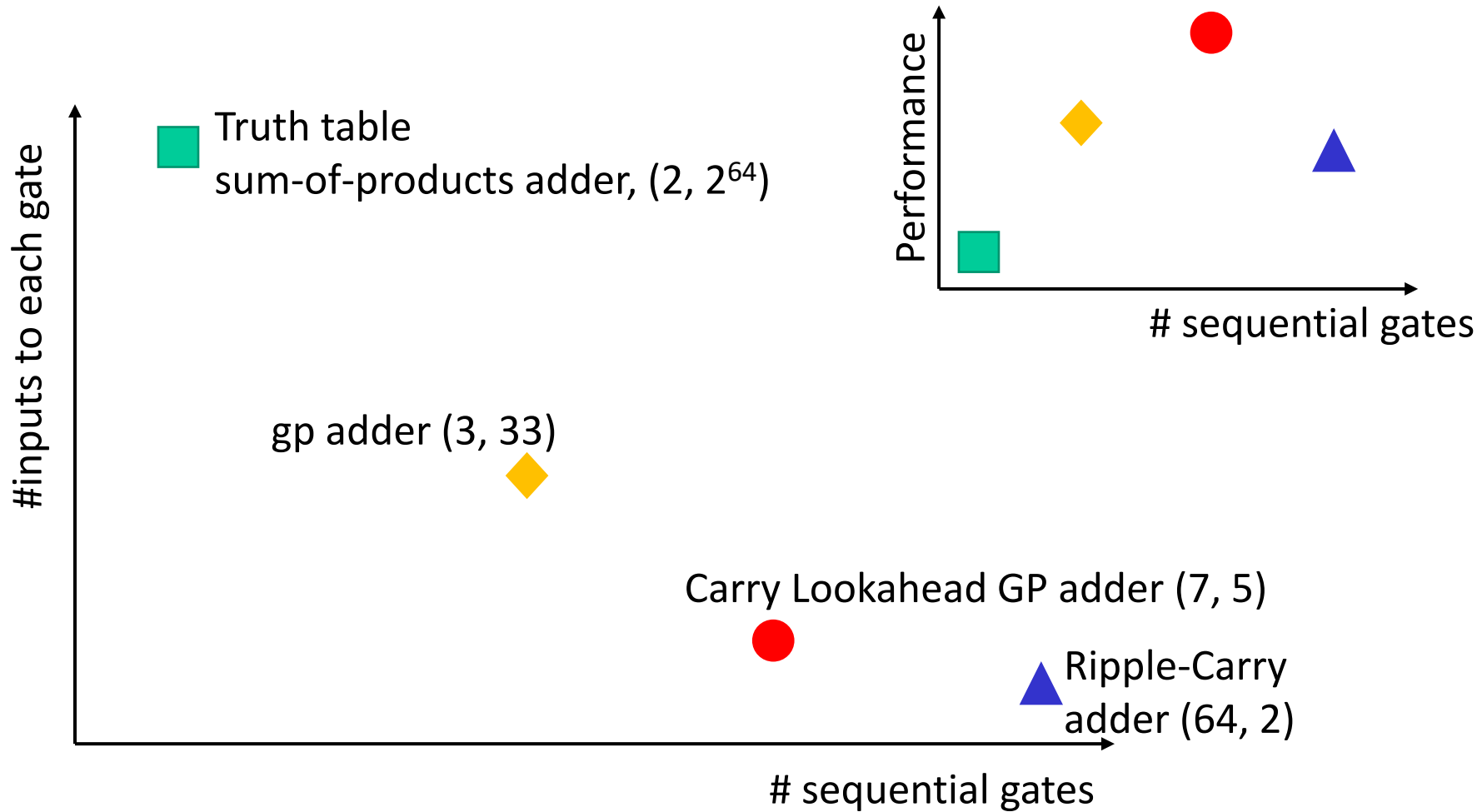


# Lecture 14: Sequential Circuits, FSM

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- Today's topics:
  - Sequential circuits
  - Finite state machines

# Trade-Off Curve



# Clocks

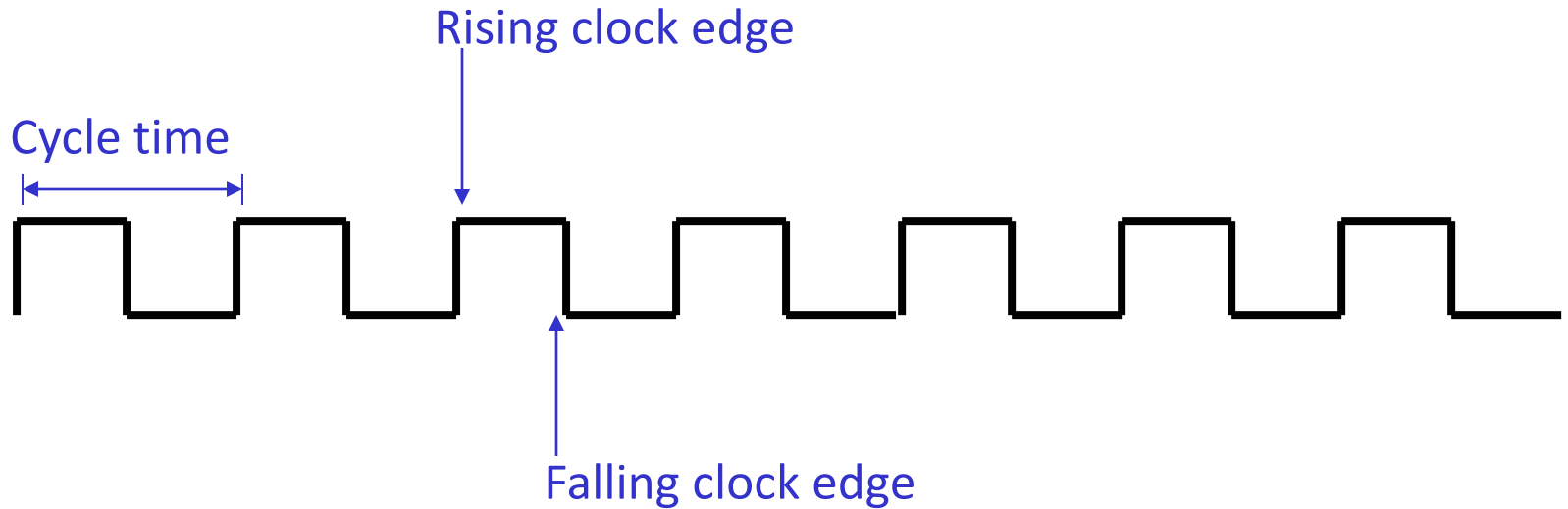
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- A microprocessor is composed of many different circuits that are operating simultaneously – if each circuit  $X$  takes in inputs at time  $TI_x$ , takes time  $TE_x$  to execute the logic, and produces outputs at time  $TO_x$ , imagine the complications in co-ordinating the tasks of every circuit
- A major school of thought (used in most processors built today): all circuits on the chip share a clock signal (a square wave) that tells every circuit when to accept inputs, how much time they have to execute the logic, and when they must produce outputs



# Clock Terminology

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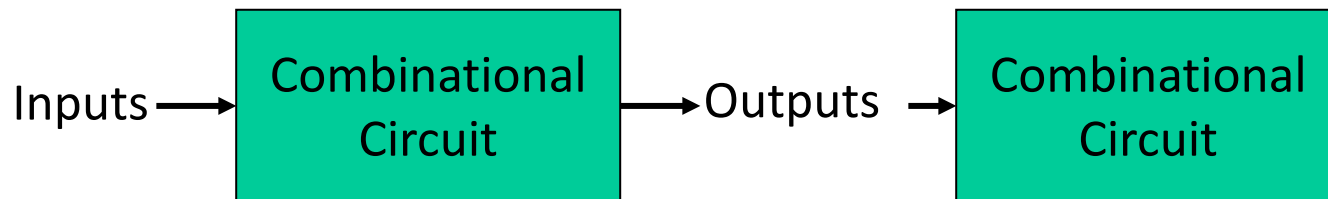


$$4 \text{ GHz} = \text{clock speed} = \frac{1}{\text{cycle time}} = \frac{1}{250 \text{ ps}}.$$

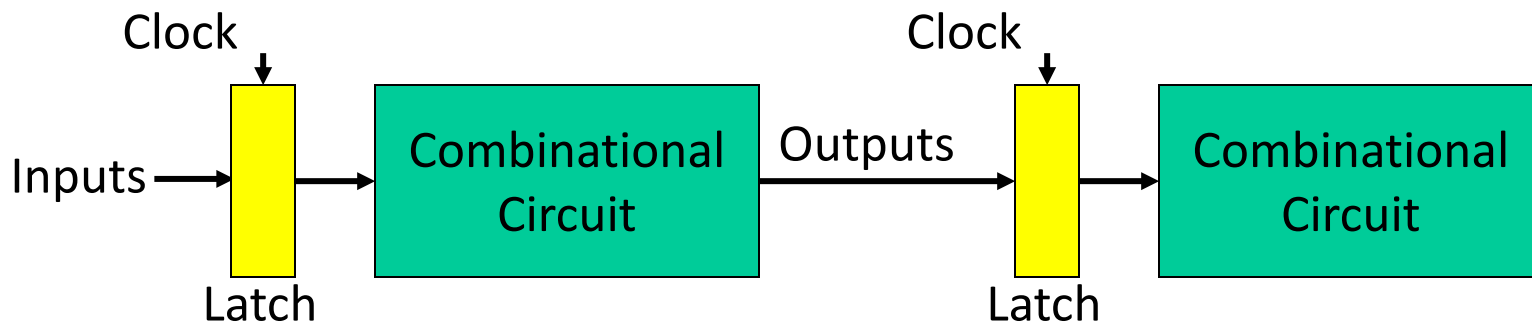
# Sequential Circuits

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- Until now, circuits were combinational – when inputs change, the outputs change after a while (time = logic delay thru circuit)

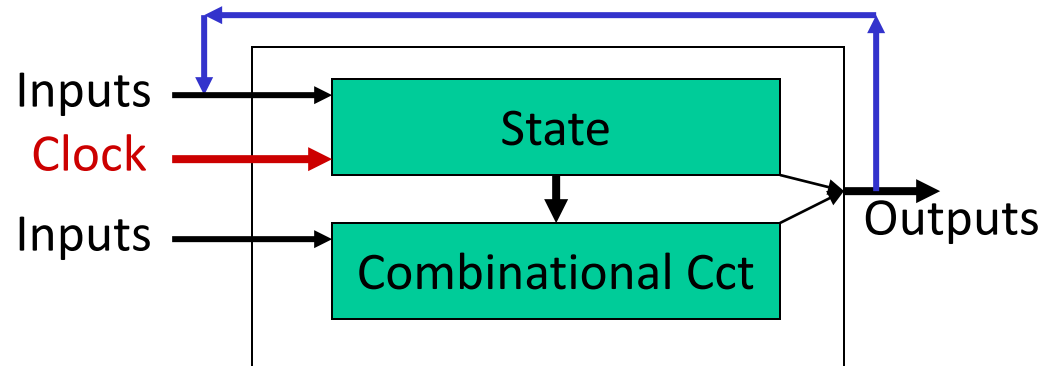


- We want the clock to act like a start and stop signal – a “latch” is a storage device that separates these circuits – it ensures that the inputs to the circuit do not change during a clock cycle



# Sequential Circuits

- Sequential circuit: consists of combinational circuit and a storage element
- At the start of the clock cycle, the rising edge causes the “state” storage to store some input values

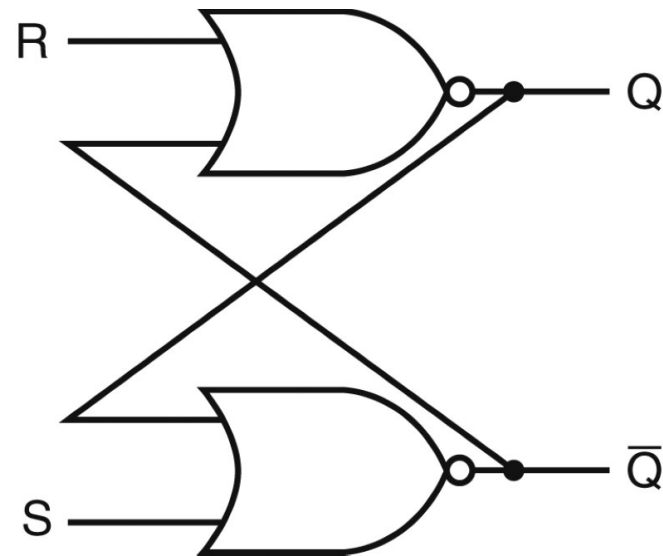


- This state will not change for an entire cycle (until next rising edge)
- The combinational circuit has some time to accept the value of “state” and “inputs” and produce “outputs”
- Some of the outputs (for example, the value of next “state”) may feed back (but through the latch so they’re only seen in the next cycle)

# Designing a Latch

- An S-R latch: set-reset latch
  - When Set is high, a 1 is stored
  - When Reset is high, a 0 is stored
  - When both are low, the previous state is preserved (hence, known as a storage or memory element)
  - Both are high – this set of inputs is not allowed

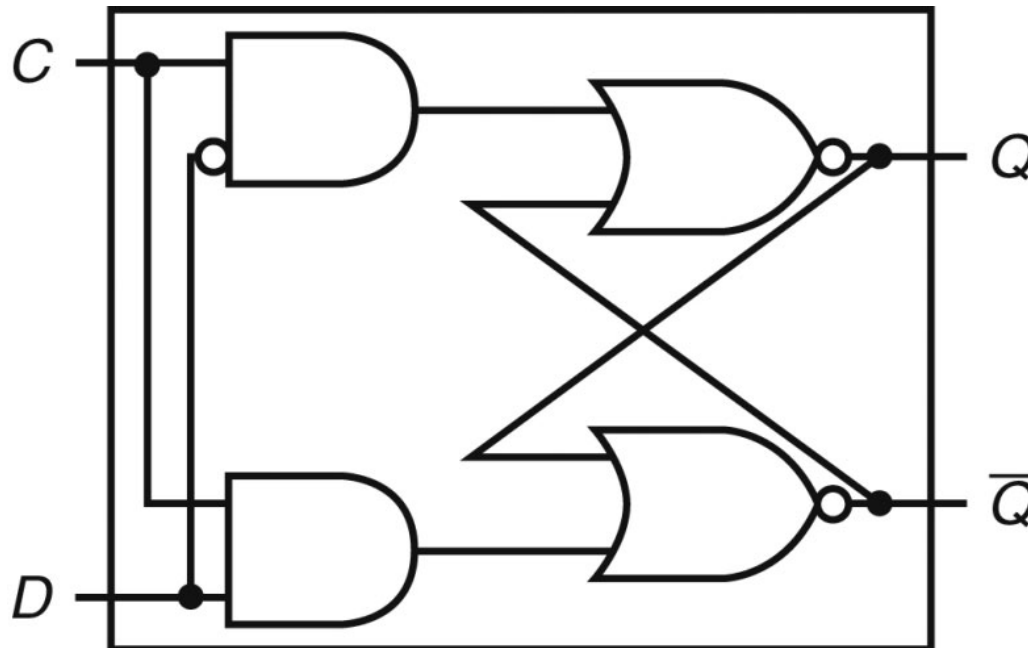
Verify the above behavior!



# D Latch

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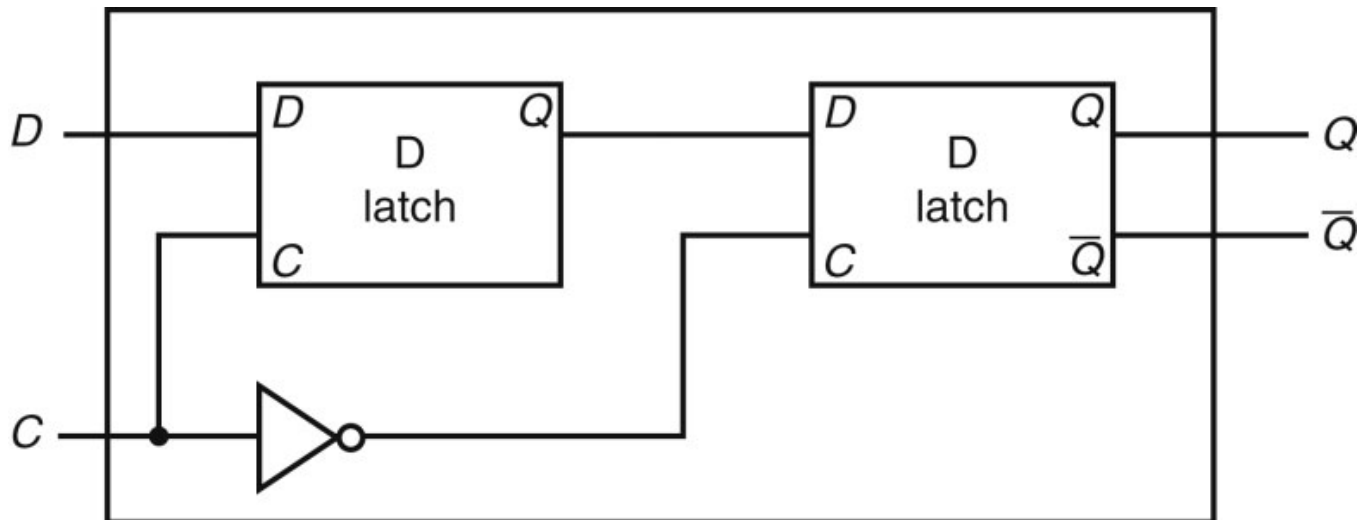
- Incorporates a clock
- The value of the input D signal (data) is stored only when the clock is high – the previous state is preserved when the clock is low





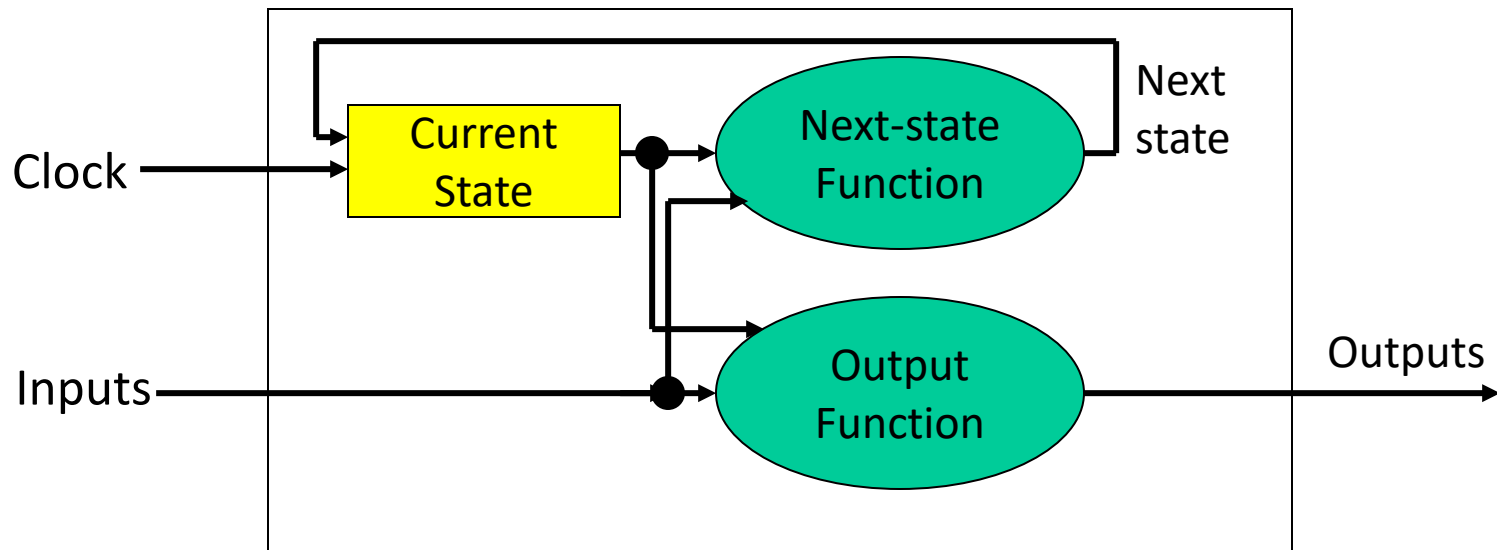
# D Flip Flop

- Terminology:  
Latch: outputs can change any time the clock is high (asserted)  
Flip flop: outputs can change only on a clock edge
- Two D latches in series – ensures that a value is stored only on the falling edge of the clock



# Finite State Machine

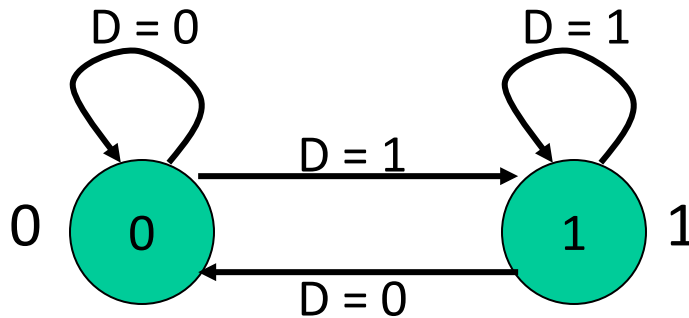
- A sequential circuit is described by a variation of a truth table – a finite state diagram (hence, the circuit is also called a finite state machine)
- Note that state is updated only on a clock edge



# State Diagrams

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- Each state is shown with a circle, labeled with the state value – the contents of the circle are the outputs
- An arc represents a transition to a different state, with the inputs indicated on the label



This is a state diagram for \_\_\_\_?

# 3-Bit Counter

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- Consider a circuit that stores a number and increments the value on every clock edge – on reaching the largest value, it starts again from 0

Draw the state diagram:

- How many states?
- How many inputs?

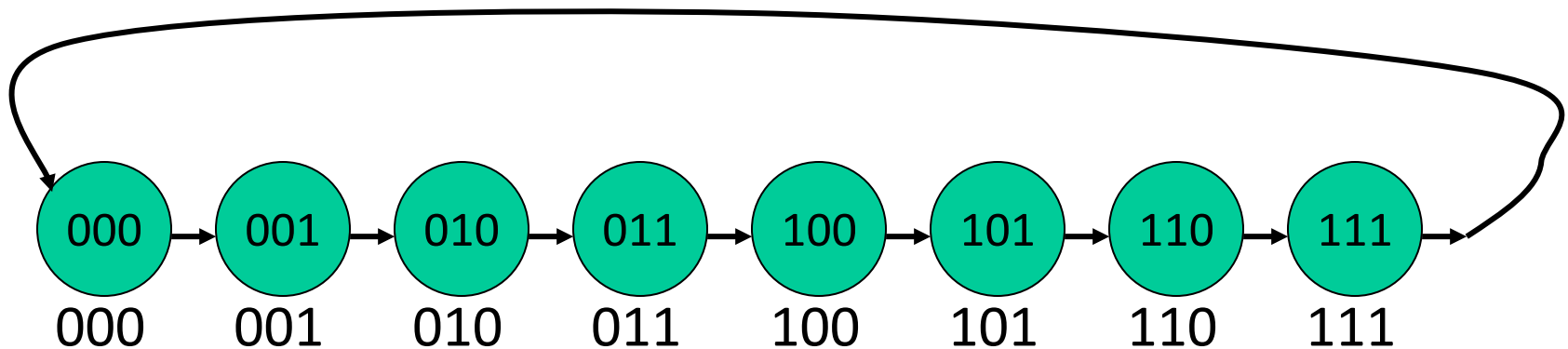
# 3-Bit Counter

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- Consider a circuit that stores a number and increments the value on every clock edge – on reaching the largest value, it starts again from 0

Draw the state diagram:

- How many states?
- How many inputs?



# Tackling FSM Problems

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- Three questions worth asking:
  - What are the possible output states? Draw a bubble for each.
  - What are inputs? What values can those inputs take?
  - For each state, what do I do for each possible input value? Draw an arc out of every bubble for every input value.

# Traffic Light Controller

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- Problem description: A traffic light with only green and red; either the North-South road has green or the East-West road has green (both can't be red); there are detectors on the roads to indicate if a car is on the road; the lights are updated every 30 seconds; a light need change only if a car is waiting on the other road

State Transition Table:

How many states?

How many inputs?

How many outputs?

# State Transition Table

---

- Problem description: A traffic light with only green and red; either the North-South road has green or the East-West road has green (both can't be red); there are detectors on the roads to indicate if a car is on the road; the lights are updated every 30 seconds; a light must change only if a car is waiting on the other road

State Transition Table:

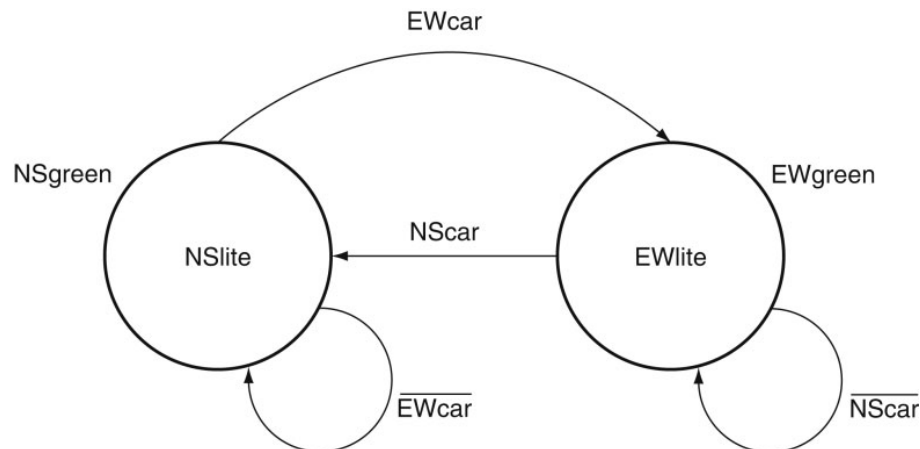
CurrState	InputEW	InputNS	NextState=Output
N	0	0	N
N	0	1	N
N	1	0	E
N	1	1	E
E	0	0	E
E	0	1	N
E	1	0	E
E	1	1	N



# State Diagram

State Transition Table:

CurrState	InputEW	InputNS	NextState=Output
N	0	0	N
N	0	1	N
N	1	0	E
N	1	1	E
E	0	0	E
E	0	1	N
E	1	0	E
E	1	1	N



Source: H&P textbook

# Tackling FSM Problems

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  - What are the possible output states? Draw a bubble for each.
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# Example – Residential Thermostat

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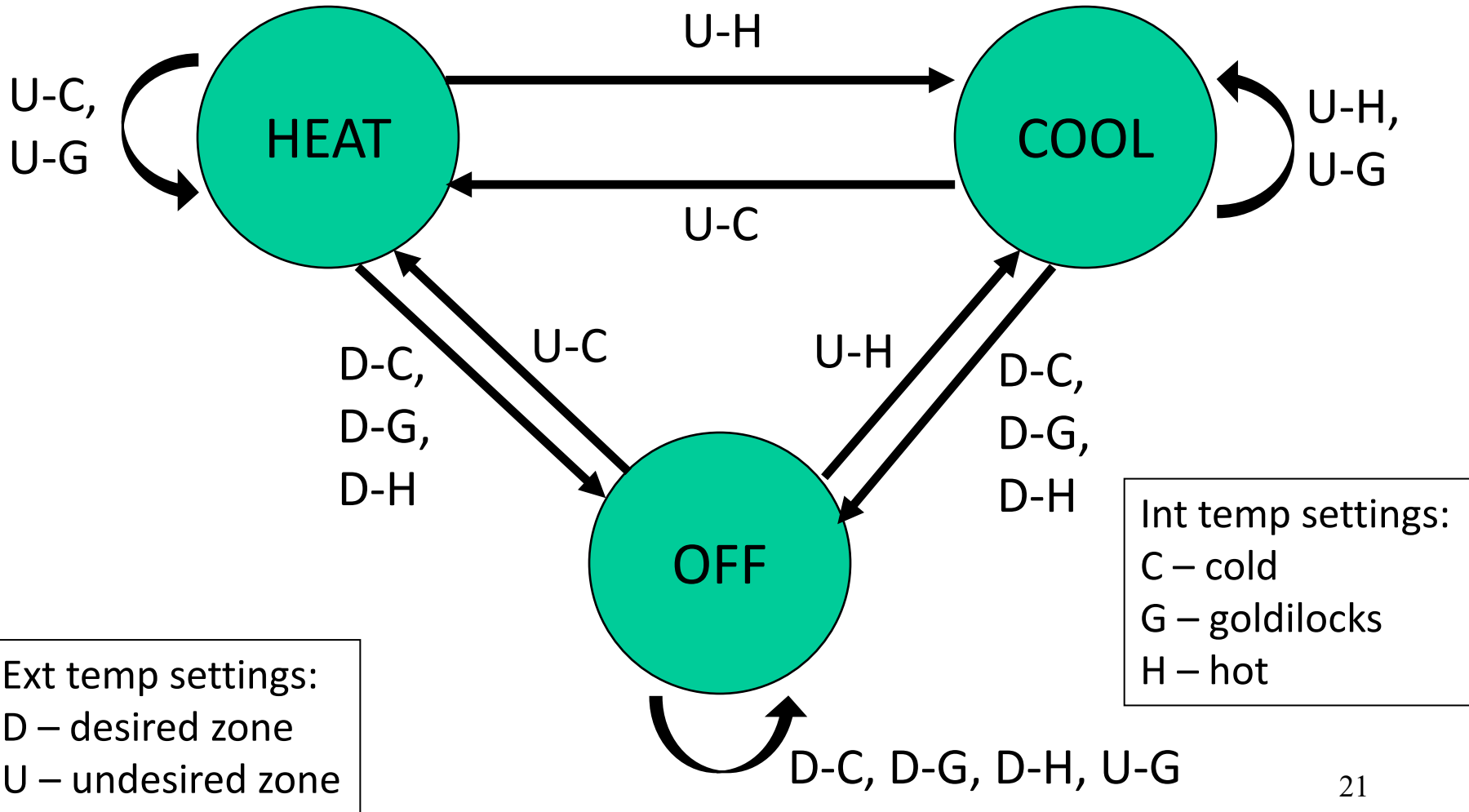
- Two temp sensors: internal and external
- If internal temp is within 1 degree of desired, don't change setting
- If internal temp is  $> 1$  degree higher than desired, turn AC on; if internal temp is  $< 1$  degree lower than desired, turn heater on
- If external temp and desired temp are within 5 degrees, disregard the internal temp, and turn both AC and heater off

# Finite State Machine Table

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Current State	Input E	Input I	Output State
HEAT	D	C	OFF
HEAT	D	G	OFF
HEAT	D	H	OFF
HEAT	U	C	HEAT
HEAT	U	G	HEAT
HEAT	U	H	COOL
COOL	D	C	OFF
COOL	D	G	OFF
COOL	D	H	OFF
COOL	U	C	HEAT
COOL	U	G	COOL
COOL	U	H	COOL
OFF	D	C	OFF
OFF	D	G	OFF
OFF	D	H	OFF
OFF	U	C	HEAT
OFF	U	G	OFF
OFF	U	H	COOL

# Finite State Diagram



# Latch vs. Flip-Flop

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- Recall that we want a circuit to have stable inputs for an entire cycle – so I want my new inputs to arrive at the start of a cycle and be fixed for an entire cycle
- A flip-flop provides the above semantics (a door that swings open and shut at the start of a cycle)
- But a flip-flop needs two back-to-back D-latches, i.e., more transistors, delay, power
- You can reduce these overheads with just a single D-latch (a door that is open for half a cycle) as long as you can tolerate stable inputs for just half a cycle