State & Finite State Machines

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CS 3410, Spring 2012
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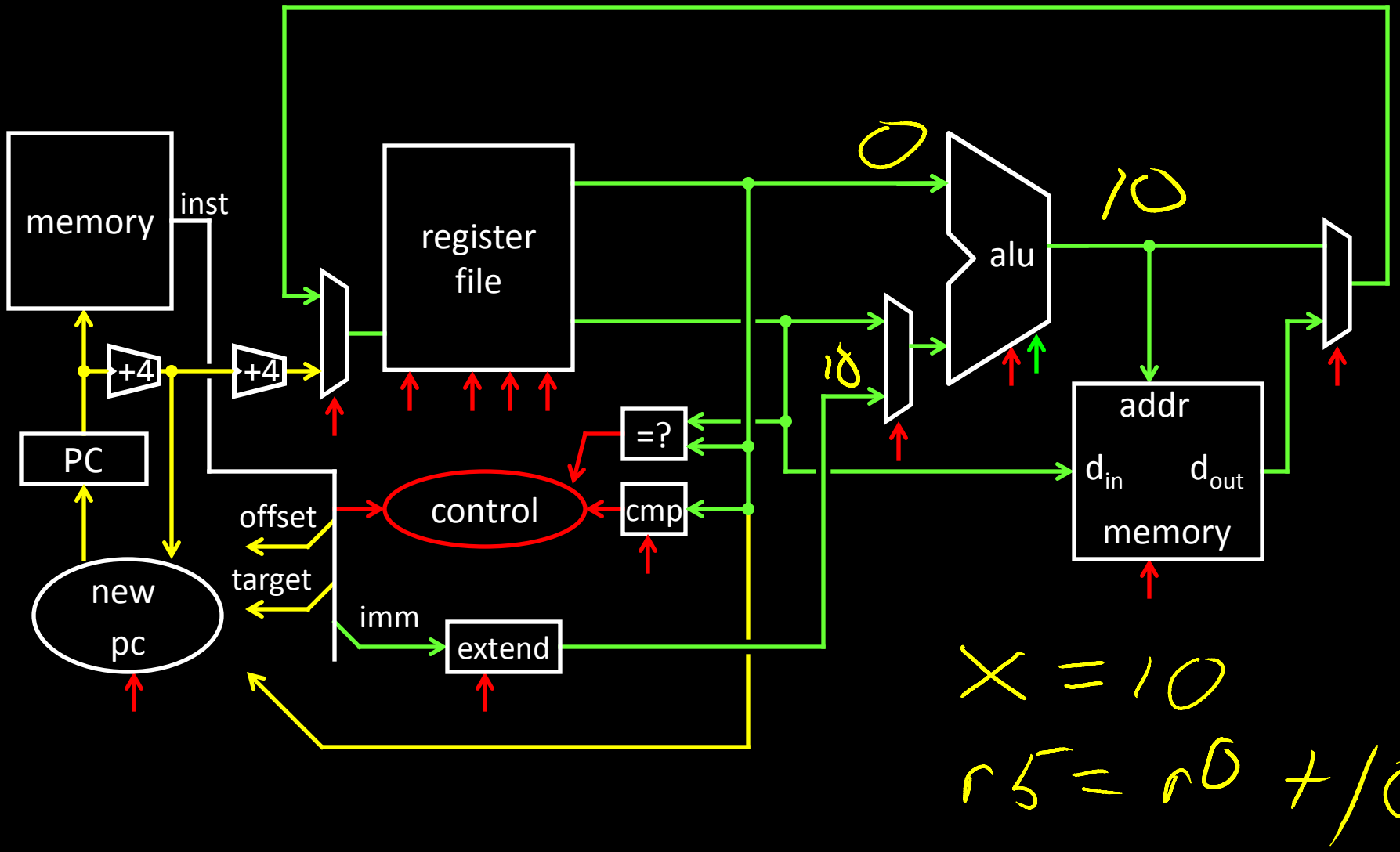
See P&H Appendix C.7. C.8, C.10, C.11

Big Picture: Building a Processor

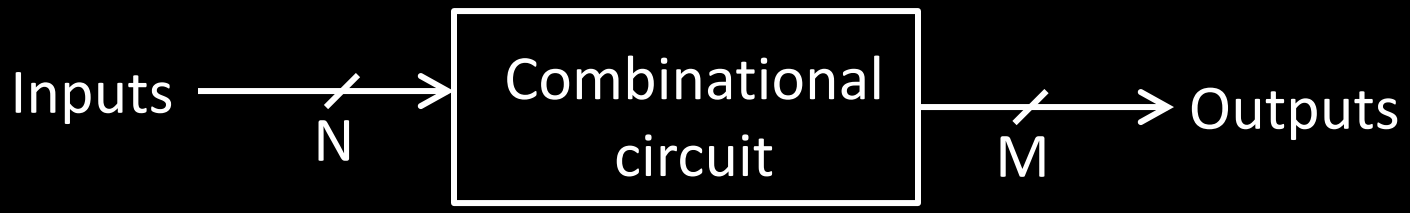


A Single cycle processor

Stateful Components

Until now is combinatorial logic

- Output is computed when inputs are present
- System has no internal state
- Nothing computed in the present can depend on what happened in the past!



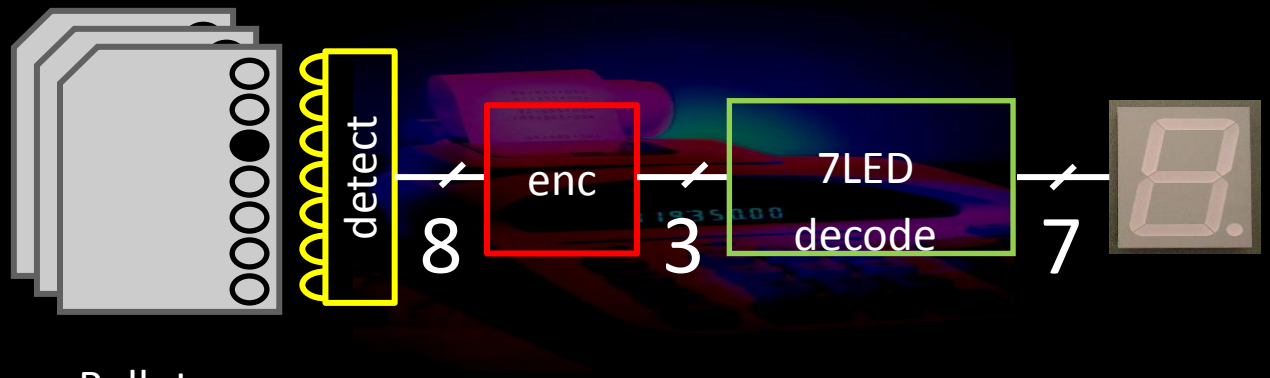
Need a way to record data

Need a way to build stateful circuits

Need a state-holding device

Finite State Machines

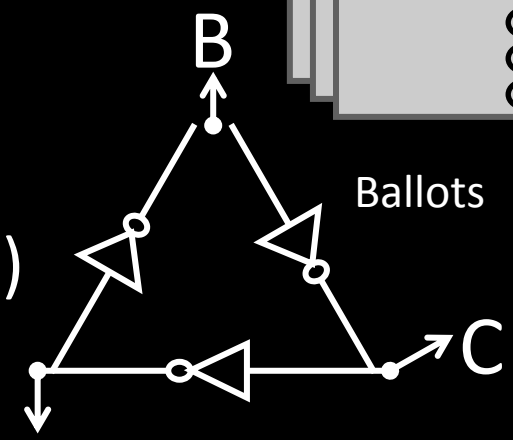
How can we store ***and*** change values?



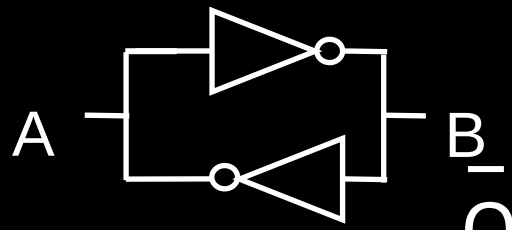
Ballots

How do we create vote counter machine

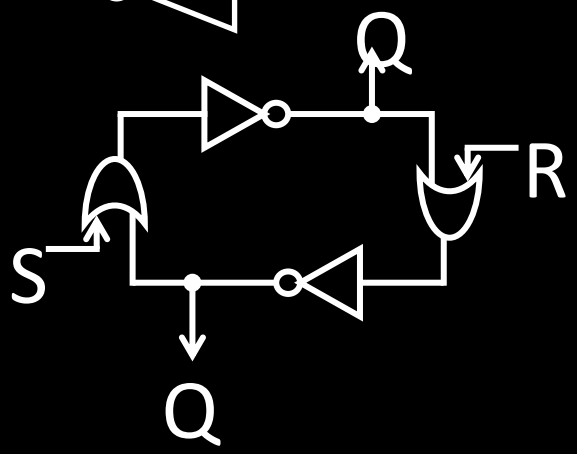
(a)



(b)



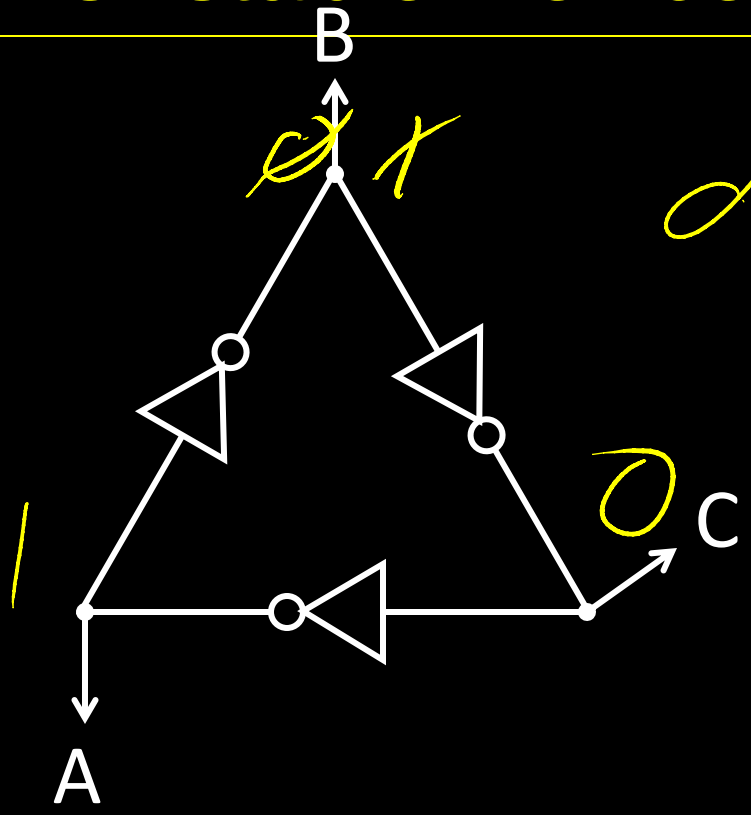
(c)



(d) All the above

(e) None

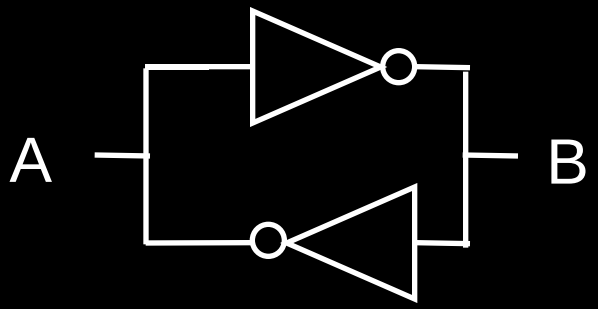
Unstable Devices



doesn't work

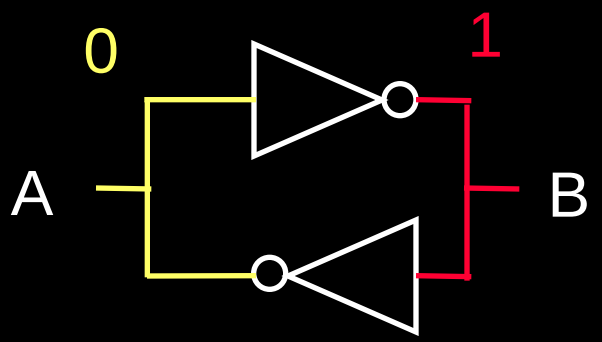
Bistable Devices

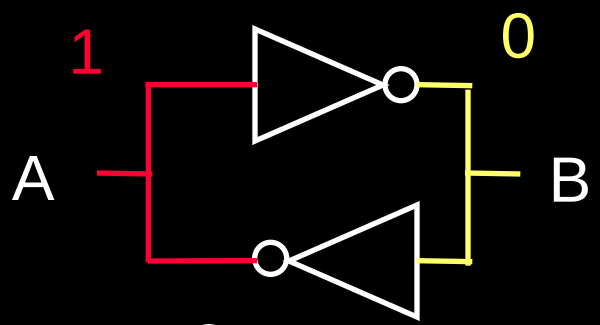
- Stable and unstable equilibria?



A Simple Device

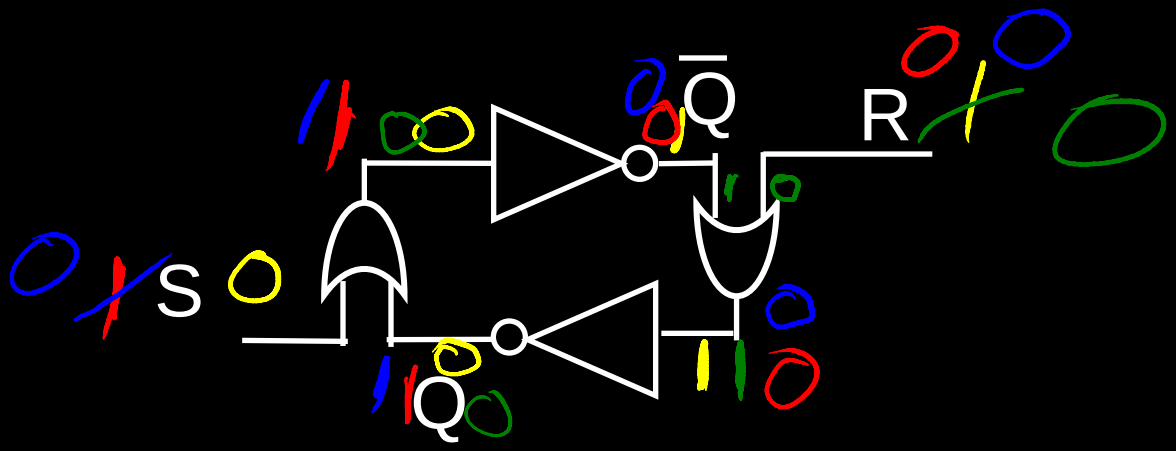
  - In stable state, $A = \bar{B}$





  - How do we change the state?

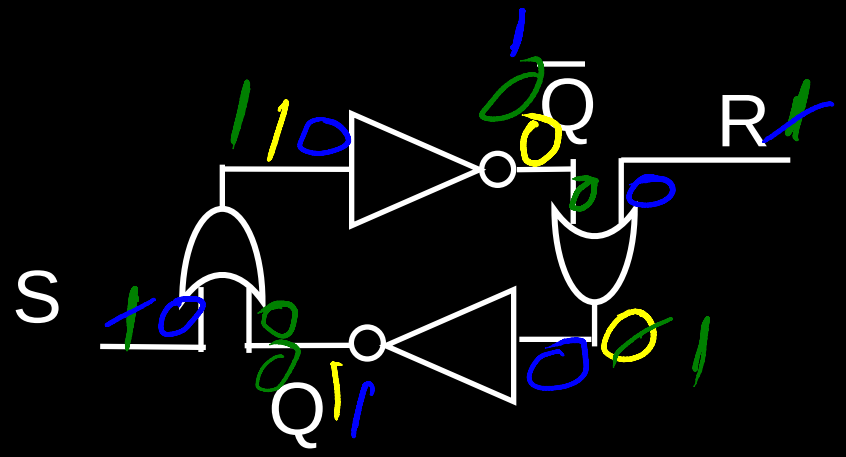
SR Latch



S	R	Q	$\overline{Q}$
0	0	Q	$\overline{Q}$
0	1	0	1
1	0	1	0
1	1		

- Set-Reset (S-R) Latch
- Stores a value Q and its complement

SR Latch

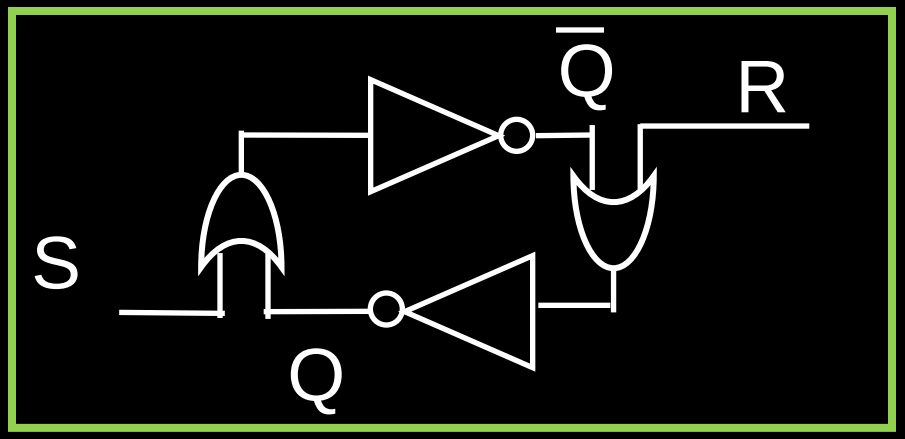


S	R	Q	$\overline{Q}$
0	0	Q	$\overline{Q}$
0	1	0	1
1	0	1	0
1	1	forbidden	

- Set-Reset (S-R) Latch
- Stores a value Q and its complement

- S=1 and R=1 ?

SR Latch

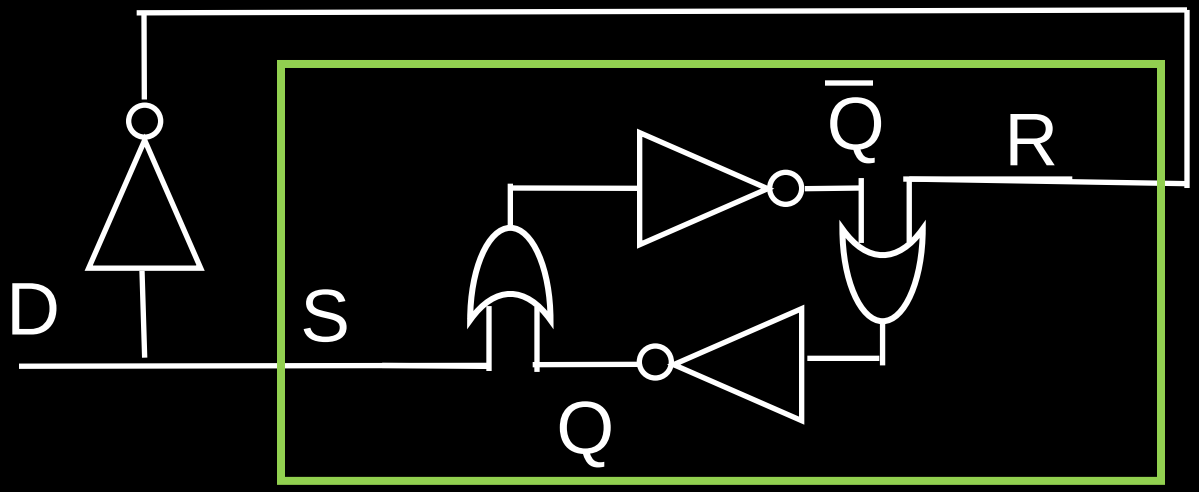


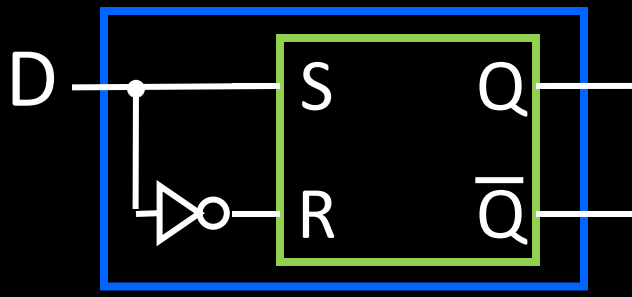
S	R	Q	$\overline{Q}$
0	0	Q	$\overline{Q}$
0	1	0	1
1	0	1	0
1	1	?	?

- Set-Reset (S-R) Latch
- Stores a value Q and its complement

- S=1 and R=1 ?

(Unclocked) D Latch

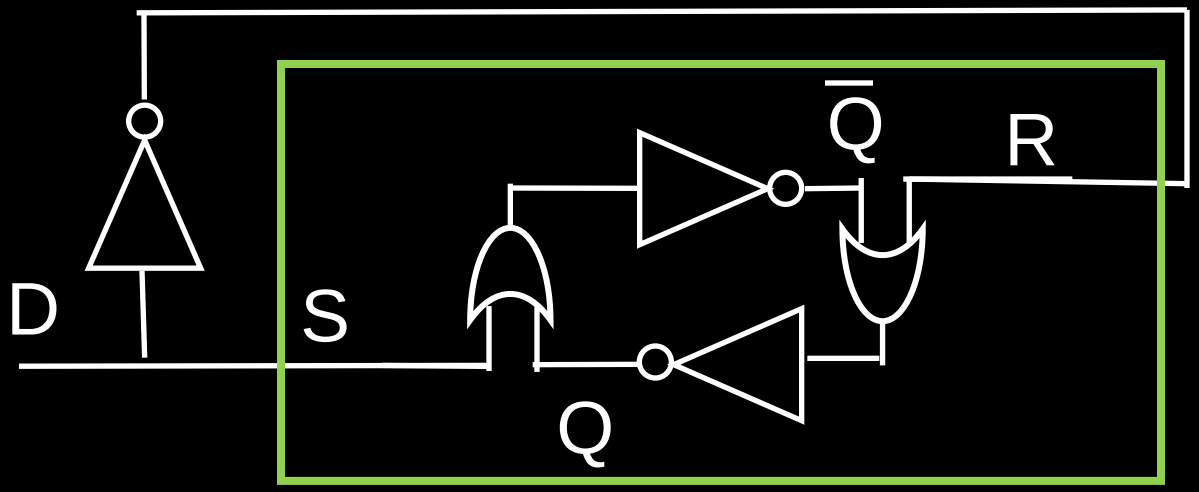


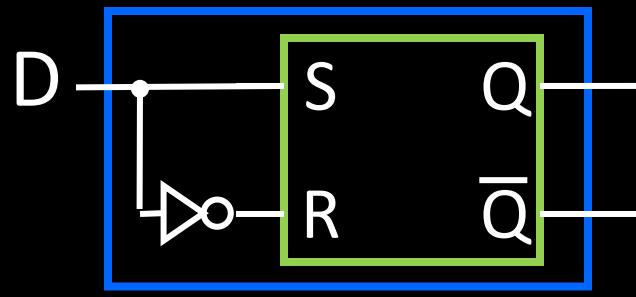


D	Q	$\overline{Q}$
0	0	1
1	1	0

- Data (D) Latch
  - Easier to use than an SR latch
  - No possibility of entering an undefined state
- When D changes, Q changes
  - … immediately (…after a delay of 2 Ors and 2 NOTs)
- Need to control when the output changes

(Unclocked) D Latch



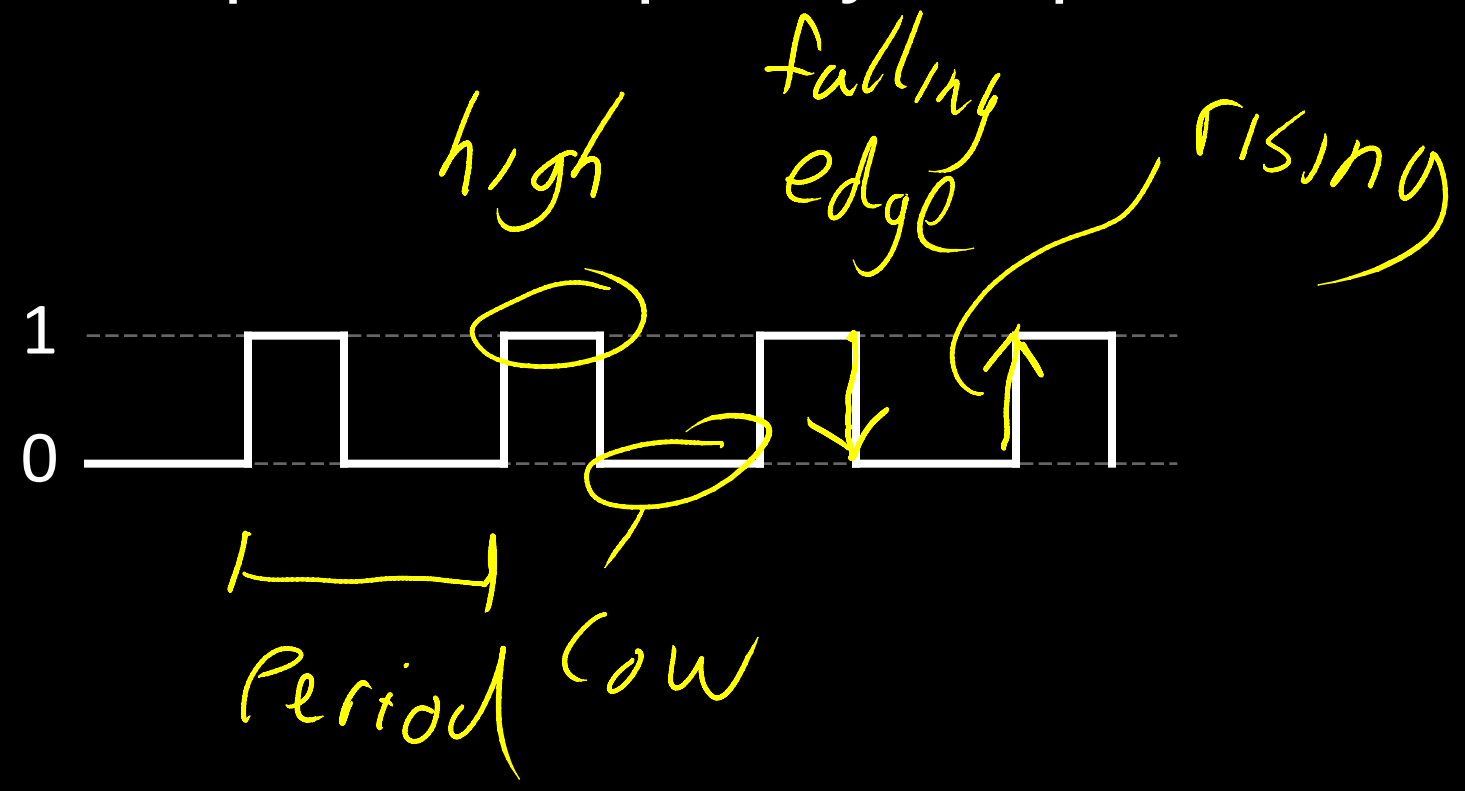


D	Q	$\overline{Q}$
0	0	1
1	1	0

- Data (D) Latch
  - Easier to use than an SR latch
  - No possibility of entering an undefined state
- When D changes, Q changes
  - … immediately (…after a delay of 2 Ors and 2 NOTs)
- Need to control when the output changes

Clocks

- Clock helps coordinate state changes
  - Usually generated by an oscillating crystal
  - Fixed period; frequency = 1/period



Edge-triggering

- Can design circuits to change on the rising or falling edge
- Trigger on rising edge = positive edge-triggered

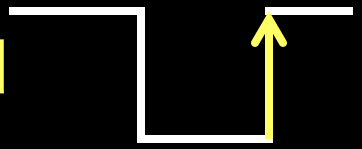
- Trigger on falling edge = negative edge-triggered

- Inputs must be stable just before the triggering edge

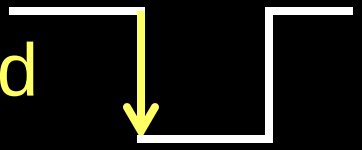
Clock Disciplines

- Level sensitive
  - State changes when clock is high (or low)
- Edge triggered
  - State changes at clock edge

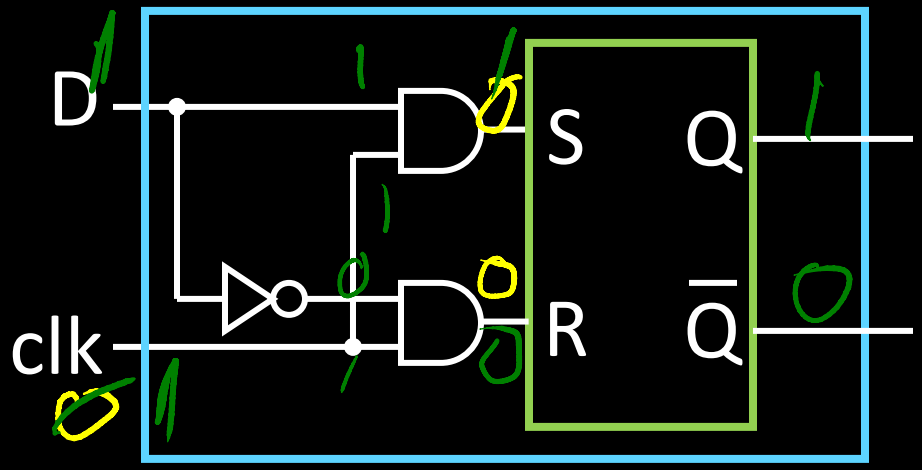
positive edge-triggered



negative edge-triggered



D Latch with Clock

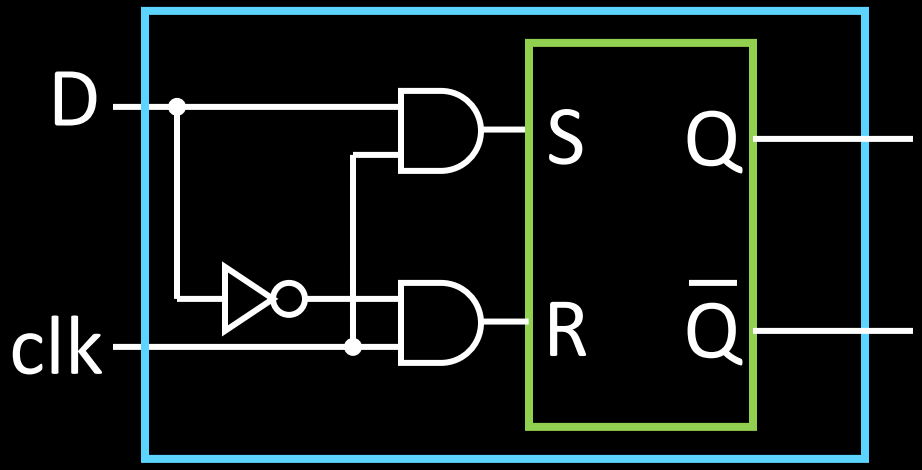


S	R	Q	$\overline{Q}$
0	0	Q	$\overline{Q}$
0	1	0	1
1	0	1	0
1	1	forbidden	

clk	D	Q	$\overline{Q}$
0	0	Q	$\overline{Q}$
0	1	Q	$\overline{Q}$
1	0	0	1
1	1	1	0

only time can set stored value to D

D Latch with Clock



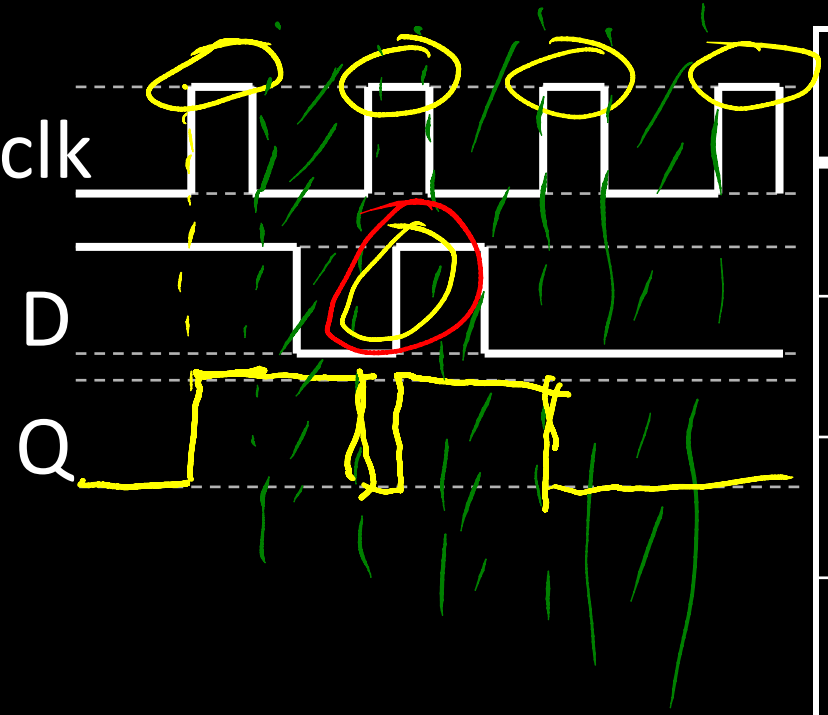
Level Sensitive D Latch

Clock high:

set/reset (according to D)

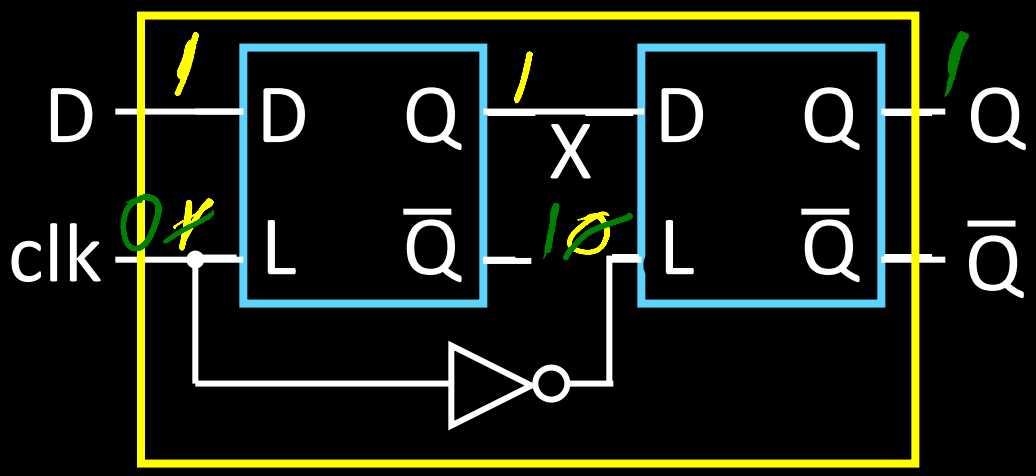
Clock low:

keep state (ignore D)



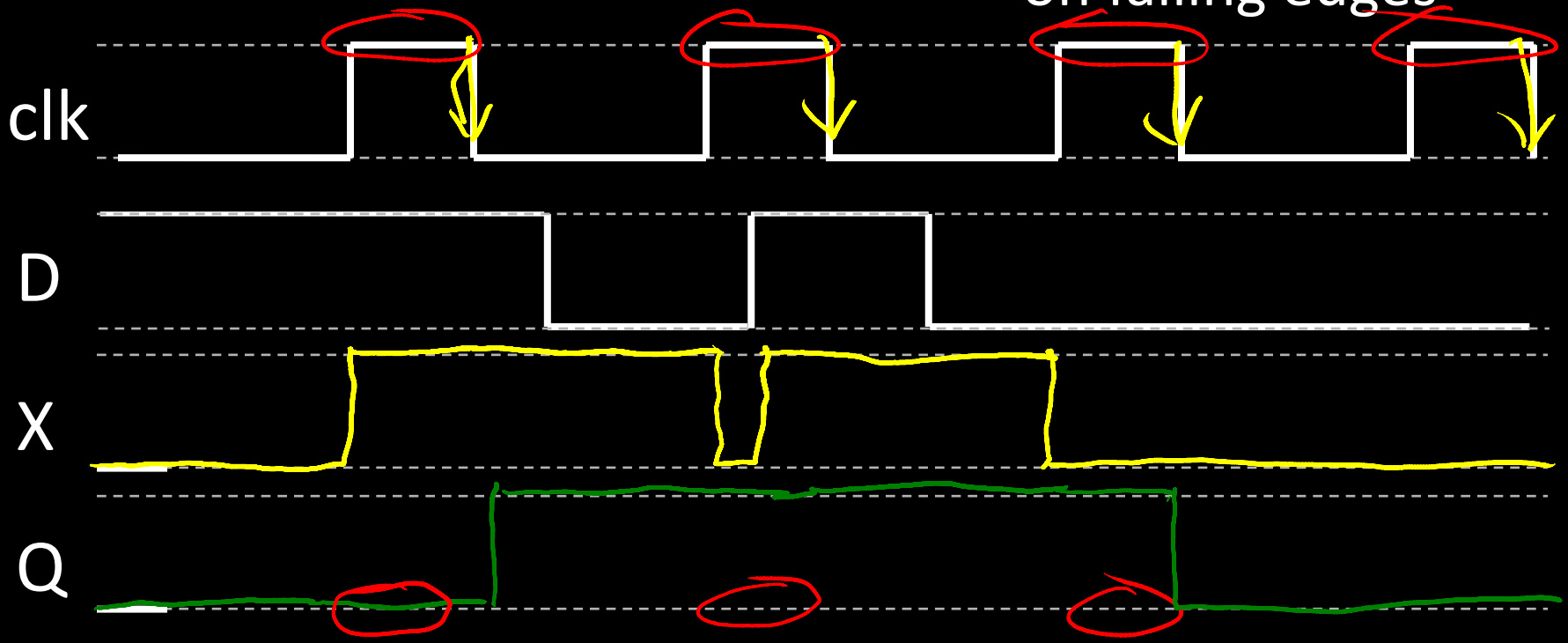
clk	D	Q	$\overline{Q}$
0	0	Q	$\overline{Q}$
0	1	Q	$\overline{Q}$
1	0	0	1
1	1	1	0

Edge-Triggered D Flip-Flop

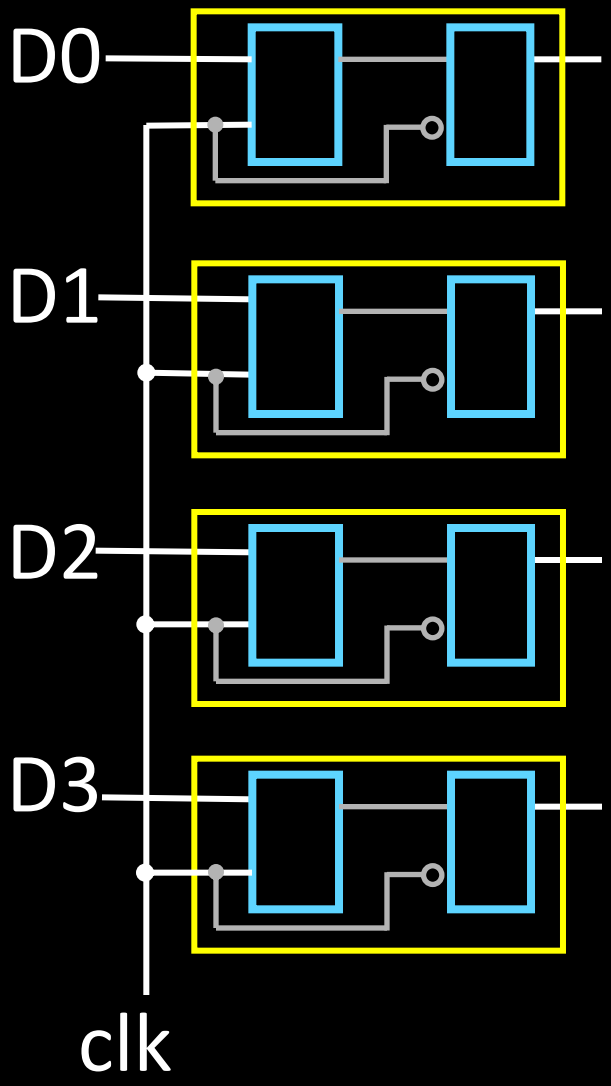


D Flip-Flop

- Edge-Triggered
- Data is captured when clock is high
- Outputs change only on falling edges

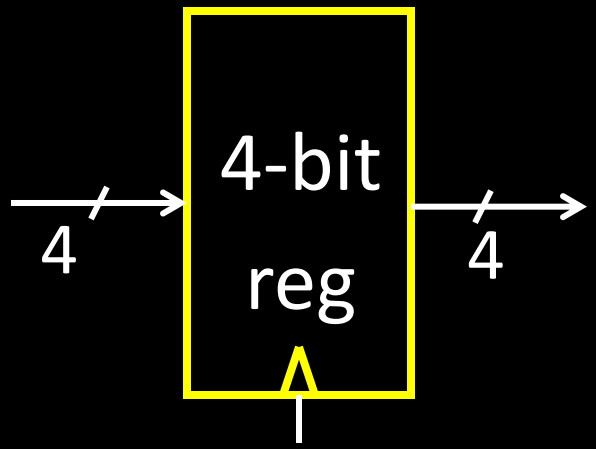


Registers



Register

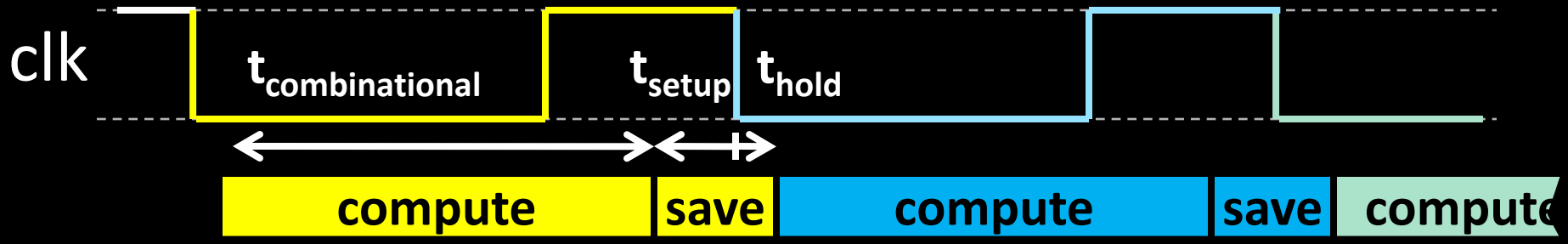
- D flip-flops in parallel
- shared clock
- extra clocked inputs: write_enable, reset, …



Clock Methodology

Clock Methodology

- Negative edge, synchronous



  - Signals must be stable near falling clock edge

- Positive edge synchronous
- Asynchronous, multiple clocks, . . .

Metastability and Asynchronous Inputs

Q: What happens if *select* input changes near clock edge?

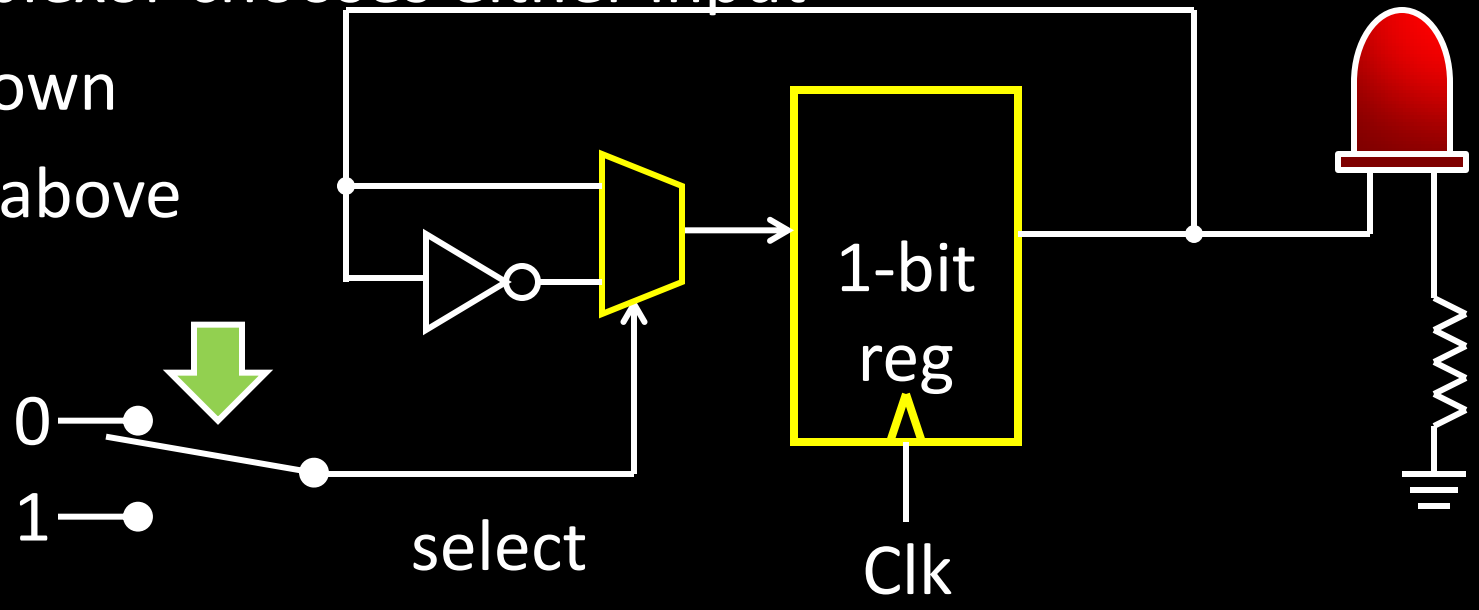
A) Multiplexor selects input 0

B) Multiplexor selects input 1

C) Multiplexor chooses either input

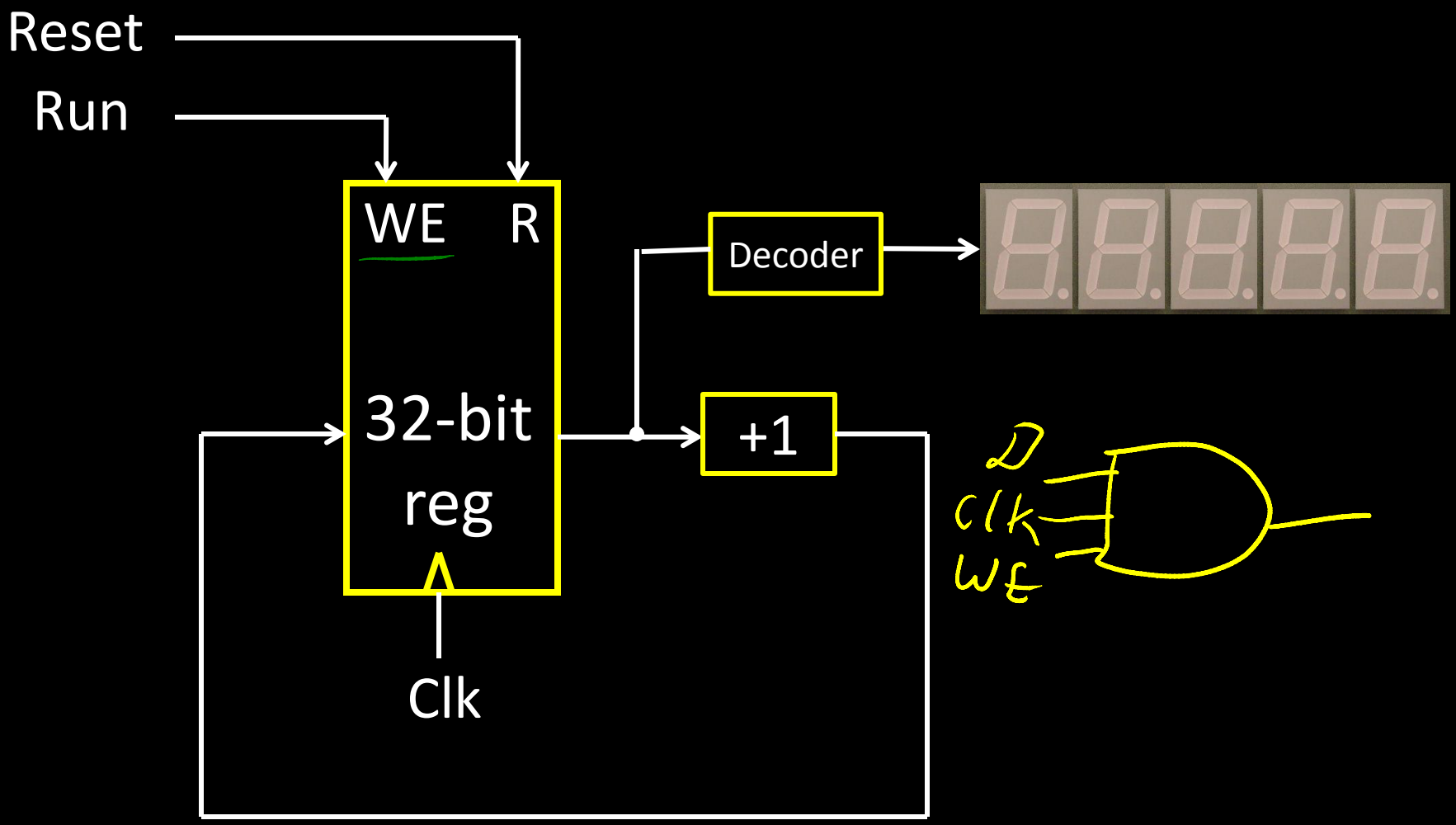
D) Unknown

E) None above



A: Google “Buridan’s Principle” by Leslie Lamport

An Example: What will this circuit do?



Recap

We can now build interesting devices with sensors

- Using combinatorial logic

We can also store data values

- In state-holding elements
- Coupled with clocks

Administrivia

Make sure partner in same Lab Section ***this week***

Lab2 is out

Due in one week, next Monday, start early

Work alone

But, use your resources

- Lab Section, Piazza.com, Office Hours, Homework Help Session,
- Class notes, book, Sections, CSUGLab

No Homework this week

Administrivia

Check online syllabus/schedule

- http://www.cs.cornell.edu/Courses/CS3410/2012sp/schedule.html

Slides and Reading for lectures

Office Hours

Homework and Programming Assignments

Prelims (in evenings):

- Tuesday, February 28th
- Thursday, March 29th
- Thursday, April 26th

Schedule is subject to change

Collaboration, Late, Re-grading Policies

"Black Board" Collaboration Policy

- Can discuss approach together on a "black board"
- Leave and write up solution independently
- Do not copy solutions

Late Policy

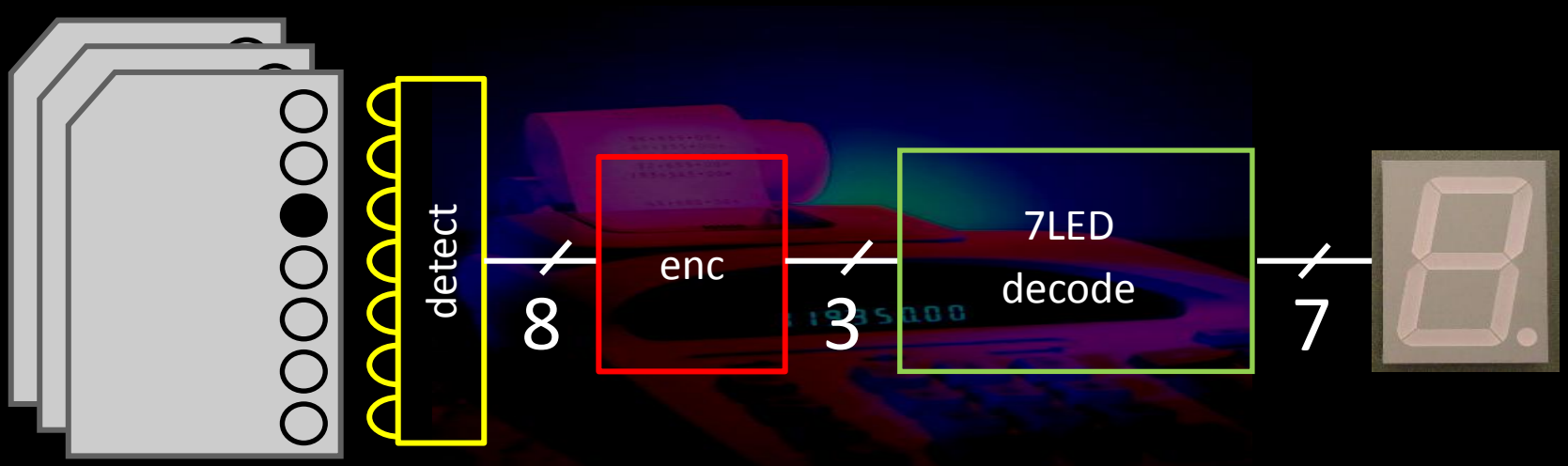
- Each person has a total of ***four*** "slip days"
- Max of ***two*** slip days for any individual assignment
- Slip days deducted first for *any* late assignment, cannot selectively apply slip days
- For projects, slip days are deducted from all partners
- 20% deducted per day late after slip days are exhausted

Regrade policy

- Submit written request to lead TA, and lead TA will pick a different grader
- Submit another written request, lead TA will regrade directly
- Submit yet another written request for professor to regrade.

Finite State Machines

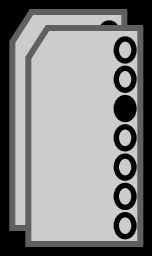
Revisit Voting Machine



Ballots

How do we create a vote counter machine

Revisit Voting Machine



Finite State Machines

An electronic machine which has

- external inputs
- externally visible outputs
- internal state

Output and next state depend on

- inputs
- current state

Abstract Model of FSM

Machine is

$$M = (\ S,\ I,\ O,\ \delta\ )$$

S: Finite set of states

I: Finite set of inputs

O: Finite set of outputs

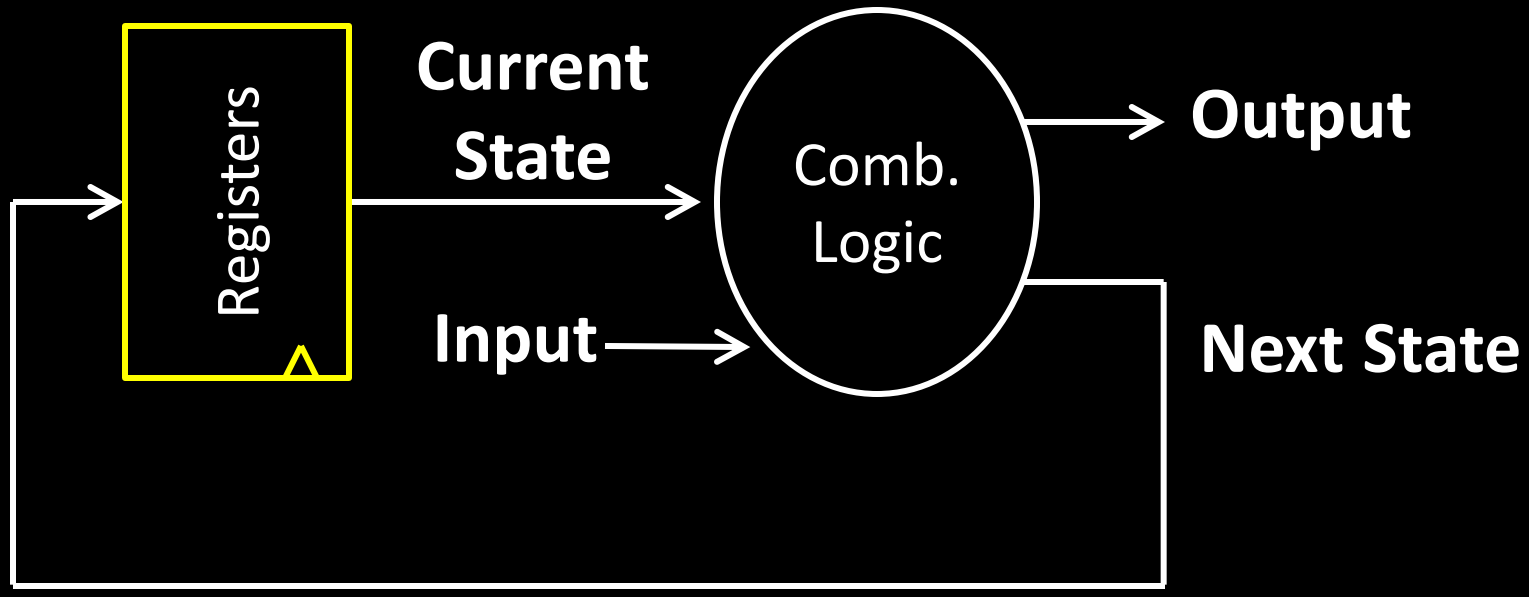
δ: State transition function

Next state depends on present input *and* present state

Revisit Voting Machine

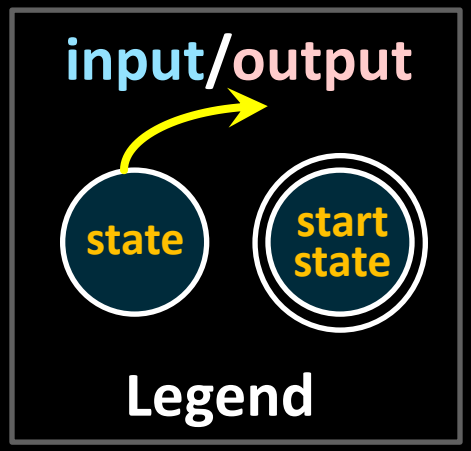
Automata Model

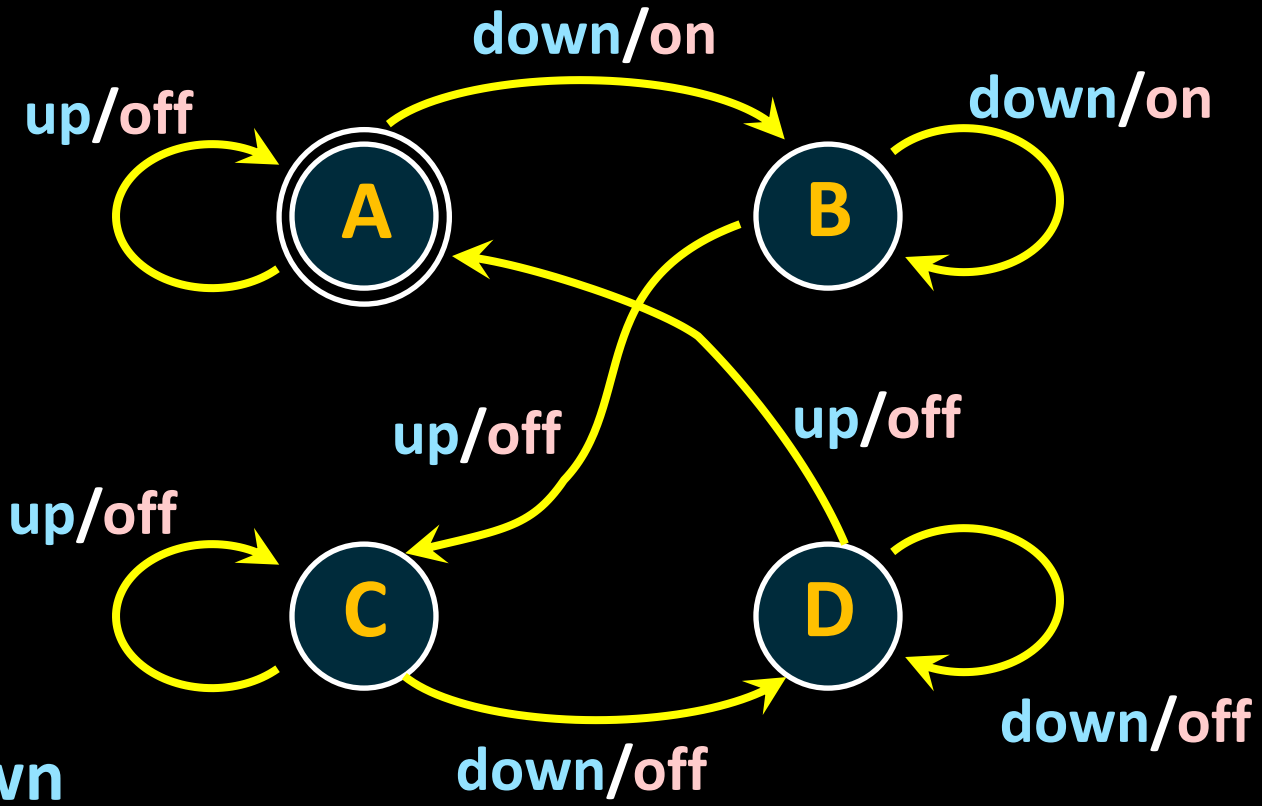
Finite State Machine



- inputs from external world
- outputs to external world
- internal state
- combinational logic

FSM Example



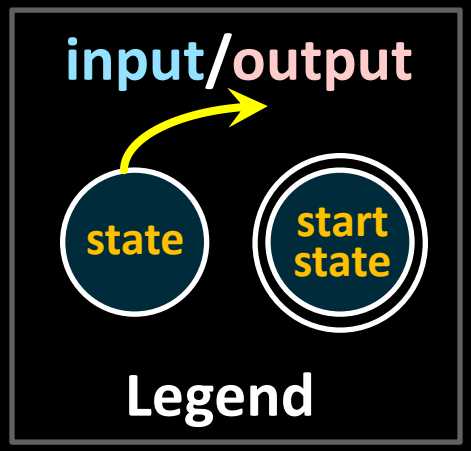


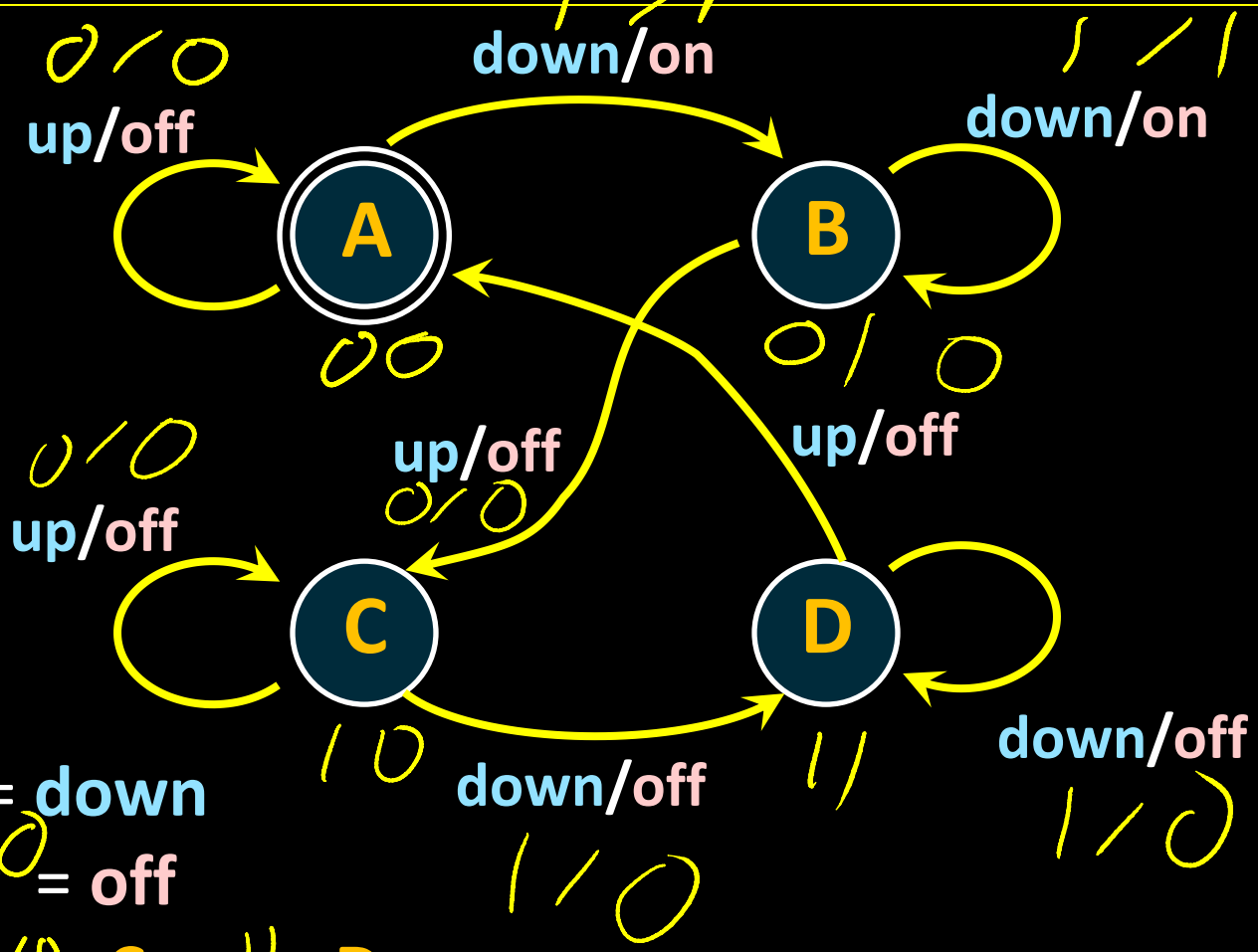
Input: **up** or **down**

Output: **on** or **off**

States: **A**, **B**, **C**, or **D**

FSM Example



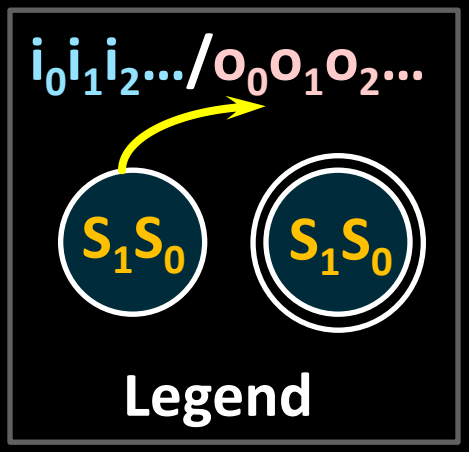


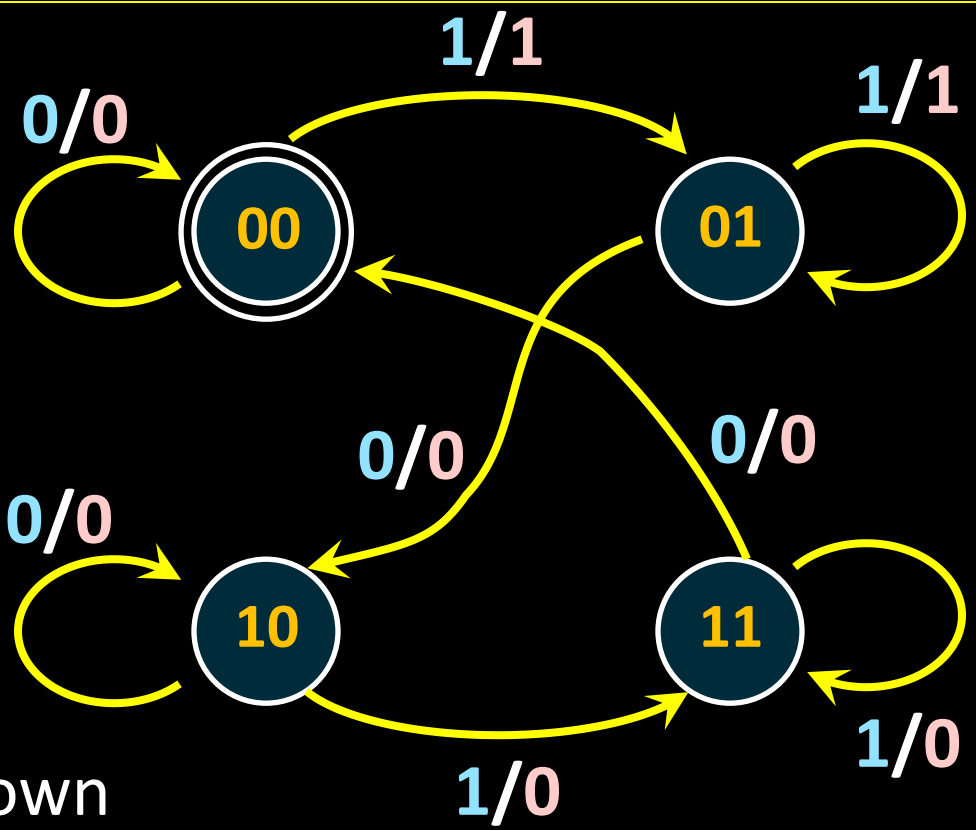
Input: 0 = up or 1 = down

Output: 1 = on or 0 = off

States: 00 = A, 01 = B, 10 = C, or 11 = D

FSM Example





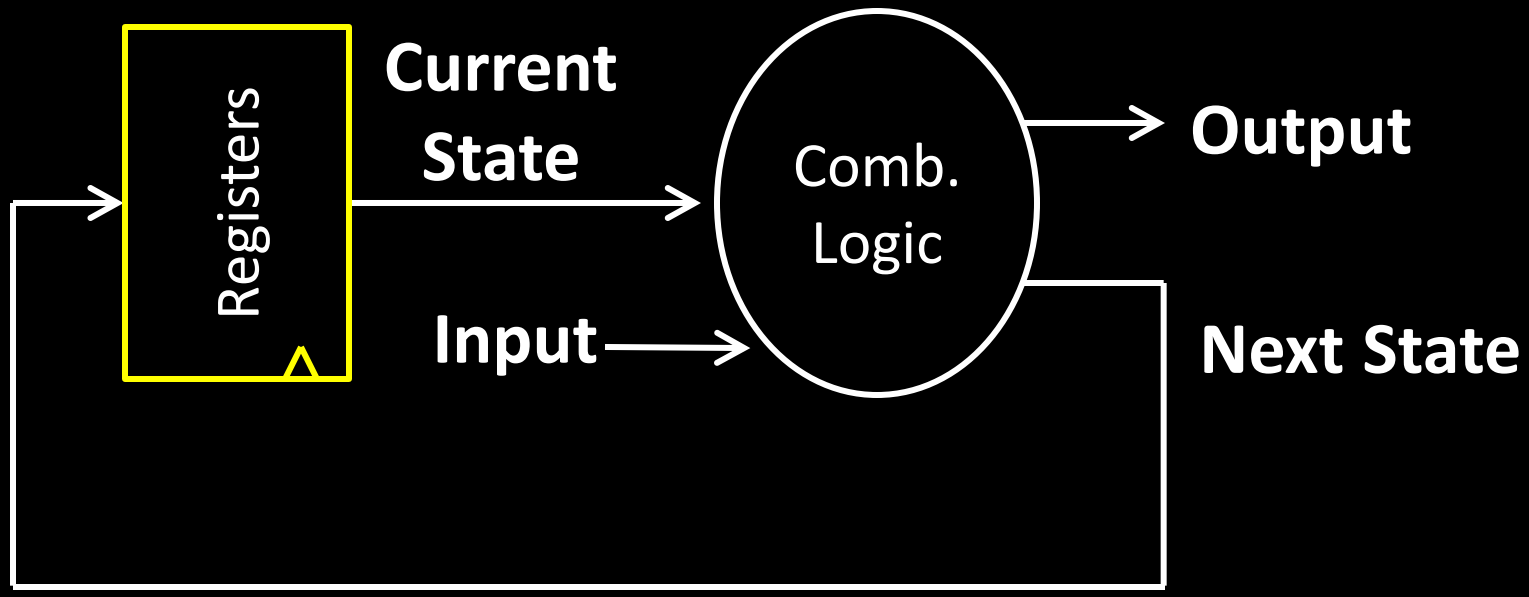
Input: **0**=up or **1**=down

Output: **1**=on or **1**=off

States: **00**=A, **01**=B, **10**=C, or **11**=D

Mealy Machine

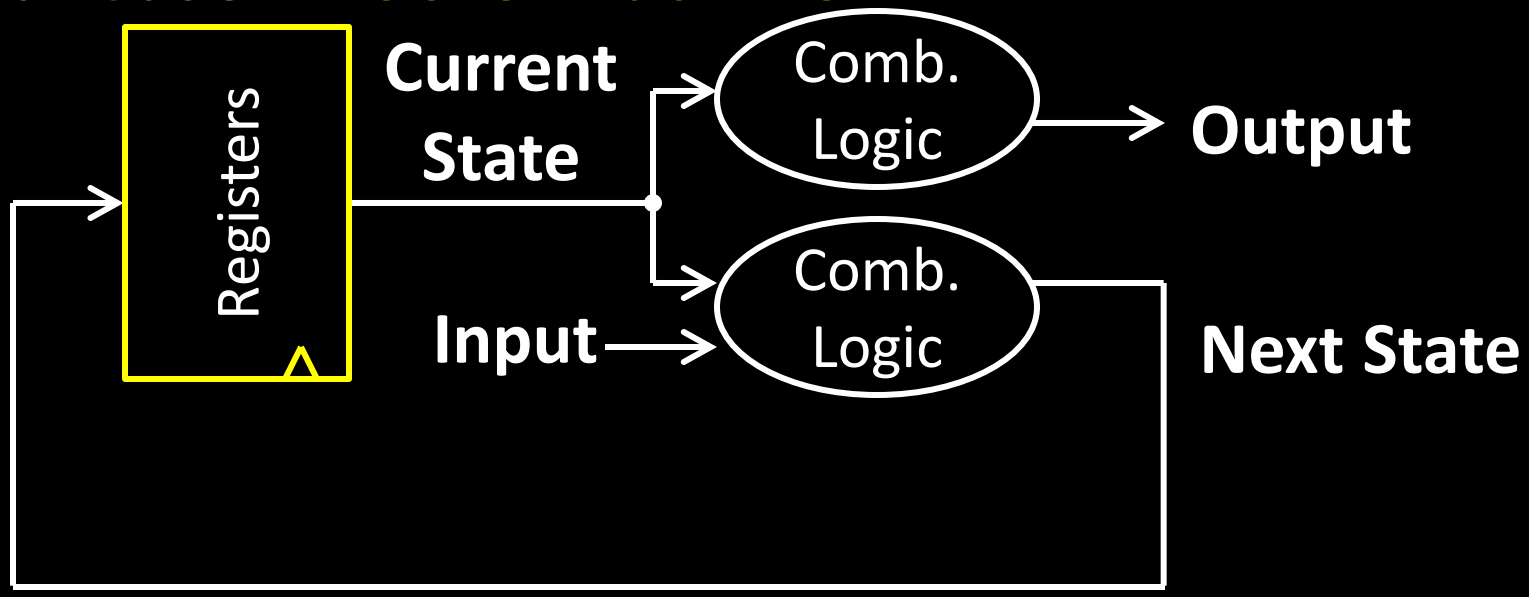
General Case: Mealy Machine



Outputs and next state depend on both current state and input

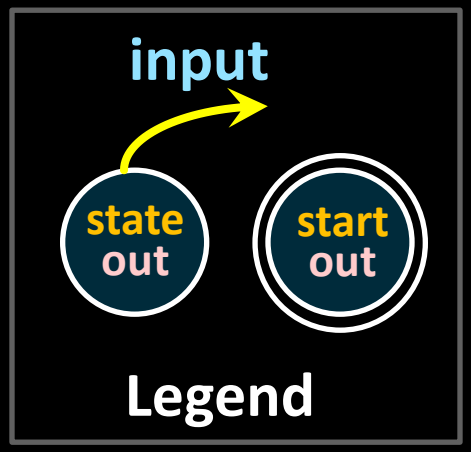
Moore Machine

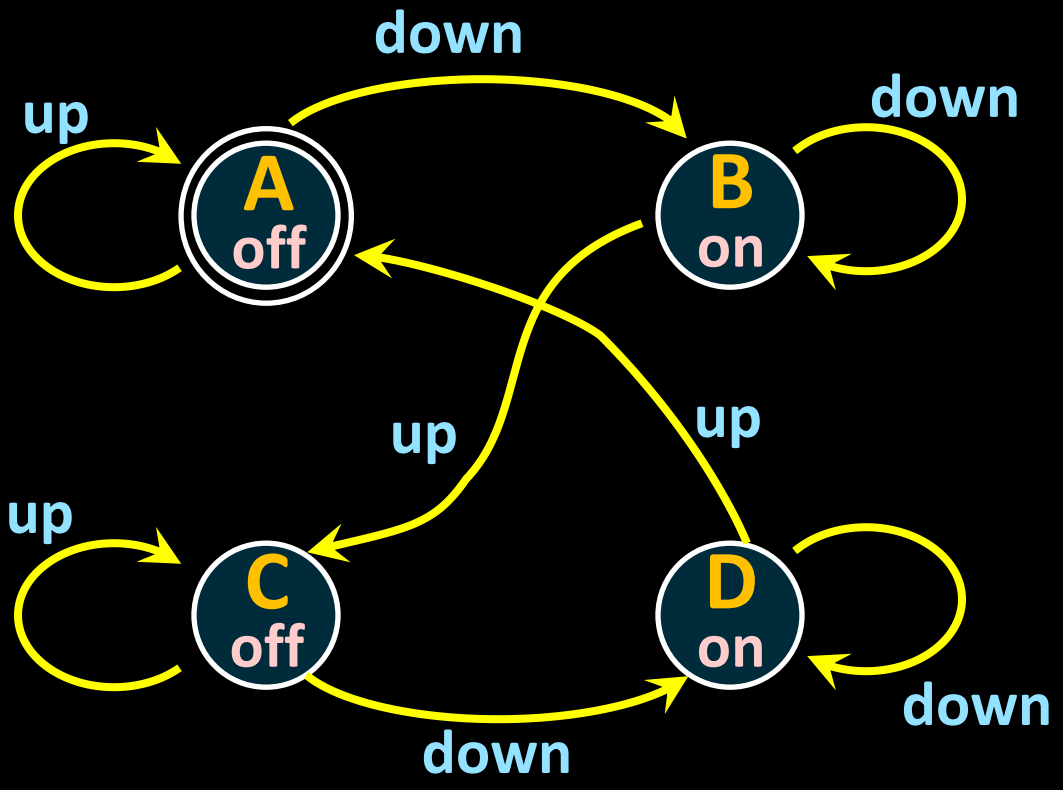
Special Case: Moore Machine



Outputs depend only on current state

Moore Machine Example





Input: **up** or **down**

Output: **on** or **off**

States: **A**, **B**, **C**, or **D**

Example: Digital Door Lock

Digital Door Lock

Inputs:

- keycodes from keypad
- clock

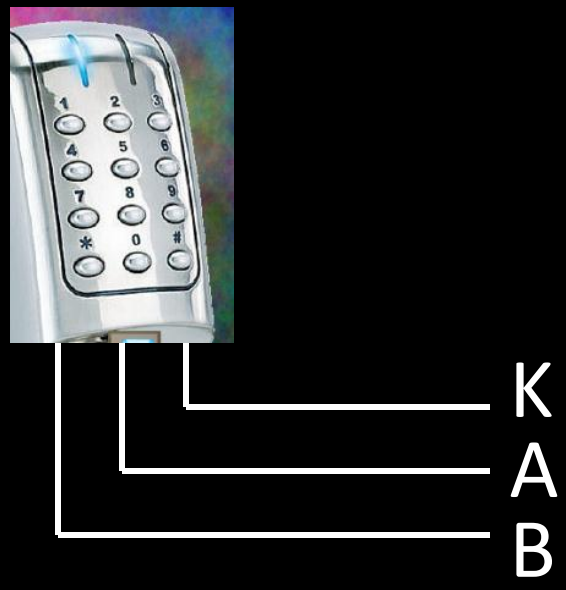
Outputs:

- “unlock” signal
- display how many keys pressed so far

Door Lock: Inputs

Assumptions:

- signals are synchronized to clock
- Password is B-A-B

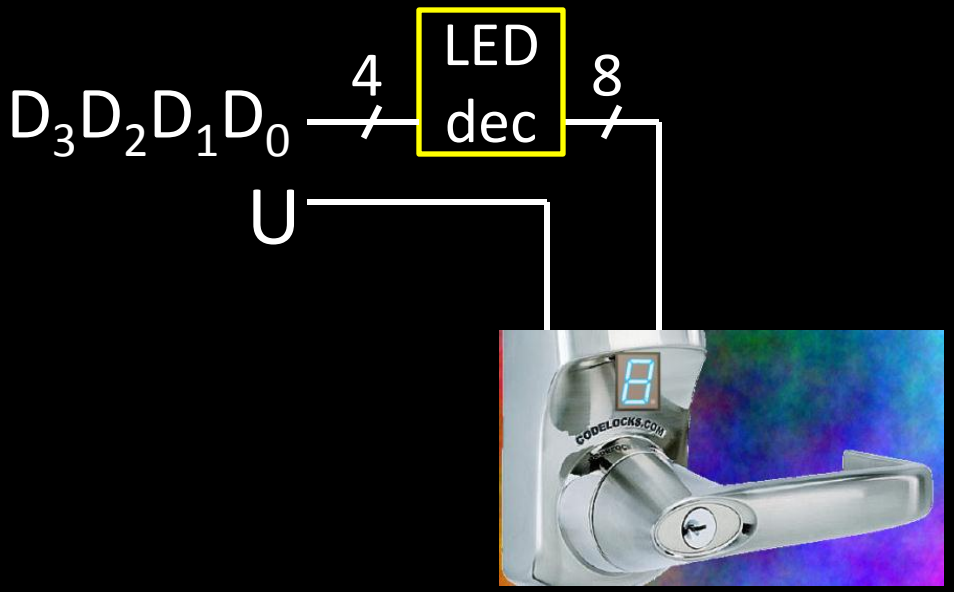


K	A	B	Meaning
0	0	0	Ø (no key)
1	1	0	‘A’ pressed
1	0	1	‘B’ pressed

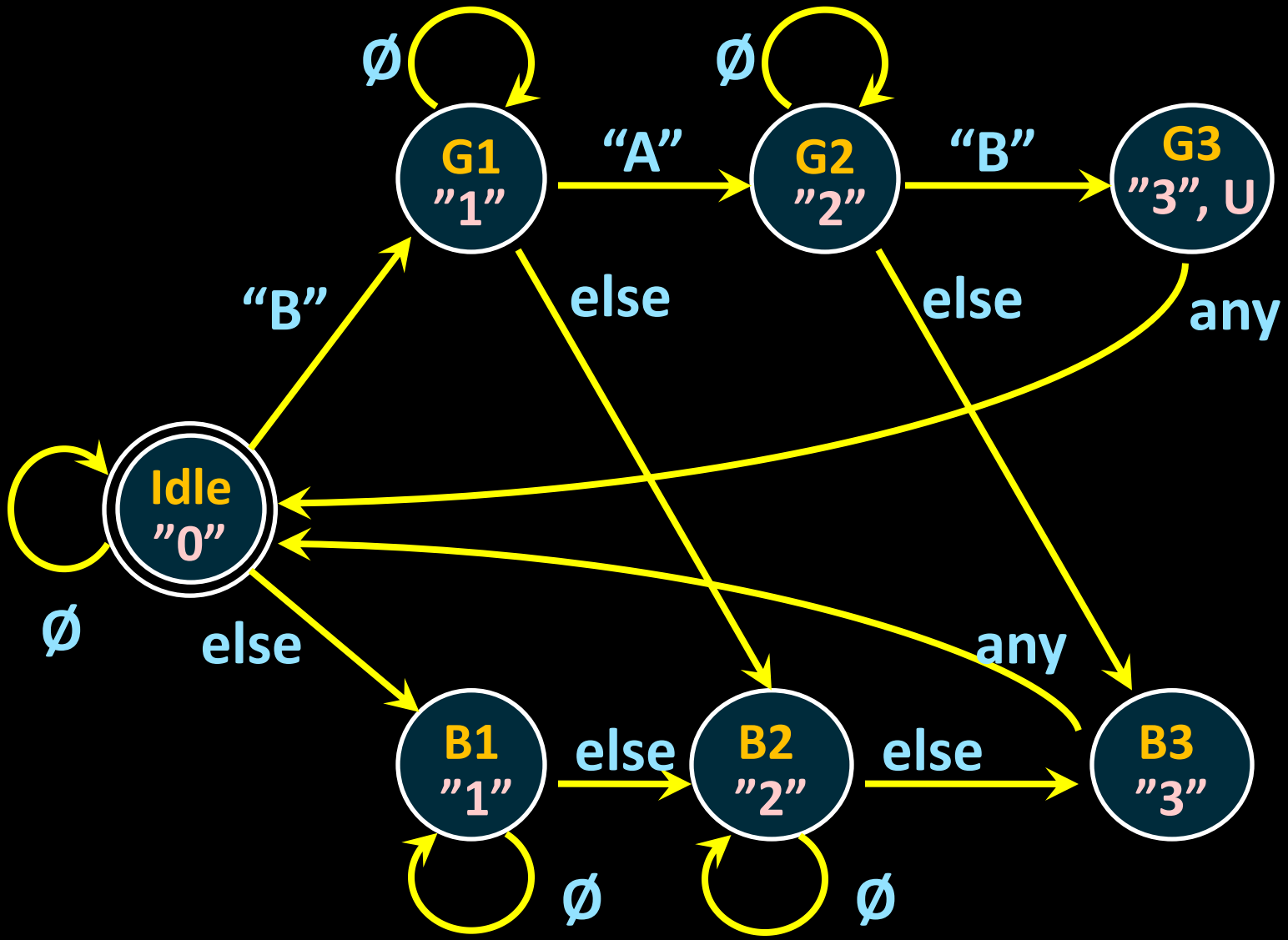
Door Lock: Outputs

Assumptions:

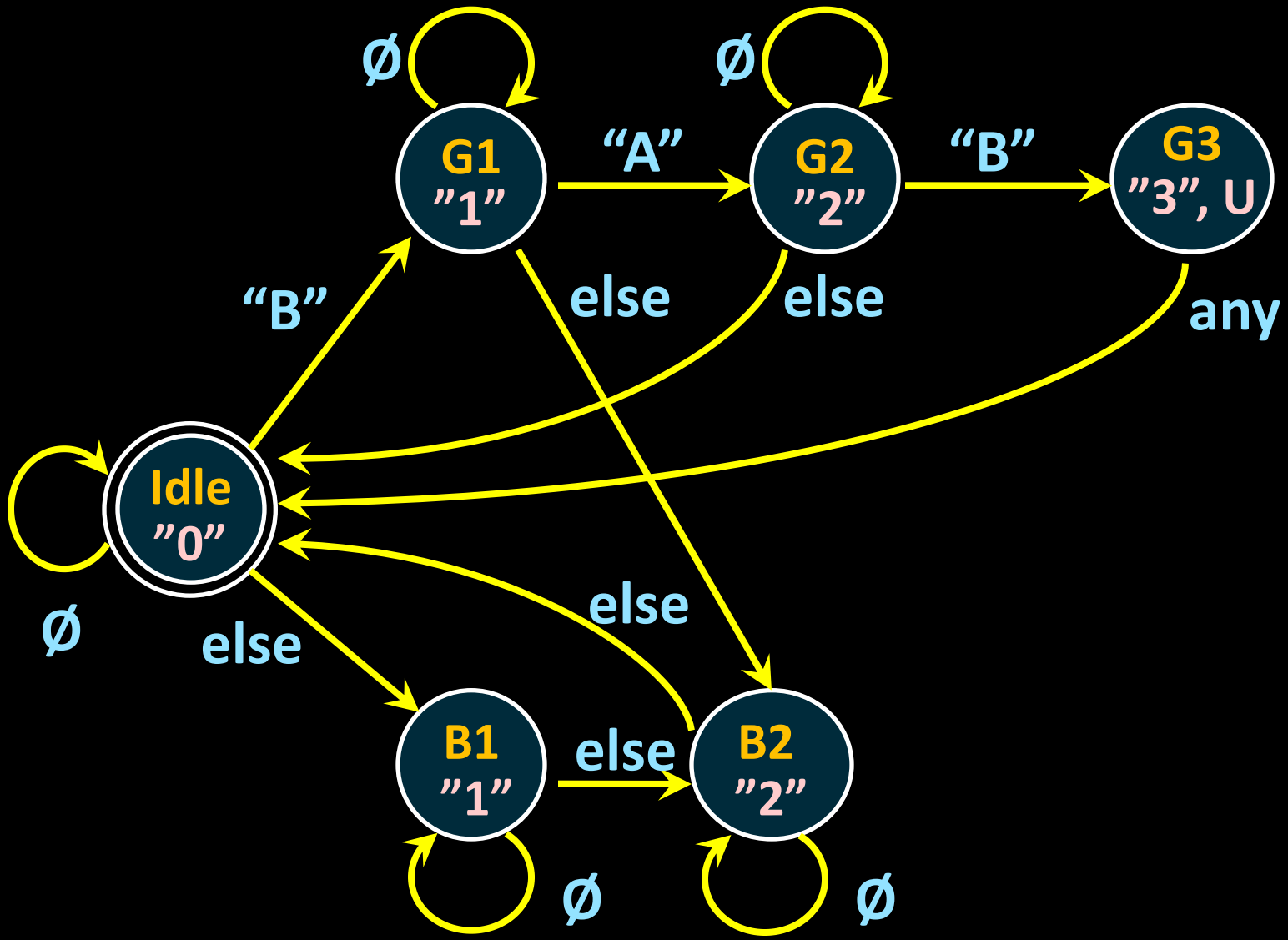
- High pulse on U unlocks door



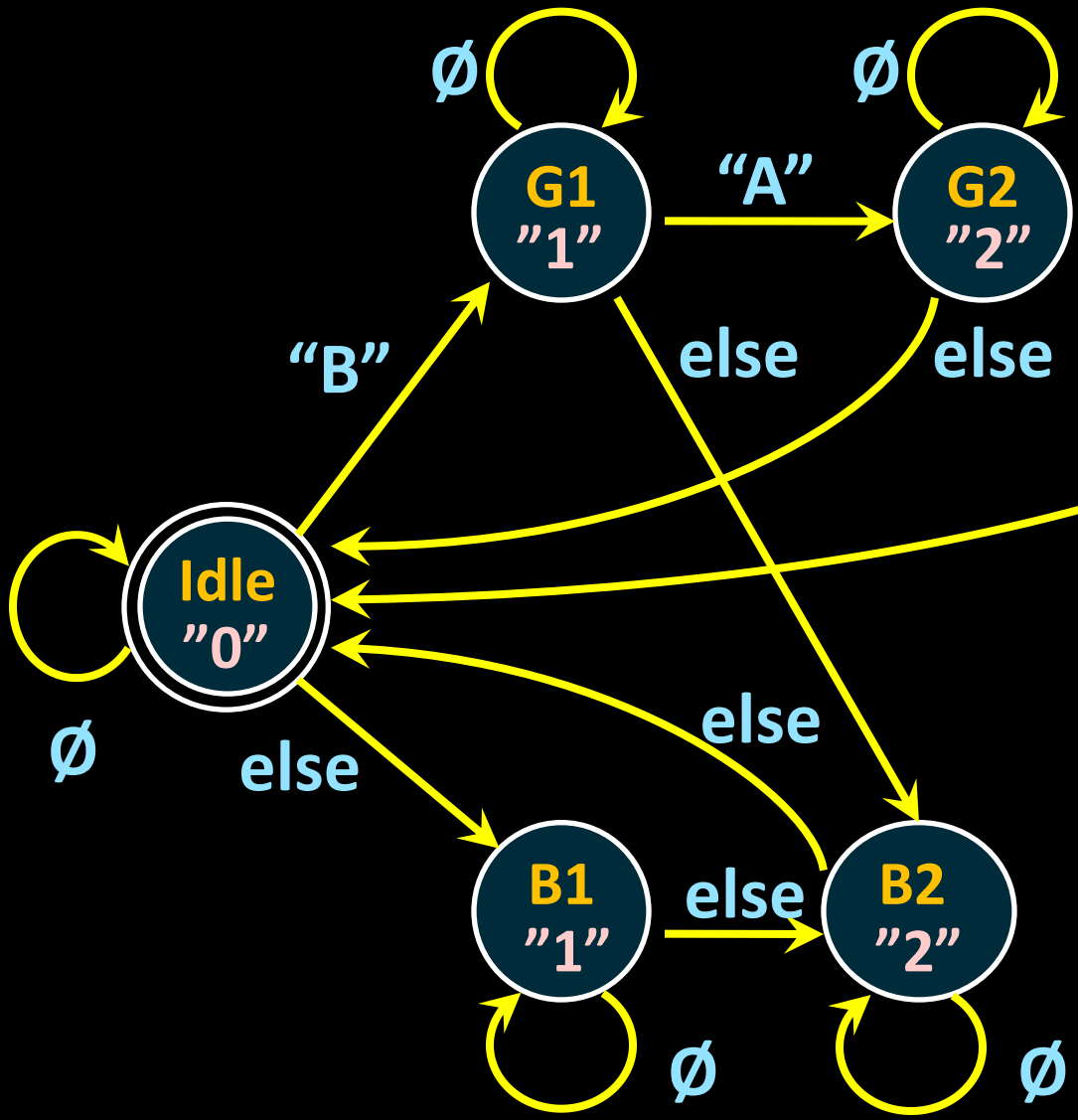
Door Lock: Simplified State Diagram



Door Lock: Simplified State Diagram

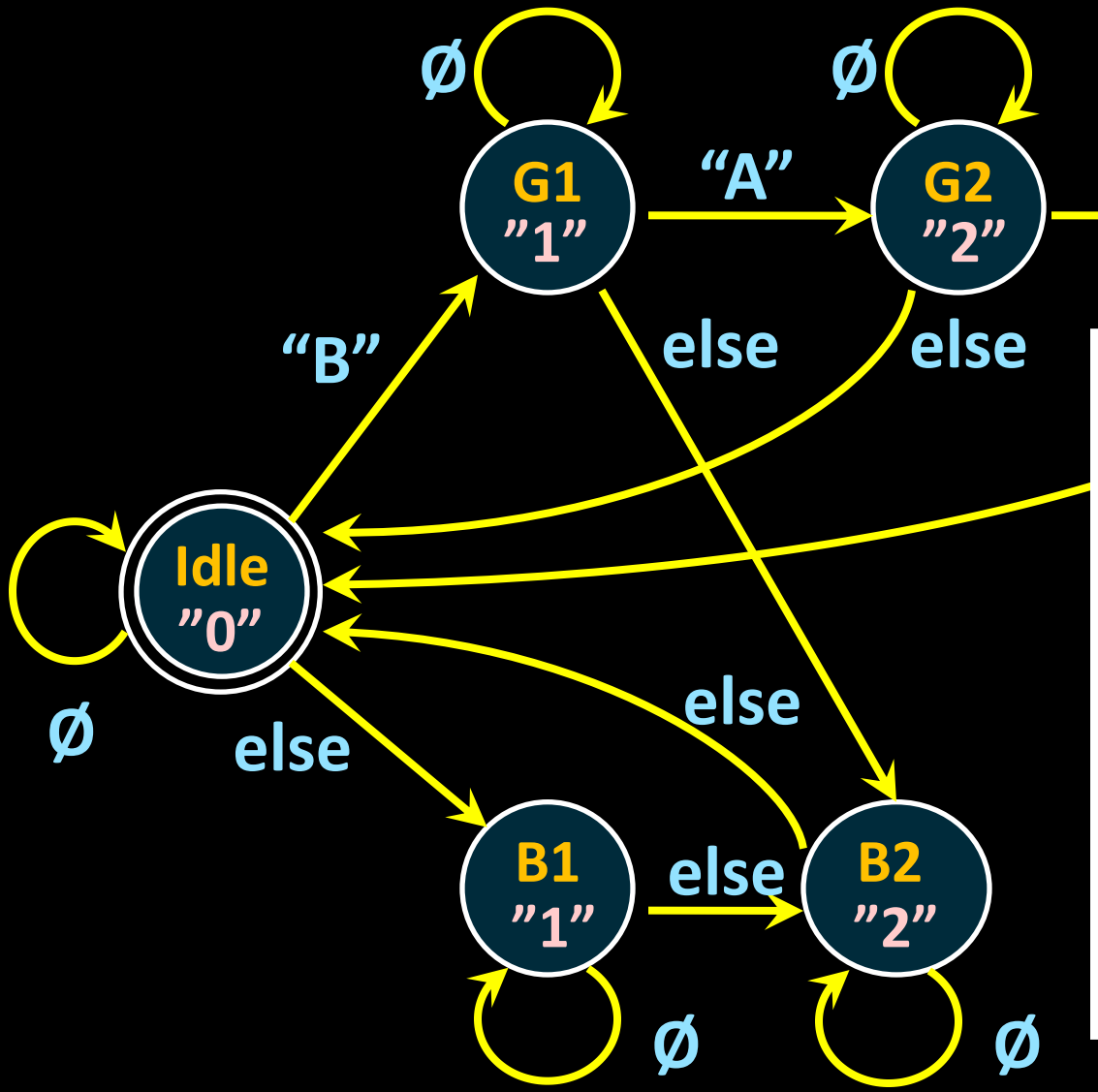


Door Lock: Simplified State Diagram



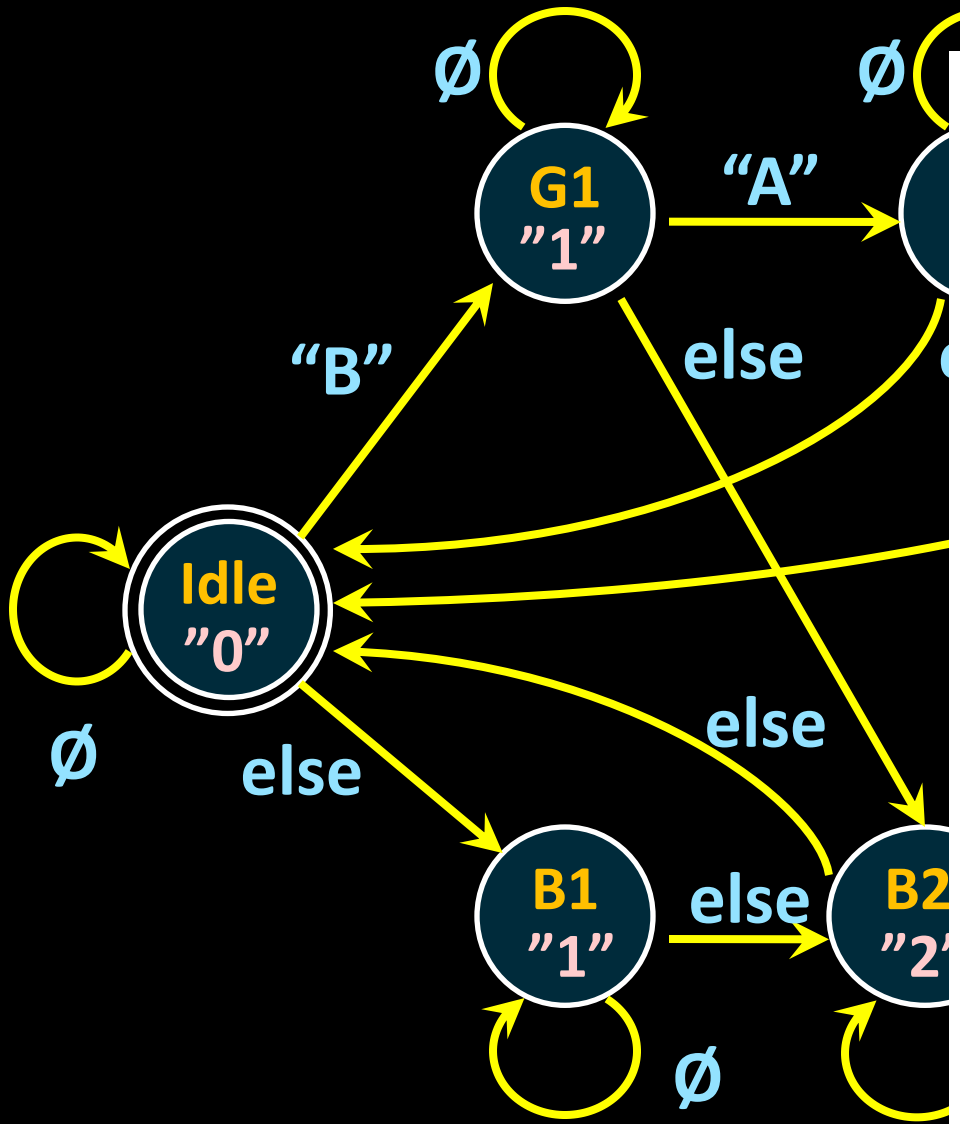
Cur. State	Output
Idle	"0"
G1	"1"
G2	"2"
G3	"3", U
B1	"1"
B2	"2"

Door Lock: Simplified State Diagram



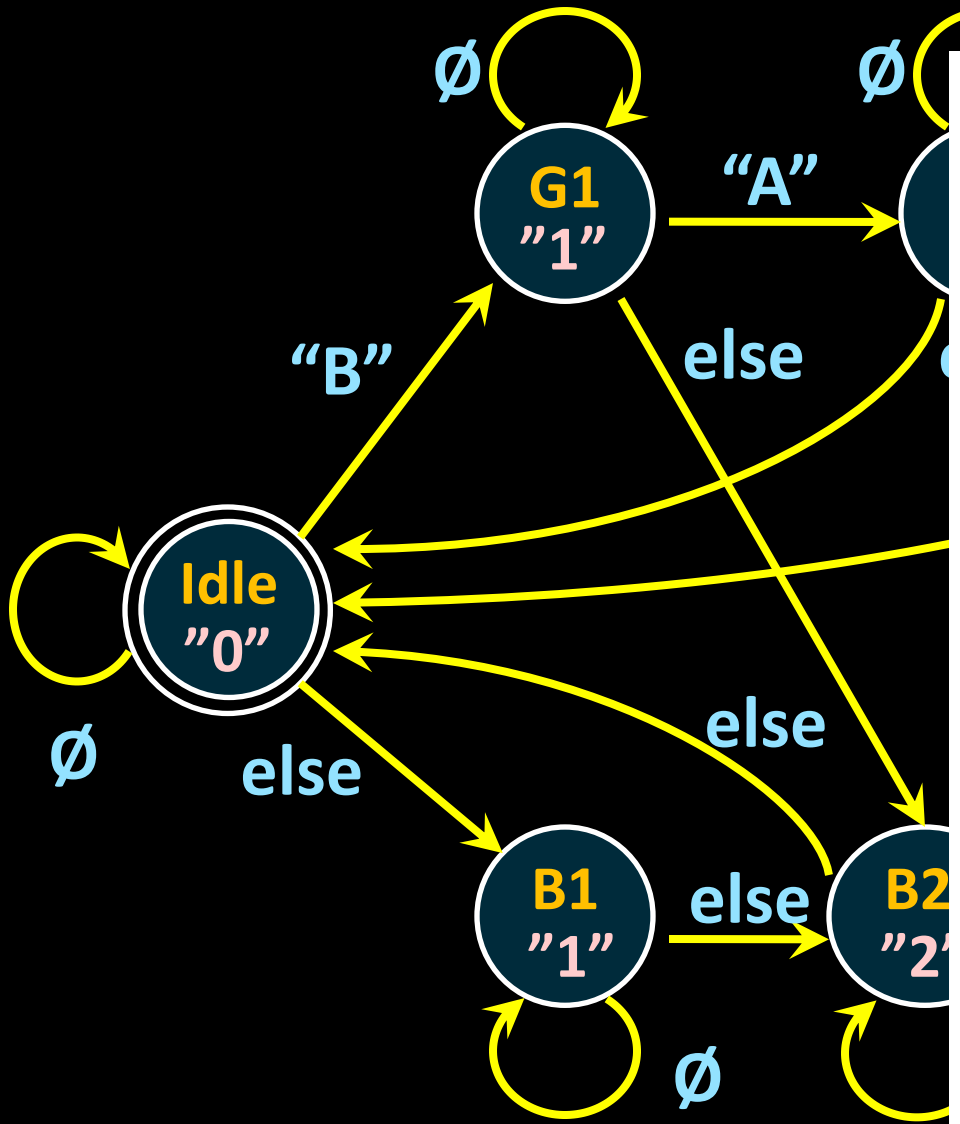
Cur. State	Output
Idle	"0"
G1	"1"
G2	"2"
G3	"3", U
B1	"1"
B2	"2"

Door Lock: Simplified State Diagram



Cur. State	Input	Next State
Idle	0	Idle
Idle	"B"	G1
Idle	"A"	G1
G1	0	G1
G1	A	G2
G1	B	B2
G2		
G2		
G2		
G3		
B1		
B1		
B2		
B2		

Door Lock: Simplified State Diagram



Cur. State	Input	Next State
Idle	Ø	Idle
Idle	"B"	G1
Idle	"A"	B1
G1	Ø	G1
G1	"A"	G2
G1	"B"	B2
G2	Ø	B2
G2	"B"	G3
G2	"A"	Idle
G3	any	Idle
B1	Ø	B1
B1	K	B2
B2	Ø	B2
B2	K	Idle

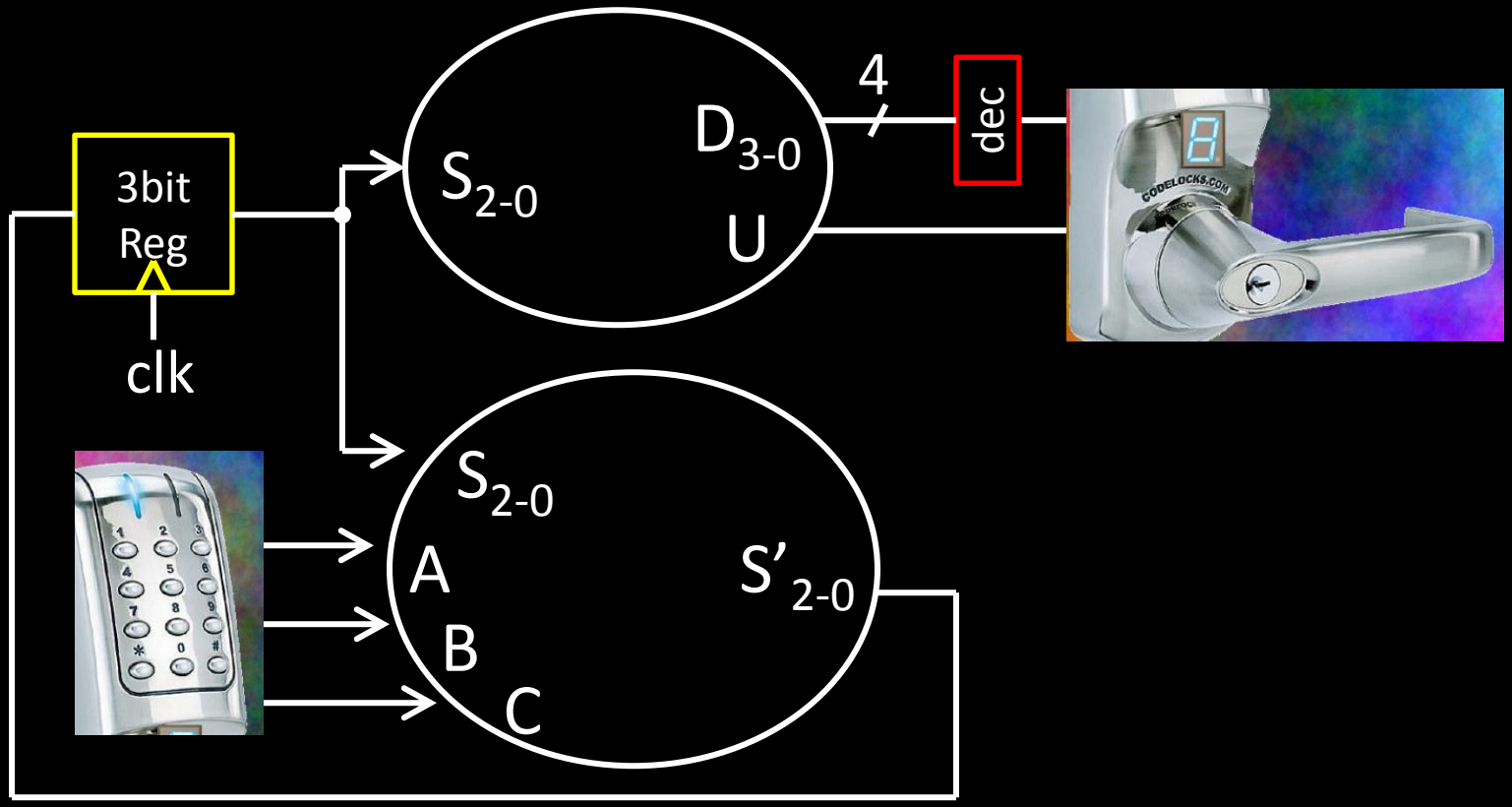
State Table Encoding

S_2	S_1	S_0	D_3	D_2	D_1	D_0	U
0	0	0	0	0	0	0	0
0	0	1	0	0	0	1	0
0	1	0	0	0	1	0	0
0	1	1	0	0	1	1	1
1	0	0	0	0	0	1	0
1	0	1	0	0	1	0	0

State	S_2	S_1	S_0
Idle	0	0	0
G1	0	0	1
G2	0	1	0
G3	0	1	1
B1	1	0	0
B2	1	0	1

S_2	S_1	S_0	K	A	B	S'_2	S'_1	S'_0
0	0	0	0	0	0	0	0	0
0	0	0	1	0	1	0	0	1
0	0	0	1	1	0	1	0	0
0	0	1	0	0	0	0	0	1
0	0	1	1	1	0	0	1	0
0	0	1	1	0	1	1	0	1
0	1	0	0	0	0	0	1	0
0	1	0	1	0	1	0	1	1
0	1	0	1	1	0	0	0	0
0	1	1	x	x	x	0	0	0
1	0	0	0	0	0	1	0	0
1	0	0	1	x	x	1	0	1
1	0	1	0	0	0	1	0	1
1	0	1	1	x	x	0	0	0

Door Lock: Implementation



Strategy:

(1) Draw a state diagram (e.g. Moore Machine)

(2) Write output and next-state tables

(3) Encode states, inputs, and outputs as bits

(4) Determine logic equations for next state and outputs

Summary

We can now build interesting devices with sensors

- Using combinational logic

We can also store data values

- Stateful circuit elements (D Flip Flops, Registers, …)
- Clock to synchronize state changes
- But be wary of asynchronous (un-clocked) inputs
- State Machines or Ad-Hoc Circuits