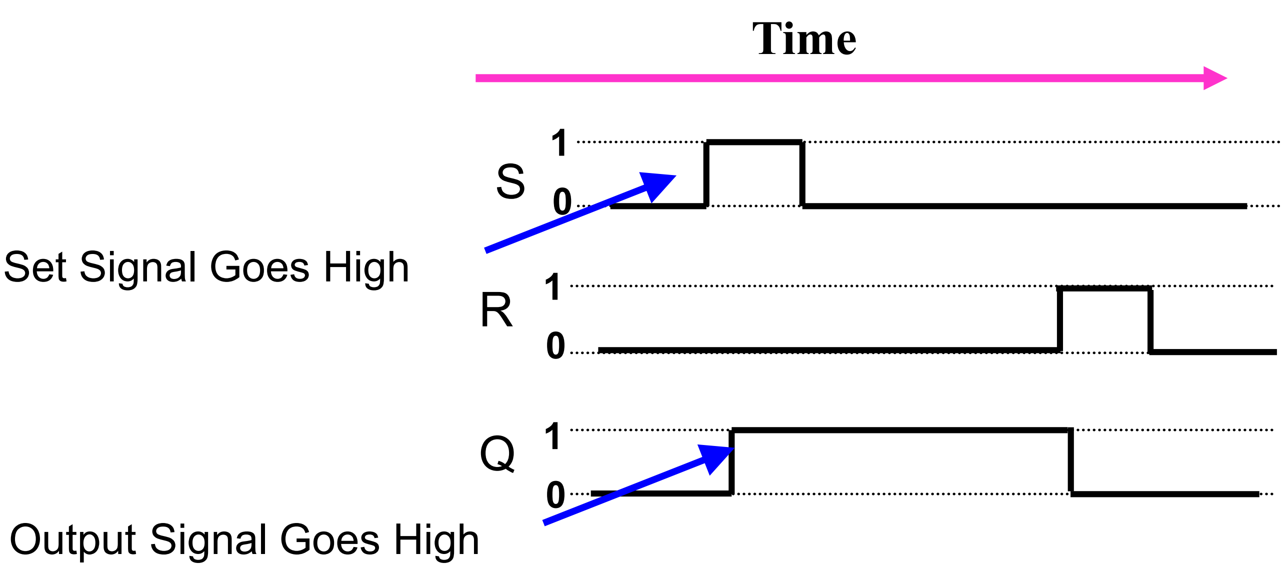




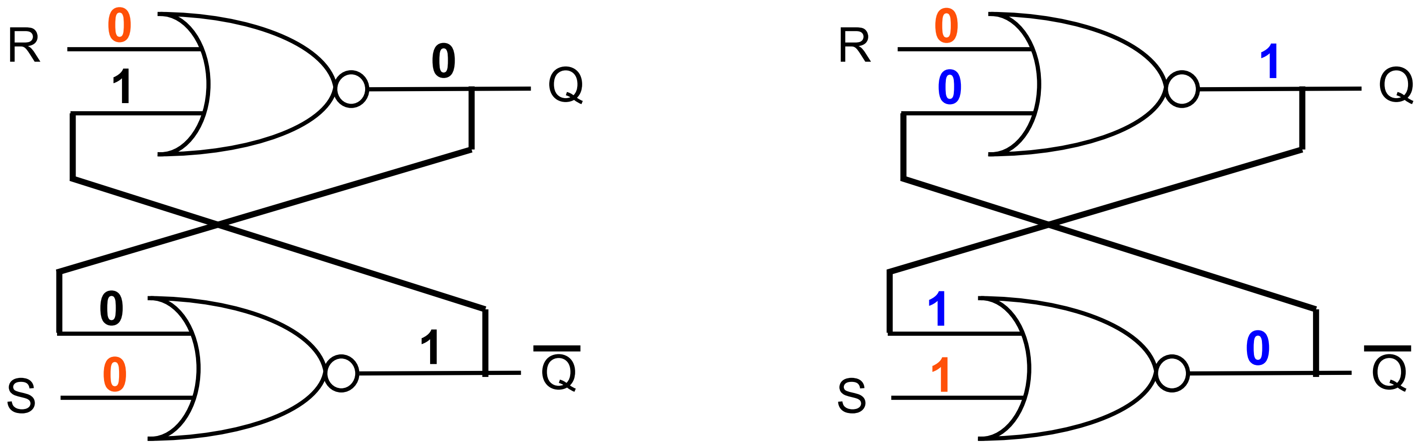


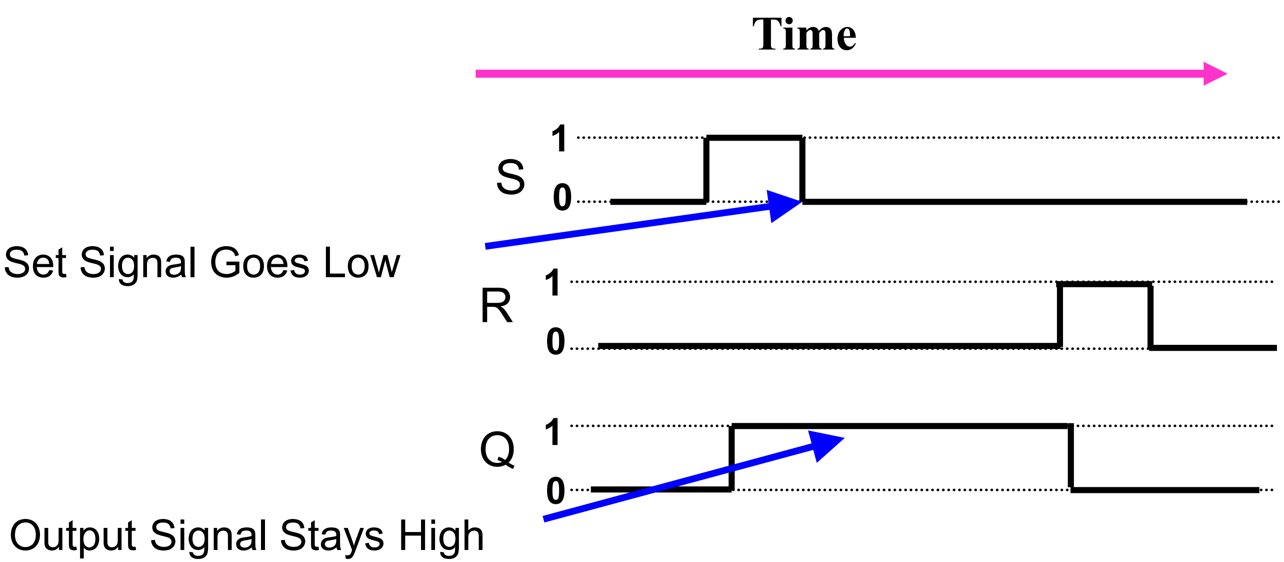
Set-Reset Latch (Continued)



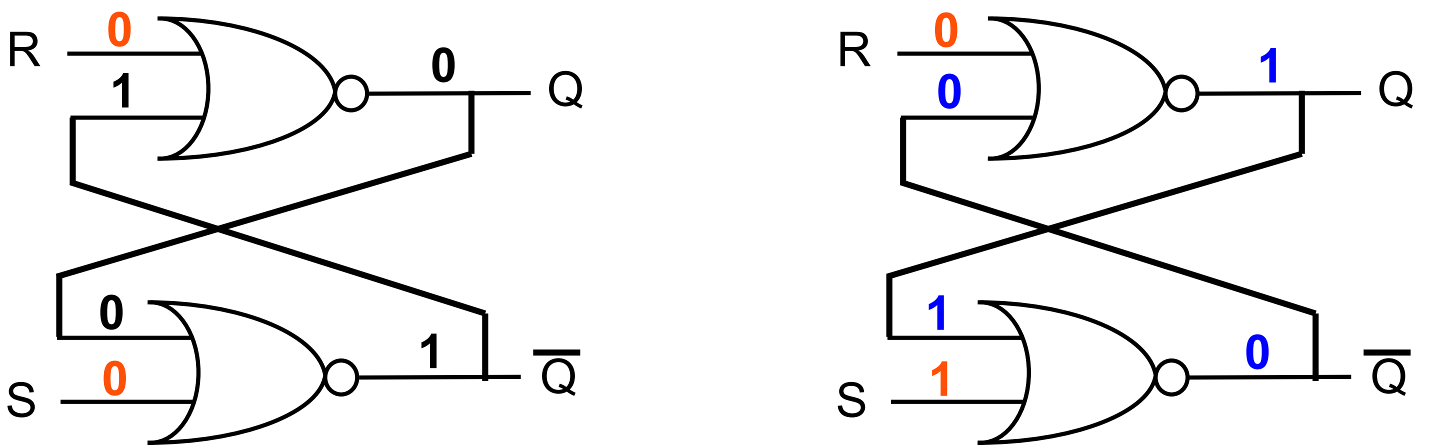


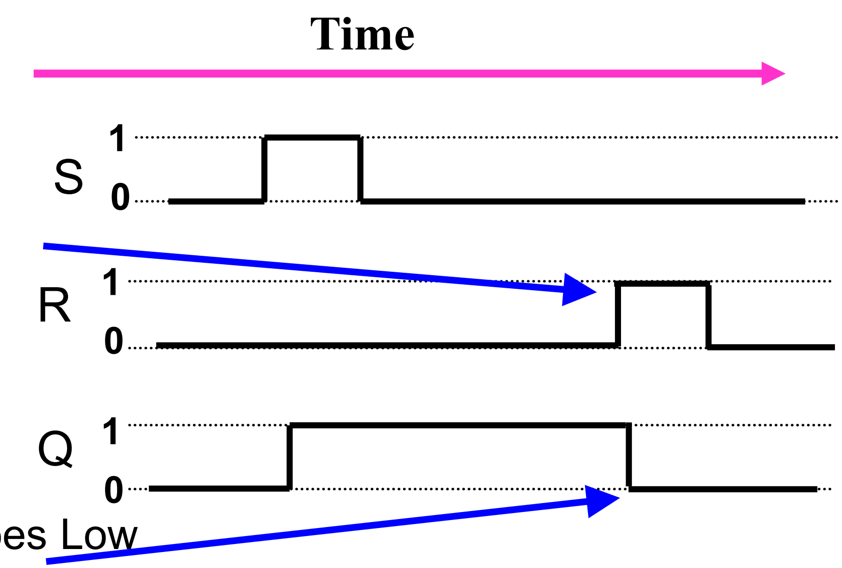
Set-Reset Latch (Continued)





Set-Reset Latch (Continued)





Until Reset Signal Goes High

Then Output Signal Goes Low

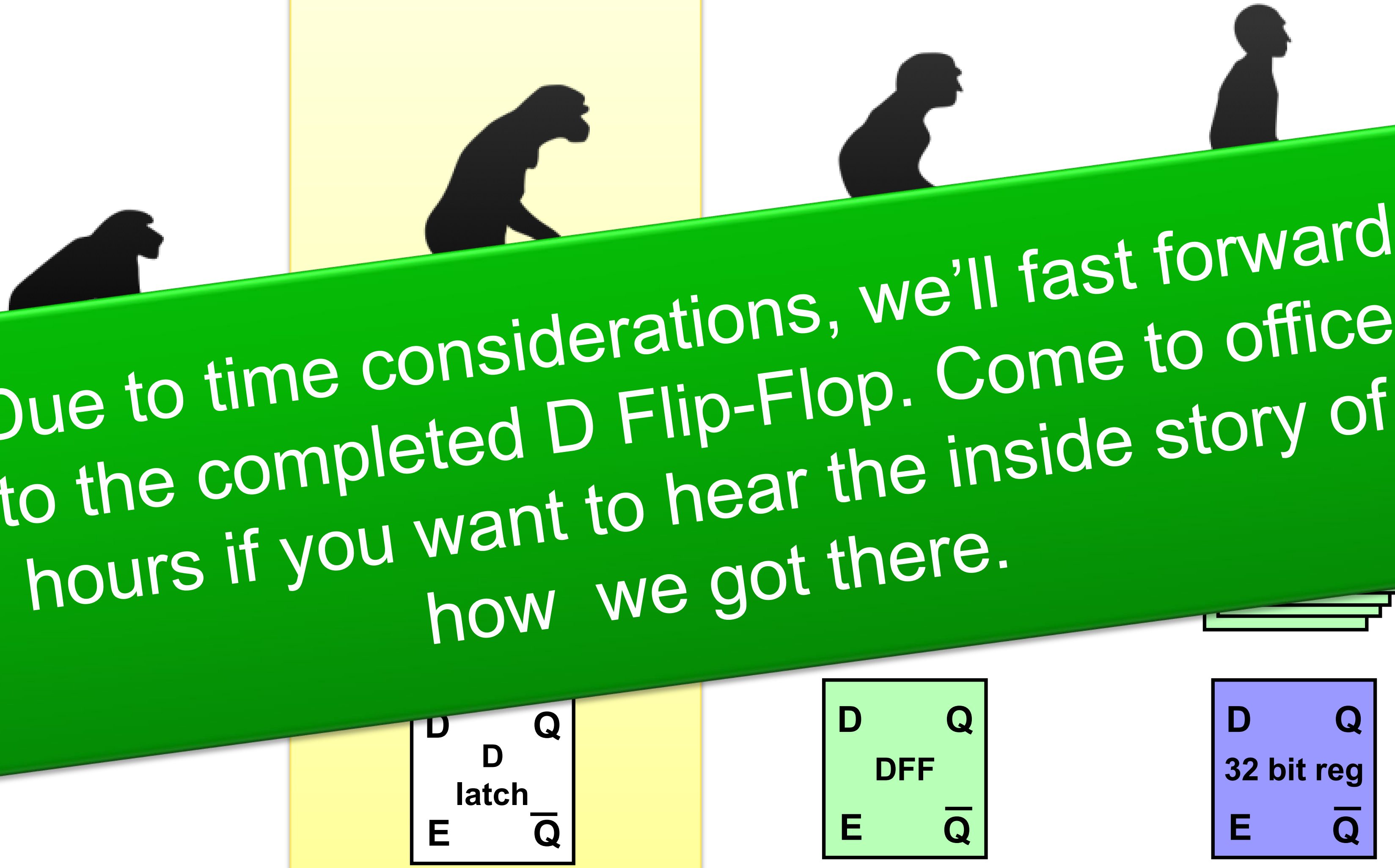
SR Latch

- Downside: S and R at once = chaos
- Downside: Bad interface

- So let's build on it to do better

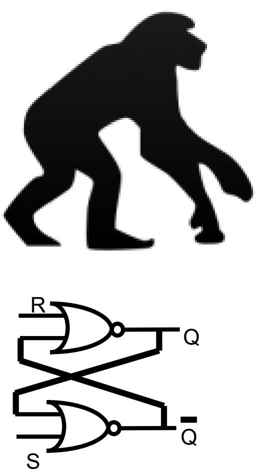
Building up to the D Flip-Flop and beyond

Due to time considerations, we'll fast forward to the completed D Flip-Flop. Come to office hours if you want to hear the inside story of how we got there.



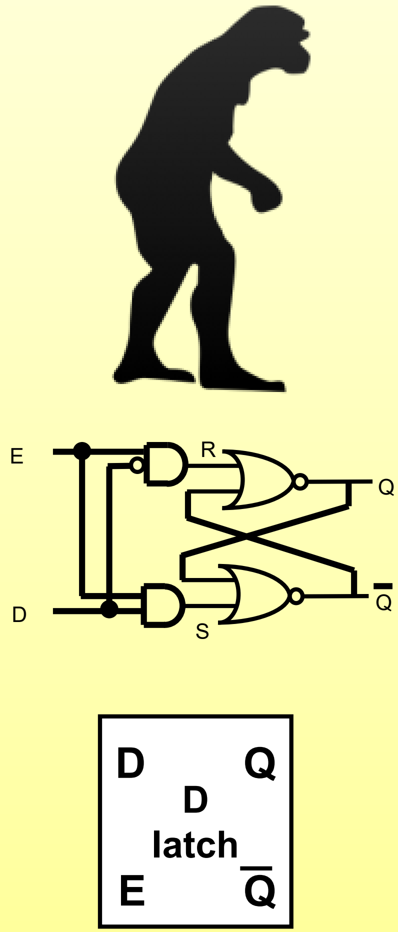
SR Latch (too awkward) | D Latch (bad timing) | D Flip-Flop (okay but only one bit) | Register (*nice!*)

Building up to the D Flip-Flop and beyond



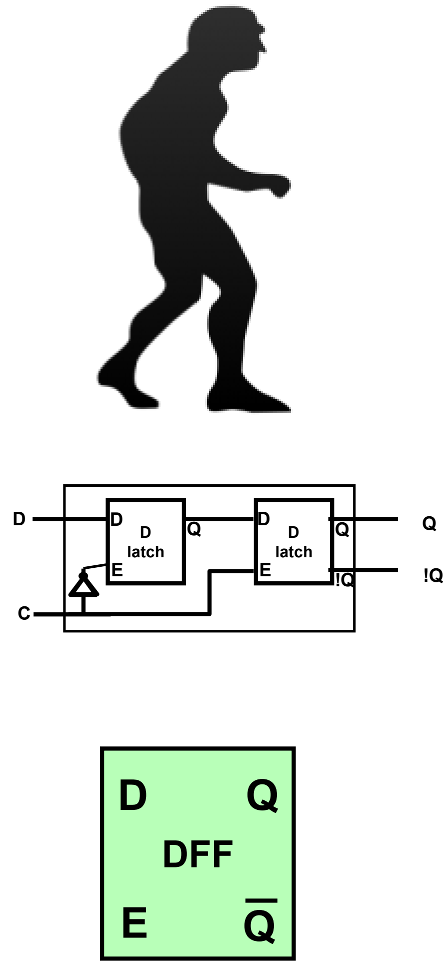
SR Latch

(too awkward)



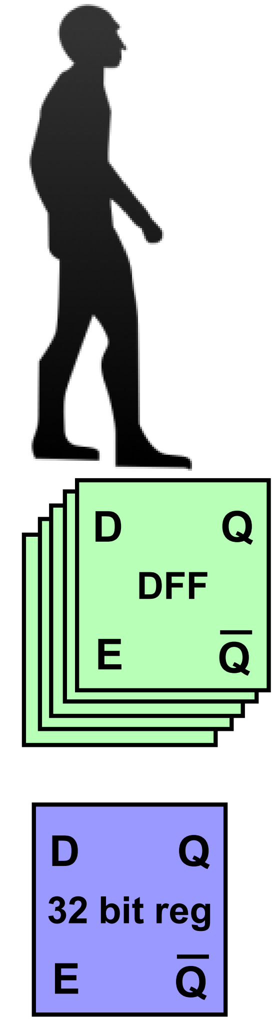
D Latch

(bad timing)



D Flip-Flop

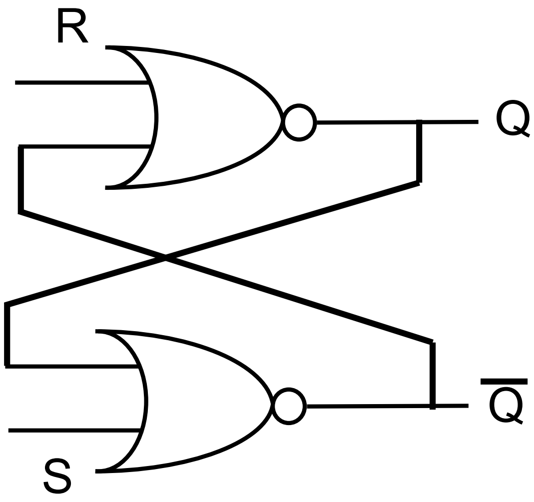
(okay but only one bit)



Register

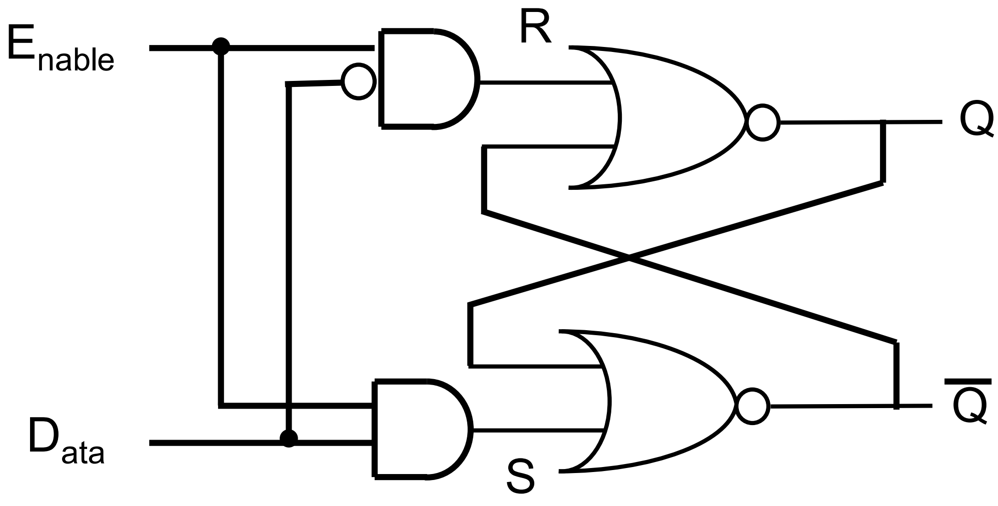
(nice!)

FF Step #2: Data Latch ("D Latch")



Starting with SR Latch

Data Latch (D Latch)



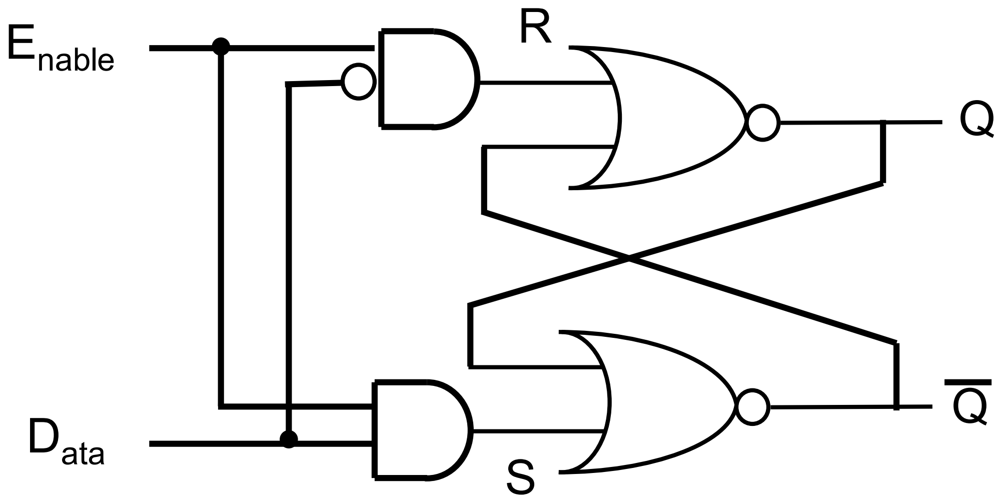
Starting with SR Latch

Change interface to
Data + Enable (D + E)

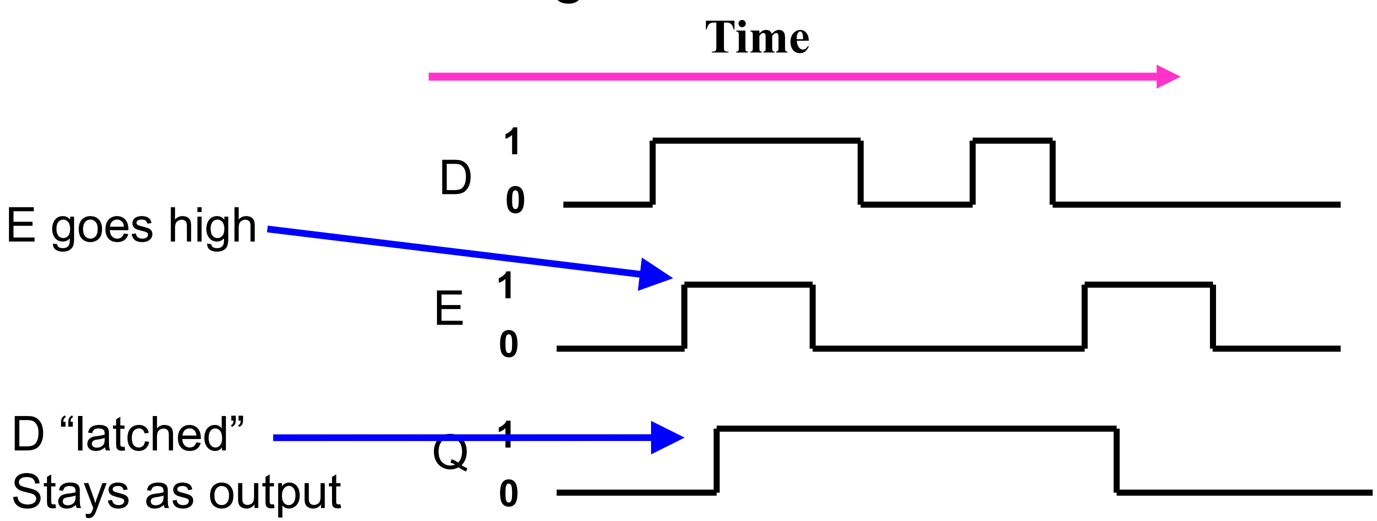
If E=0, then R=S=0.
If E=1, then S=D and R=!D

Enable is our first clock, of a sort!

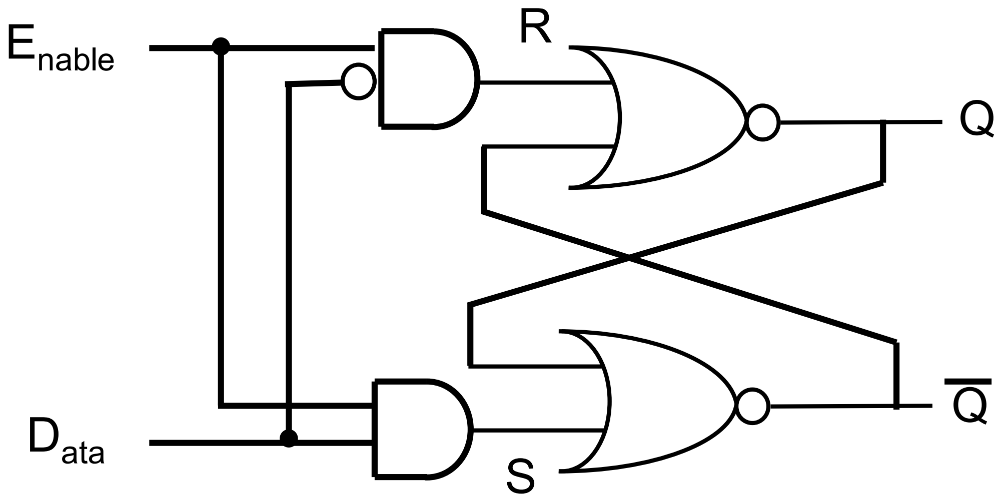
Data Latch (D Latch)



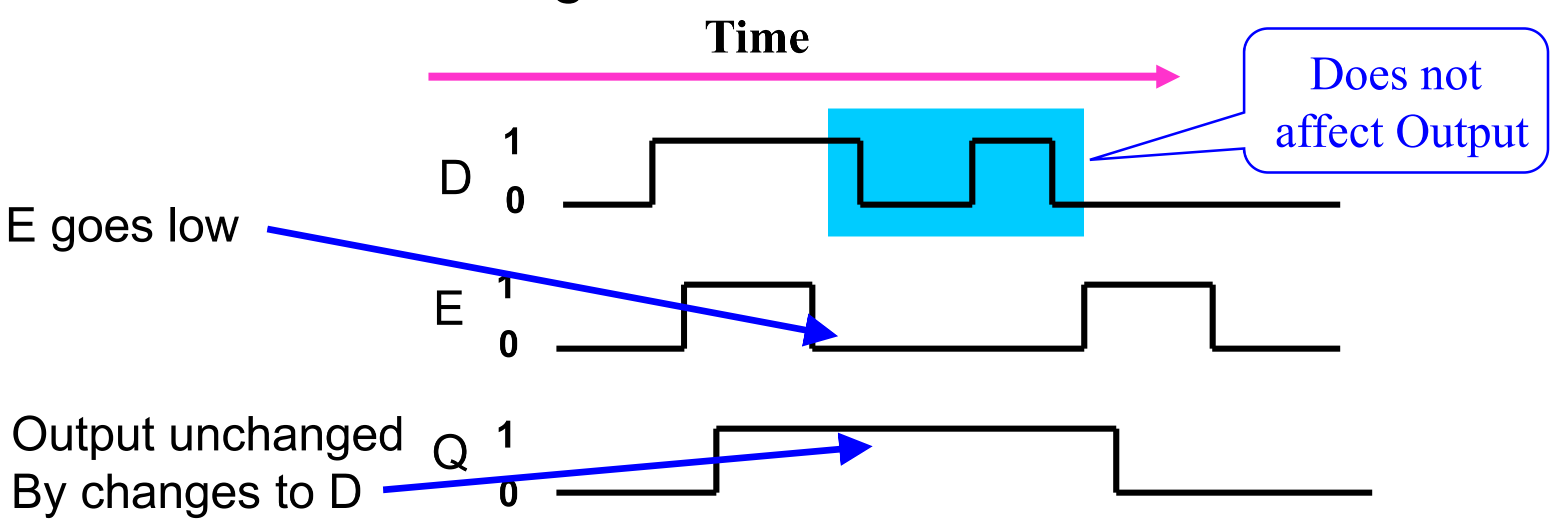
D	E	Q
0	1	0
1	1	1
–	0	Q



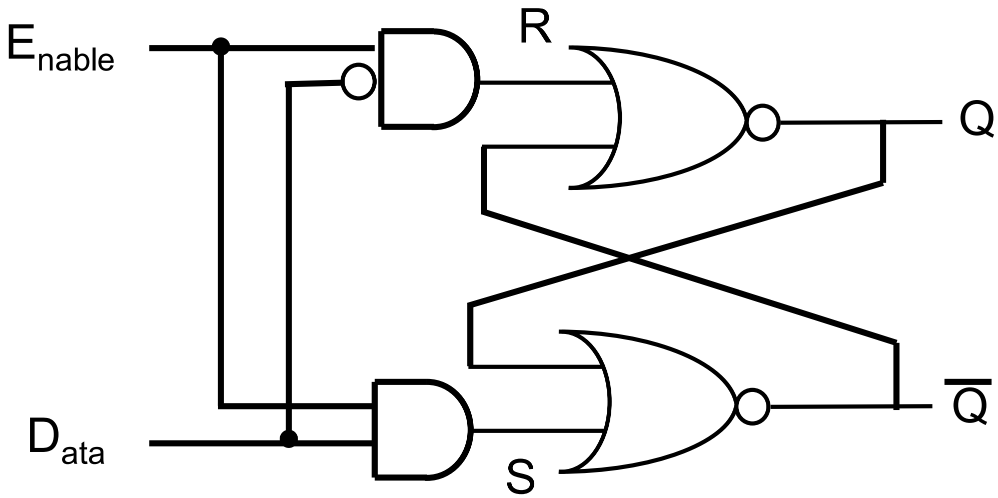
Data Latch (D Latch)



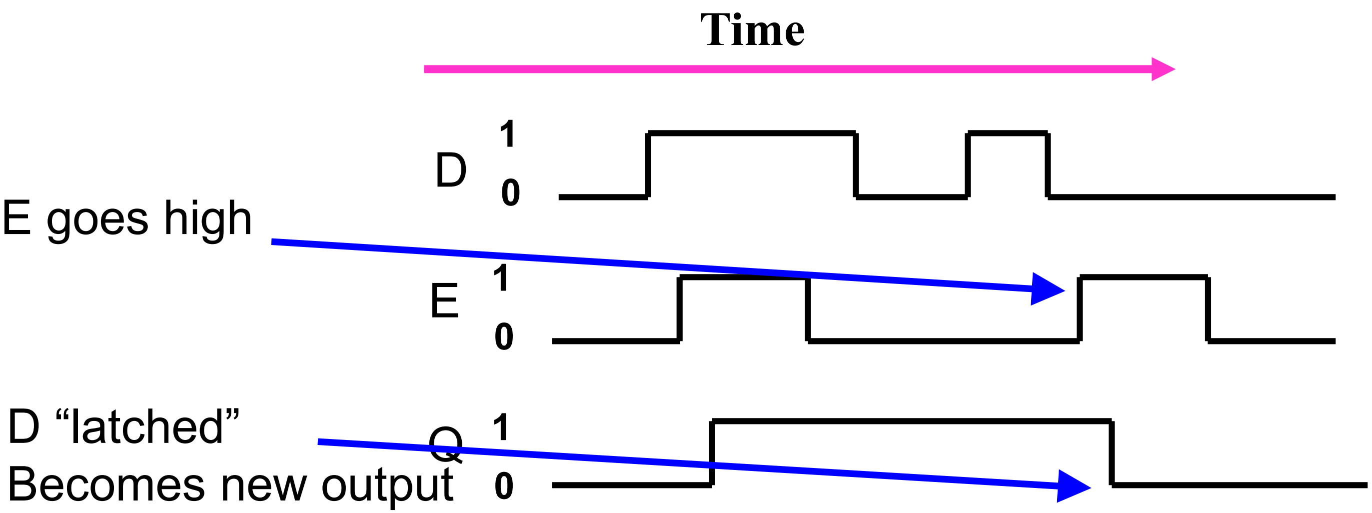
D	E	Q
0	1	0
1	1	1
–	0	Q



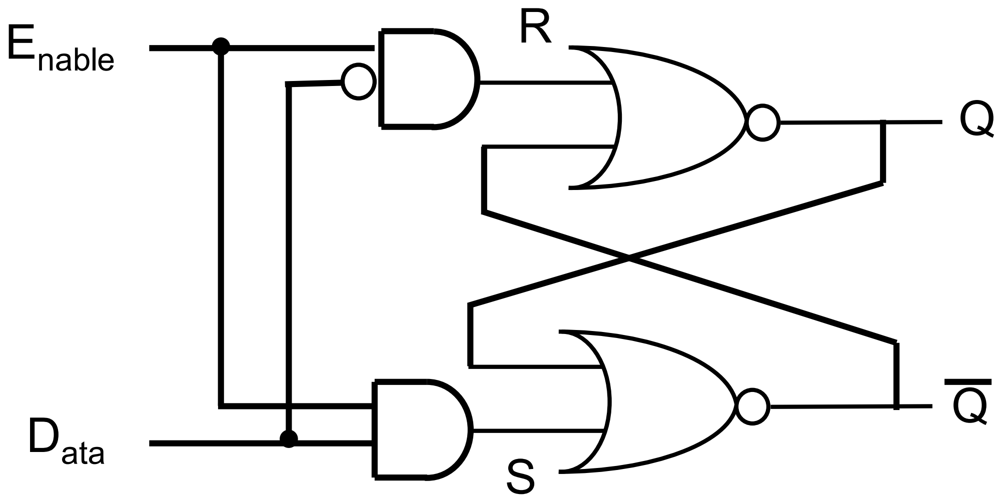
Data Latch (D Latch)



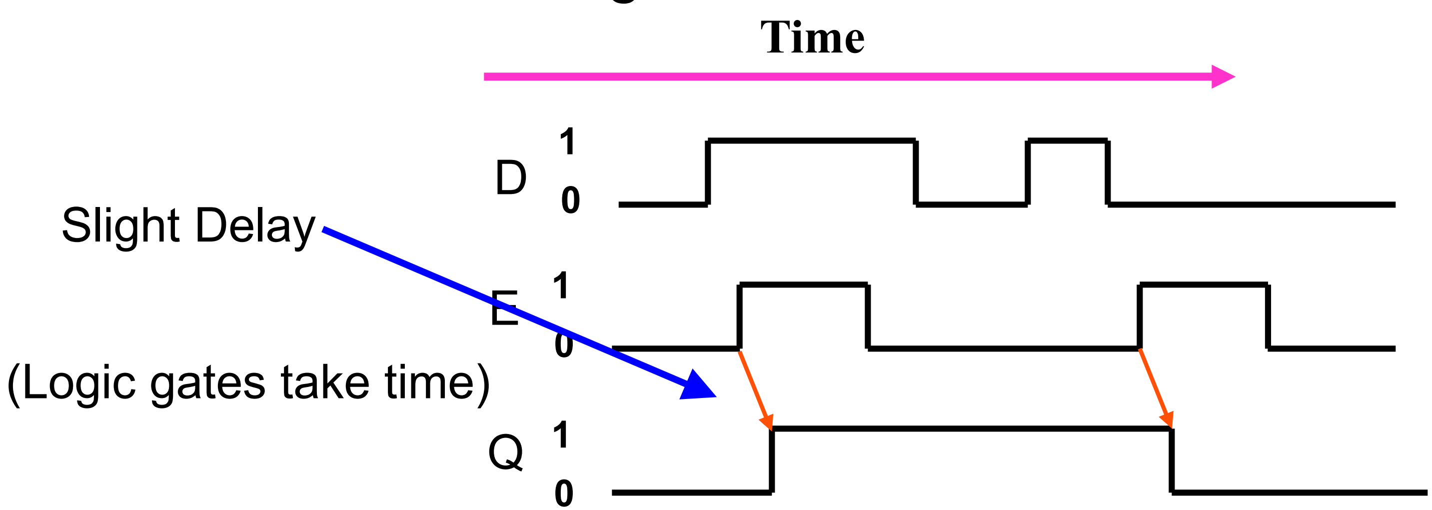
D	E	Q
0	1	0
1	1	1
-	0	Q



Data Latch (D Latch)



D	E	Q
0	1	0
1	1	1
–	0	Q

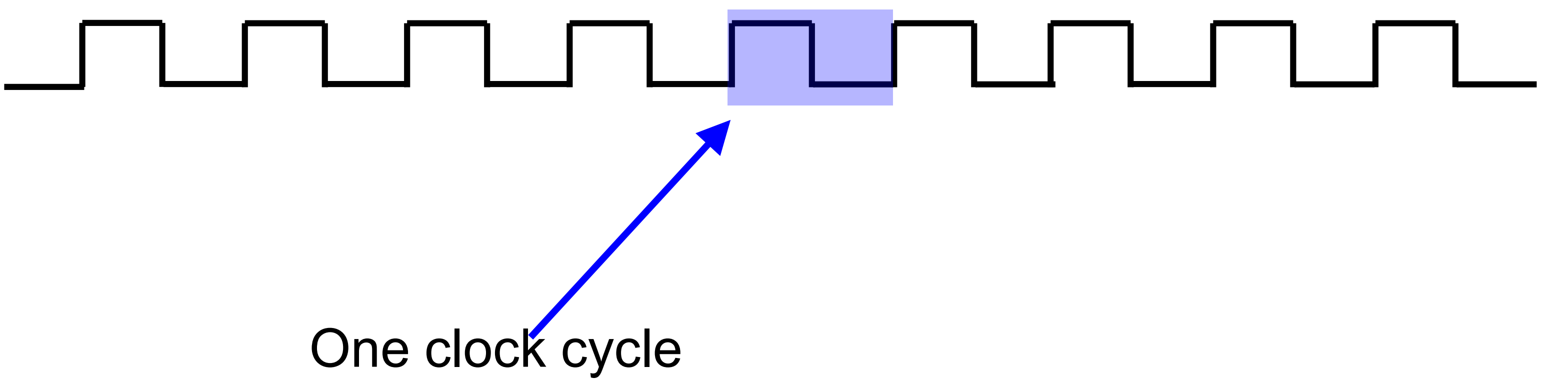


Logic Takes Time

- Logic takes time:
  - Gate delays: delay to switch each gate
  - Wire delays: delay for signal to travel down wire
  - Other factors (not going into them here)
- Need to make sure that signals timing is right
  - Don't want to have races or wacky conditions..

Clocks

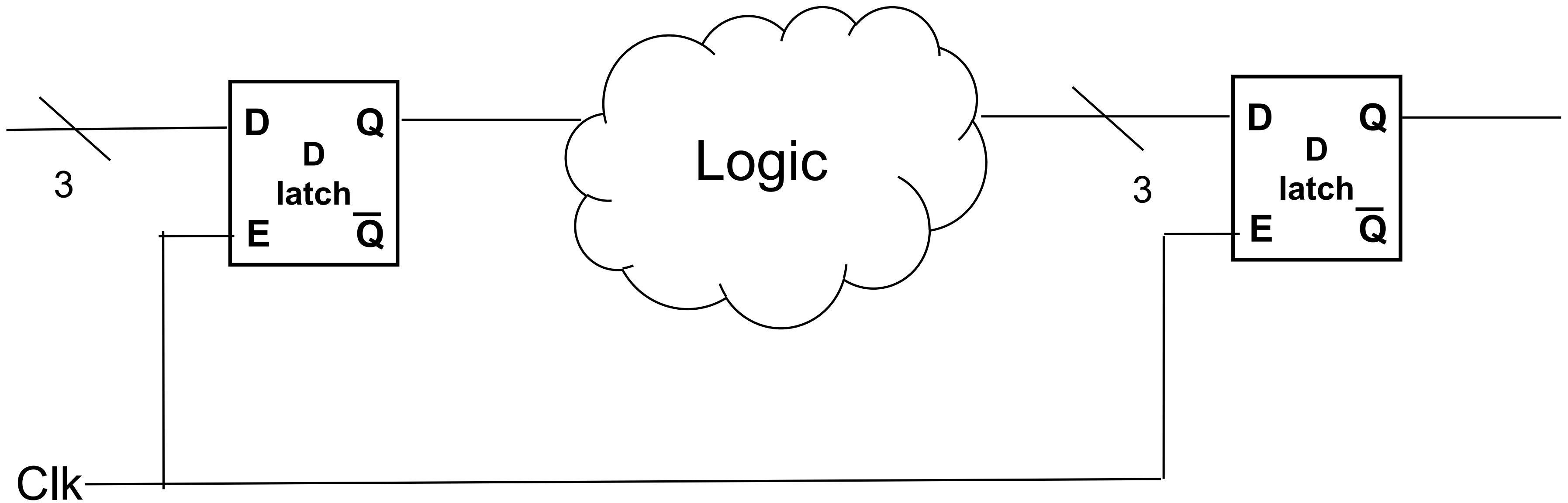
- Processors have a clock:
  - Alternates 0 1 0 1
  - Like the processor's internal metronome
  - Latch → logic → latch in one clock cycle



  - 3.4 GHz processor = 3.4 Billion clock cycles/sec

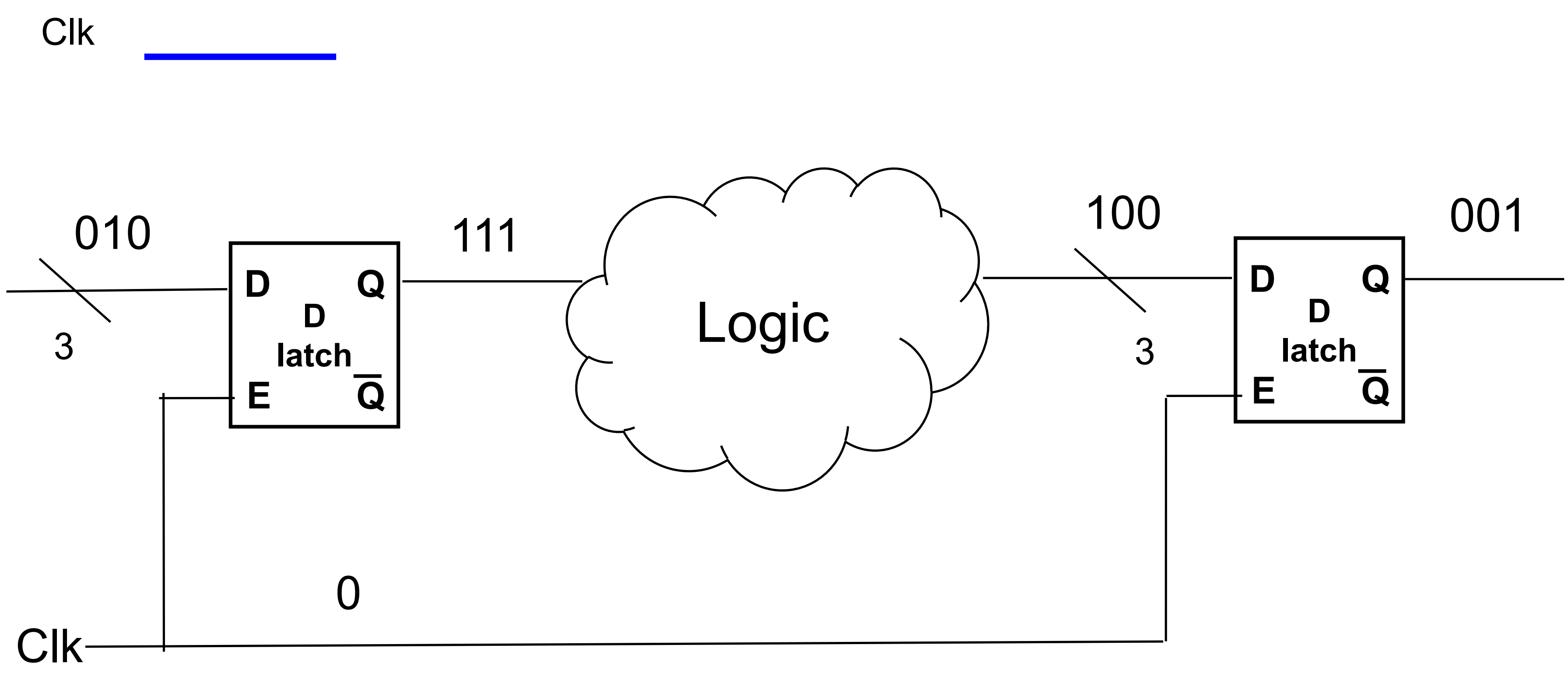
FF Step #3: Using Level-Triggered D Latches

- First thoughts: Level Triggered
  - Latch enabled when clock is high
  - Hold value when clock is low



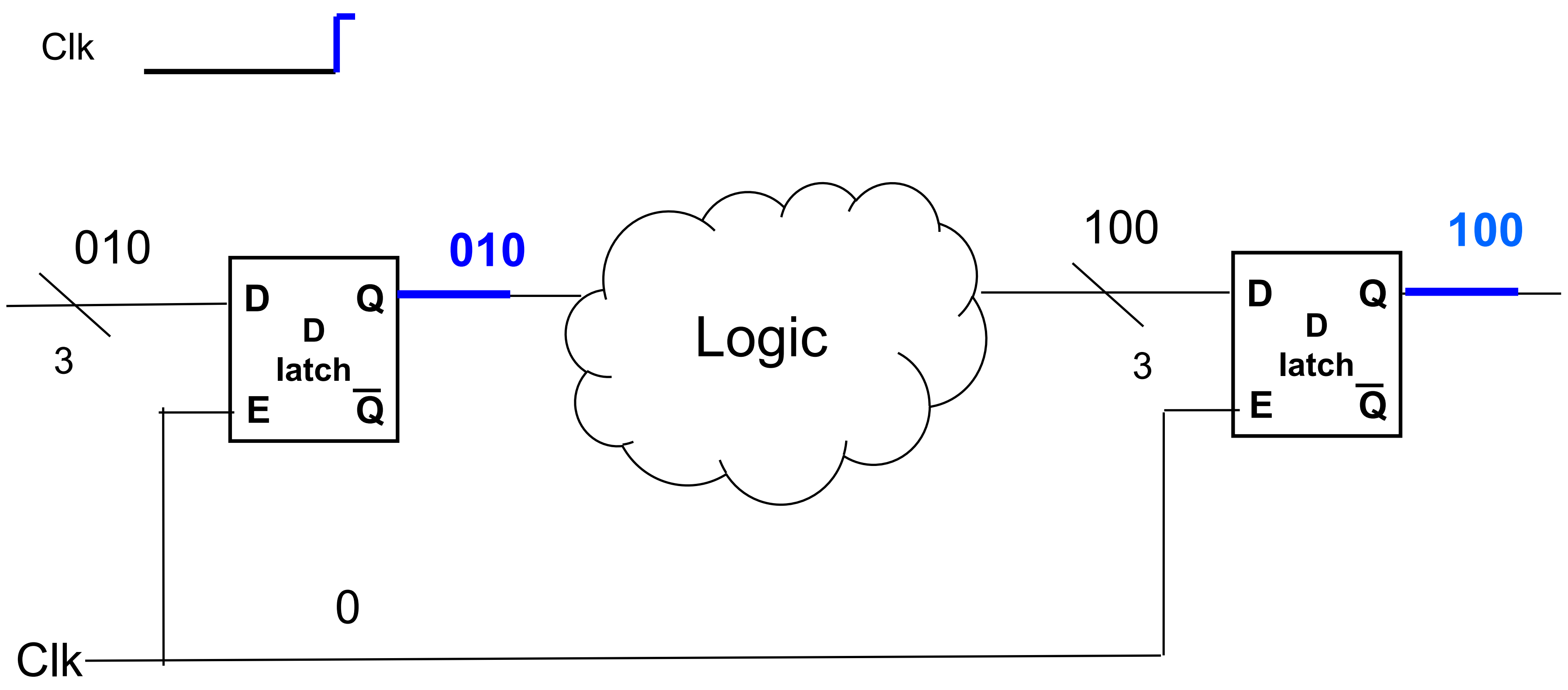
Strawman: Level Triggered

- How we'd like this to work
  - Clock is low, all values stable



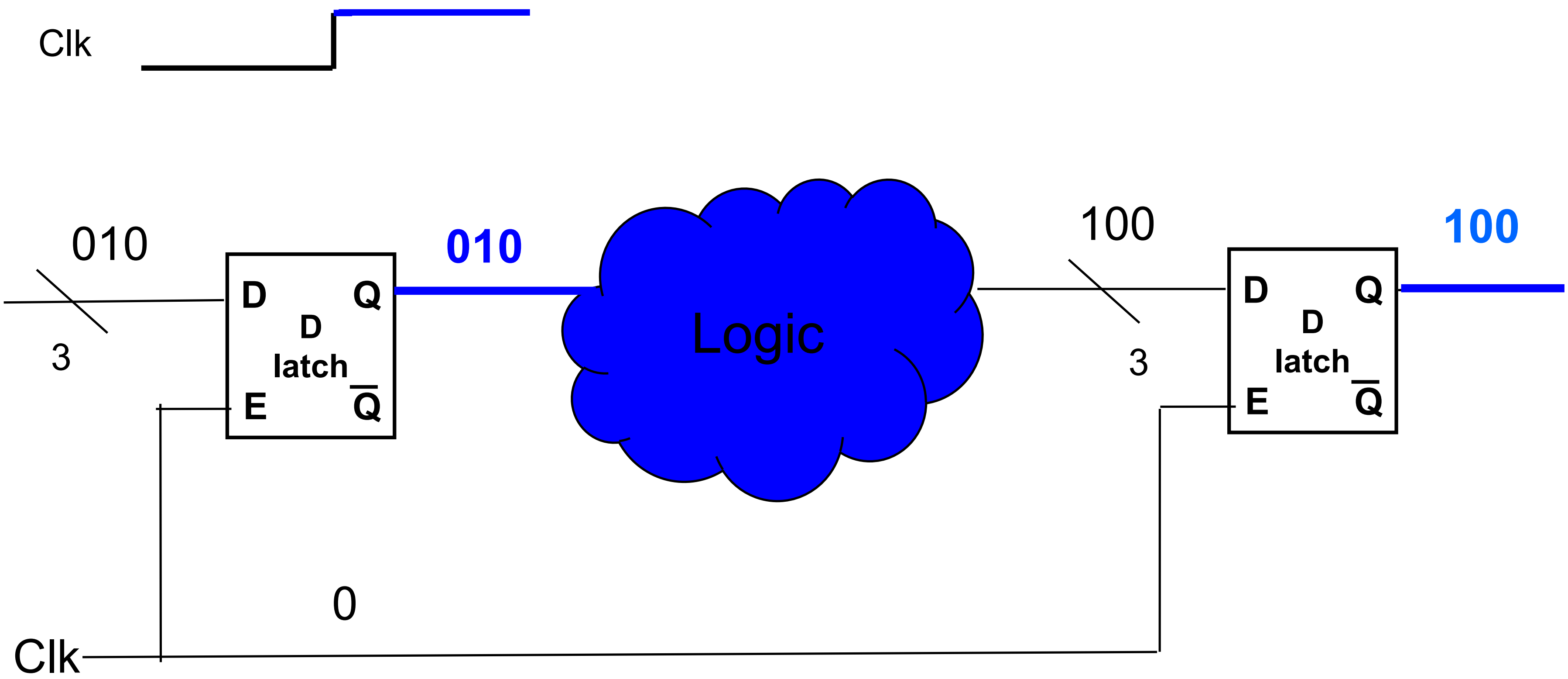
Strawman: Level Triggered

- How we'd like this to work
  - Clock goes high, latches capture and xmit new val



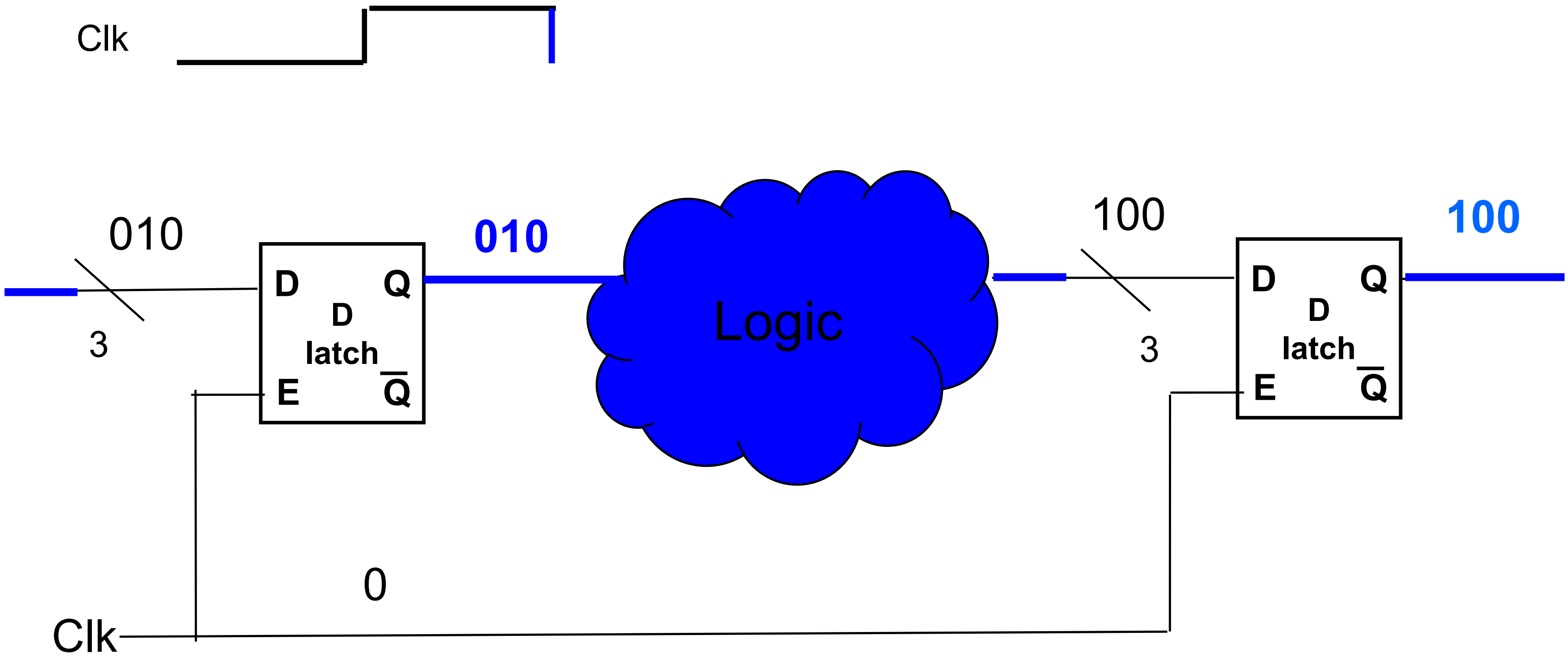
Strawman: Level Triggered

- How we'd like this to work
  - Signals work their way through logic w/ high clk



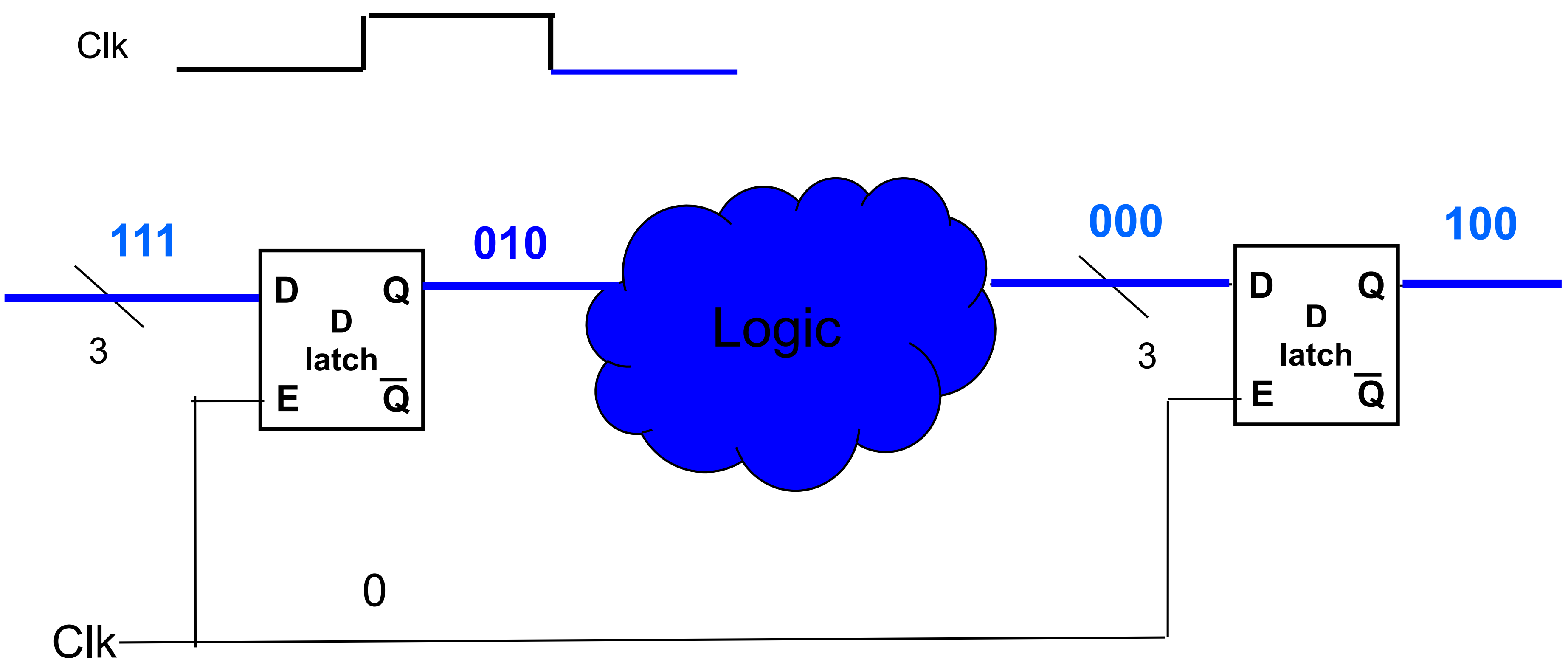
Strawman: Level Triggered

- How we'd like this to work
  - Clock goes low before signals reach next latch



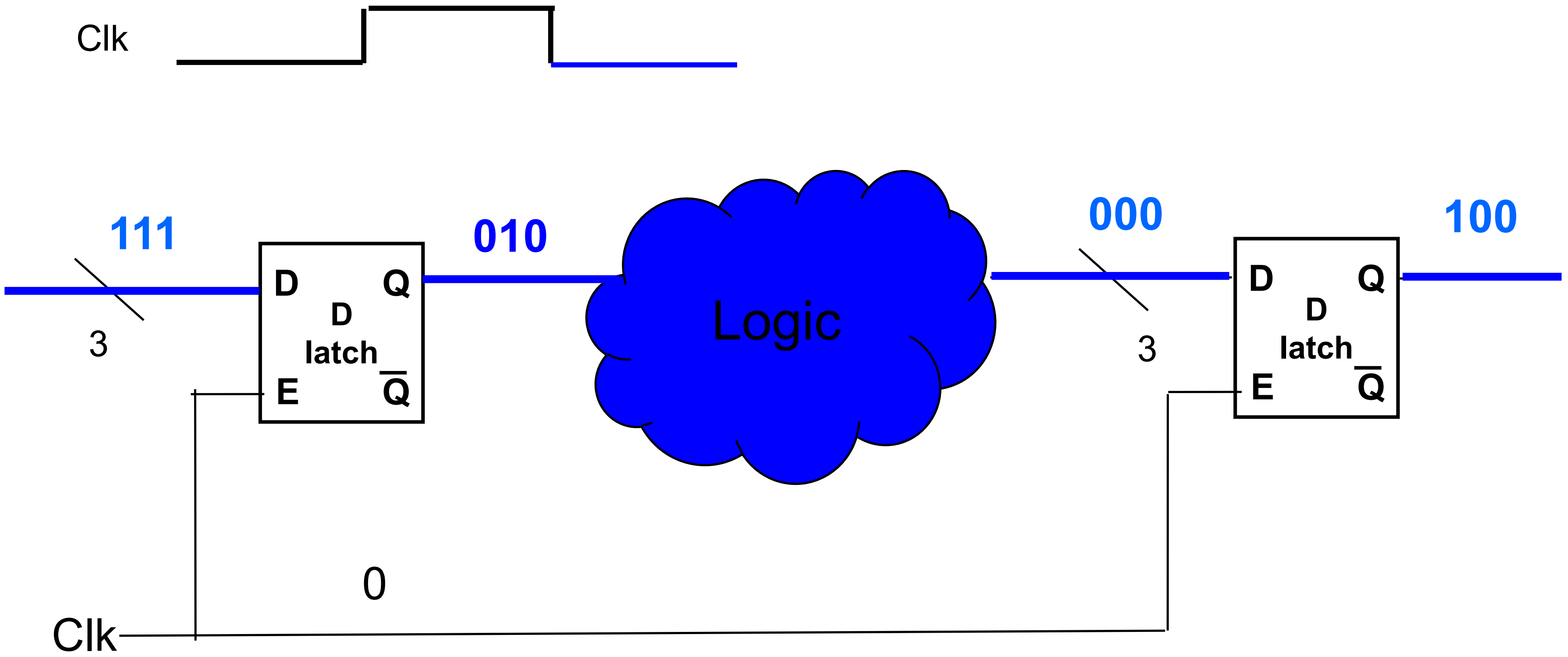
Strawman: Level Triggered

- How we'd like this to work
  - Clock goes low before signals reach next latch



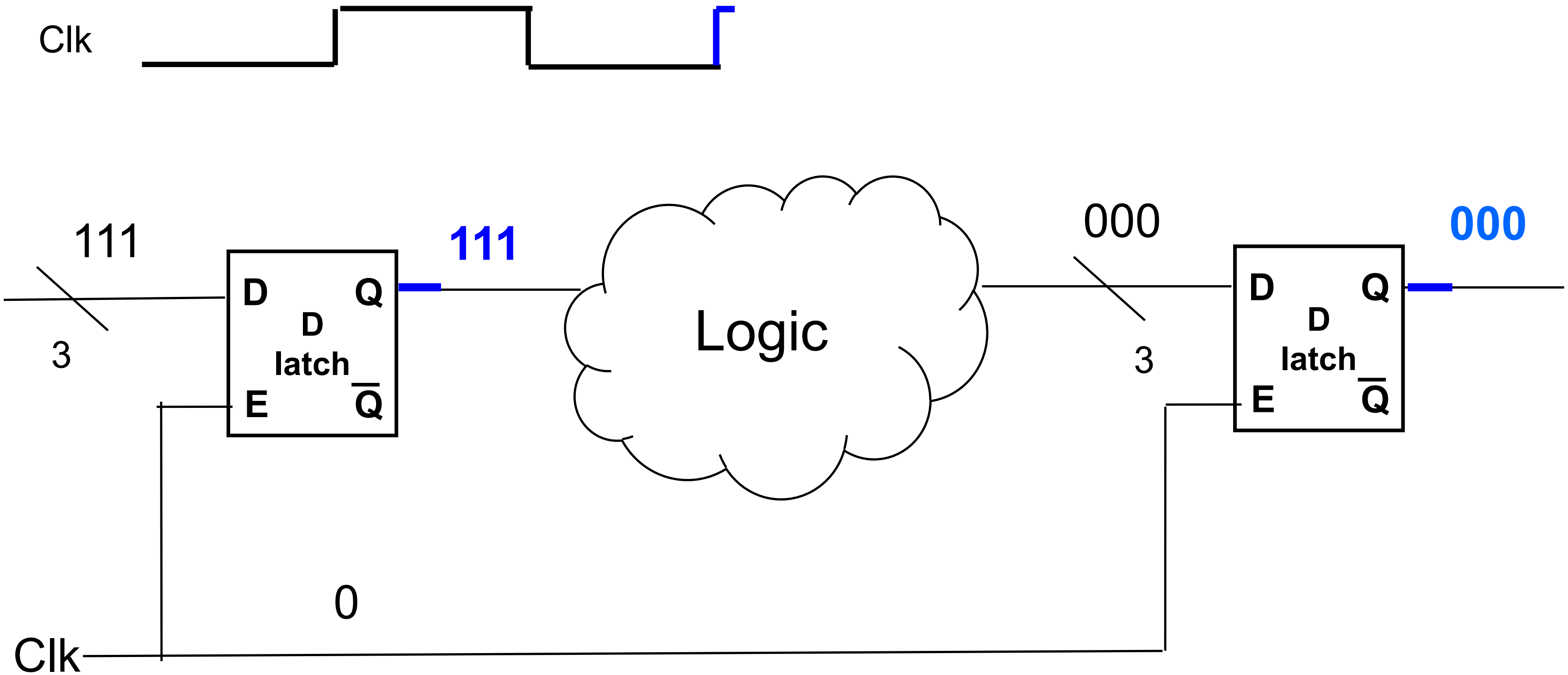
Strawman: Level Triggered

- How we'd like this to work
  - Everything stable before clk goes high



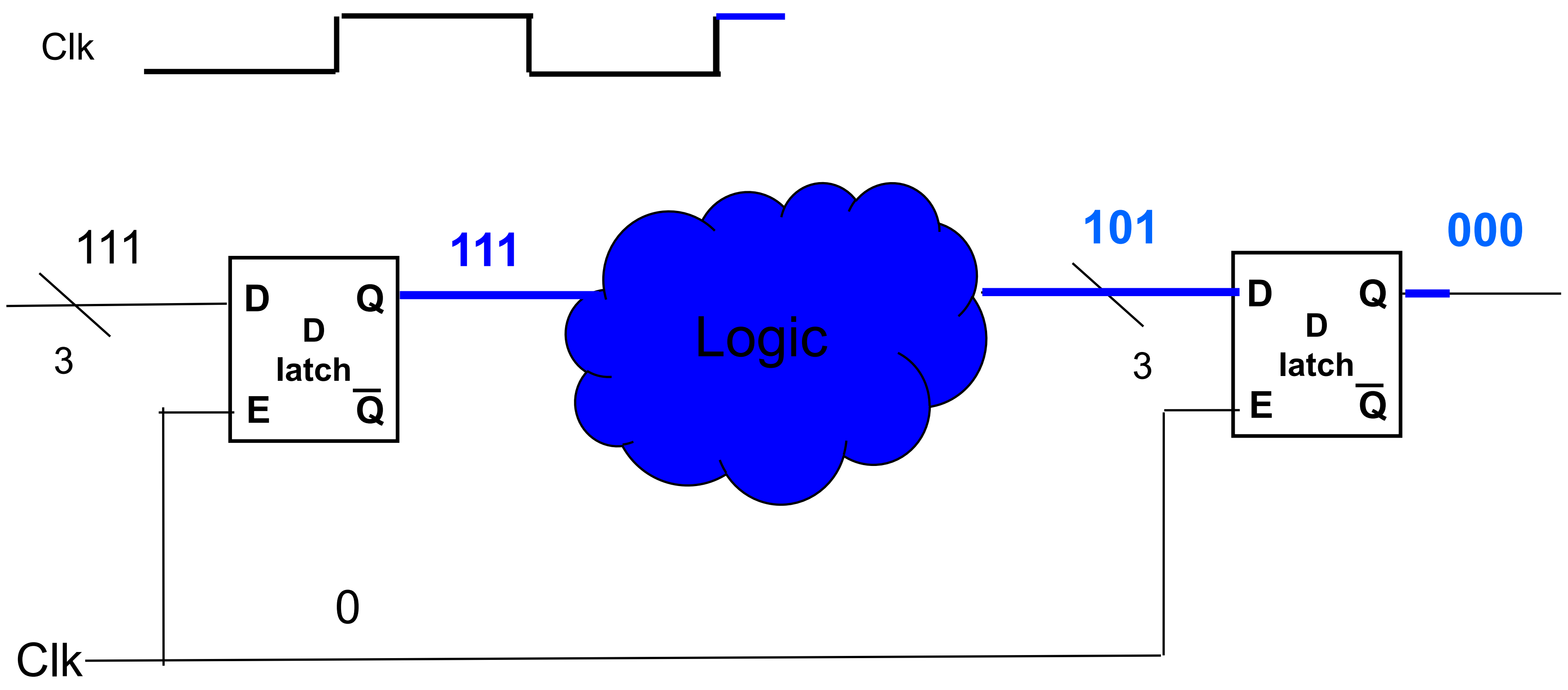
Strawman: Level Triggered

- How we'd like this to work
  - Clk goes high again, repeat



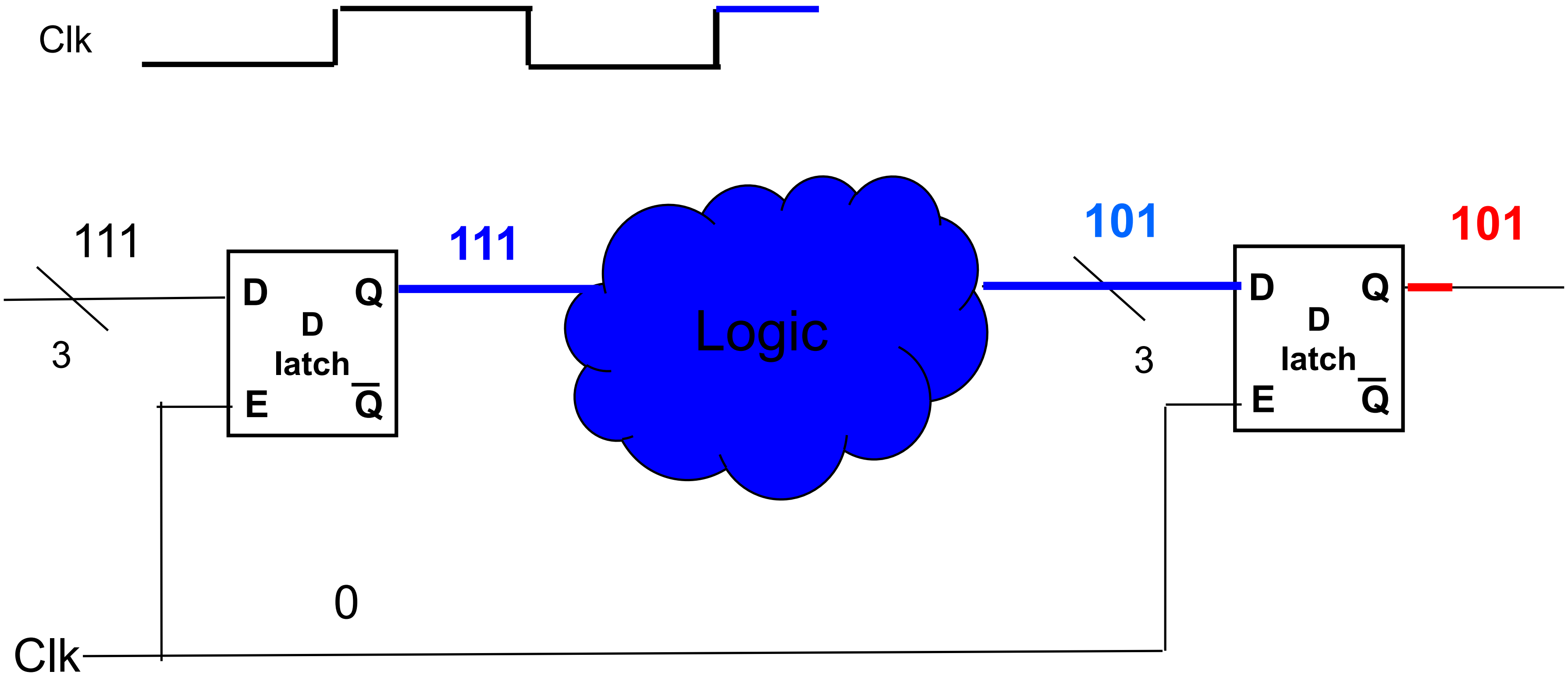
Strawman: Level Triggered

- Problem: What if signal reaches latch too early?
  - I.e., while clk is still high



Strawman: Level Triggered

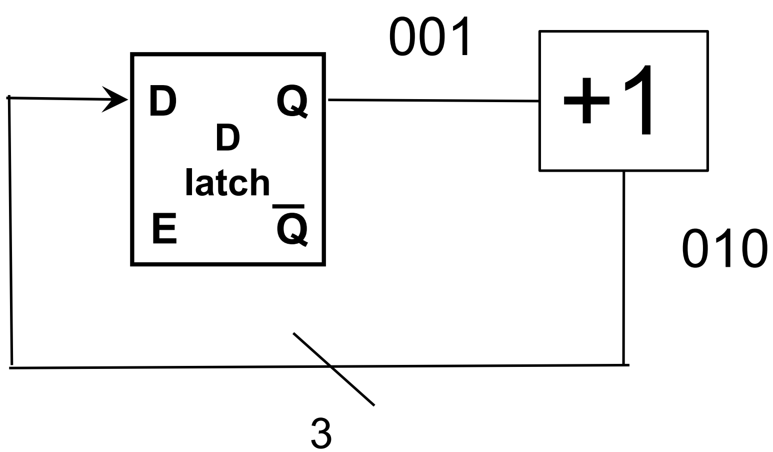
- Problem: What if signal reaches latch too early?
  - Signal goes right through latch, into next stage..



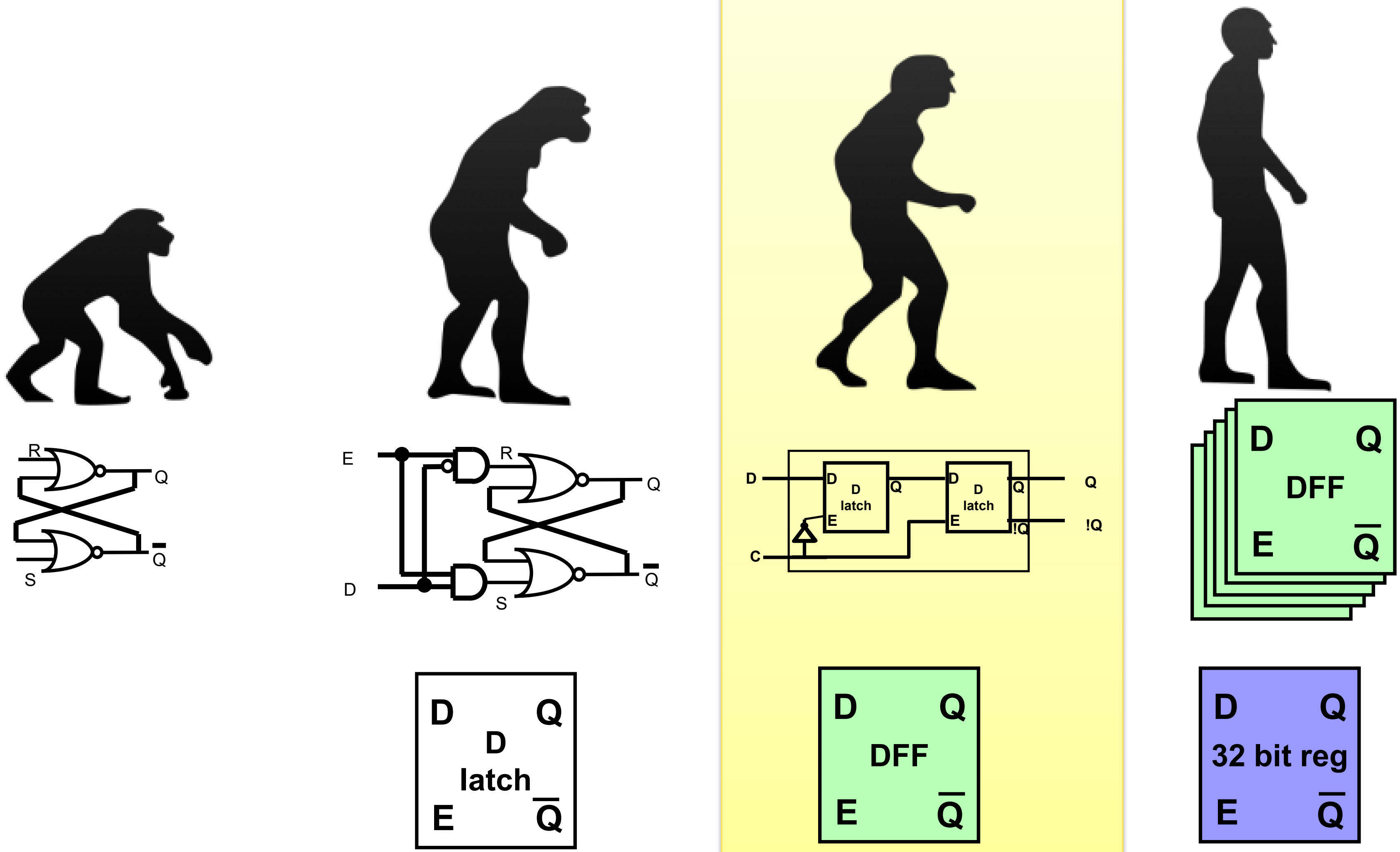
That would be bad…

- Getting into a stage too early is bad
  - Something else is going on there → corrupted
  - Also may be a loop with one latch

- Consider incrementing counter (or PC)
  - Too fast: increment twice? Eeek…



Building up to the D Flip-Flop and beyond



SR Latch
(too awkward)

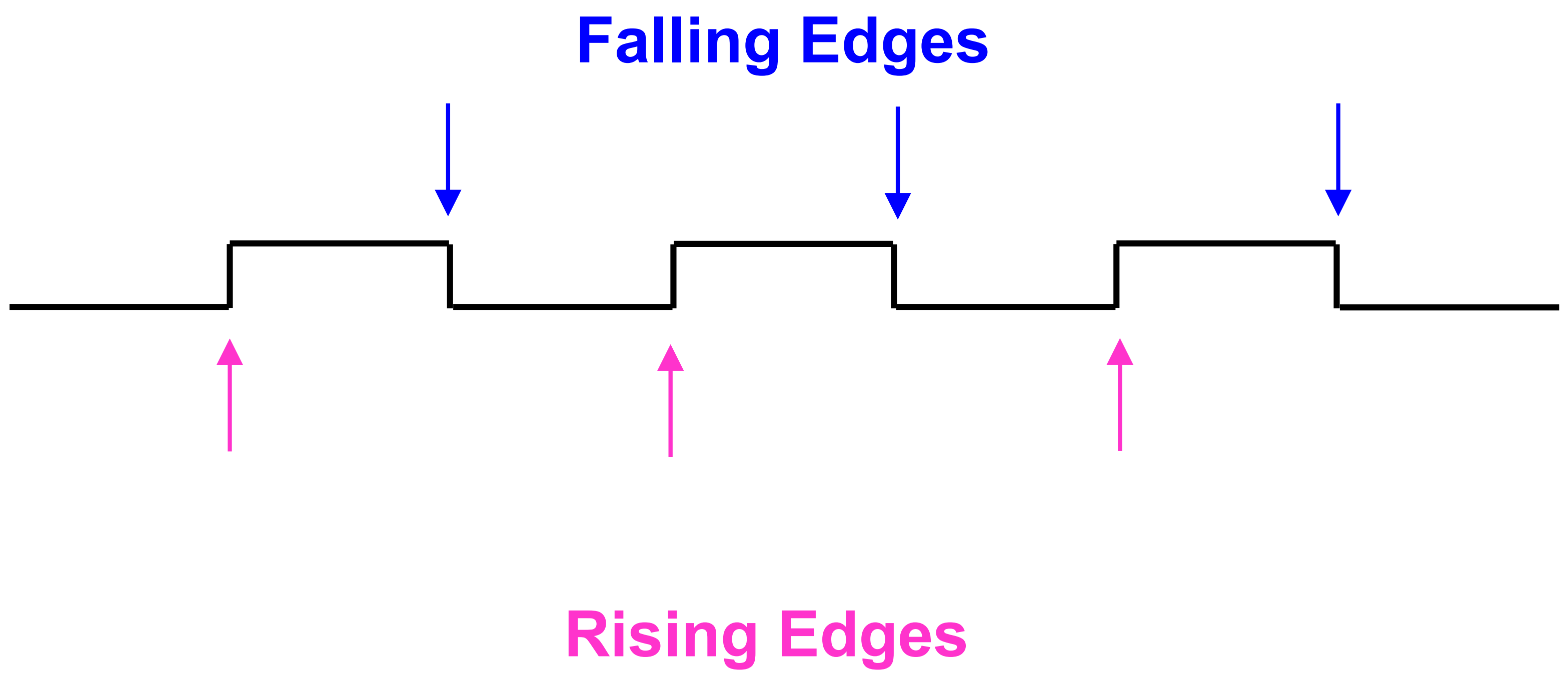
D Latch
(bad timing)

D Flip-Flop
(okay but only one bit)

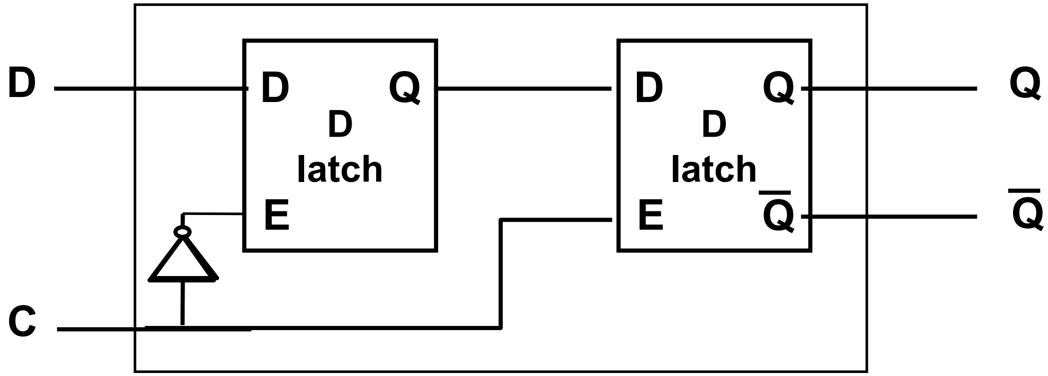
Register
(*nice!*)

FF Step #4: Edge Triggered

- Instead of level triggered
  - Latch a new value at a clock level (high or low)
- We use edge triggered
  - Latch a value at an clock edge (rising or falling)

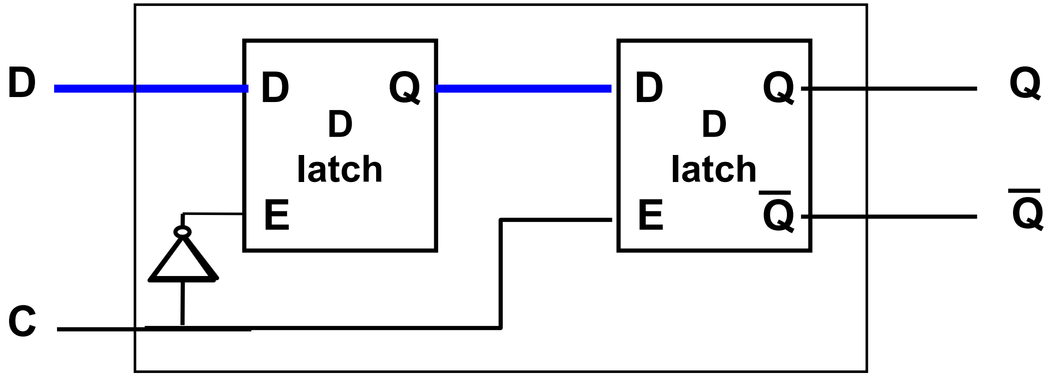


Our Ultimate Goal: D Flip-Flop



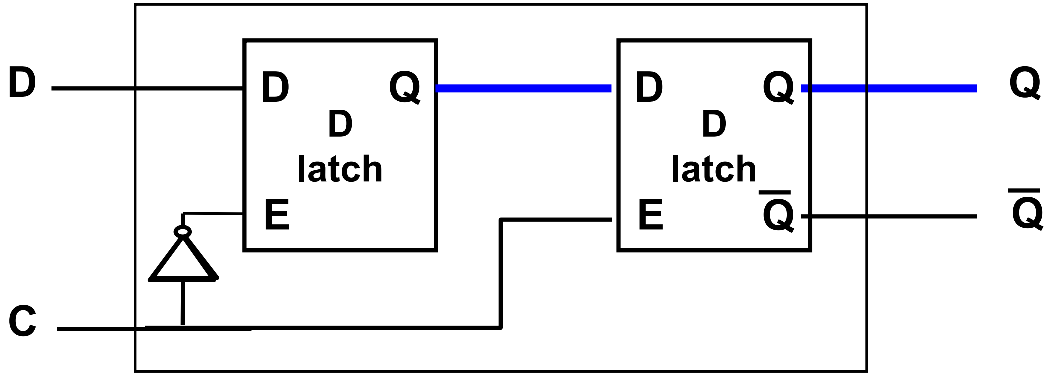
- Rising edge triggered D Flip-flop
  - Two D Latches w/ opposite clking of enables

D Flip-Flop



- Rising edge triggered D Flip-flop
  - Two D Latches w/ opposite clking of enables
  - On Low Clk, first latch enabled (propagates value)
    - Second not enabled, maintains value

(Postitive Edge Triggered) D Flip-Flop

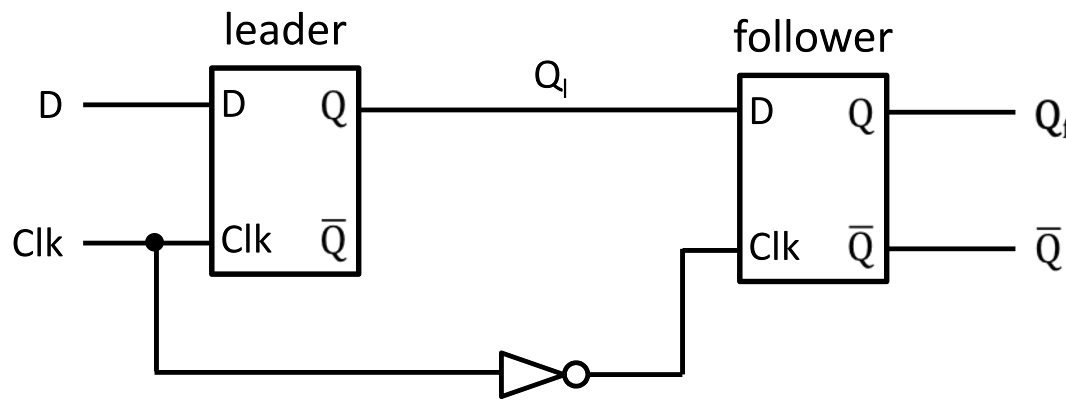


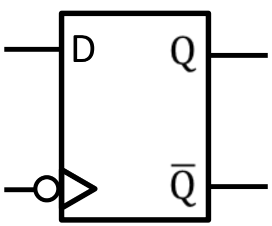
- Rising edge triggered D Flip-flop
  - Two D Latches w/ opposite clking of enables
  - On Low Clk, first latch enabled (propagates value)
    - Second not enabled, maintains value
  - On High Clk, second latch enabled
    - First latch not enabled, maintains value

Leader Follower Negative Edge Triggered D Flip Flip

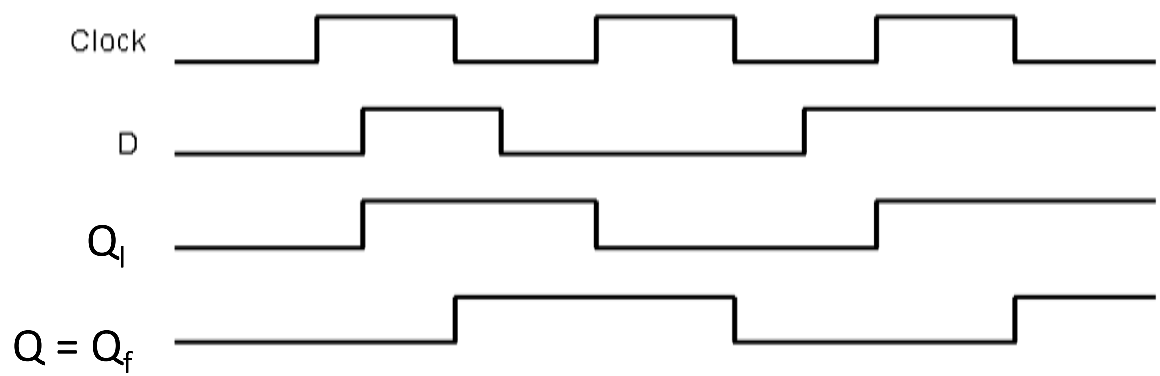
Output Q changes on "negative edge" of Clock

D could change many times while clock high, but only value of D when clock edge falls is captured by follower



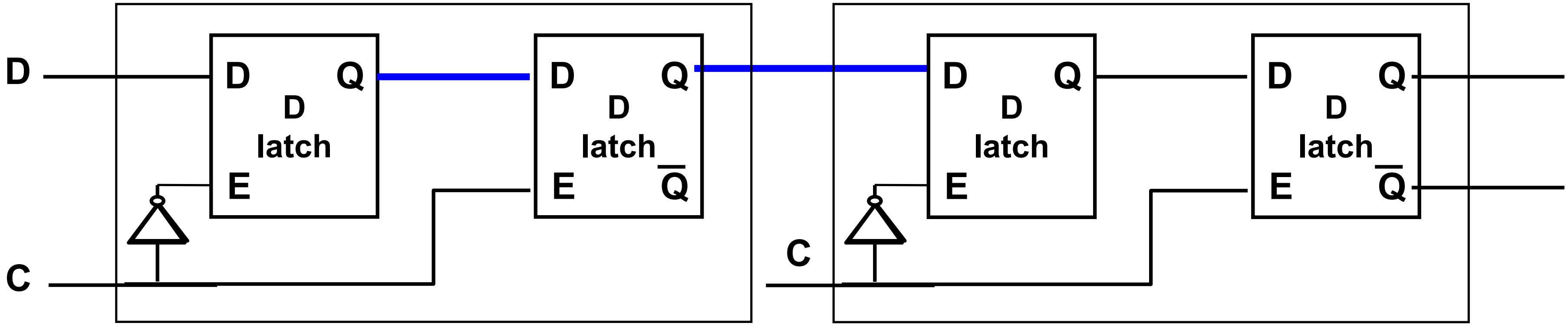


"arrow head" indicates edge triggered. Circle-> negative edge



(b) Timing diagram

D Flip-Flop



- No possibility of "races" anymore
  - Even if I put 2 DFFs back-to-back…
  - By the time signal gets through 2nd latch of 1st DFF
  1st latch of 2nd DFF is disabled
- Still must ensure signals reach DFF before clk rises
  - Important concern in logic design "making timing"

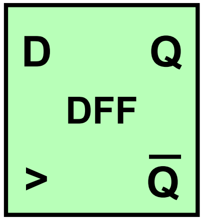
D Flip-flops (continued…)

- Could also do falling edge triggered
  - Switch which latch has NOT on clk

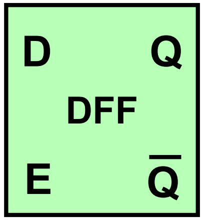
- D Flip-flop is ubiquitous
  - Typically people just say "latch" and mean DFF (BUT THEY SHOULD BE MORE PRECISE! – jab)
  - Which edge: doesn't matter
    - As long as consistent in entire design
    - We'll use rising edge
    - "real" designs exploit rising and falling edges separately in same clockcycle

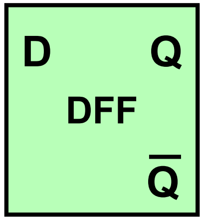
D flip flops

- Generally don't draw clk input
  - Have one global clk, assume it goes there
  - Often see > as symbol meaning clk



- Maybe have explicit enable
  - Might not want to write every cycle
  - If no enable signal shown, implies always enabled
  - Inside DFF, E signal is ANDed with Clk:
    if E is off, Clk is ignored (so we don't commit changes)

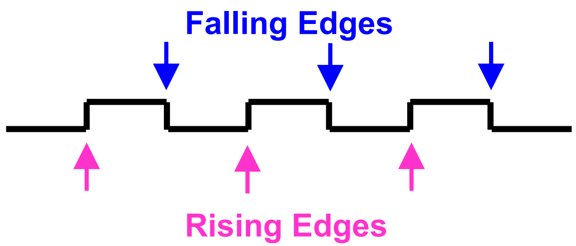




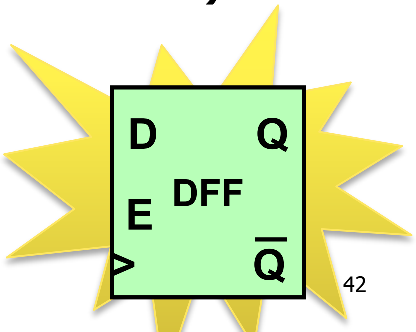
- Get output and NOT(output) for "free"

Skipping ahead to the D Flip-flop

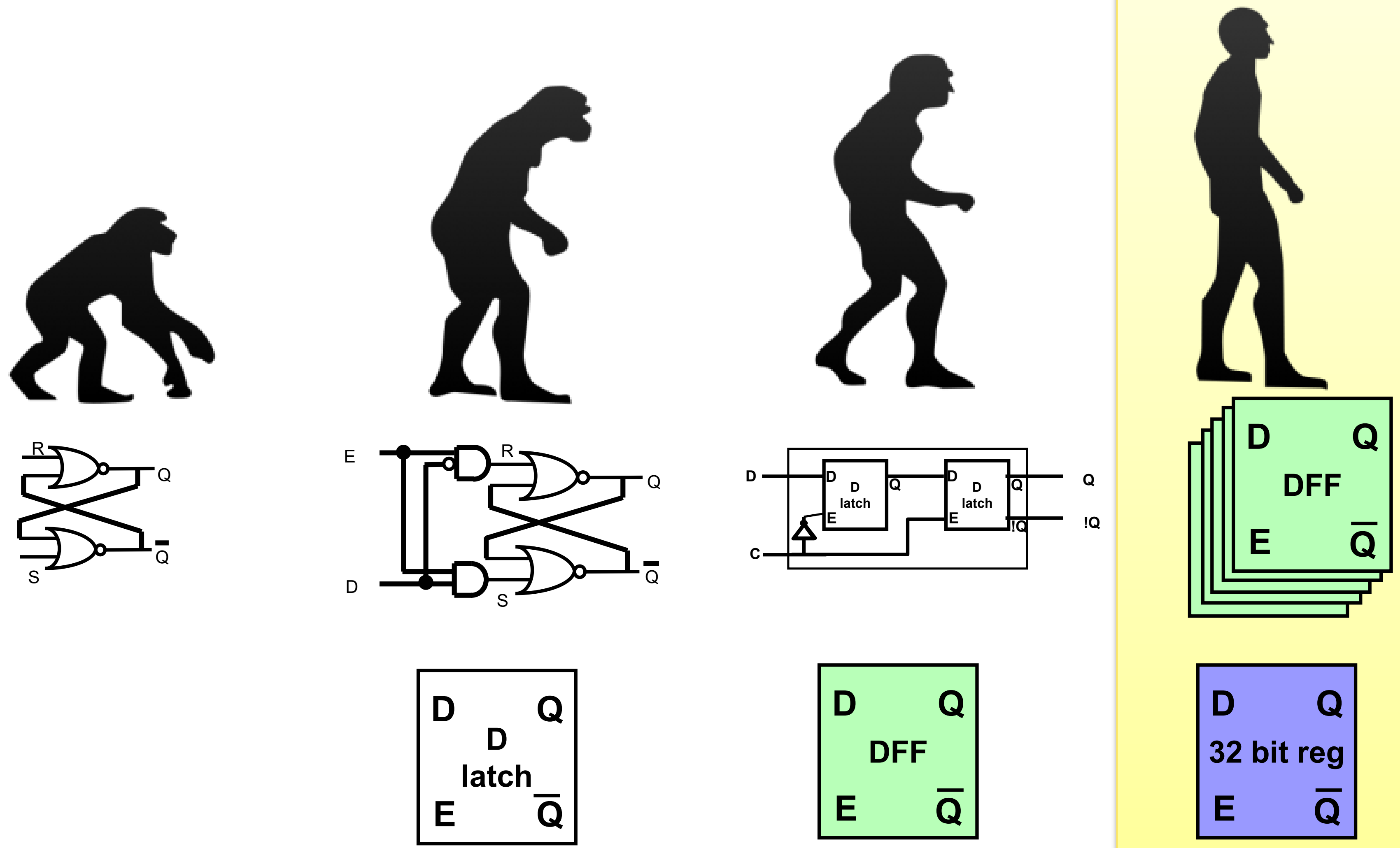
- There's the **Data** input – what to be saved
- There's a **clock**: a regular oscillation between 0 and 1 that tells us *when* to save a value; it's **edge triggered**
    - Configured to store at every rising edge (default) or every falling edge
    - Generally drawn as a **>** notch in the component; may be omitted in schematics (a single global clock is implied)



- There may be an **Enable** line: clock edges that occur when disabled don't "count". (If omitted, then always enabled)
- Stored data comes out on the **Q** line
    - Also get its negation on the **!Q** line for free



Building up to the D Flip-Flop and beyond



SR Latch
(too awkward)

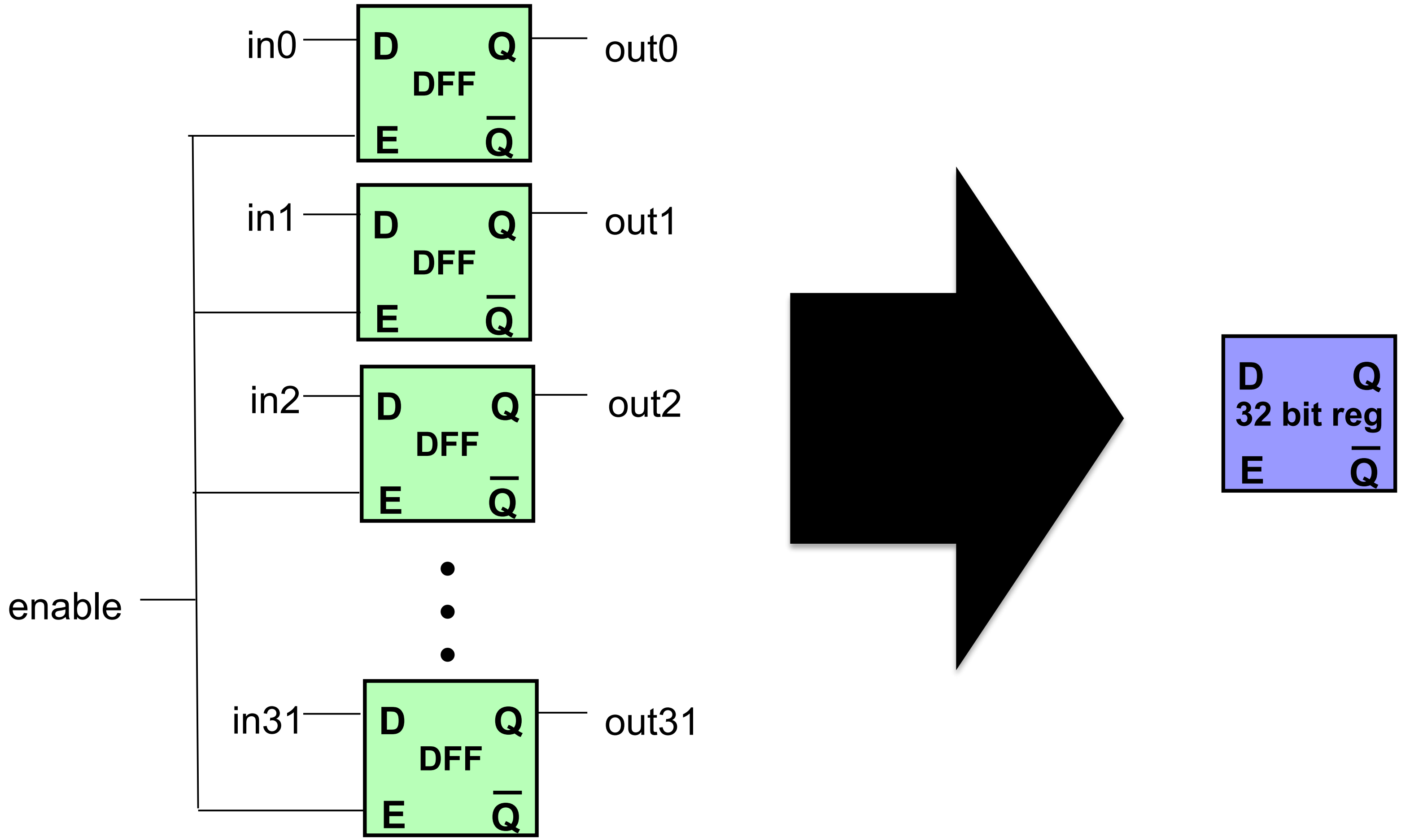
D Latch
(bad timing)

D Flip-Flop
(okay but only one bit)

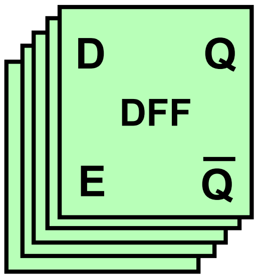
Register
(nice!)

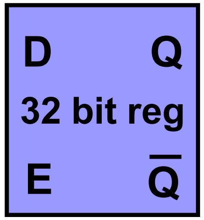
Stick a bunch of DFFs together to make a register

- Make an n-bit register? Combine n DFFs together!
  - A MIPS register can be made with 32 flip flops



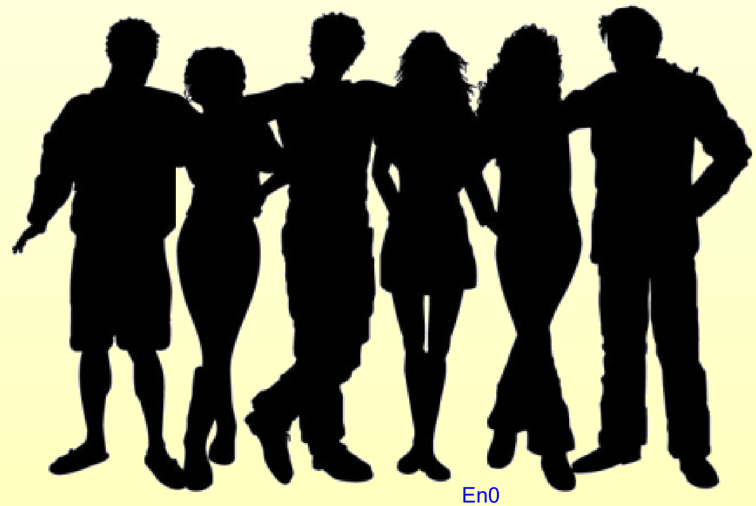
Next evolution: multiple registers

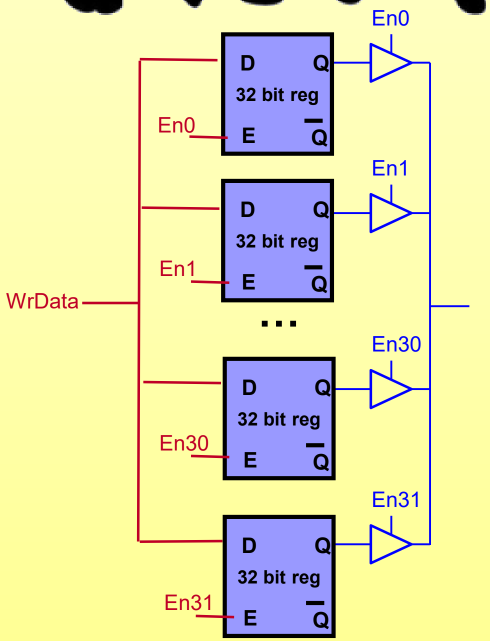




Register

(*nice!*)





Register File

(*Tremendous!*)

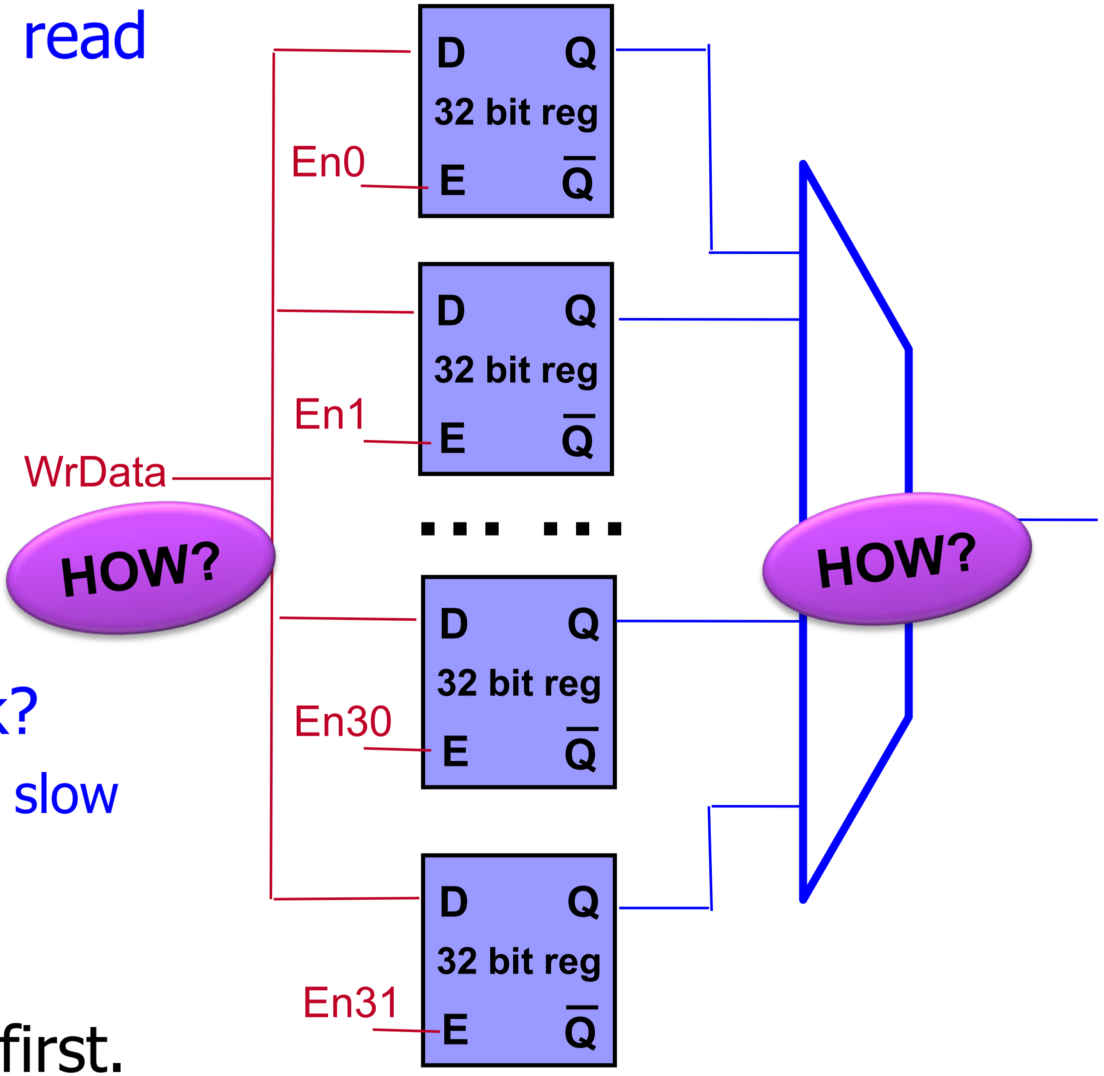
Multiple registers: Register File

- So do we just replicate this 32 times to get the 32 registers for a MIPS processor?
  - Not exactly

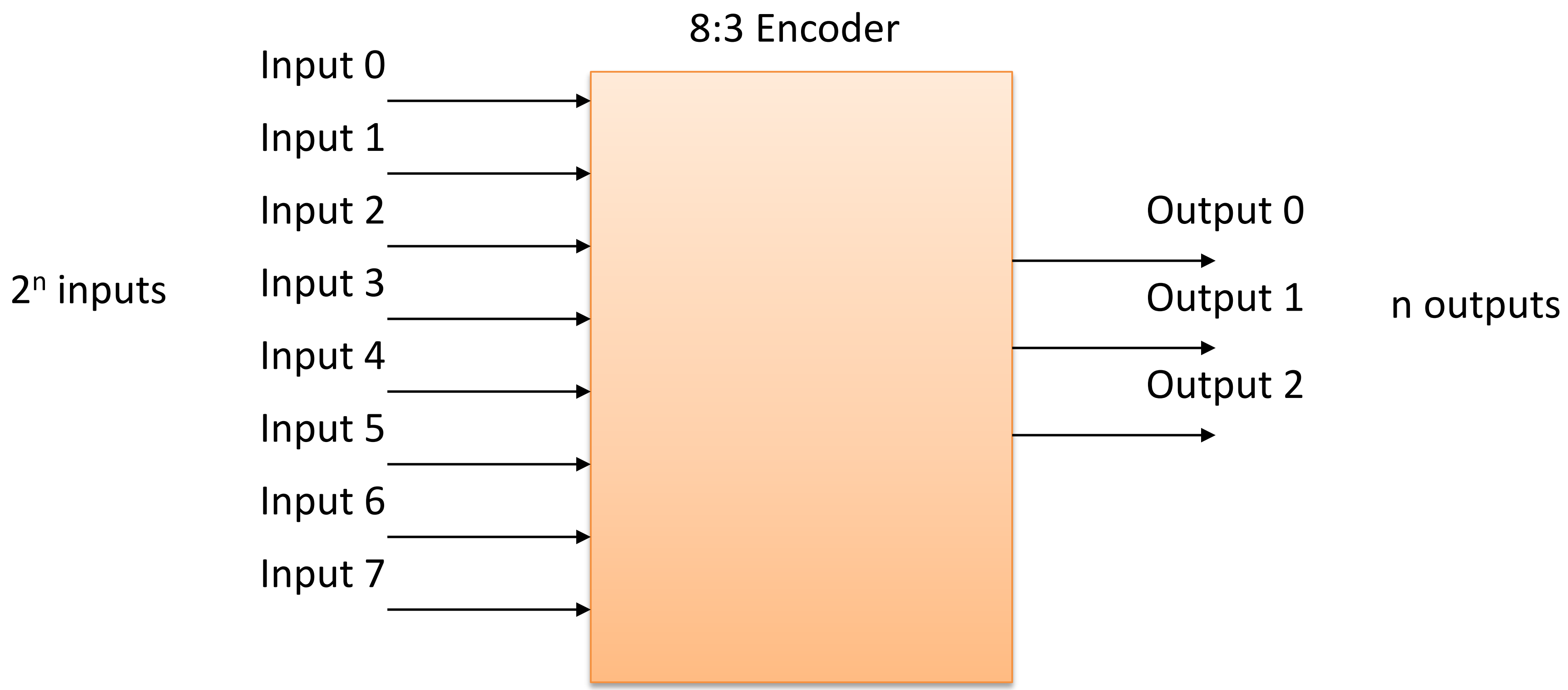
- Register File (the physical storage for the regs)
  - MIPS register file has 32 32-bit registers
- How do we build a Register File using D Flip-Flops?
- What other components do we need?

Register File Design

- Two problems: write and read
- **Writing** the registers
  - Need to pick which reg
  - Have reg num (e.g., 19)
  - Need to make En19=1
    - En0, En1,… = 0
- **Read**: Use a mux to pick?
  - 32-input mux = works but slow
  - Need a better method…
- Let's talk about **writing** first.

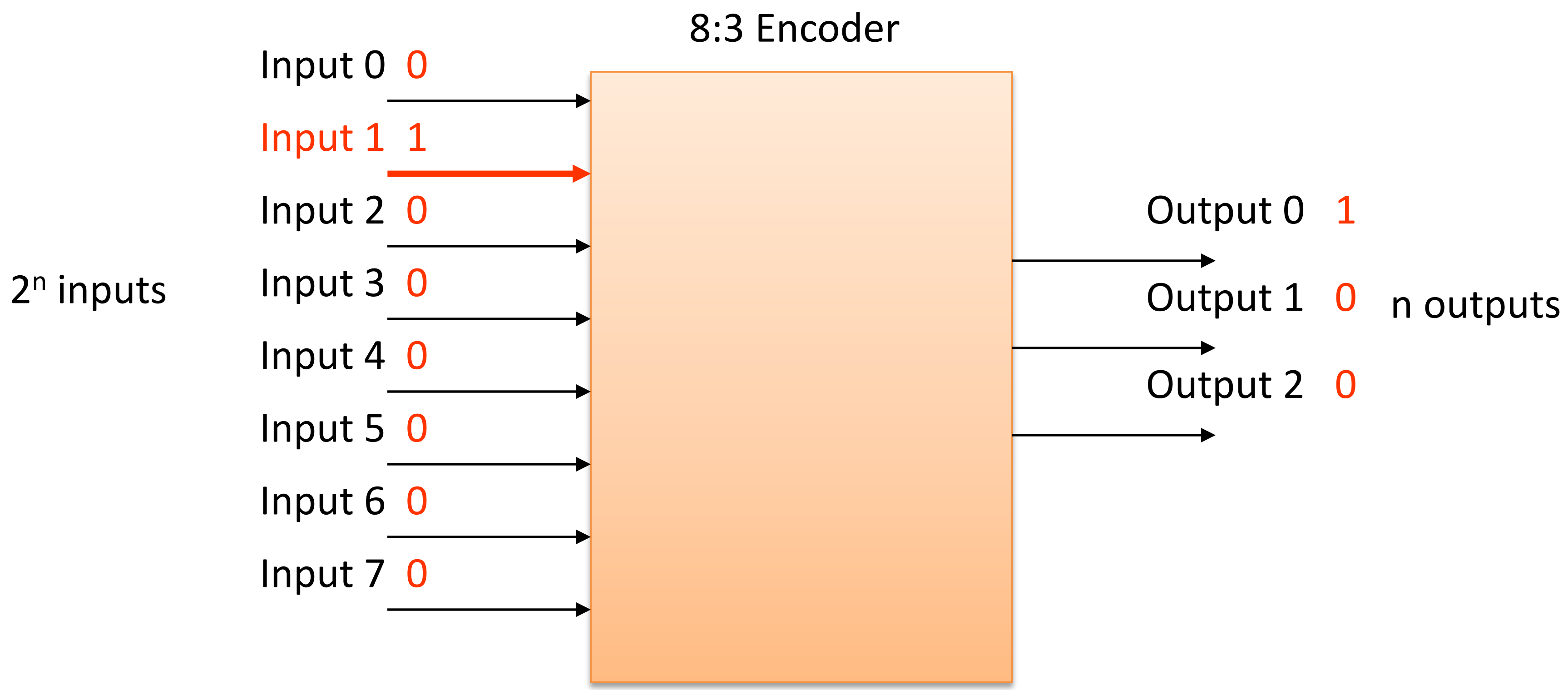


Encoder



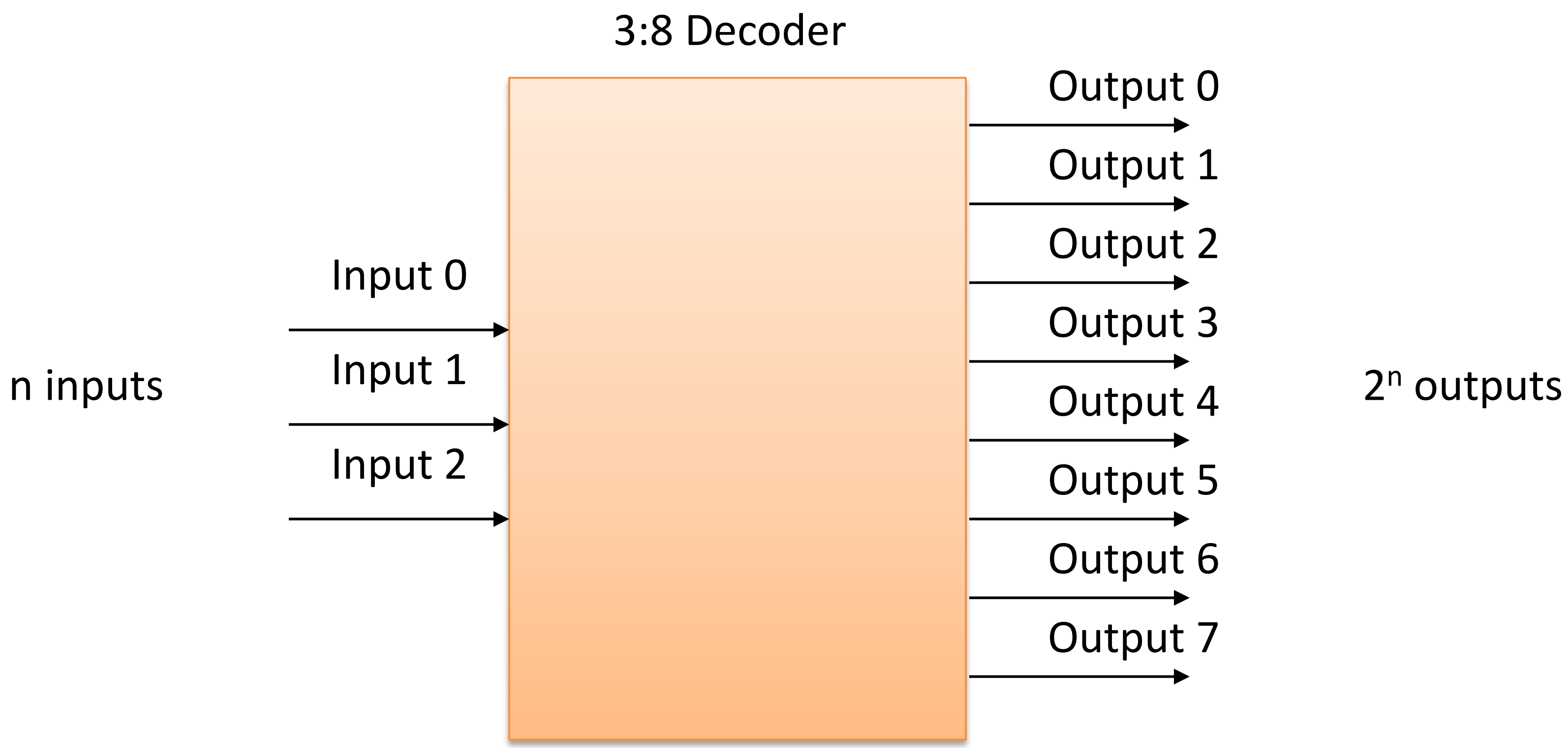
Constraint: exactly one input on (can't have all 0 inputs for instance – behavior undefined)

Encoder



Constraint: exactly one input on

Decoders


3:8 Decoder
n inputs
Input 0
Input 1
Input 2
Output 0
Output 1
Output 2
Output 3
Output 4
Output 5
Output 6
Output 7
2^n outputs

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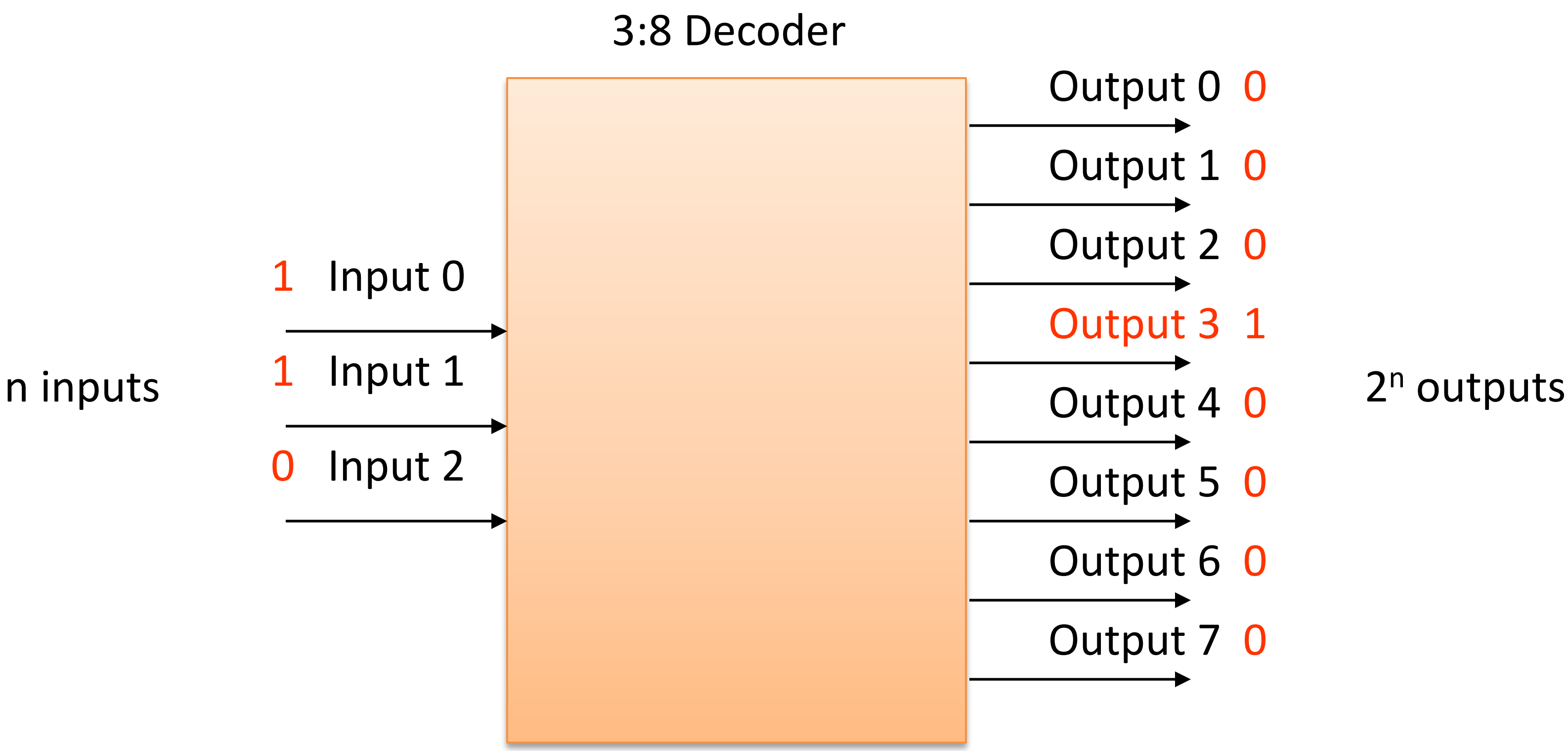
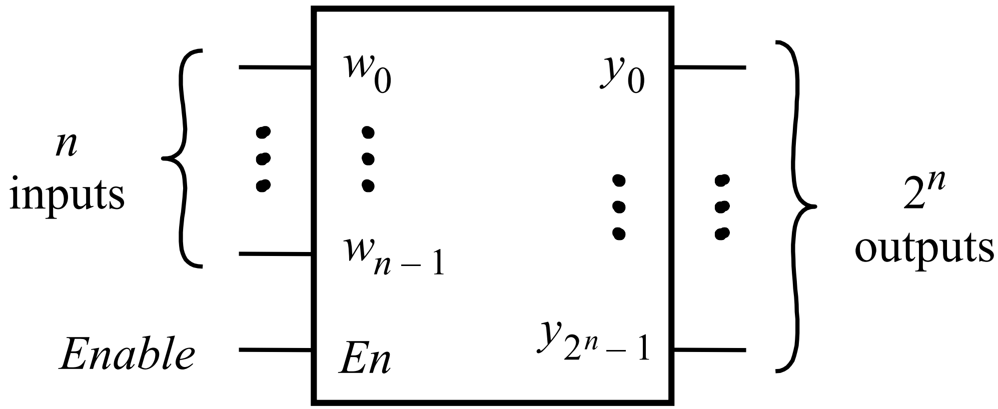
Decoders



Exactly one output on all the times, no "off" condition! (again might add an enable signal in a more general design

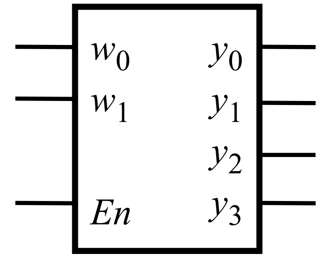


An n-to-2^n binary decoder.

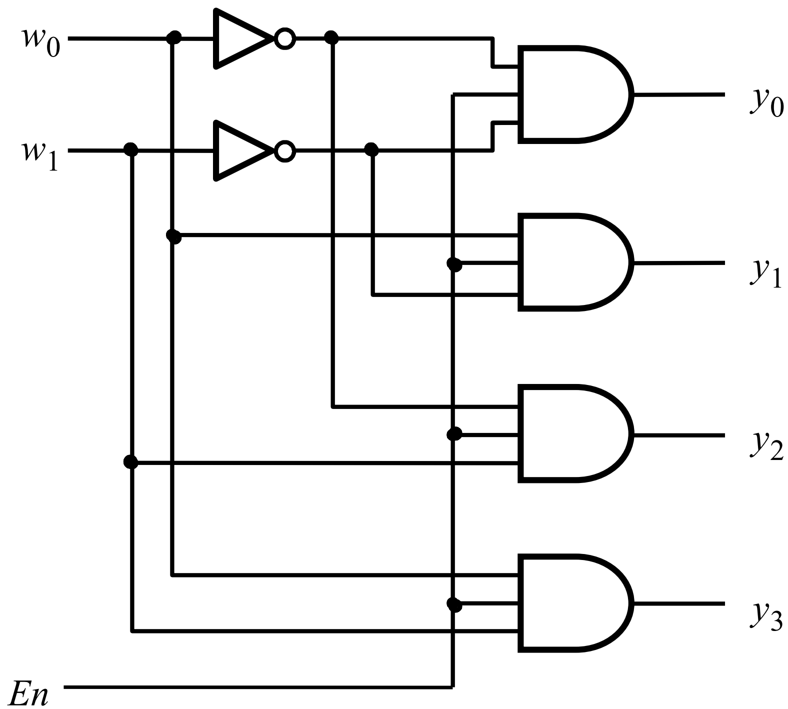
En	w_1	w_0	y_0	y_1	y_2	y_3
1	0	0	1	0	0	0
1	0	1	0	1	0	0
1	1	0	0	0	1	0
1	1	1	0	0	0	1
0	x	x	0	0	0	0

(a) Truth table

X: Don't Care



(b) Graphical symbol



(c) Logic circuit

A 2-to-4 decoder.

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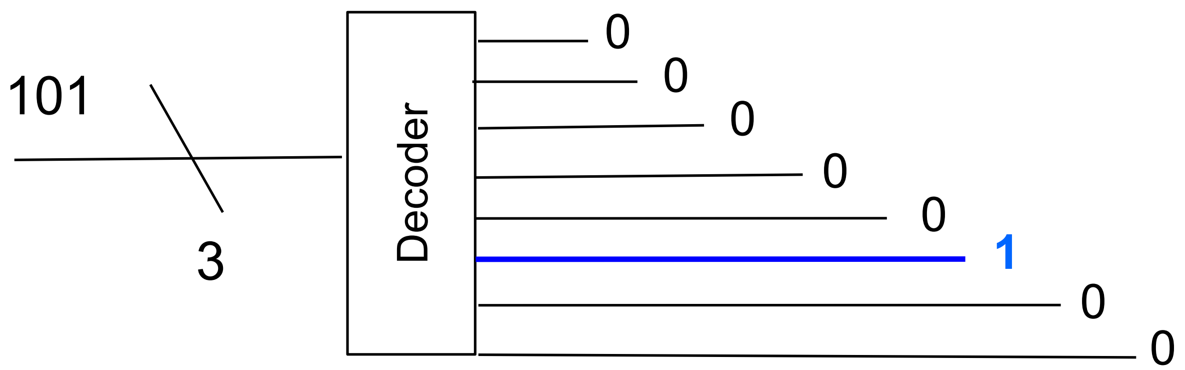
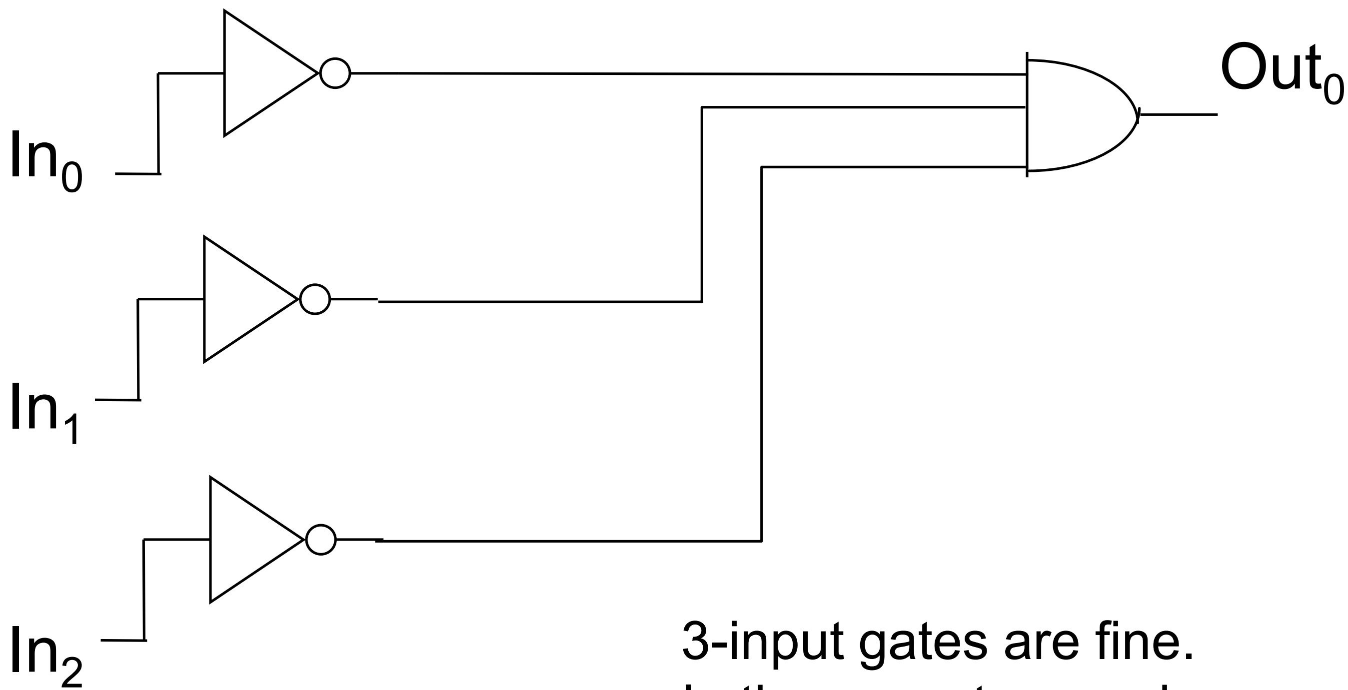
First: A Decoder

- First task: convert binary number to "one hot"
  - N bits in
  - 2^N bits out
  - 2^N-1 bits are 0, 1 bit (matching the input) is 1



Decoder Logic

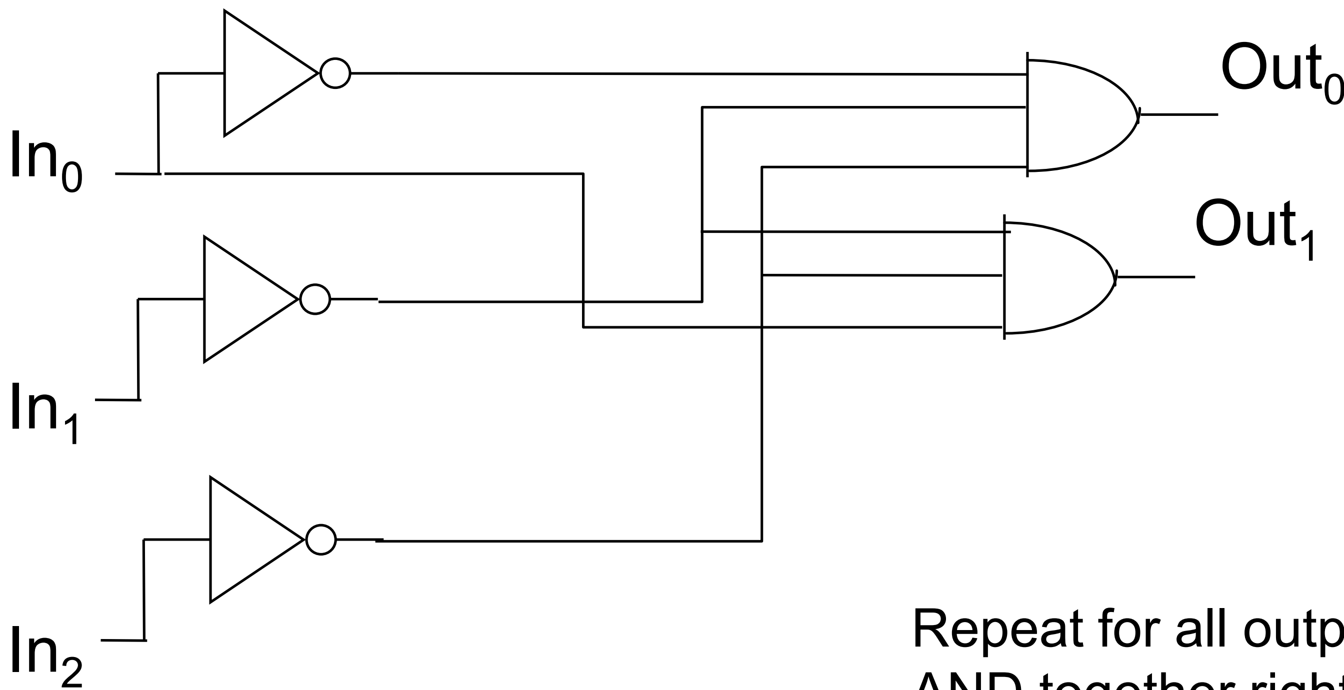
- Decoder basically AND gates for each output:
  - Out_0 only on if input 000



3-input gates are fine.
In theory, gates can have any # of inputs
In practice >4 converted to multiple gates

Decoder Logic

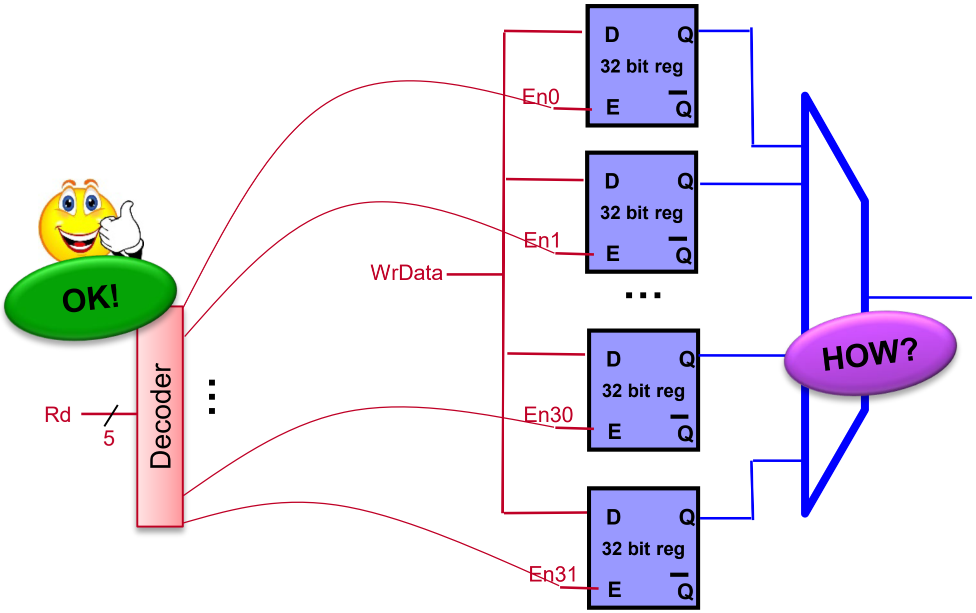
- Decoder basically AND gates for each output:
  - Out_1 only on if input 001



Repeat for all outputs:
AND together right bits
(gets messy fast on a slide)

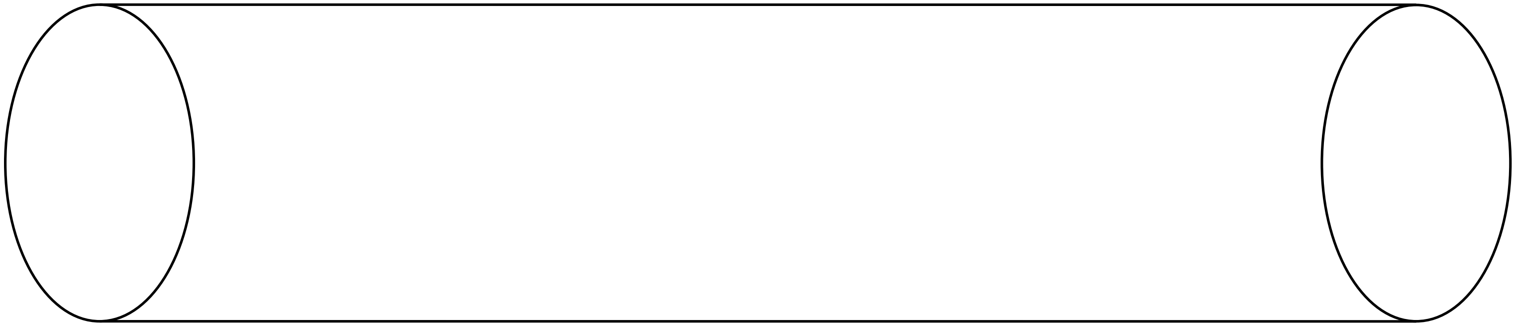
Register File

- Now we know how to **write**:
  - Send write data to all regs
  - Use decoder to convert reg # to one hot
  - Use one hot encoding of reg # to enable right reg
- Still need to fix **read** side
  - 32 input mux (the way we've made it) not realistic
  - To do this: expand our world from {1,0} to {1, 0, Z}



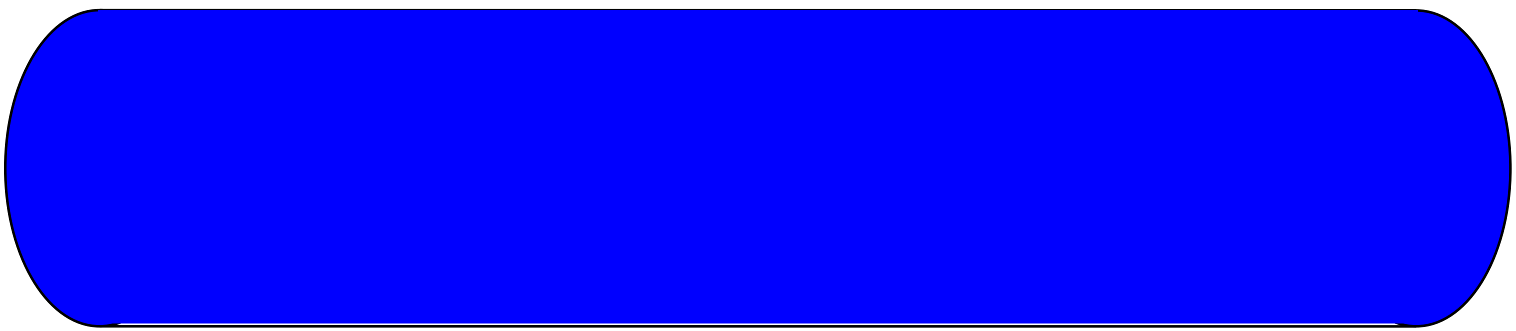
Kind of like water in a pipe…

- To understand Z, let’s make an analogy
  - Think of a wire as a pipe
    - Has water = 1
    - Has water = 0
  - This wire is 0 (it has no water)



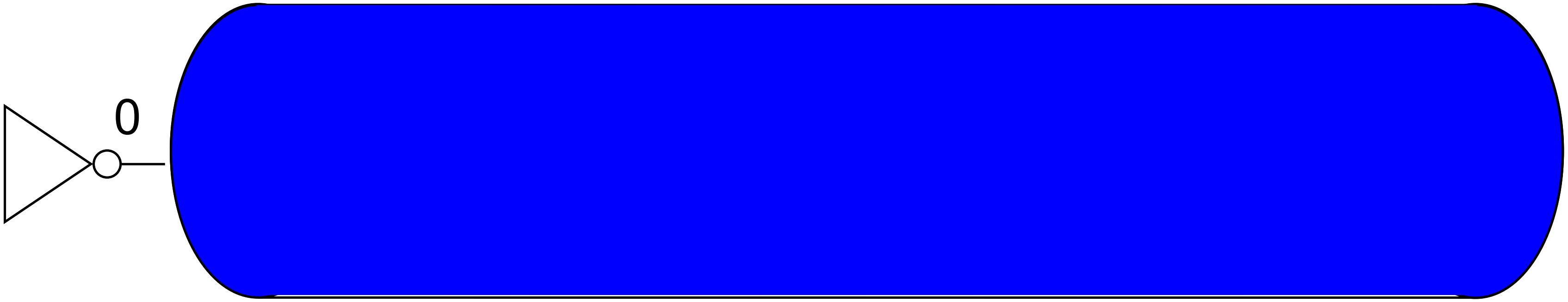
Kind of like water in a pipe…

- To understand Z, let's make an analogy
  - Think of a wire as a pipe
    - Has water = 1
    - Has water = 0
  - This wire is 1 (it is full of water)



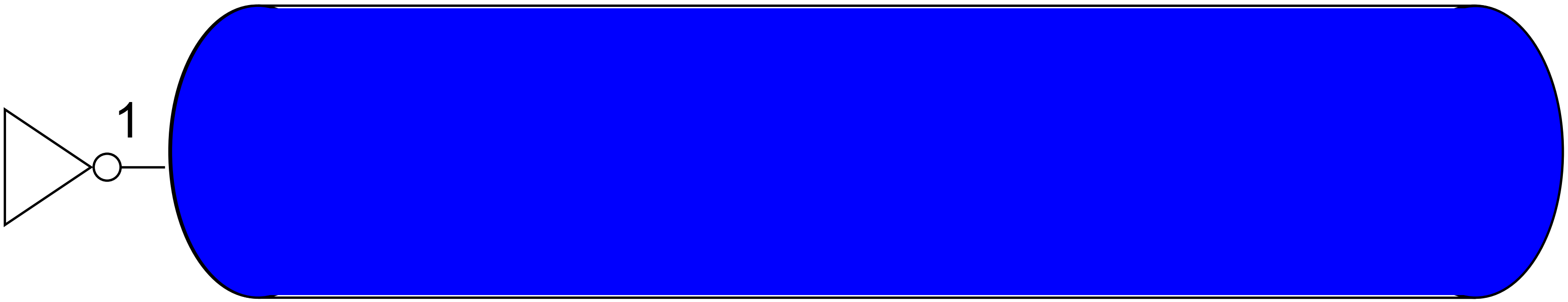
Kind of like water in a pipe…

- To understand Z, let's make an analogy
  - Think of a wire as a pipe
    - Has water = 1
    - Has water = 0
  - Suppose a gate drives a 0 onto this wire
    - Think of it as sucking the water out



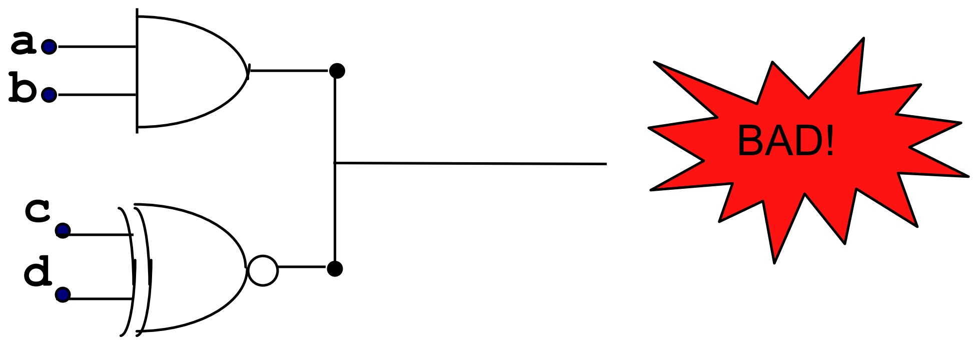
Kind of like water in a pipe…

- To understand Z, let’s make an analogy
  - Think of a wire as a pipe
    - Has water = 1
    - Has water = 0
  - Suppose the gate now drives a 1
    - Think of it as pumping water in



Remember this rule?

- Remember I told you not to connect two outputs?

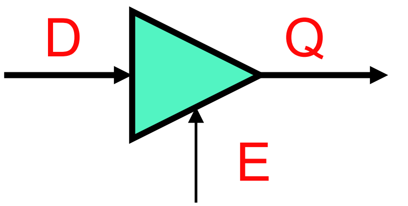


- If one gate tries to drive a 1 and the other drives a 0
  - One pumps water in.. The other sucks it out
  - Except it's electric charge, not water
  - "Short circuit" → lots of current → lots of heat – something literally burns up

Another read port implementation

- A read port that uses muxes is fine for 4 registers
  - Not so good for 32 registers (32-to-1 mux is very slow)
- Alternative implementation uses **tri-state buffers**
  - Normal buffer: Q=1 -> current flowing out of buffer (High voltage)
  - Normal buffer: Q=0 -> current flowing in to buffer (Low voltage)
  - Add additional buffer enable signal E:
  - Truth table (E = enable, D = input, Q = output)

E	D	→	Q
1	D	→	D
0	D	→	**Z**



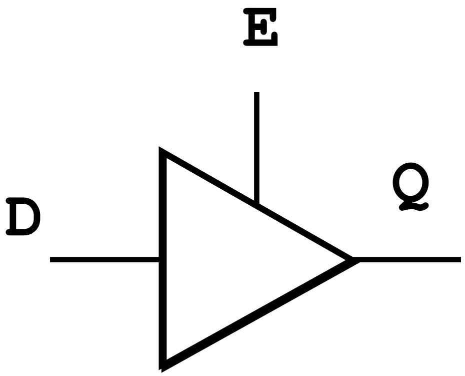
  - **Z**: "high impedance" state, no current flowing
  - Mux: connect multiple 3-stated buses to one output bus
  - Key: only one input "driving" at any time, all others must be in "Z"

from Sorin / Roth / Lebeck

So this third option: Z

- There is a third possibility: Z (“high impedance”)
  - Neither pushing water in, nor sucking it out
  - Just closed off/blocked
  - Prevents electricity from flowing through

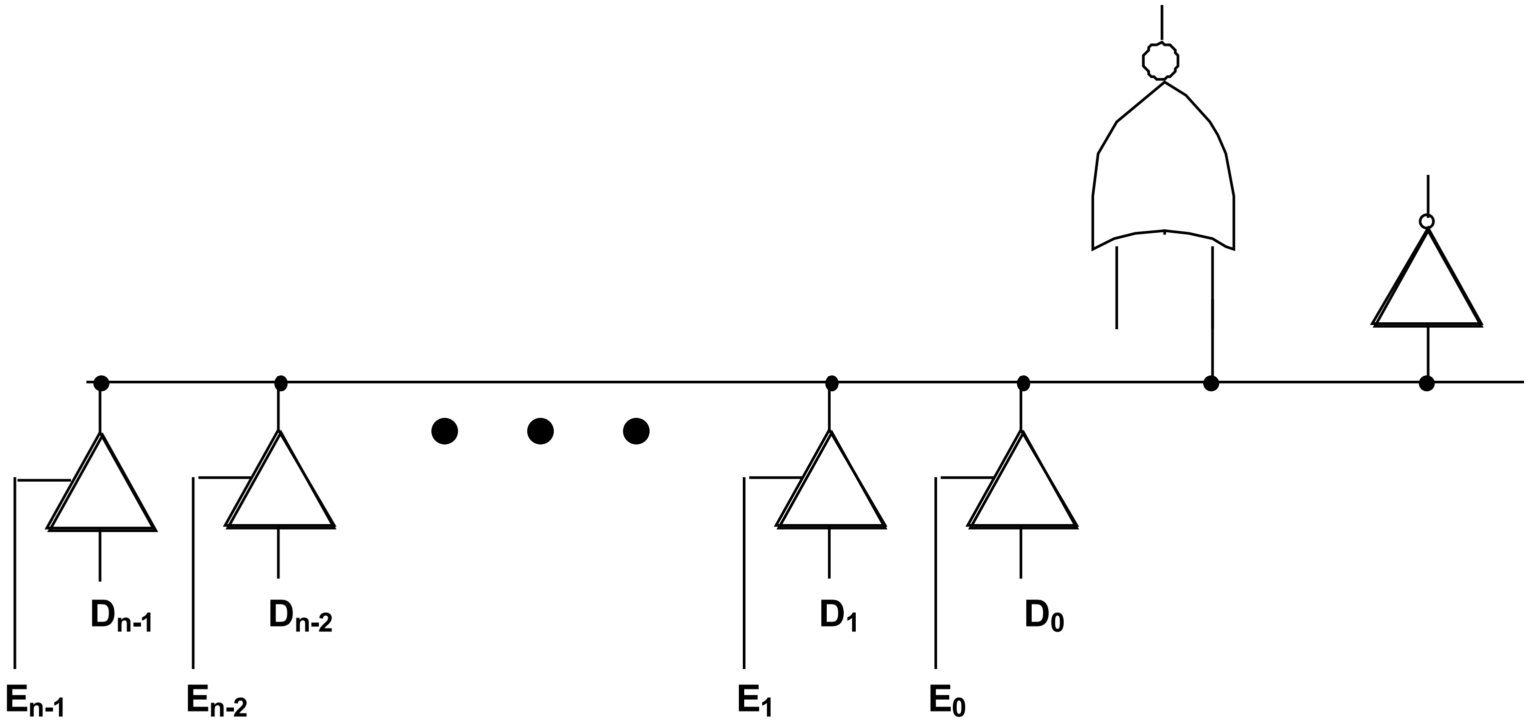
- Gate that gives us Z : Tri-state



D	E	Q
0	1	0
1	1	1
-	0	Z

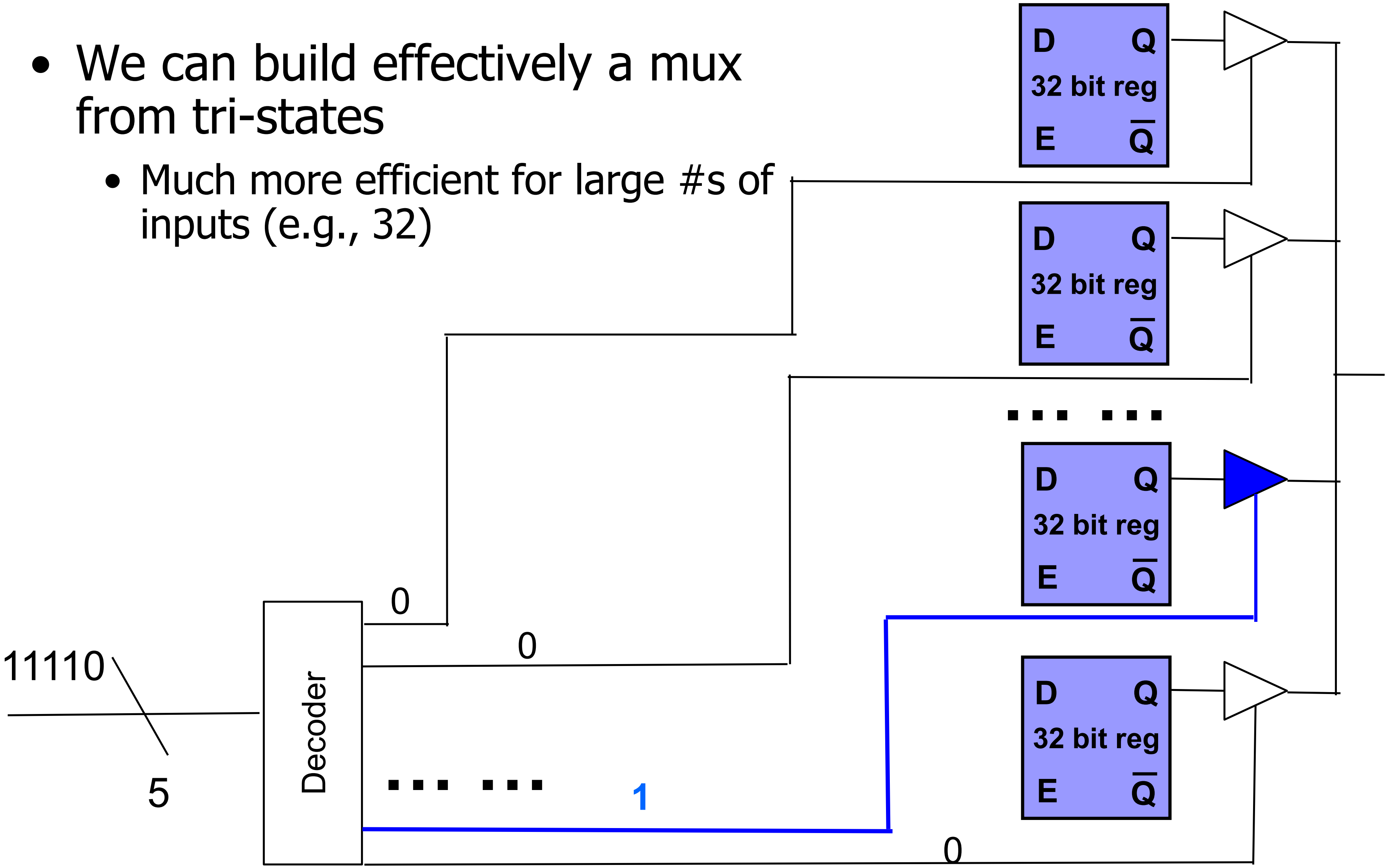
We've had this rule one day… and you break it

It's ok to connect multiple outputs together
Under one circumstance:
All but one must be outputting Z at any time



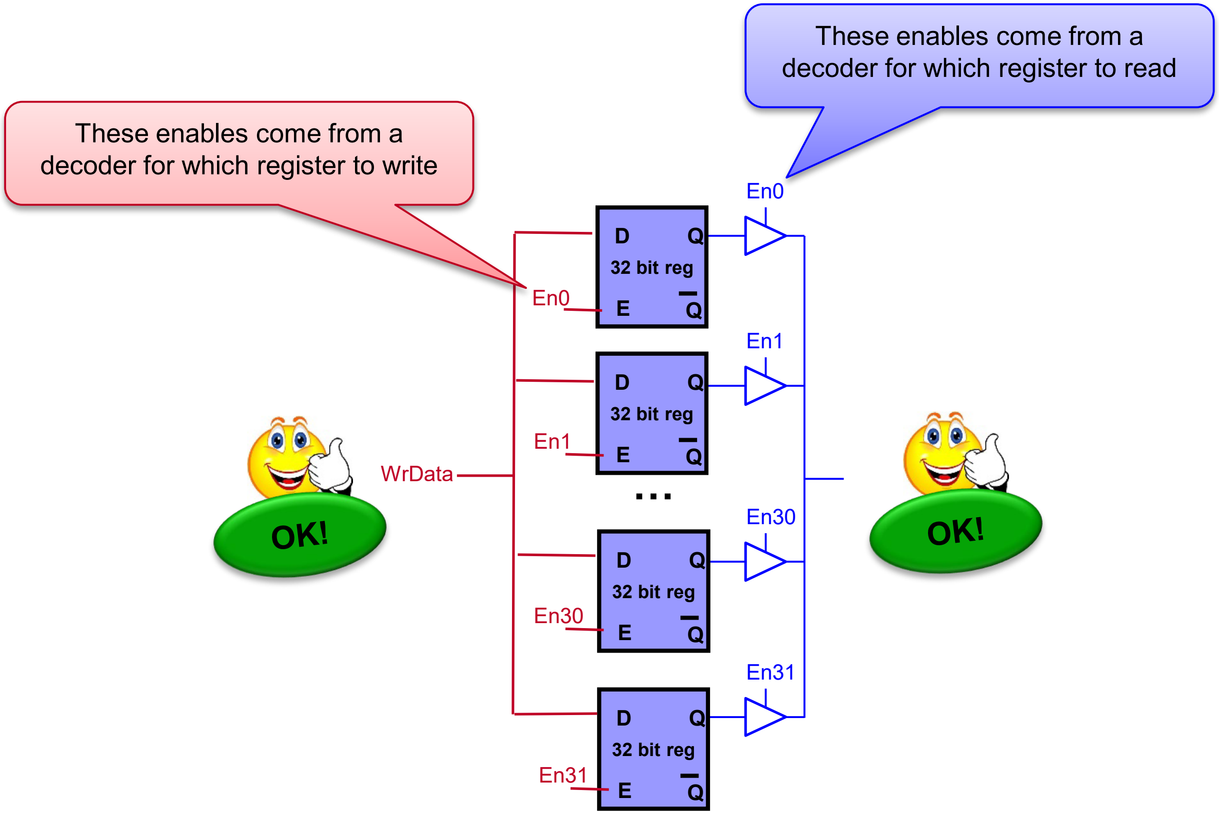
Mux, implemented with tri-states

- We can build effectively a mux from tri-states
  - Much more efficient for large #s of inputs (e.g., 32)



Register File

- Now we can **write** and **read** in one clock cycle!



Ports

- What we just saw: **read** port
  - Ability to do one read / clock cycle
  - May want more: read 2 source registers per instr
    - Maybe even more if we do many instrs at once
  - This design: can just replicate port
    - Another decoder
    - Another set of tri-states
    - Another output bus (wire connecting the tri-states)

- Earlier: **write** port
  - Ability to do one write/cycle
  - Could add more

Minor Detail

- FYI: This is not how a modern register file is implemented
  - (Though it is how other things are implemented)
  - Actually done with SRAM
  - We'll see that later this semester…

Summary

Can layout logic to compute things

- Add, subtract,…

Now can store things

- D flip-flops
- Registers

Also understand clocks

Just about ready to make a datapath!