ECE/CS 250
Computer Architecture

Summer 2019

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

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

So far…

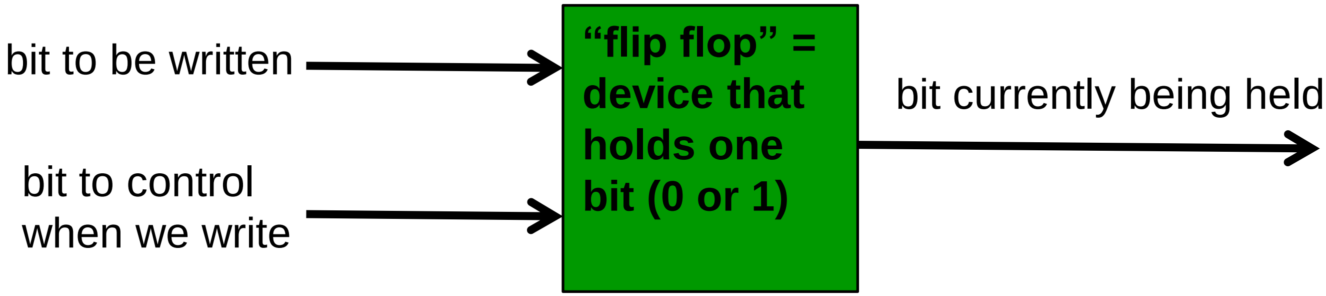
- We can make logic to compute "math"
  - Add, subtract … and you can do mul/div in 350
    - Assume for now that mul/div can be built
  - Bitwise: AND, OR, NOT,…
  - Shifts (left or right)
  - Selection (MUX)
  - …pretty much anything
- But processors need state (hold value)
  - Registers
  - …

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

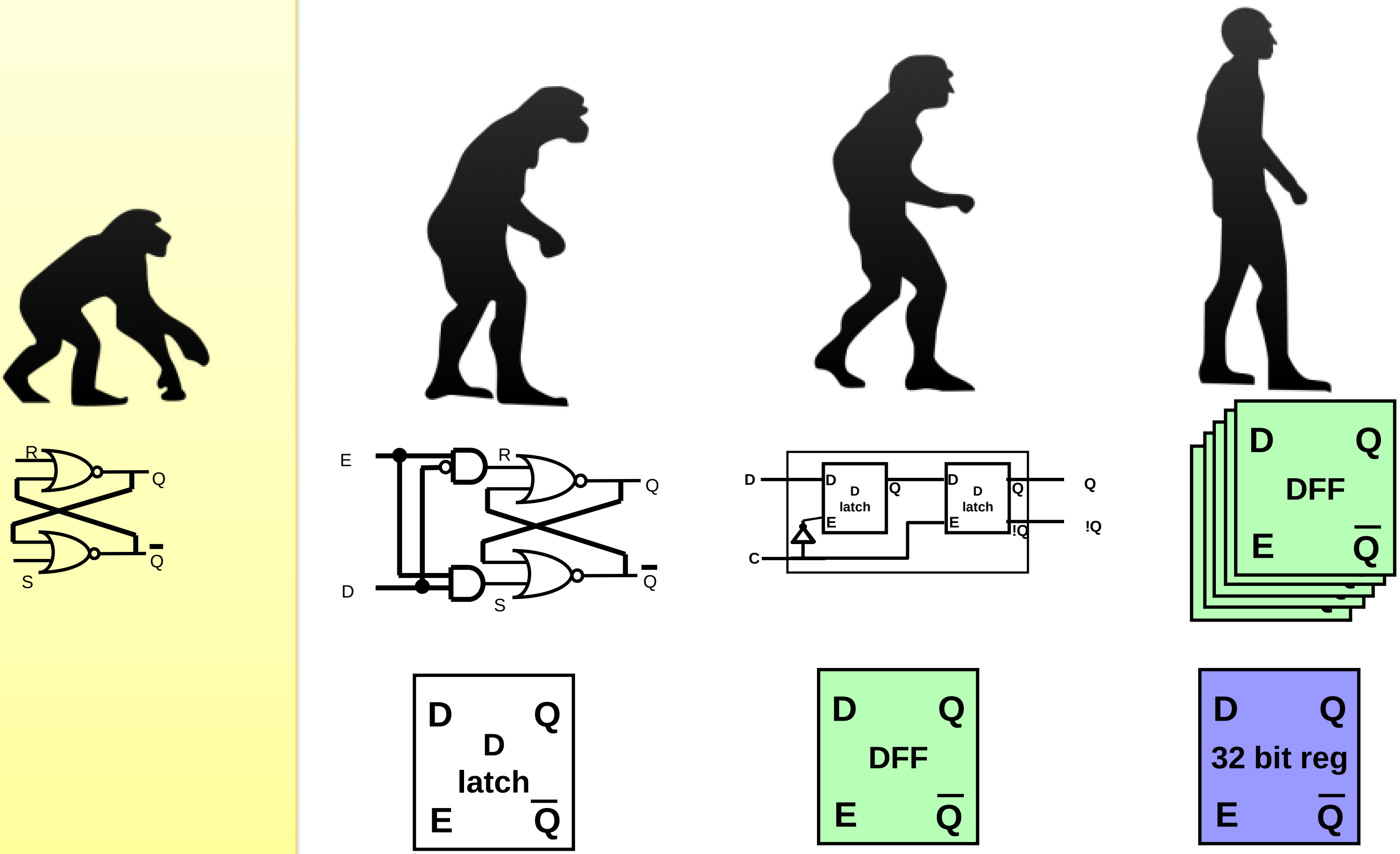
Ideal Storage – Where We're Headed

- 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"

Building up to the D Flip-Flop and beyond



SR Latch

(too awkward)

D Latch

(bad timing)

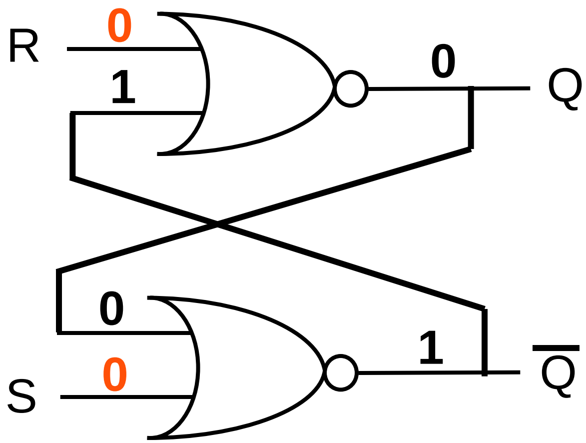
D Flip-Flop

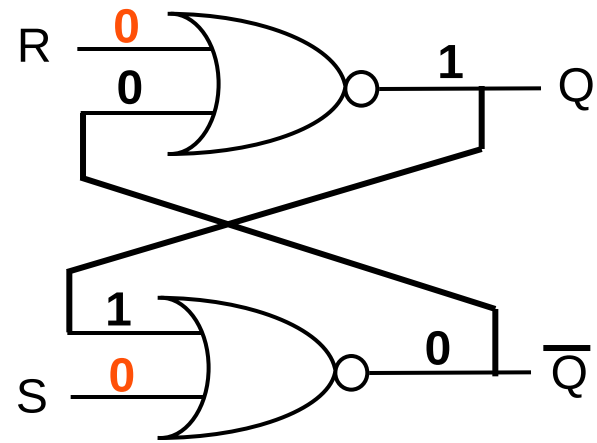
(okay but only one bit)

Register

(*nice!*)

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

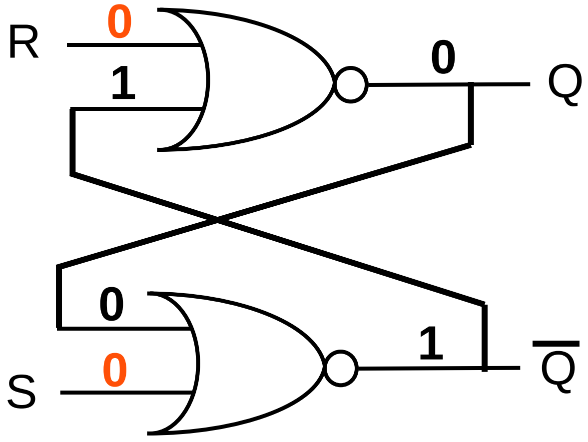


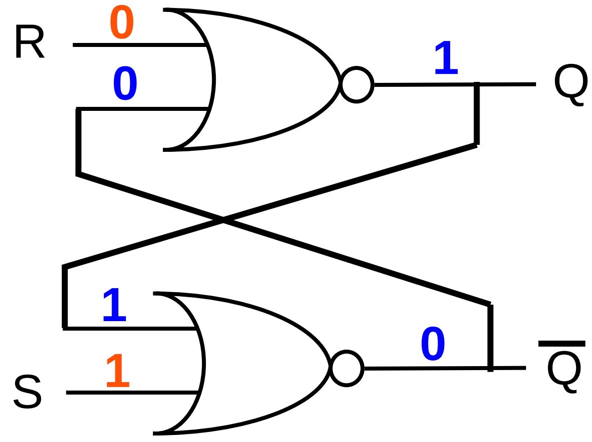


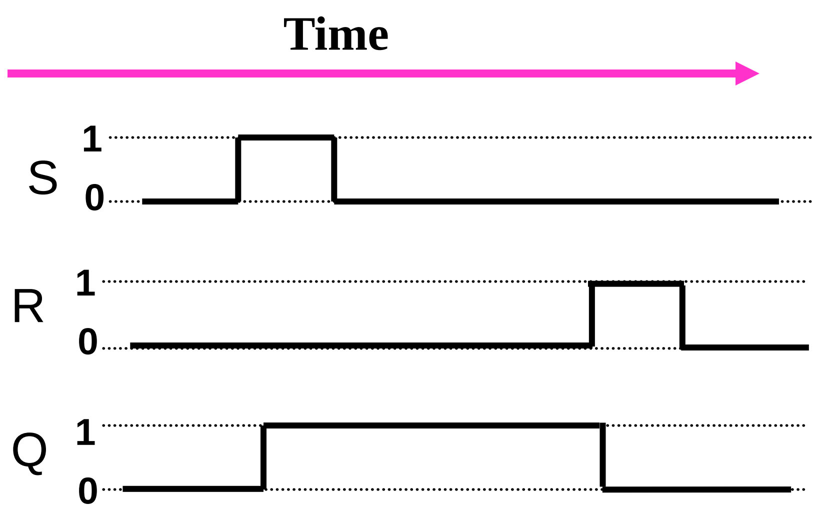
R	S	Q
0	0	Q
0	1	1
1	0	0
1	1	–

Don't set both S & R to 1.
Seriously, don't do it.

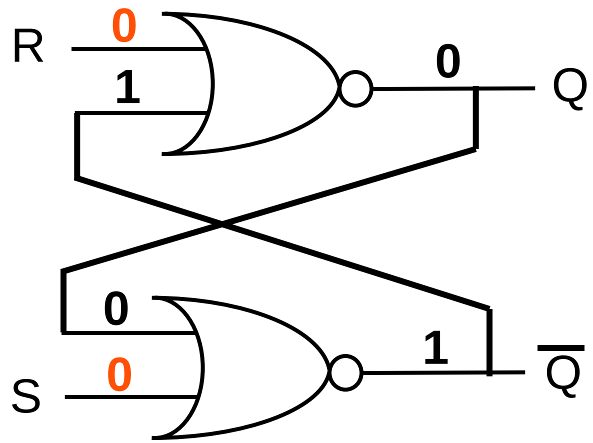
Set-Reset Latch (Continued)

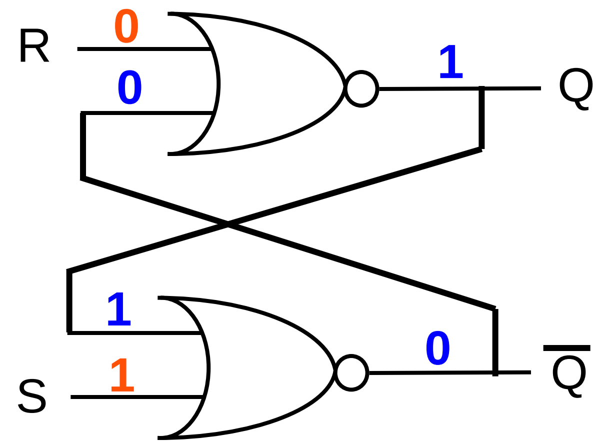


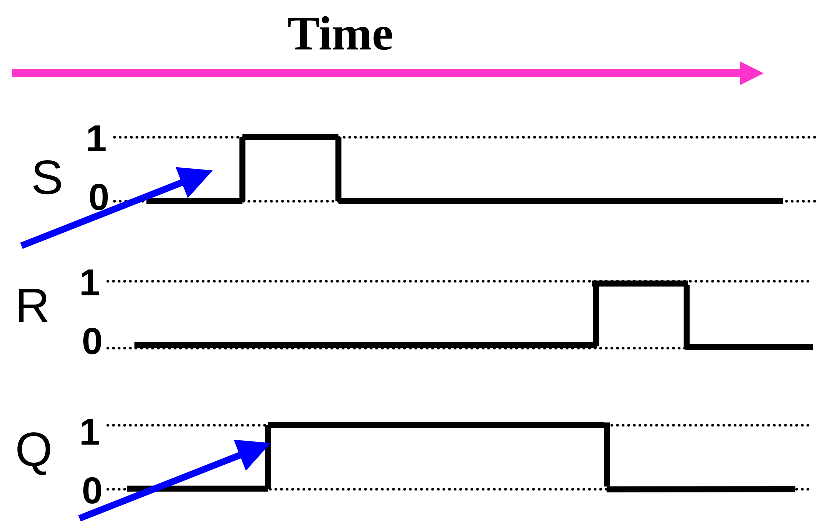




Set-Reset Latch (Continued)



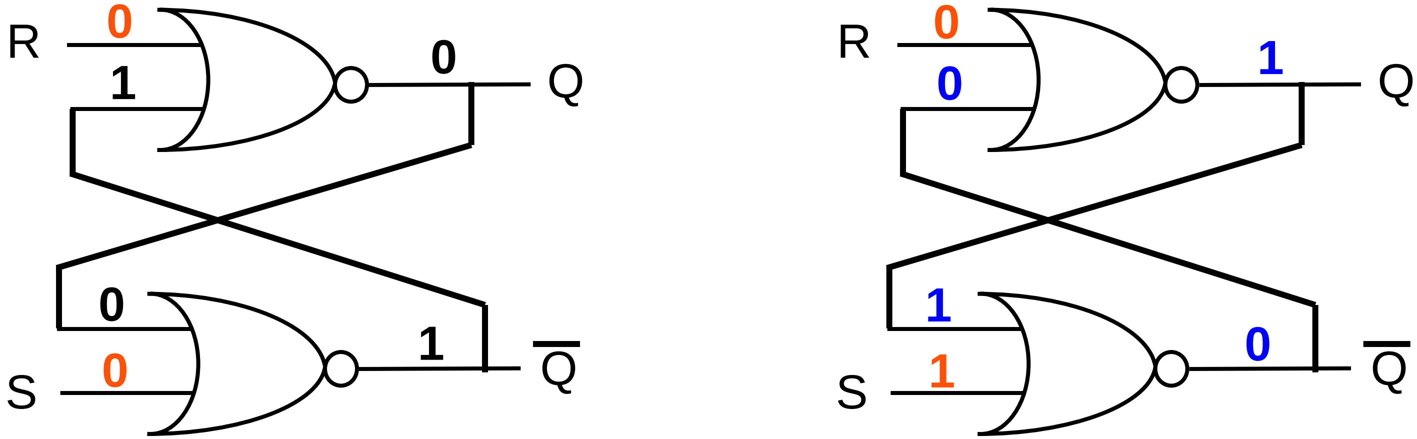


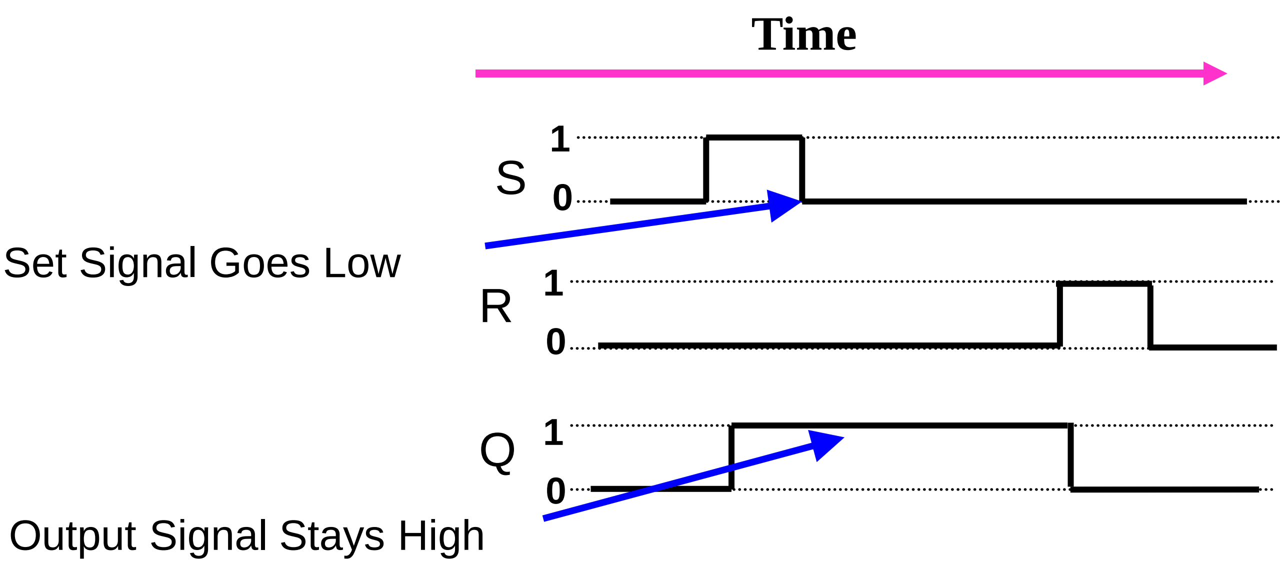


Set Signal Goes High

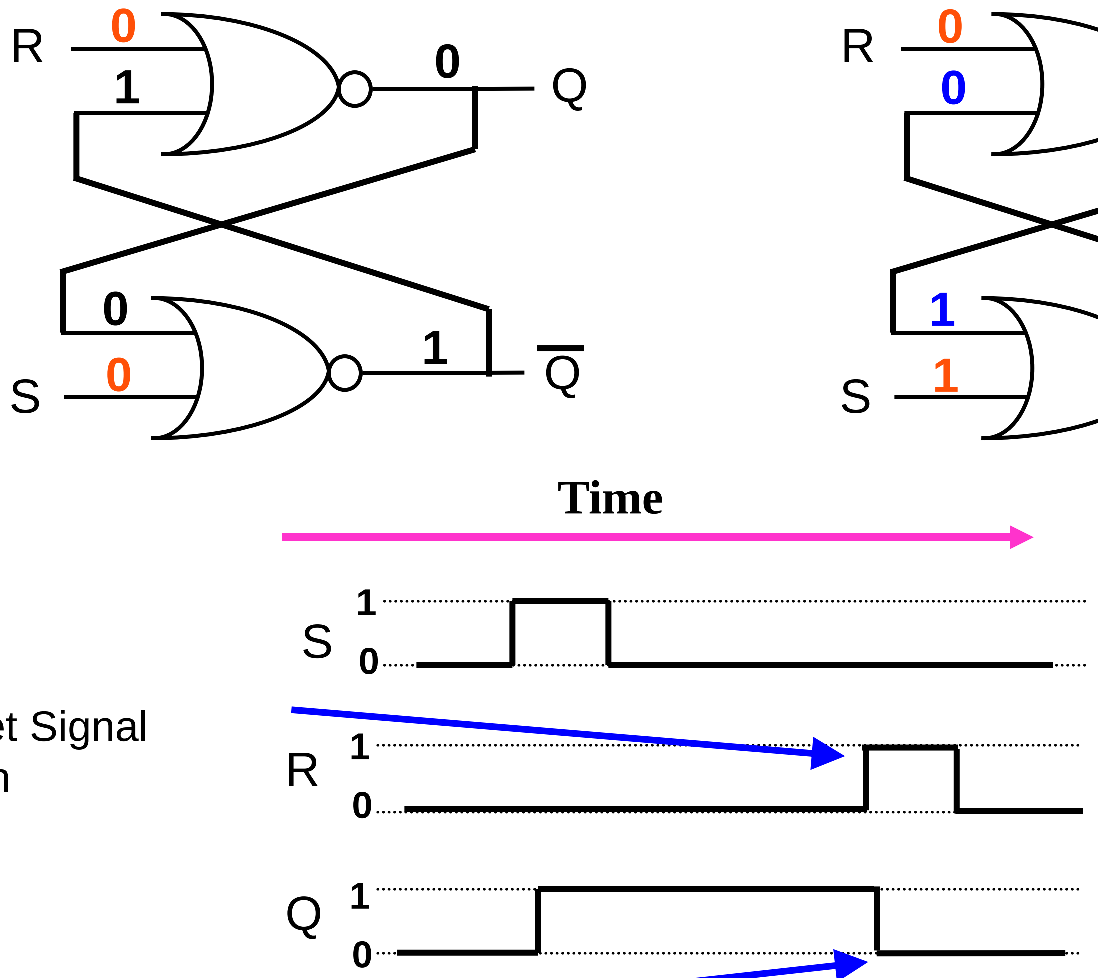
Output Signal Goes High

Set-Reset Latch (Continued)





Set-Reset Latch (Continued)



Until Reset Signal
Goes High

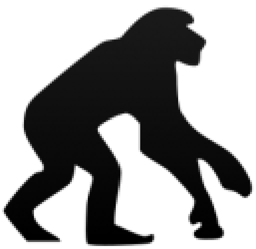
Then Output Signal Goes Low

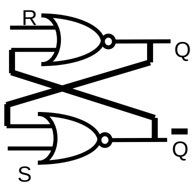
SR Latch

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

- So let's build on it to do better

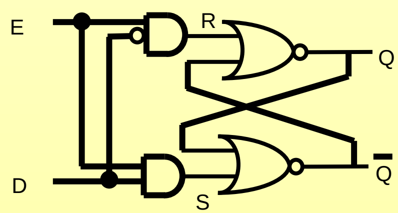
Building up to the D Flip-Flop and beyond

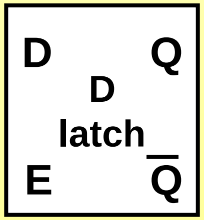




SR Latch

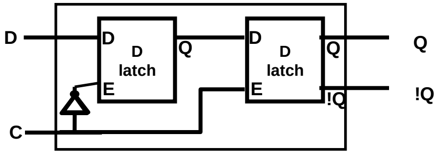
(too awkward)

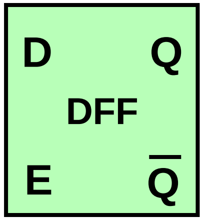




D Latch

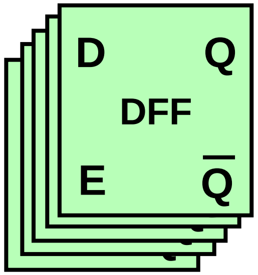
(bad timing)

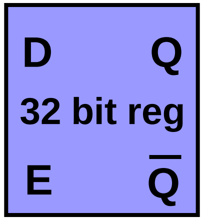




D Flip-Flop

(okay but only one bit)

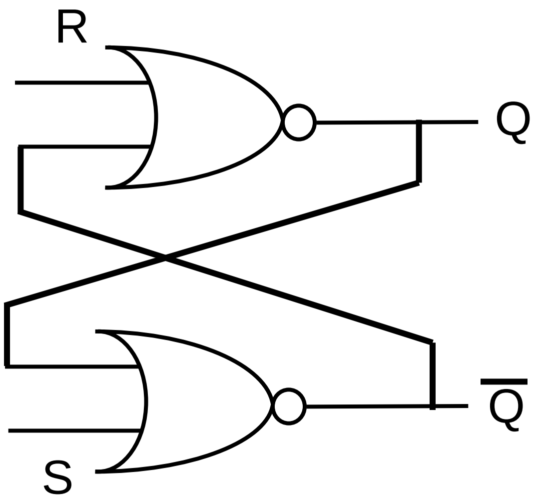




Register

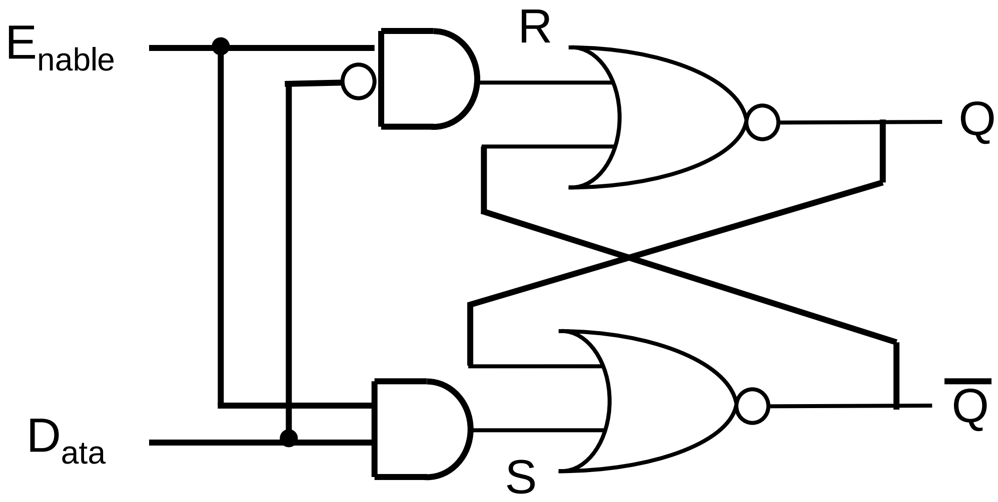
(nice!)

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



Starting with SR Latch

Data Latch (D Latch)

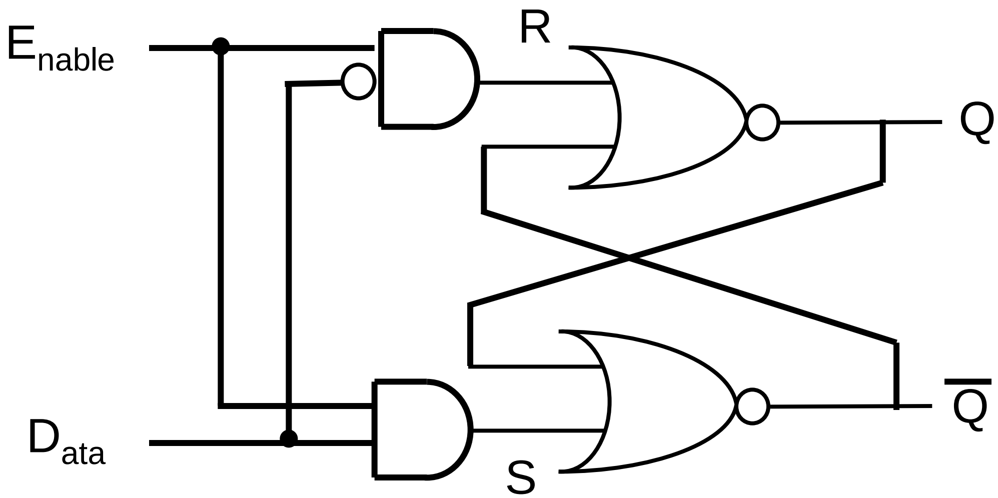


Starting with SR Latch

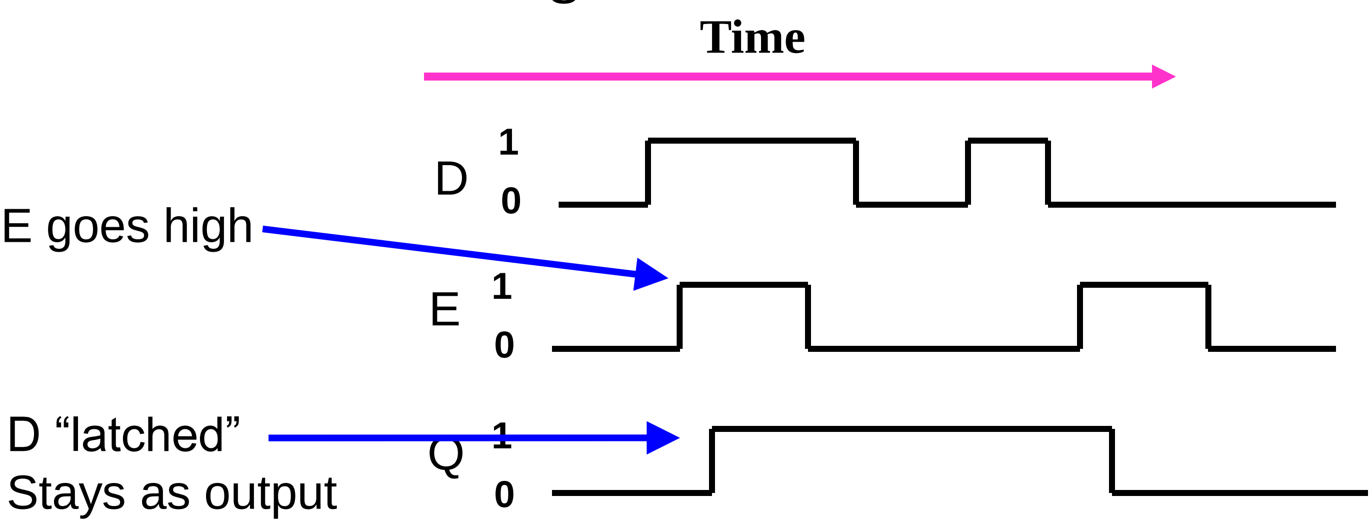
Change interface to
 Data + Enable (D + E)

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

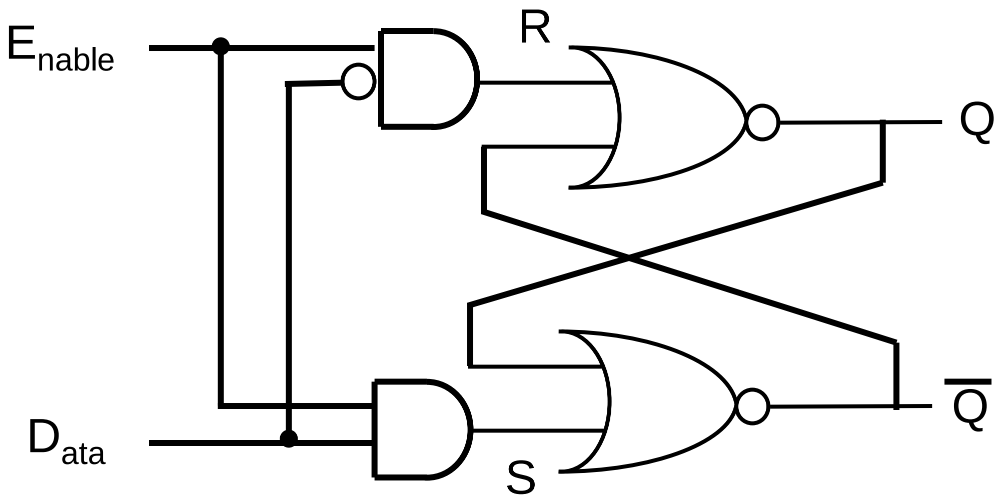
Data Latch (D Latch)



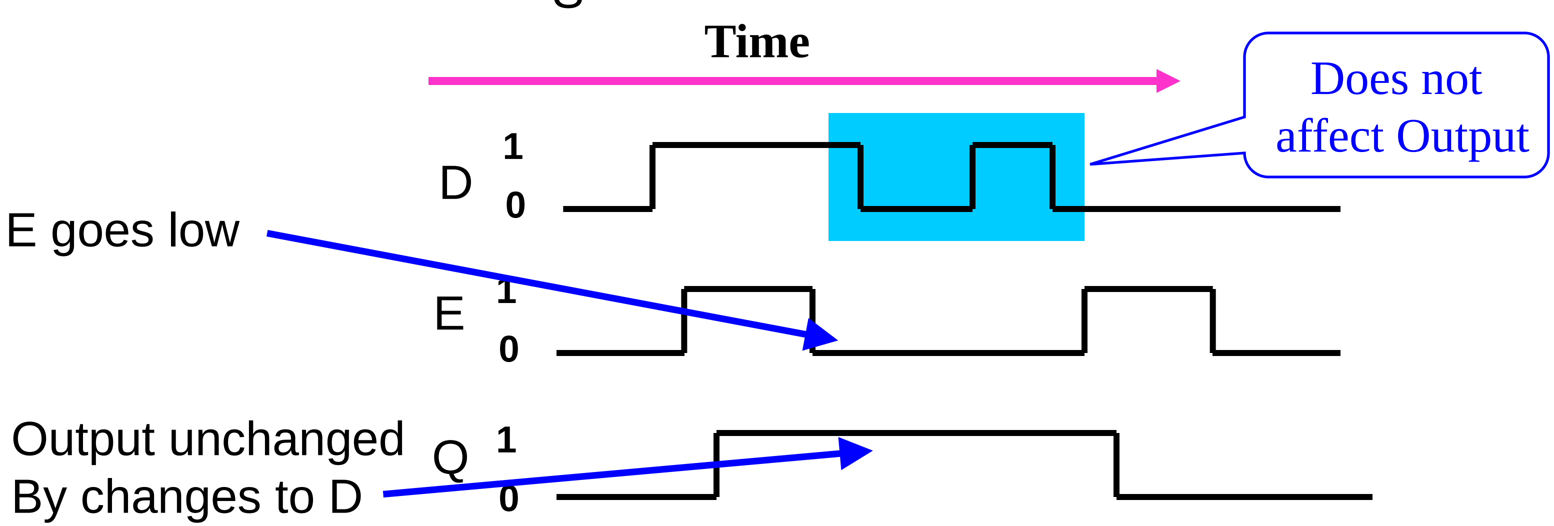
D	E	Q
0	1	0
1	1	1
–	0	Q



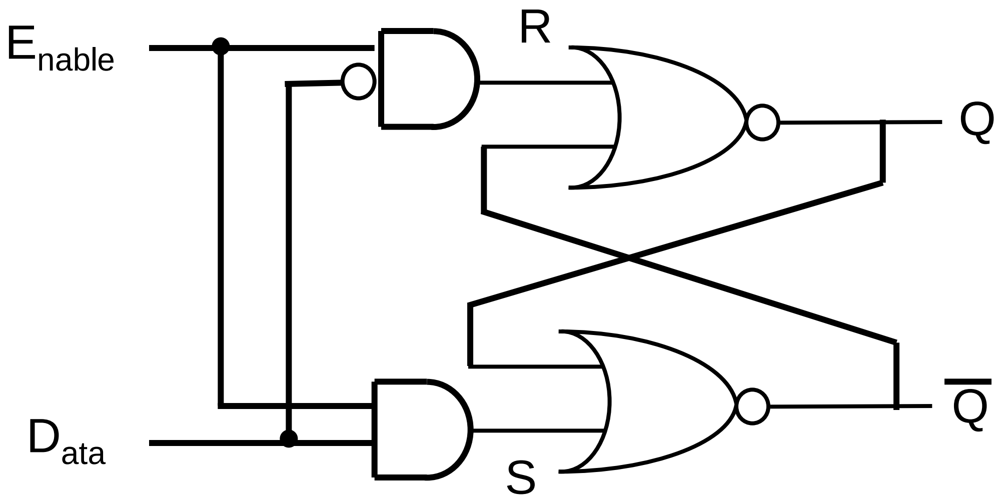
Data Latch (D Latch)



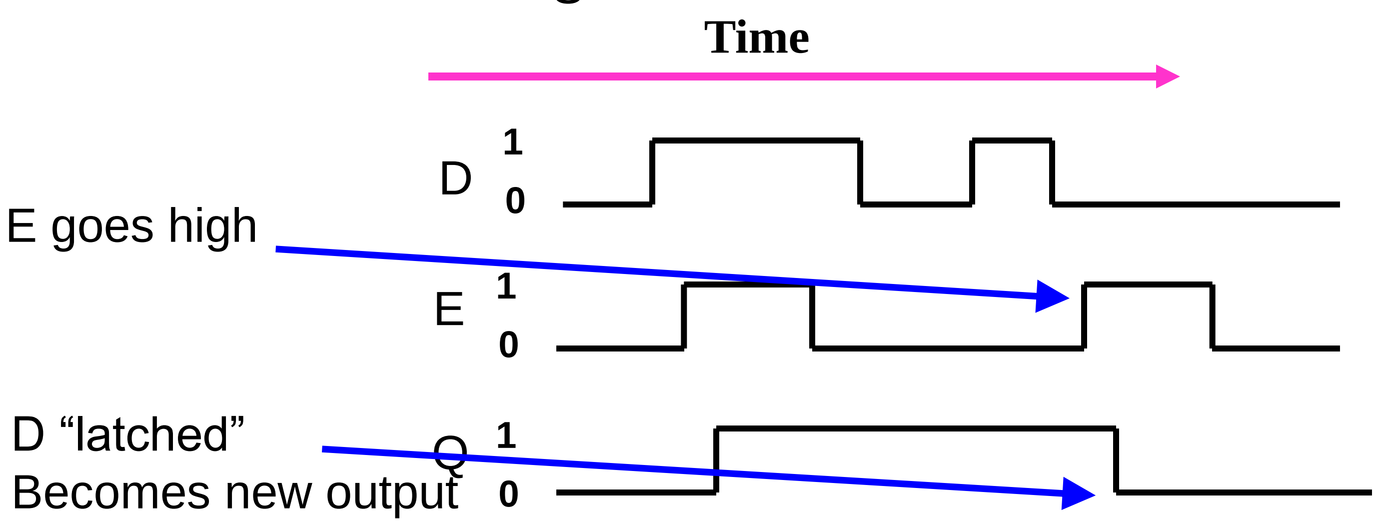
D	E	Q
0	1	0
1	1	1
-	0	Q



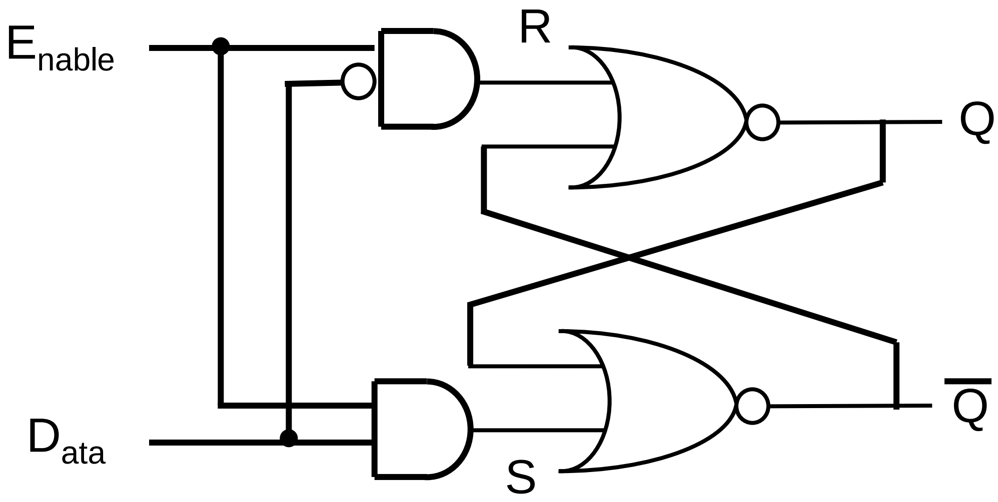
Data Latch (D Latch)



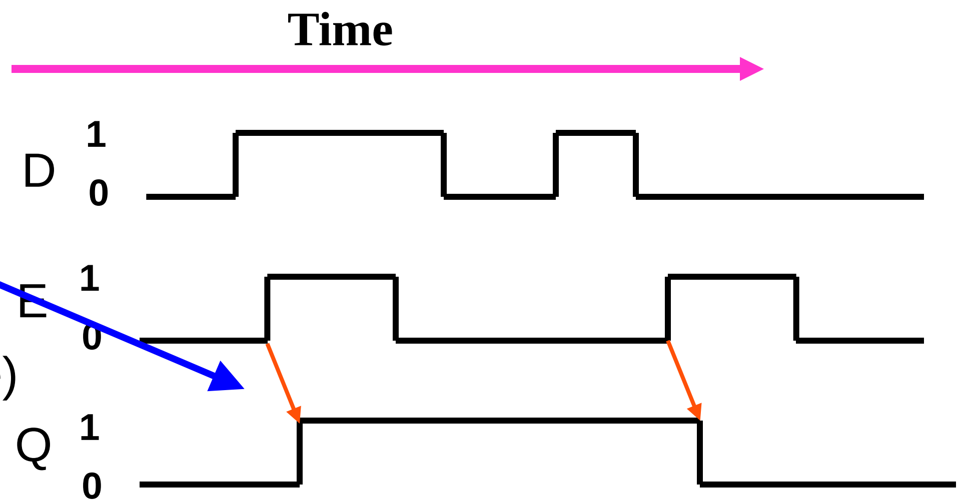
D	E	Q
0	1	0
1	1	1
–	0	Q



Data Latch (D Latch)



D	E	Q
0	1	0
1	1	1
–	0	Q



Slight Delay

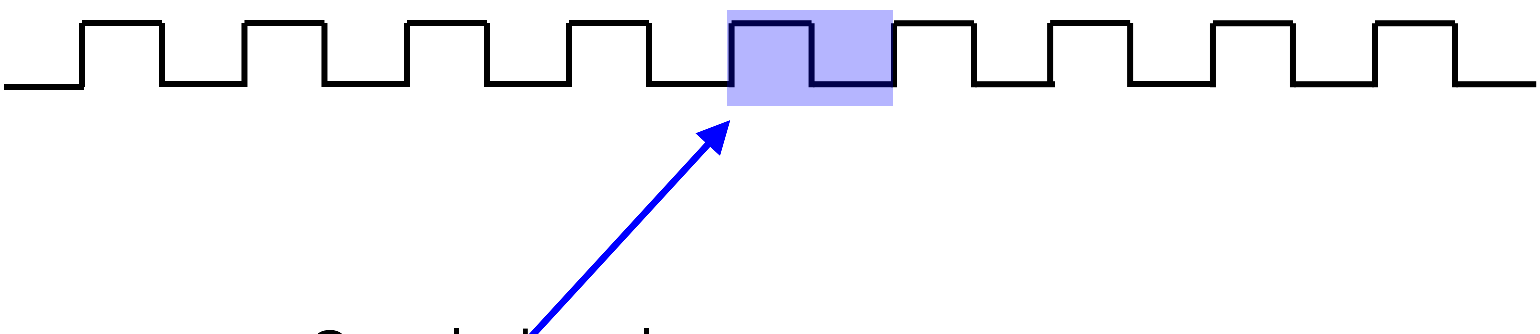
(Logic gates take time)

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

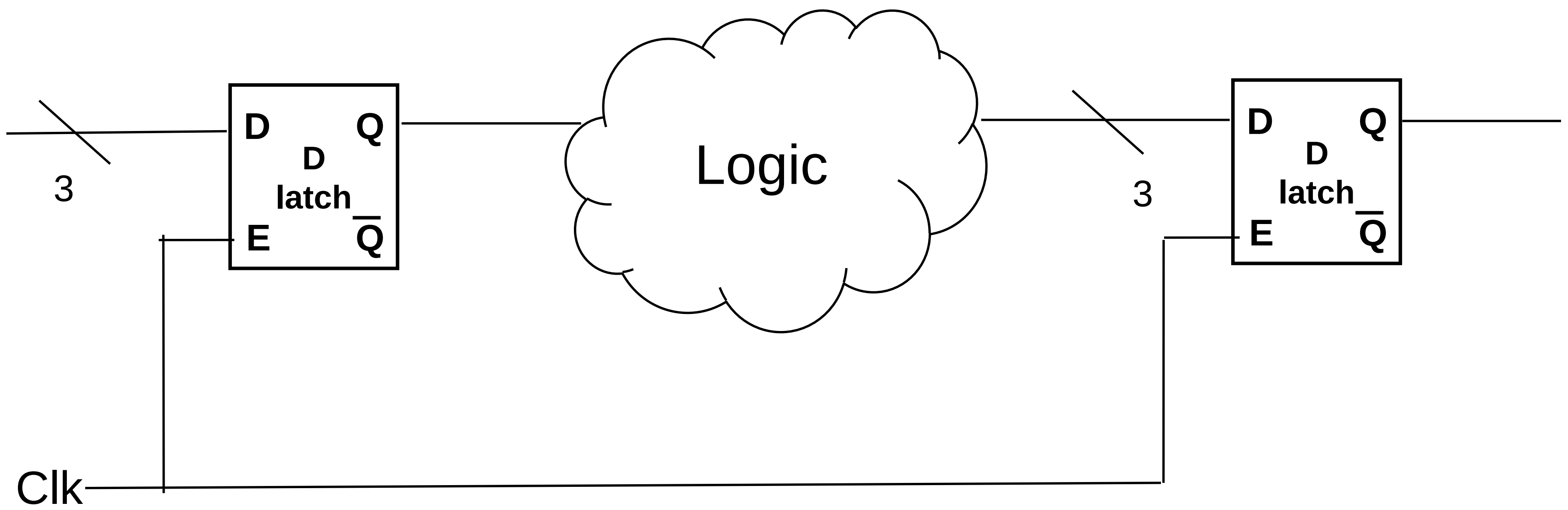


One clock cycle

  - 3.4 GHz processor = 3.4 Billion clock cycles/sec

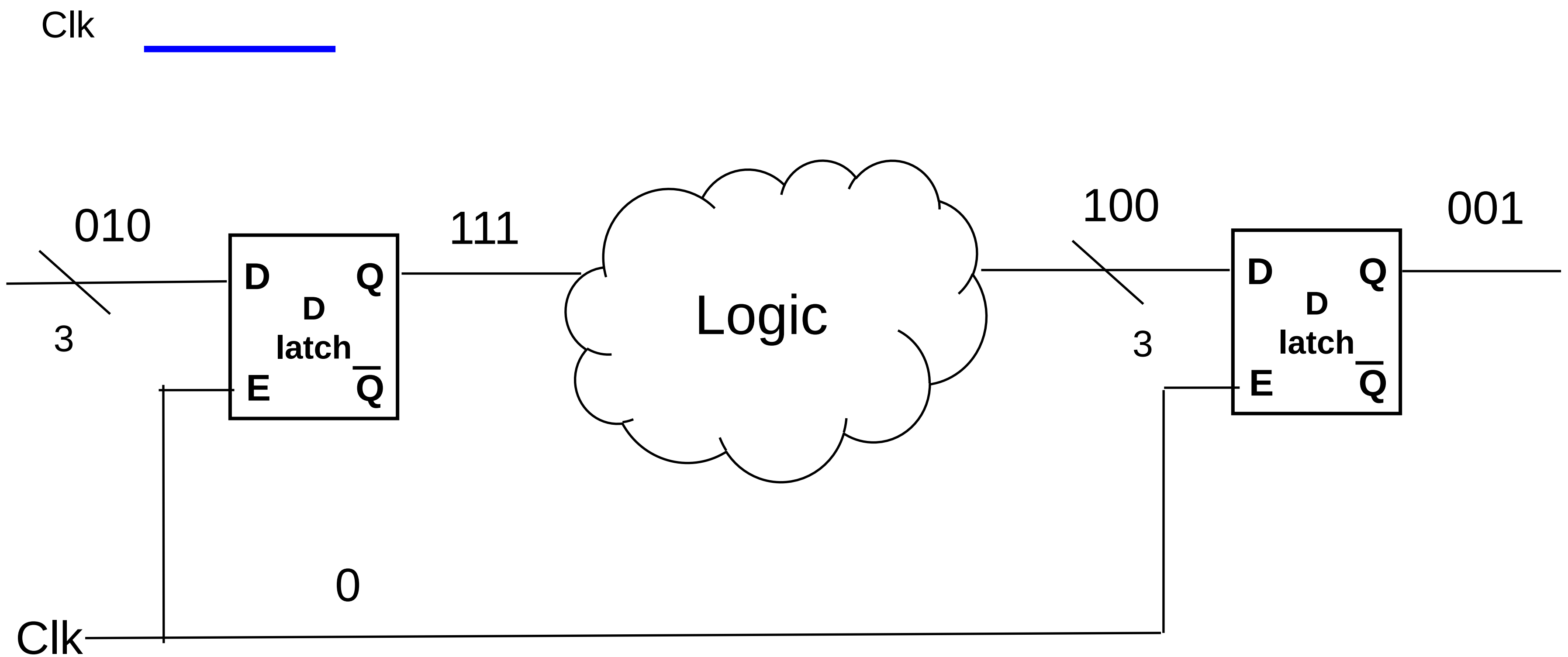
FF Step #3: Using Level-Triggered D Latches

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



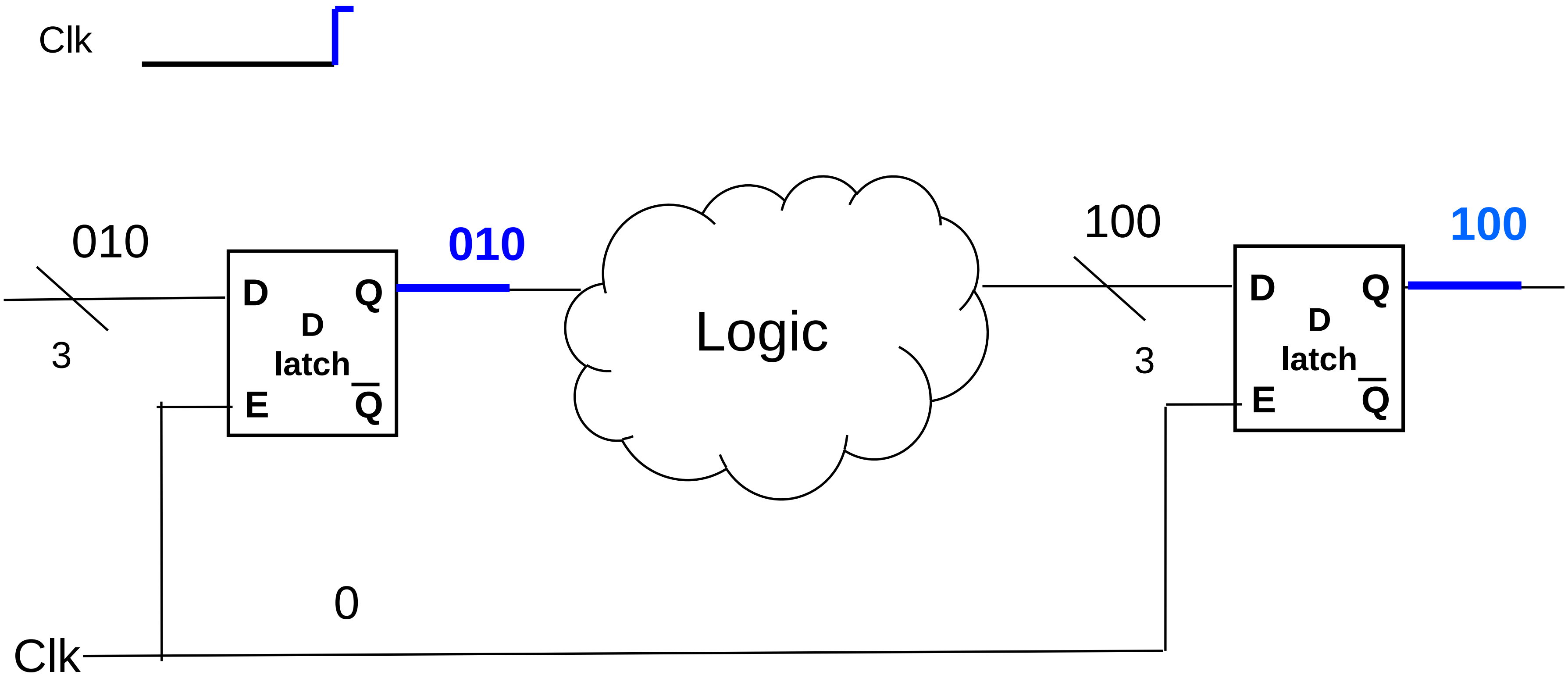
Strawman: Level Triggered

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



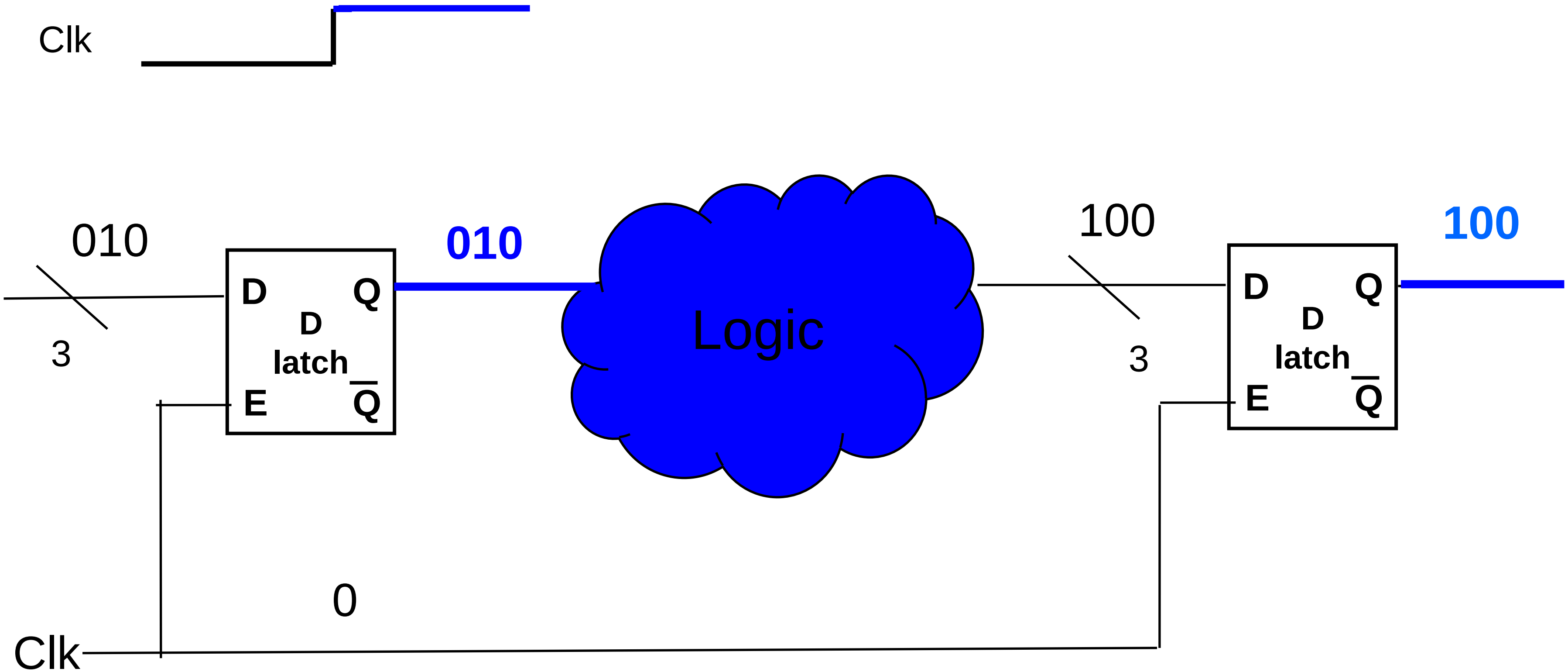
Strawman: Level Triggered

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



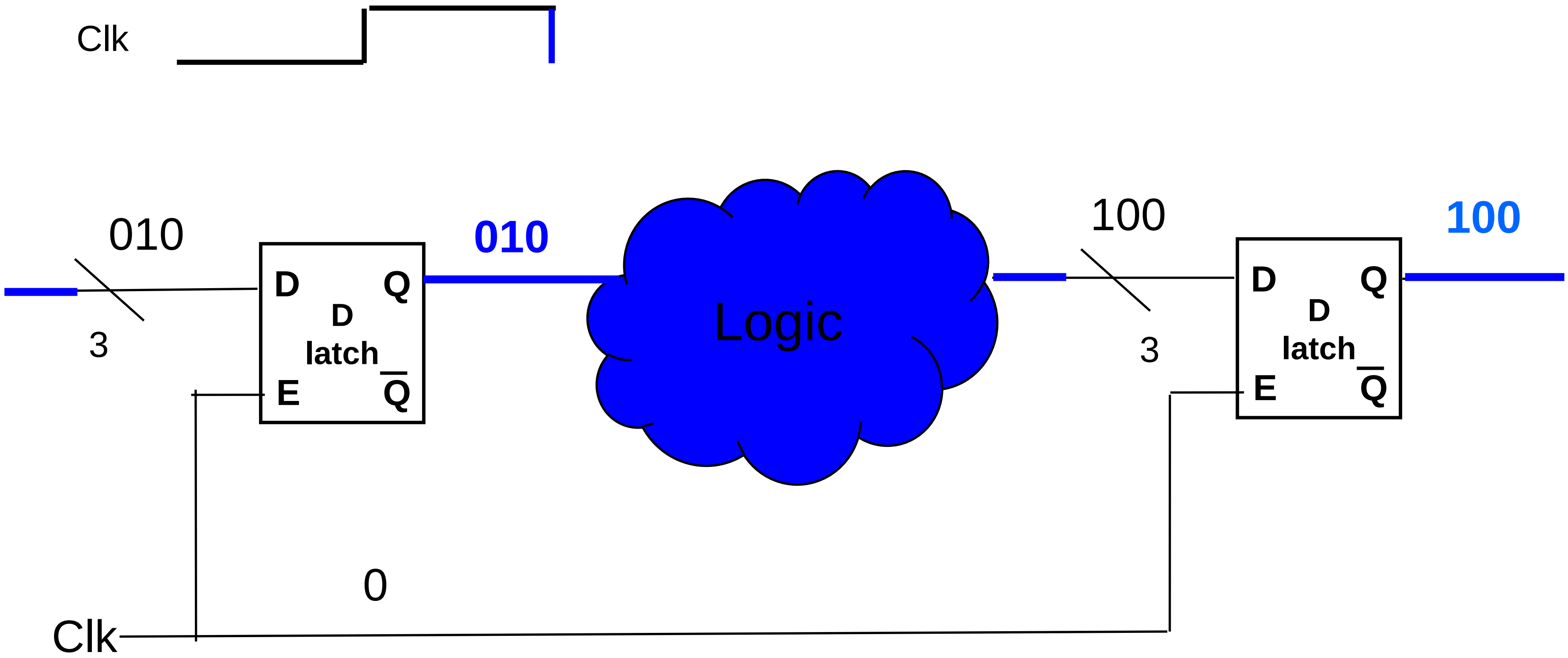
Strawman: Level Triggered

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



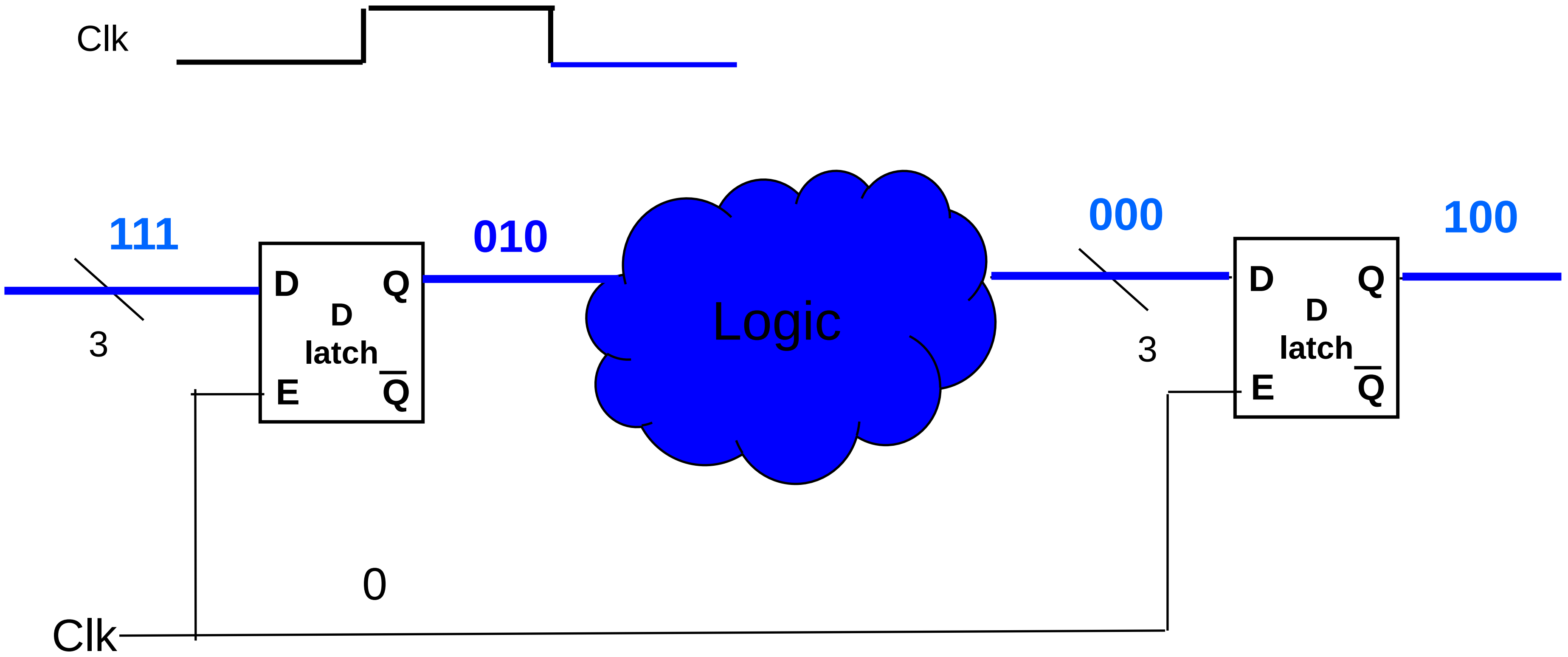
Strawman: Level Triggered

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



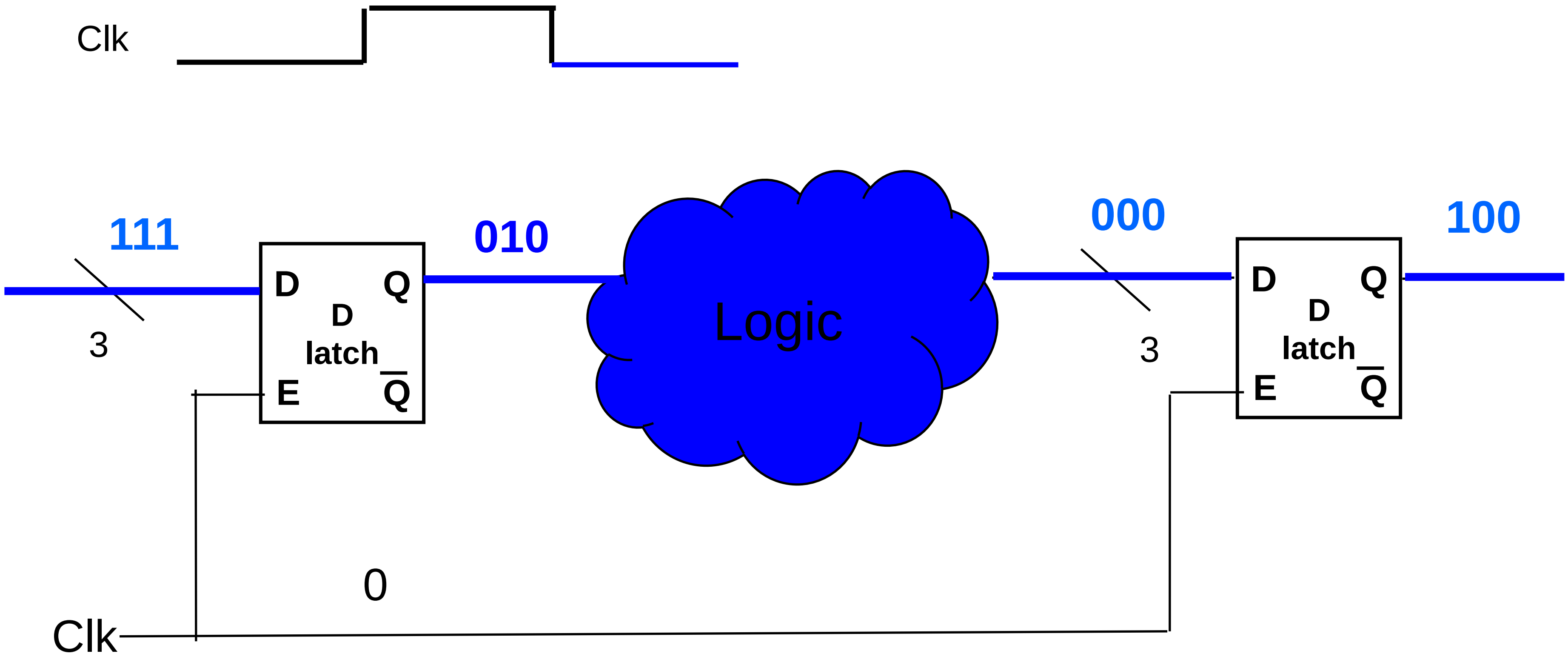
Strawman: Level Triggered

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



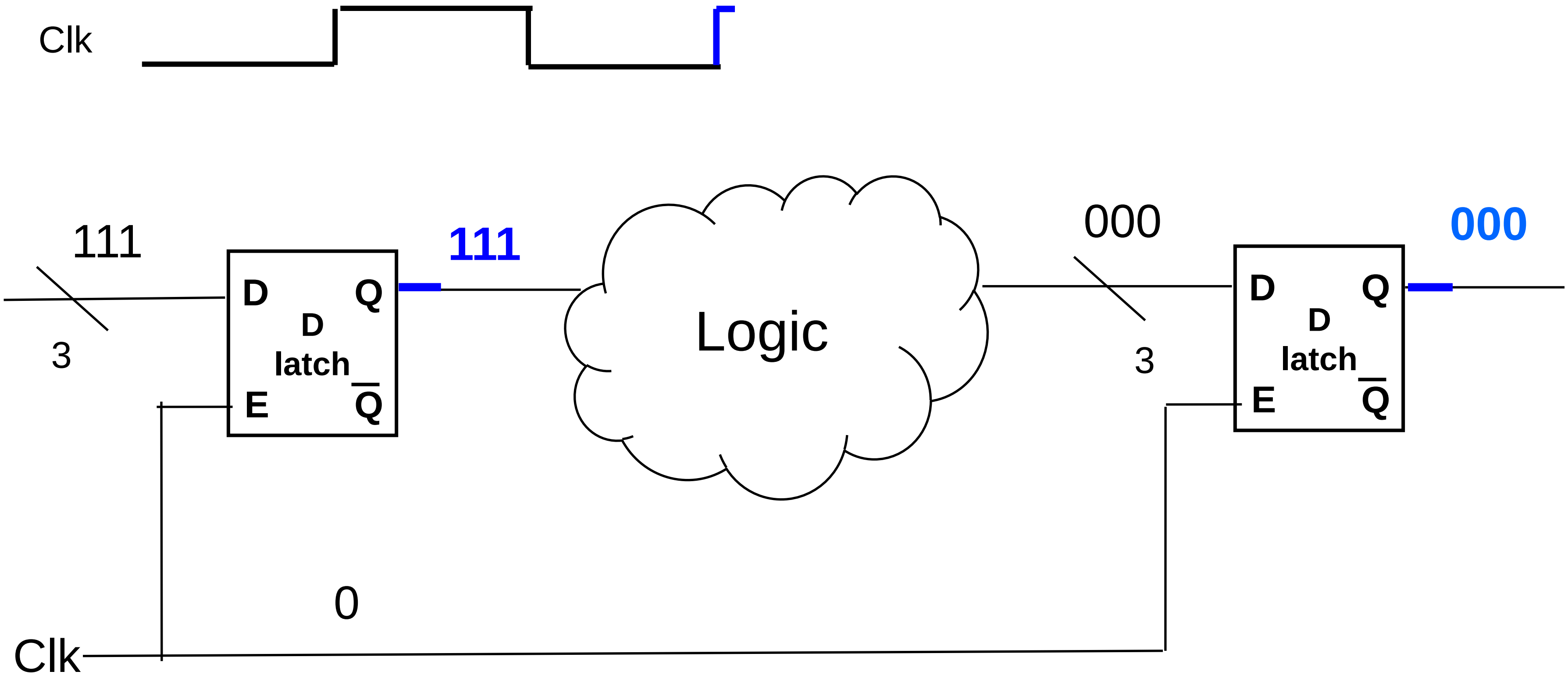
Strawman: Level Triggered

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



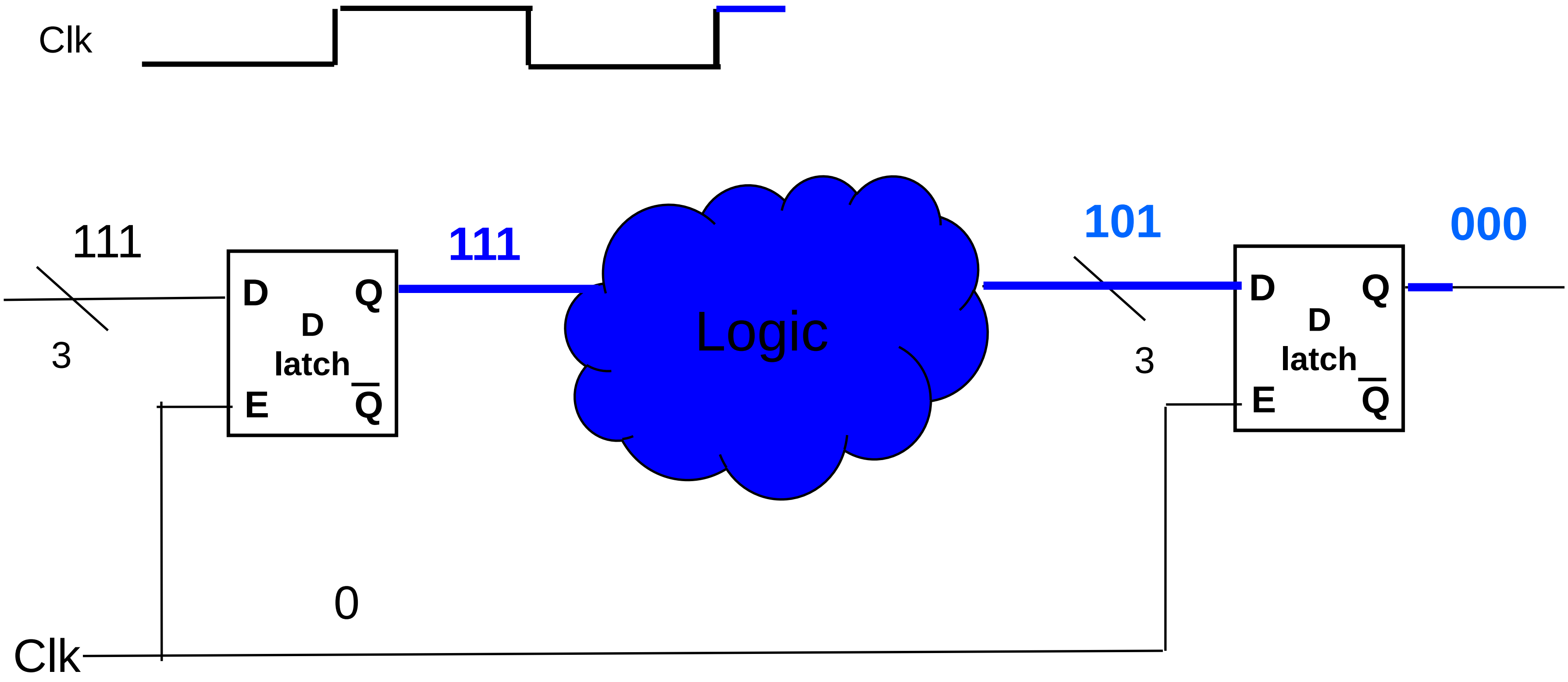
Strawman: Level Triggered

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



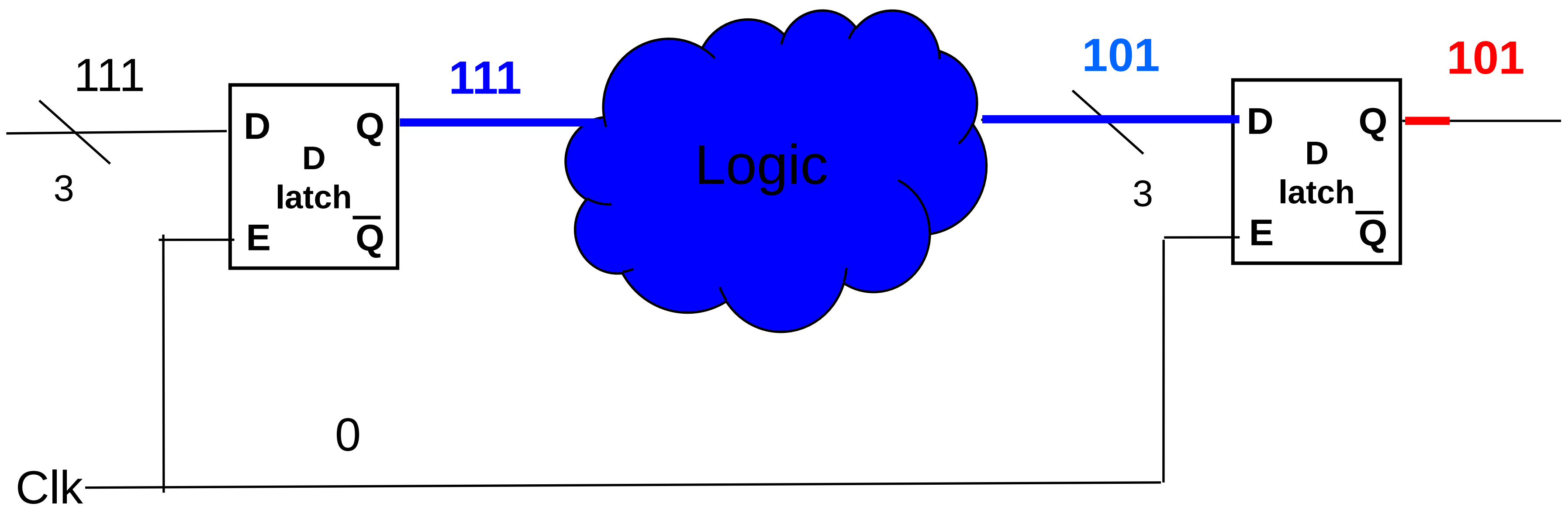
Strawman: Level Triggered

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



Strawman: Level Triggered

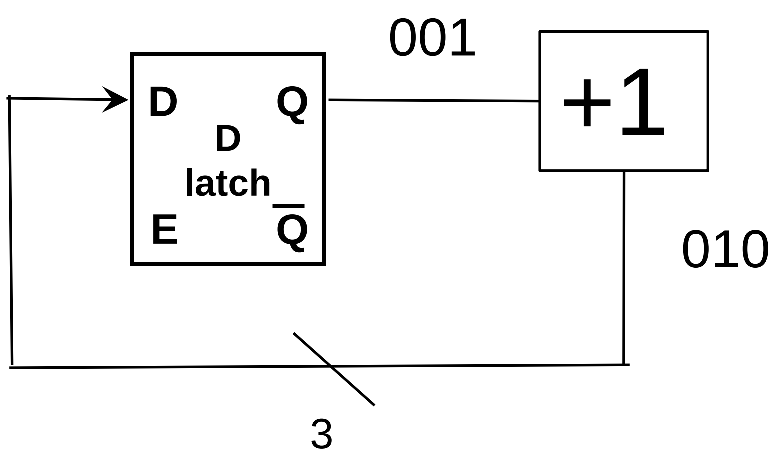
- Problem: What if signal reaches latch too early?
  - Signal goes right through latch, into next stage..



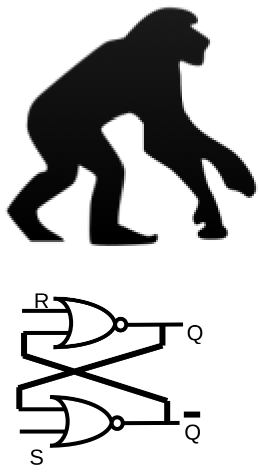
That would be bad…

- 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…

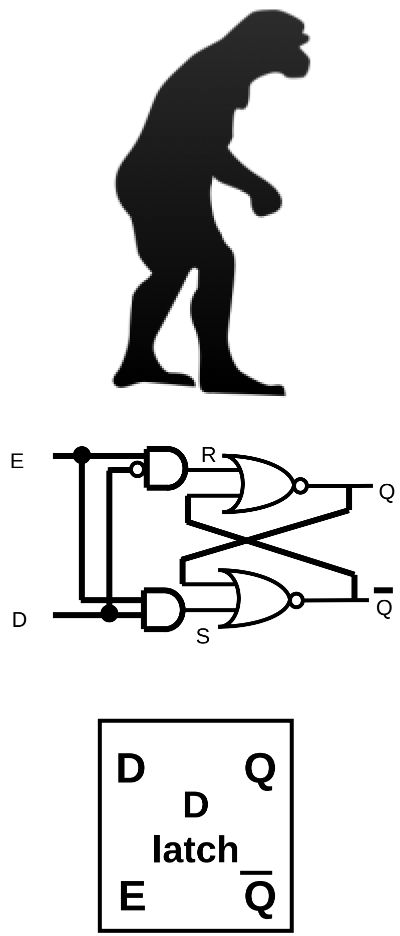


Building up to the D Flip-Flop and beyond



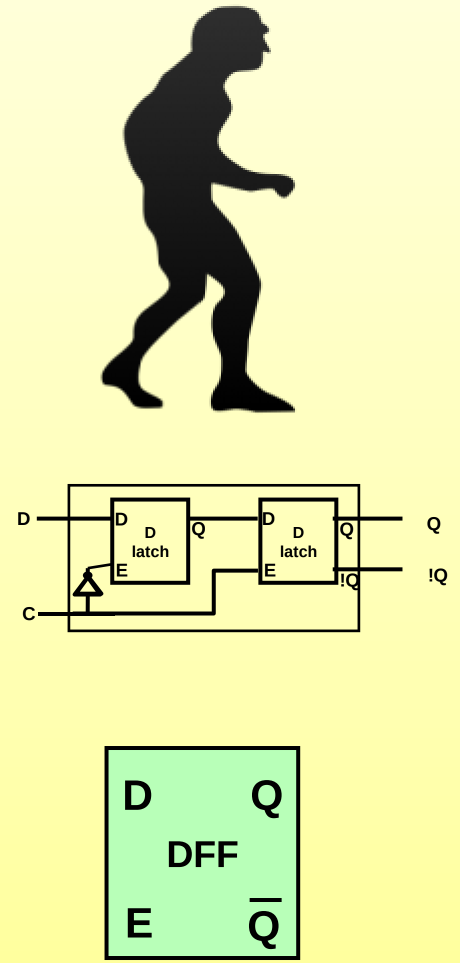
SR Latch

(too awkward)



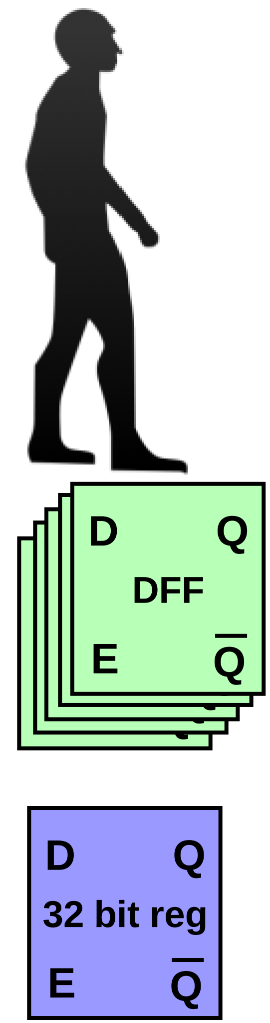
D Latch

(bad timing)



D Flip-Flop

(okay but only one bit)

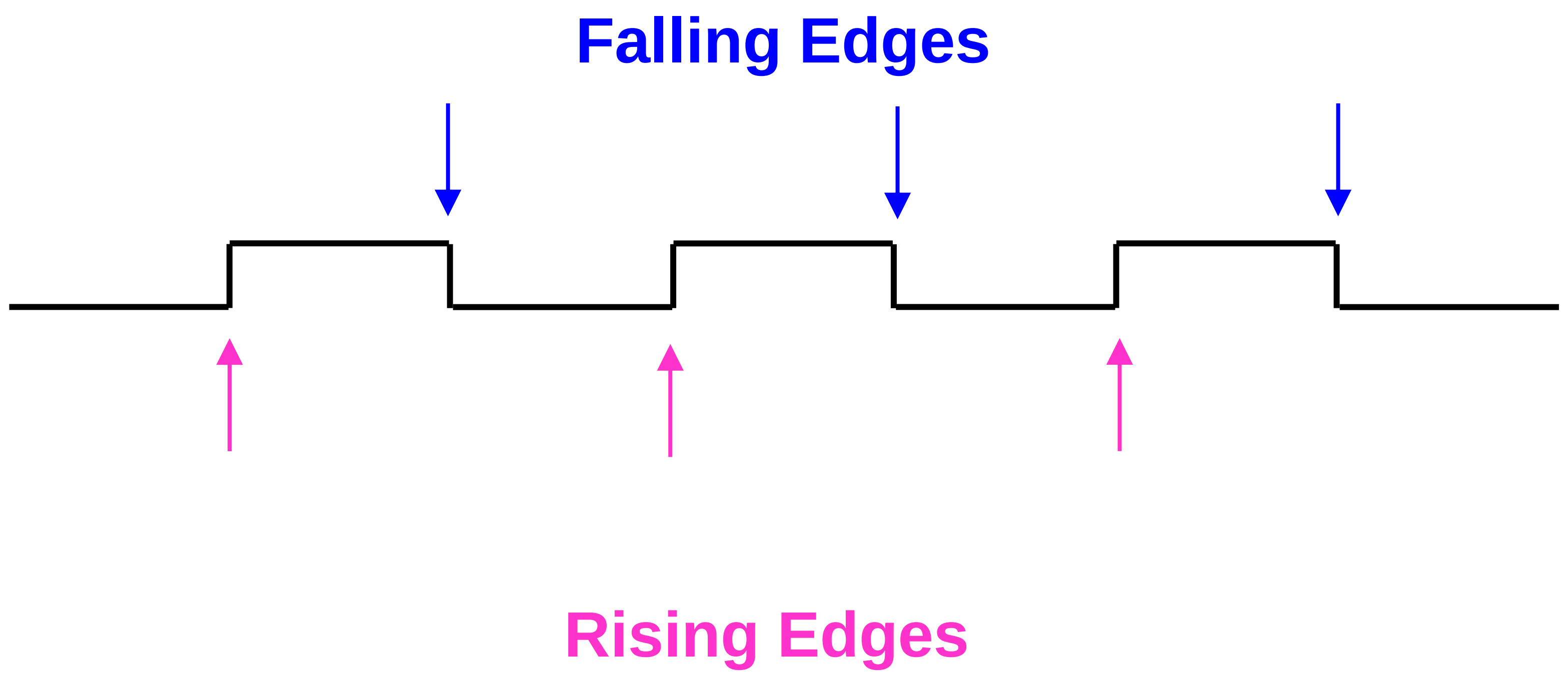


Register

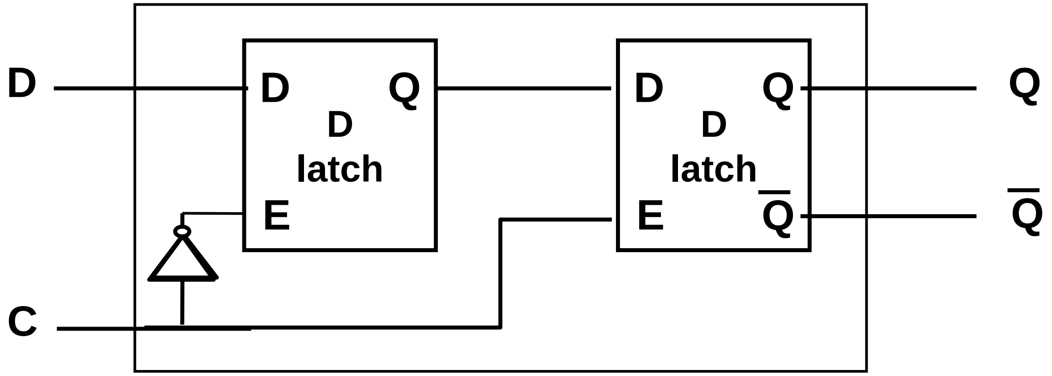
(*nice!*)

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)

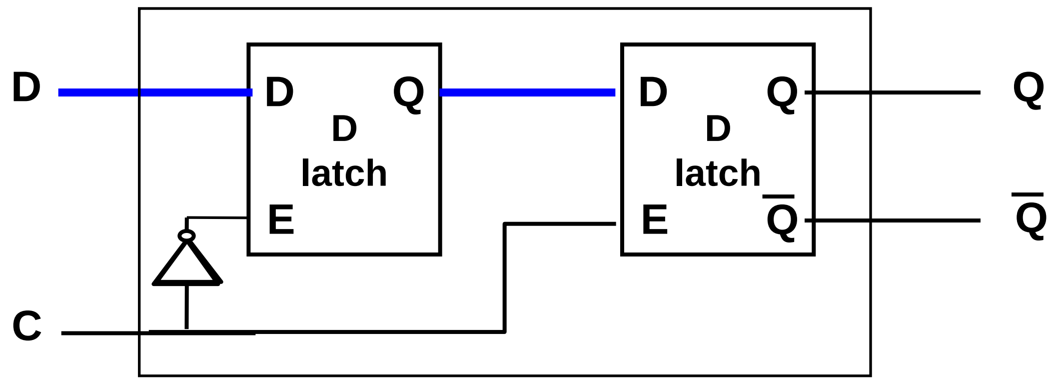


Our Ultimate Goal: D Flip-Flop



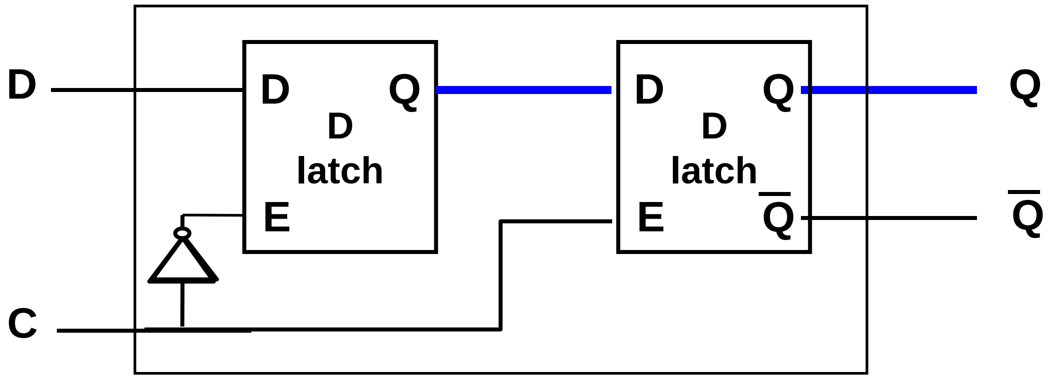
- Rising edge triggered D Flip-flop
  - Two D Latches w/ opposite clking of enables

D Flip-Flop



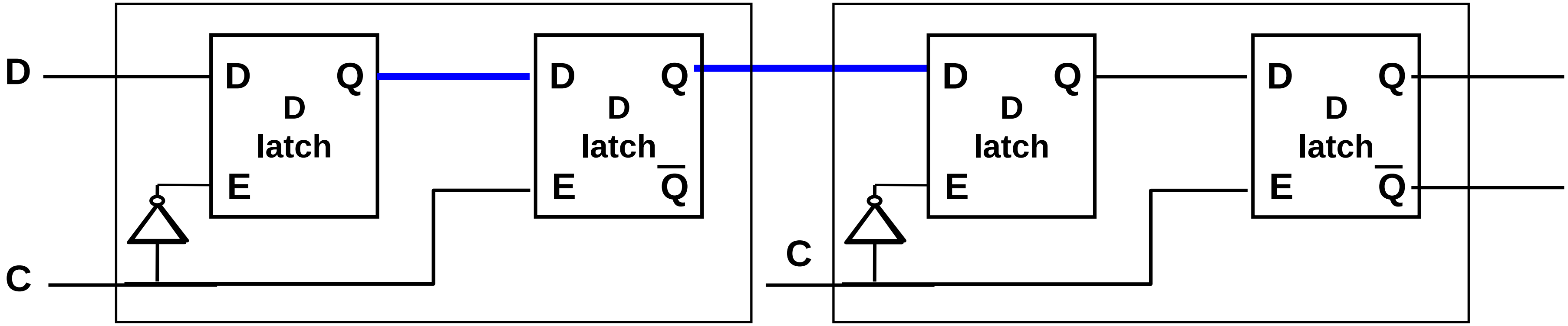
- Rising edge triggered D Flip-flop
  - Two D Latches w/ opposite clking of enables
  - On Low Clk, first latch enabled (propagates value)
    - Second not enabled, maintains value

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

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"

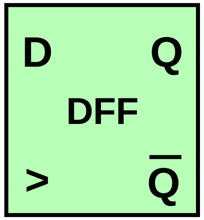
D Flip-flops (continued…)

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

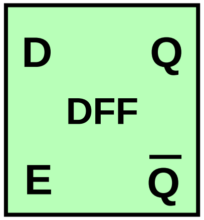
- D Flip-flop is ubiquitous
  - Typically people just say “latch” and mean DFF
  - Which edge: doesn’t matter
    - As long as consistent in entire design
    - We’ll use rising edge

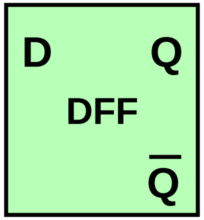
D flip flops

- 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)





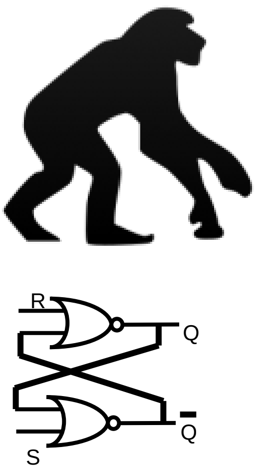
- Get output and NOT(output) for "free"

More Storage Than A D FF: Register File

- A MIPS register can be made with 32 flip flops
- One register can store one 32-bit value
- So do we just replicate this 32 times to get the 32 registers for a MIPS processor?
  - Not exactly

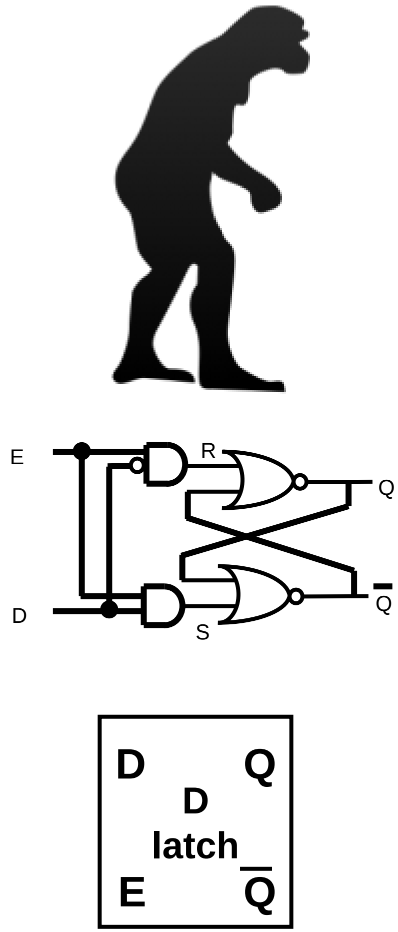
- Register File (the physical storage for the regs)
  - MIPS register file has 32 32-bit registers
- How do we build a Register File using D Flip-Flops?
- What other components do we need?

Building up to the D Flip-Flop and beyond



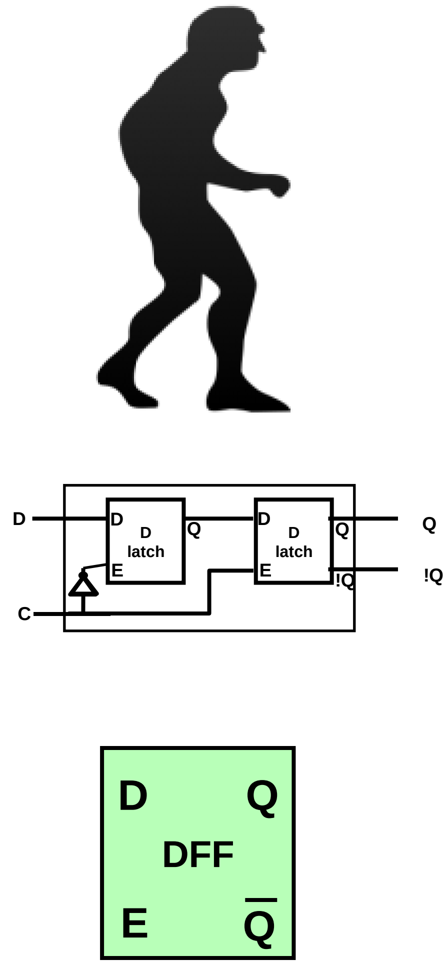
SR Latch

(too awkward)



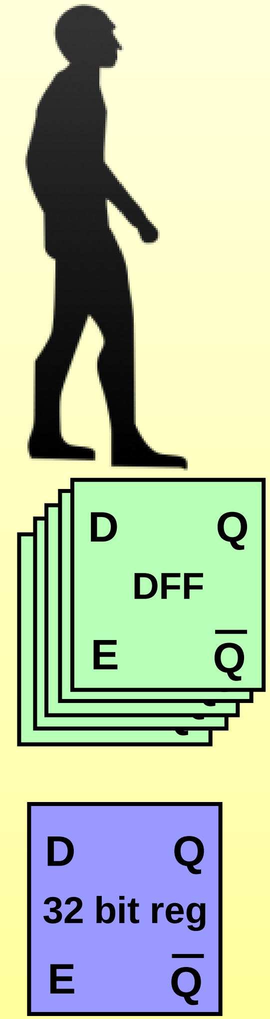
D Latch

(bad timing)



D Flip-Flop

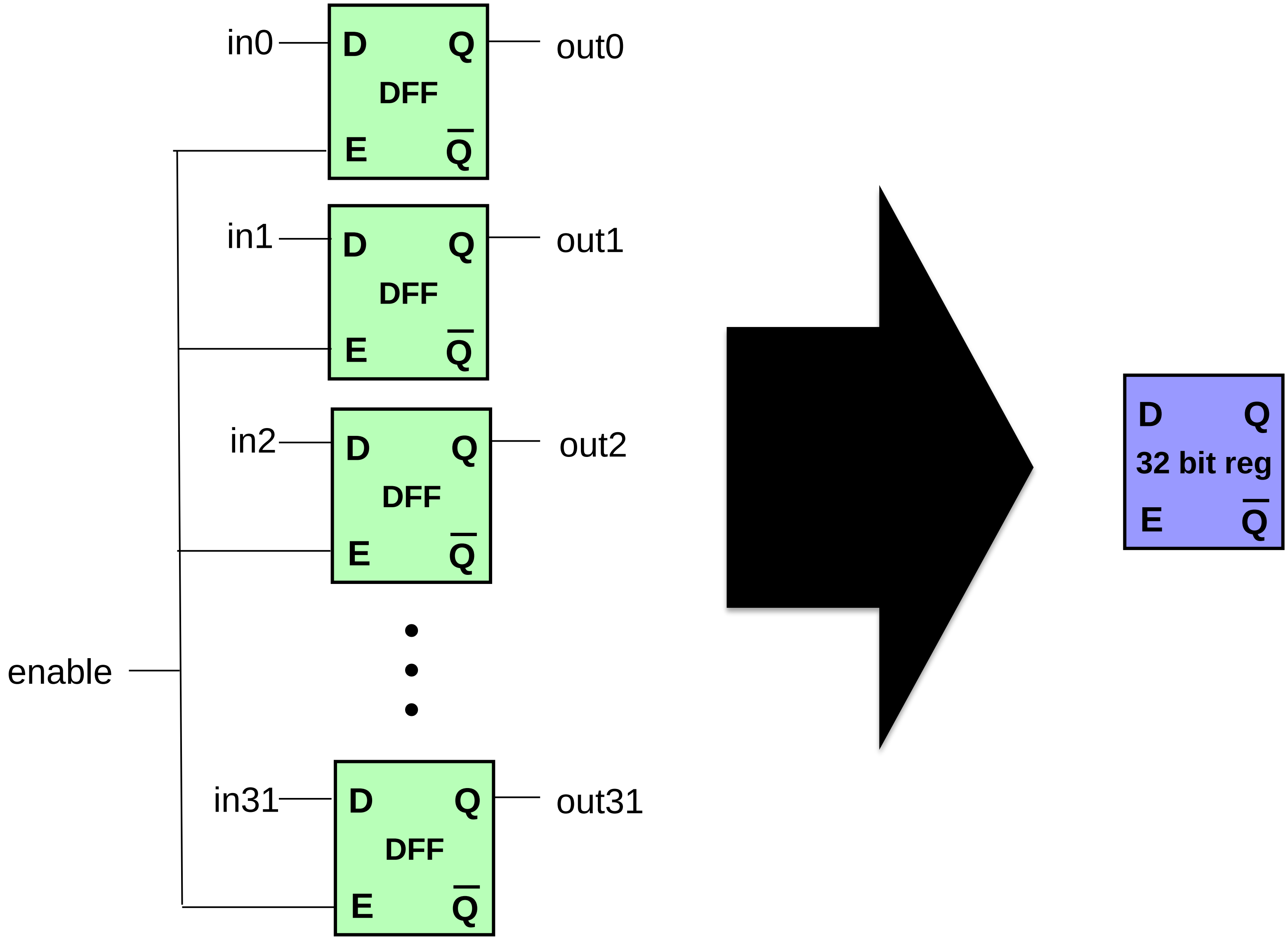
(okay but only one bit)



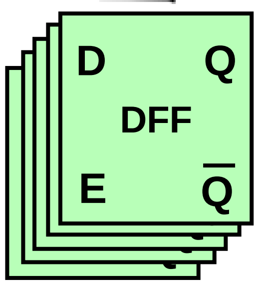
Register

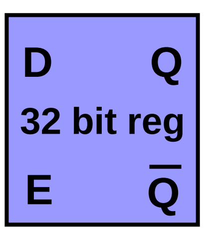
(nice!)

Stick a bunch of DFFs together to make a register



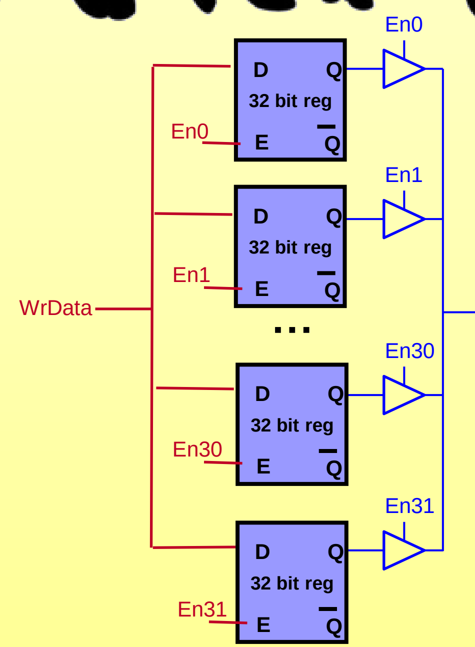
Next evolution: multiple registers





Register

(*nice!*)

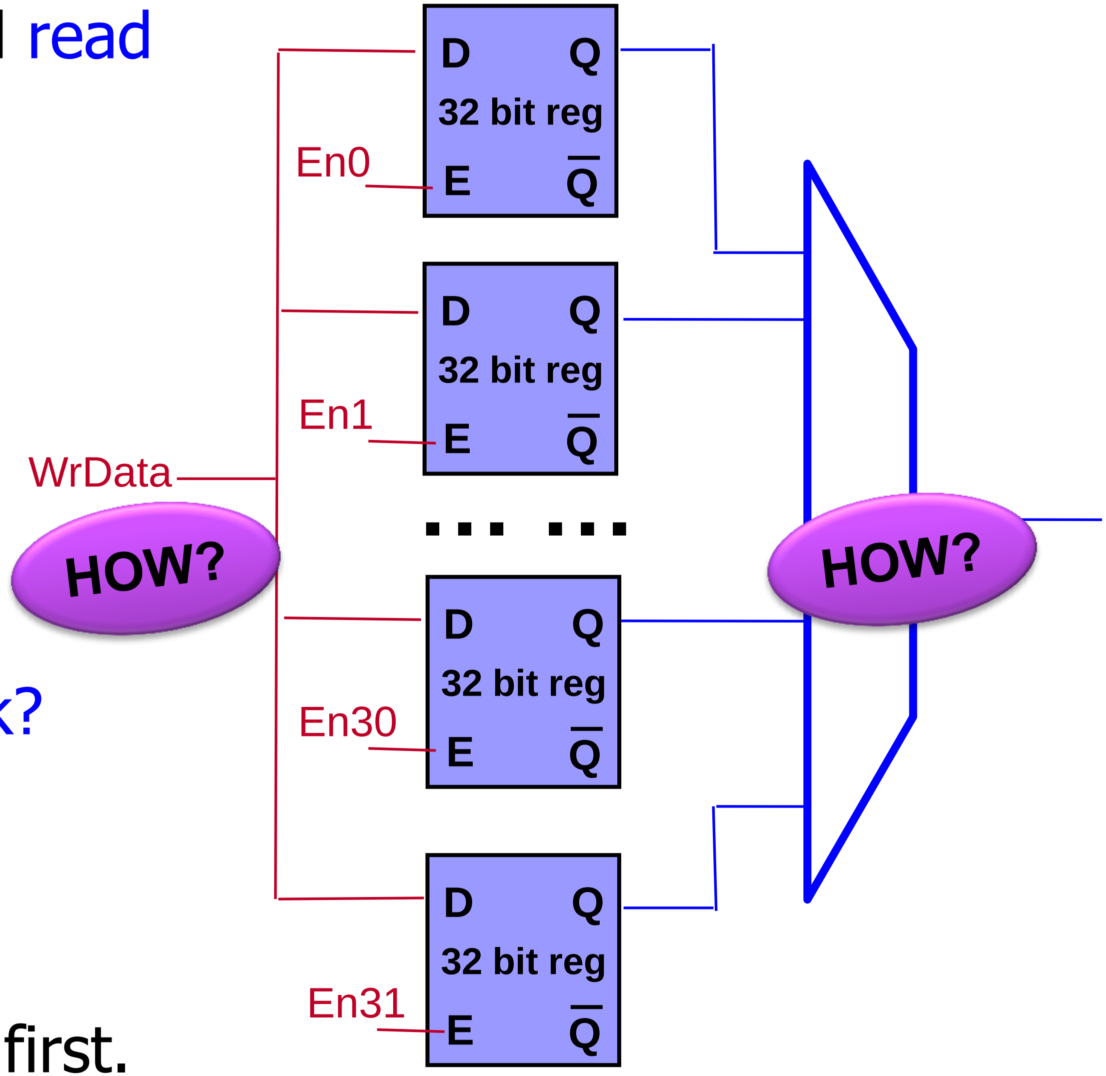


Register File

(*Tremendous!*)

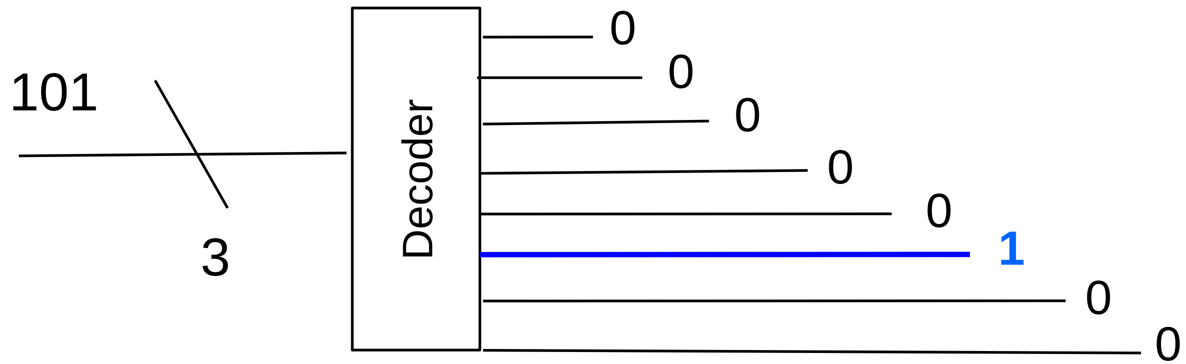
Register File Design

- 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 = slow
  - Need a better method…
- Let's talk about **writing** first.



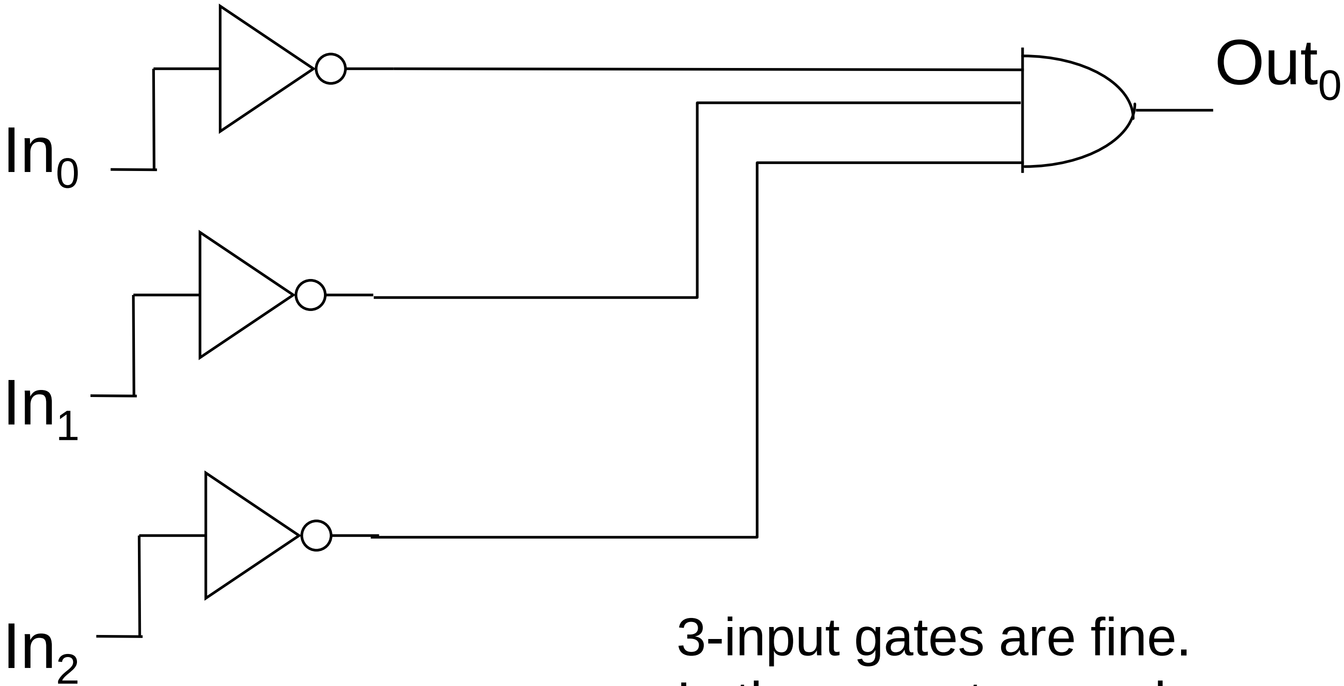
First: A Decoder

- 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

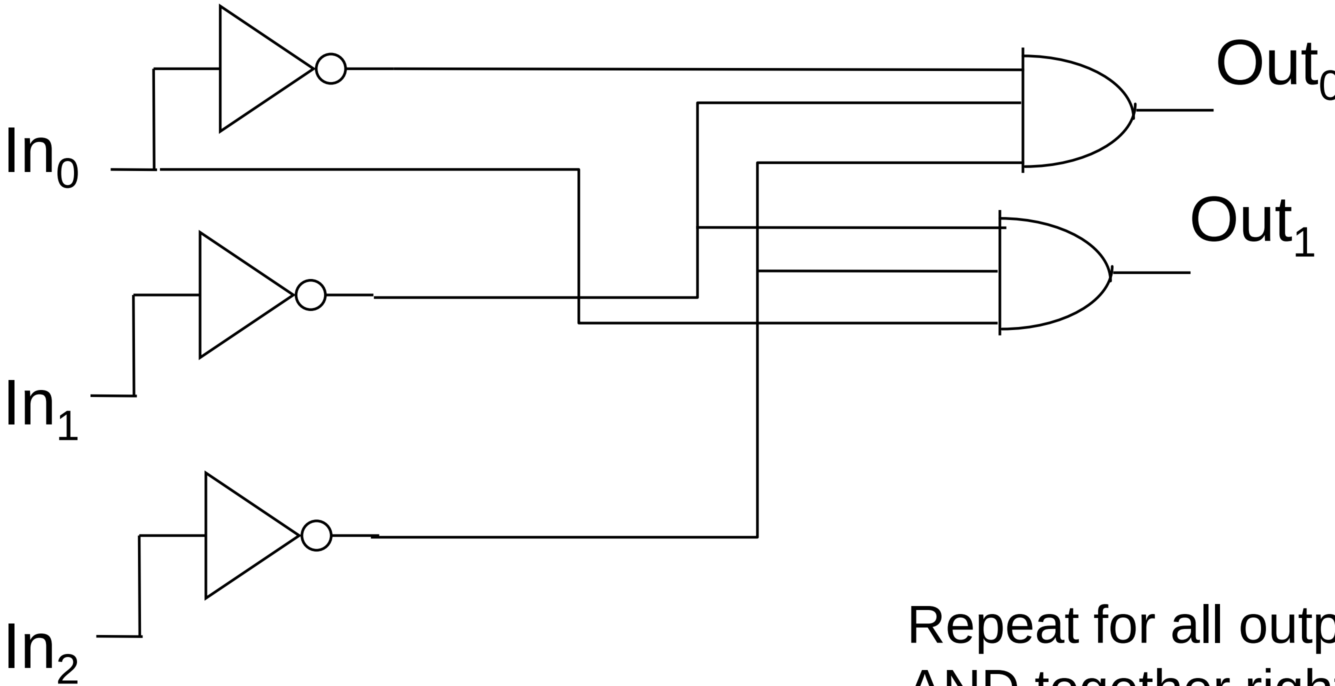
- Decoder basically AND gates for each output:
  - Out_0 only on if input 000



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

Decoder Logic

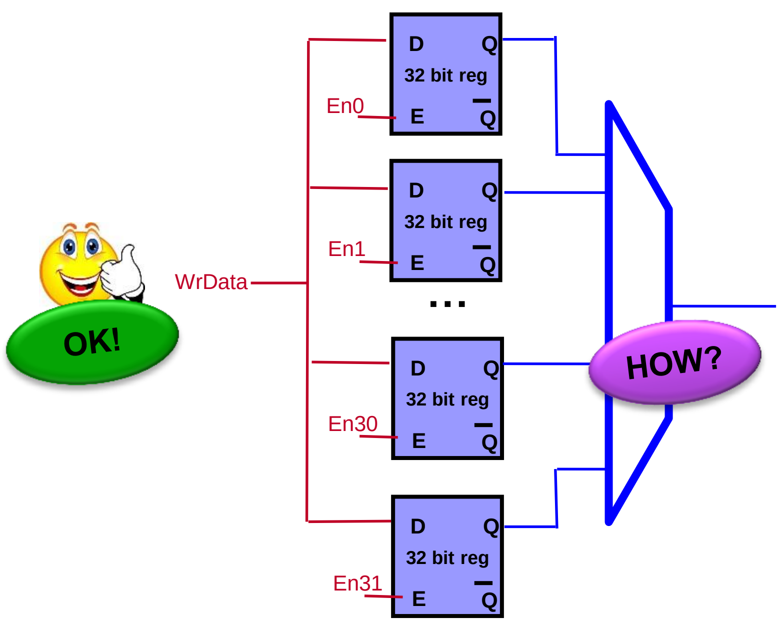
- Decoder basically AND gates for each output:
  - Out_1 only on if input 001



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

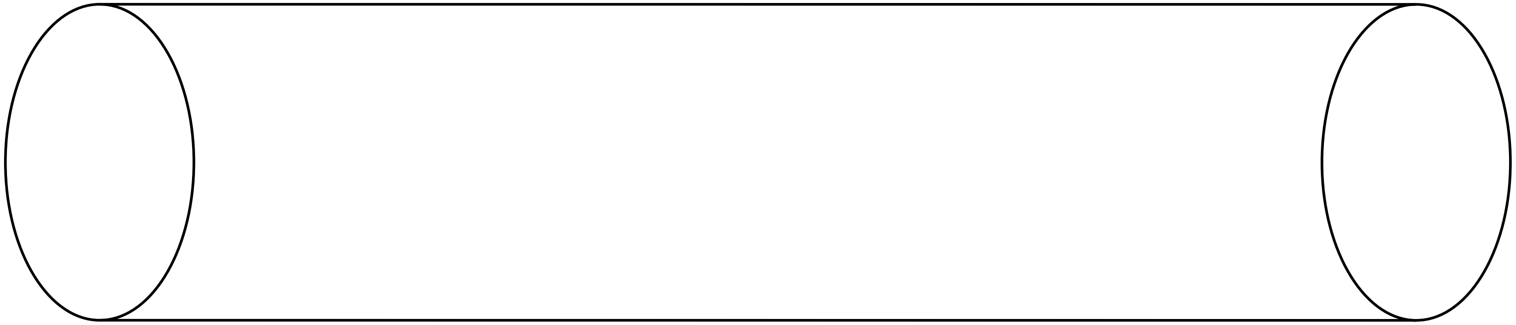
Register File

- Now we know how to **write**:
  - Use decoder to convert reg # to one hot
  - Send write data to all regs
  - 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}



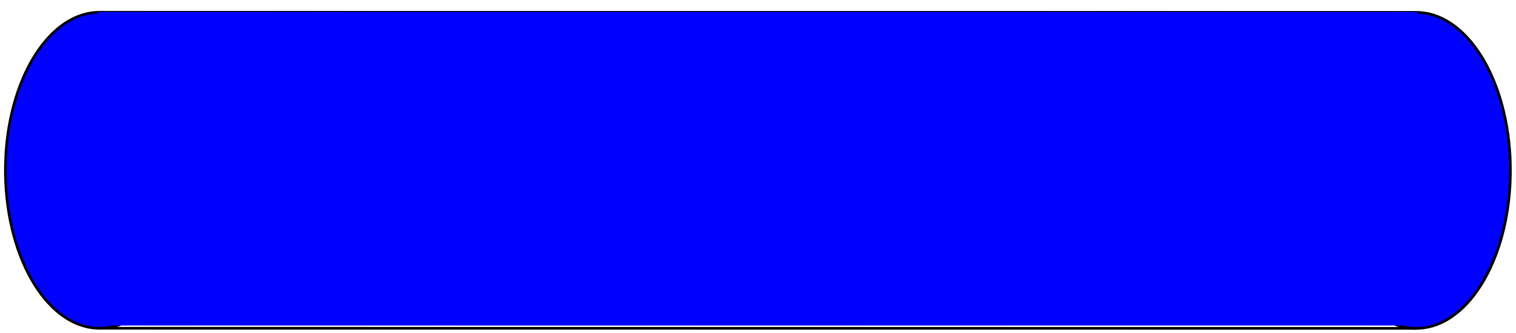
Kind of like water in a pipe…

- 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)



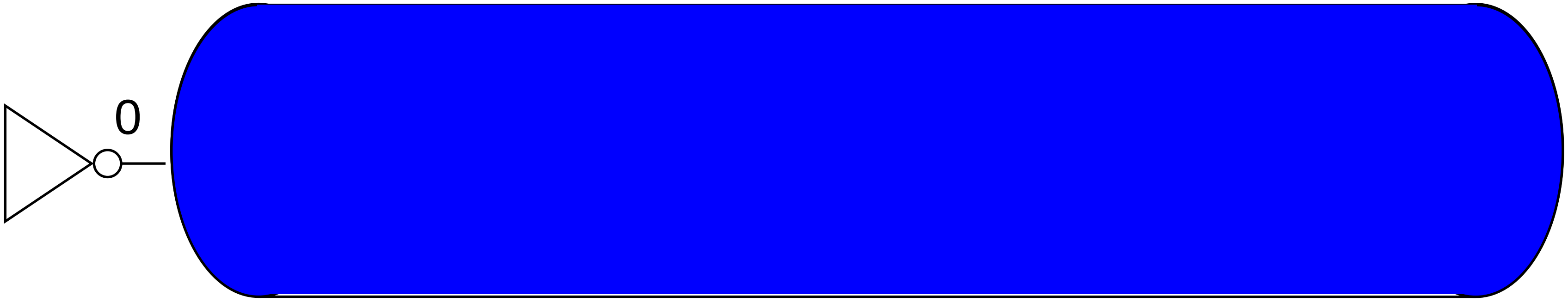
Kind of like water in a pipe…

- 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)



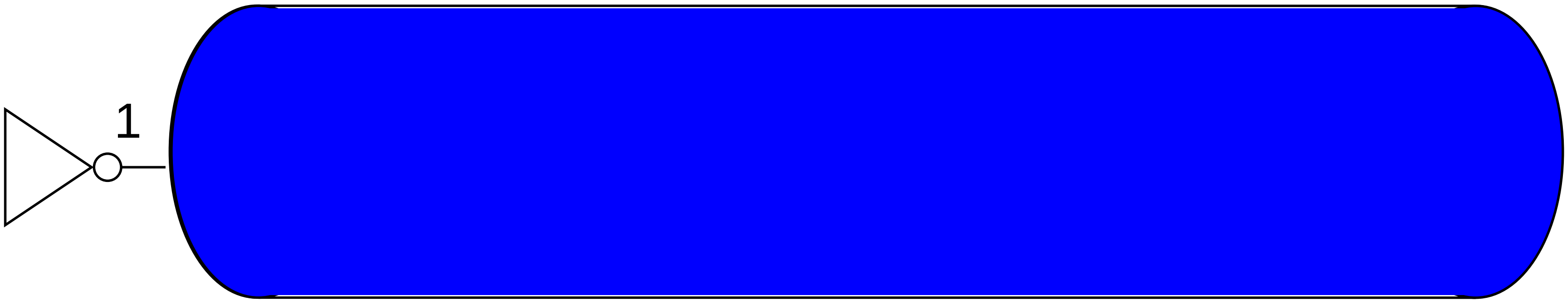
Kind of like water in a pipe…

- 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



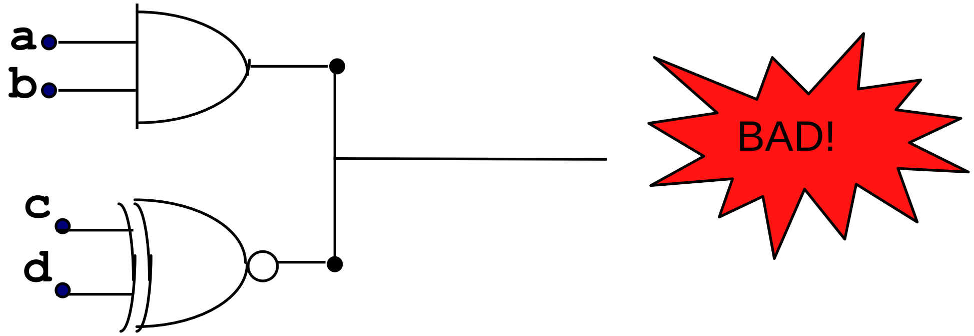
Kind of like water in a pipe…

- 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?

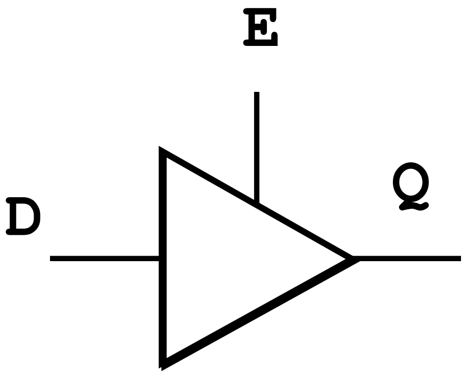


- If one gate tries to drive a 1 and the other drives a 0
  - One pumps water in.. The other sucks it out
  - Except it's electric charge, not water
  - "Short circuit" → lots of current → lots of heat

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

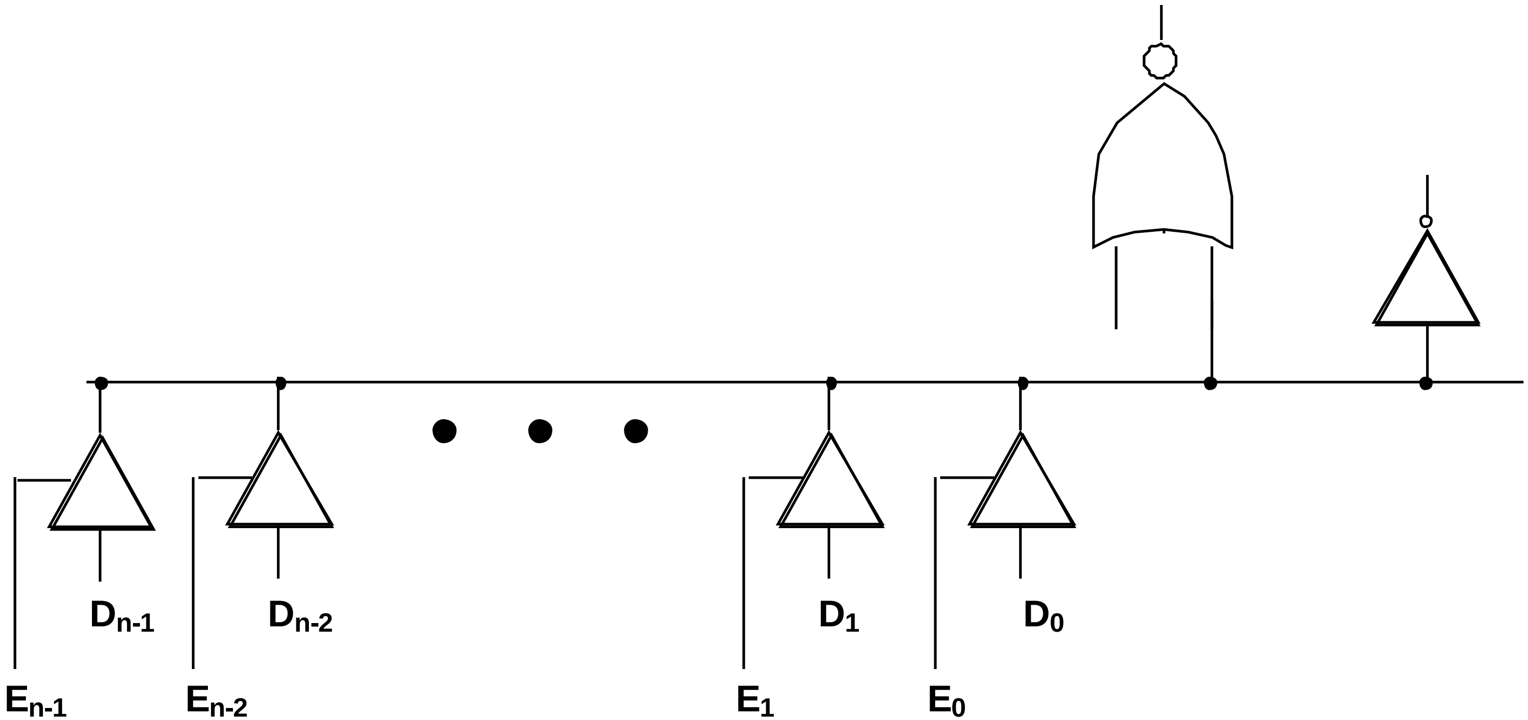


D	E	Q
0	1	0
1	1	1
-	0	Z

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

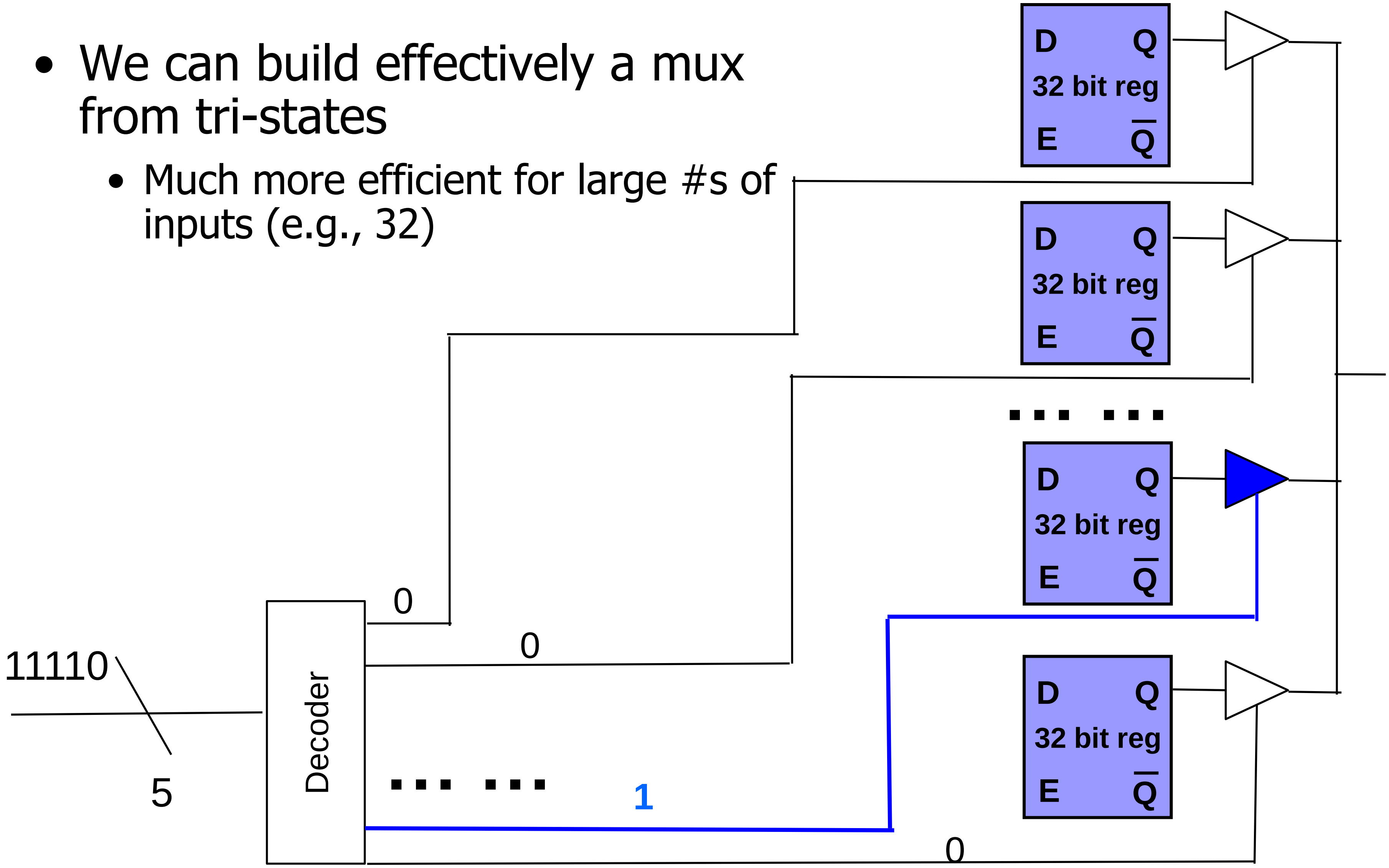
It's ok to connect multiple outputs together
Under one circumstance:

All but one must be outputting Z at any time



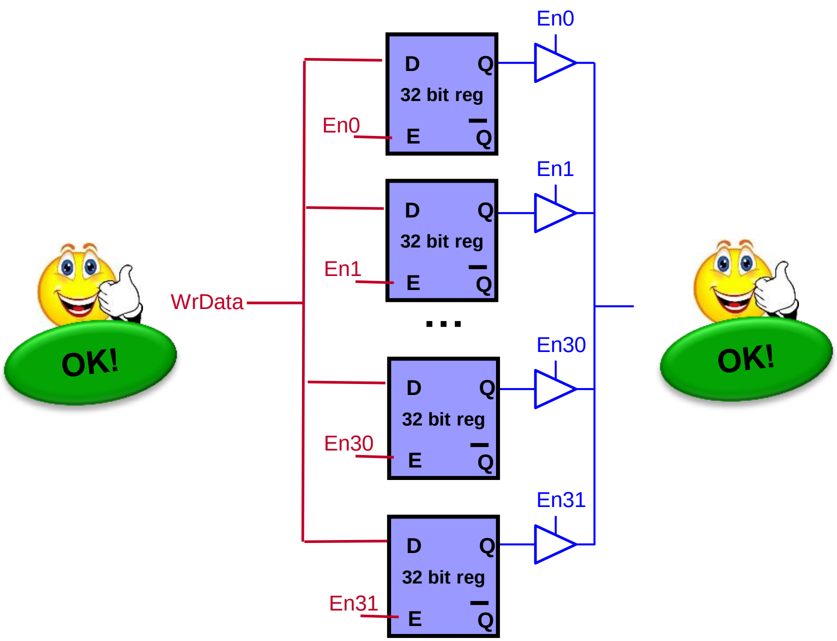
Mux, implemented with tri-states

- 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: need muxes to pick wr values

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!