
Logic and Computer Design Fundamentals

Chapter 5 – Sequential Circuits

Part 1 – Storage Elements and Sequential Circuit Analysis

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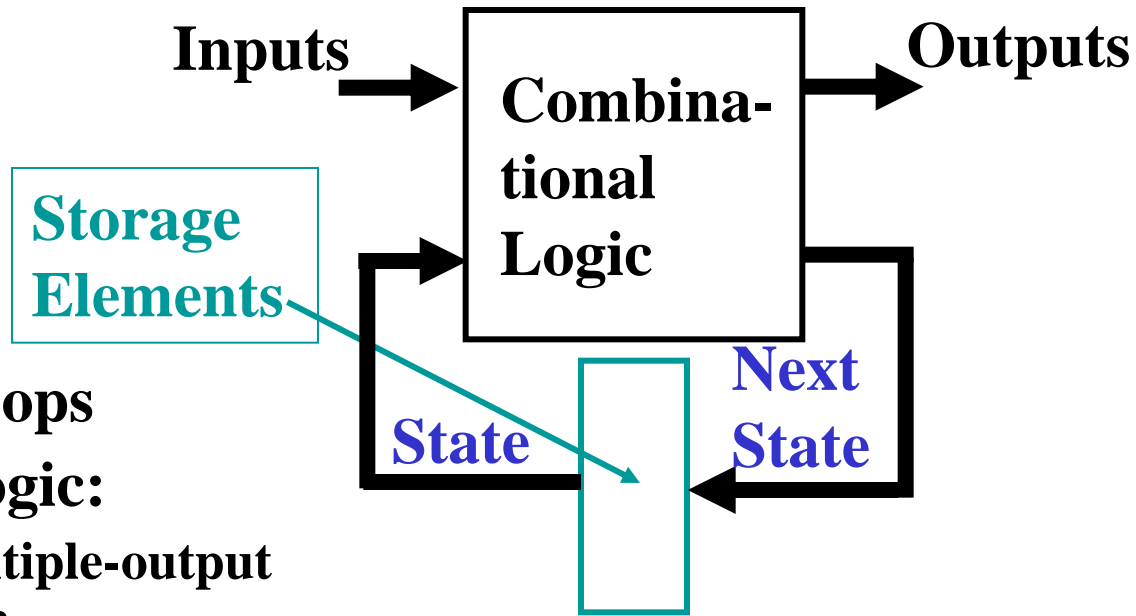
Overview

- **Part 1 - Storage Elements and Analysis**
 - Introduction to sequential circuits
 - Types of sequential circuits
 - Storage elements
 - Latches
 - Flip-flops
 - Sequential circuit analysis
 - State tables
 - State diagrams
 - Equivalent states
 - Moore and Mealy Models
- **Part 2 - Sequential Circuit Design**
- **Part 3 – State Machine Design**

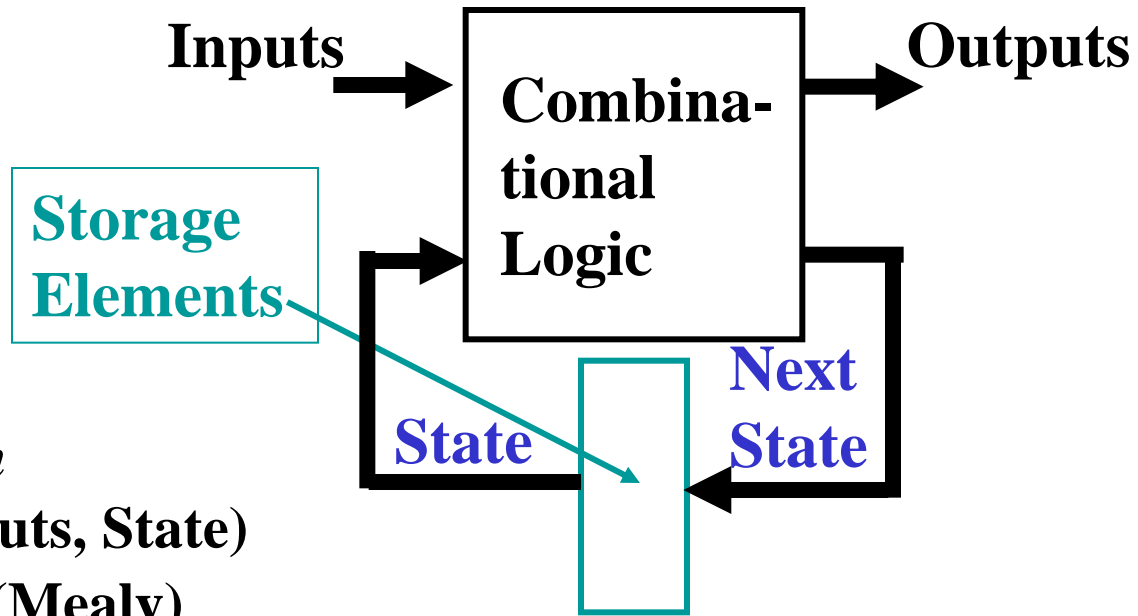
Introduction to Sequential Circuits

- A Sequential circuit contains:

- Storage elements: Latches or Flip-Flops
- Combinational Logic:
 - Implements a multiple-output switching function
 - Inputs are signals from the outside.
 - Outputs are signals to the outside.
 - Other inputs, State or Present State, are signals from storage elements.
 - The remaining outputs, Next State are inputs to storage elements.



Introduction to Sequential Circuits



- **Combinatorial Logic**
 - *Next state function*
 $\text{Next State} = f(\text{Inputs}, \text{State})$
 - *Output function (Mealy)*
 $\text{Outputs} = g(\text{Inputs}, \text{State})$
 - *Output function (Moore)*
 $\text{Outputs} = h(\text{State})$
- **Output function type depends on specification and affects the design significantly**

Types of Sequential Circuits

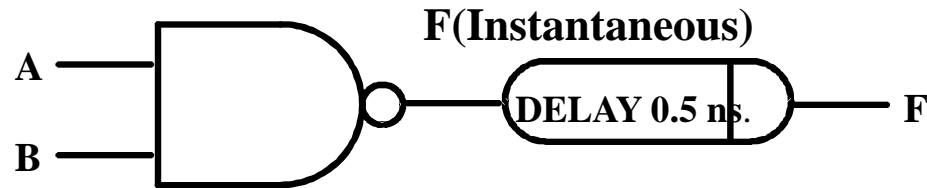
- Depends on the times at which:
 - storage elements observe their inputs, and
 - storage elements change their state
- Synchronous
 - Behavior defined from knowledge of its signals at discrete instances of time
 - Storage elements observe inputs and can change state only in relation to a timing signal (clock pulses from a clock)
- Asynchronous
 - Behavior defined from knowledge of inputs at any instant of time and the order in continuous time in which inputs change
 - If clock just regarded as another input, all circuits are asynchronous!
 - Nevertheless, the synchronous abstraction makes complex designs tractable!

Discrete Event Simulation

- In order to understand the time behavior of a sequential circuit we use discrete event simulation.
- Rules:
 - Gates modeled by an ideal (instantaneous) function and a fixed gate delay
 - Any change in input values is evaluated to see if it causes a change in output value
 - Changes in output values are scheduled for the fixed gate delay after the input change
 - At the time for a scheduled output change, the output value is changed along with any inputs it drives

Simulated NAND Gate

- **Example: A 2-Input NAND gate with a 0.5 ns. delay:**

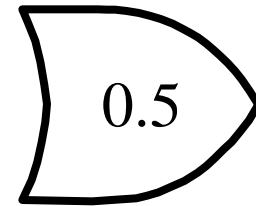
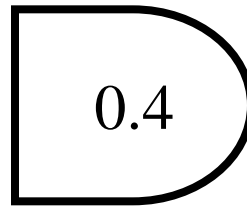
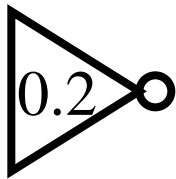


- Assume A and B have been 1 for a long time
- At time $t=0$, A changes to a 0 at $t= 0.8$ ns, back to 1.

t (ns)	A	B	F(I)	F	Comment
$-\infty$	1	1	0	0	A=B=1 for a long time
0	$1 \Rightarrow 0$	1	$1 \Leftarrow 0$	0	F(I) changes to 1
0.5	0	1	1	$1 \Leftarrow 0$	F changes to 1 after a 0.5 ns delay
0.8	$1 \Leftarrow 0$	1	$1 \Rightarrow 0$	1	F(Instantaneous) changes to 0
0.13	1	1	0	$1 \Rightarrow 0$	F changes to 0 after a 0.5 ns delay

Gate Delay Models

- Suppose gates with delay n ns are represented for $n = 0.2$ ns, $n = 0.4$ ns, $n = 0.5$ ns, respectively:

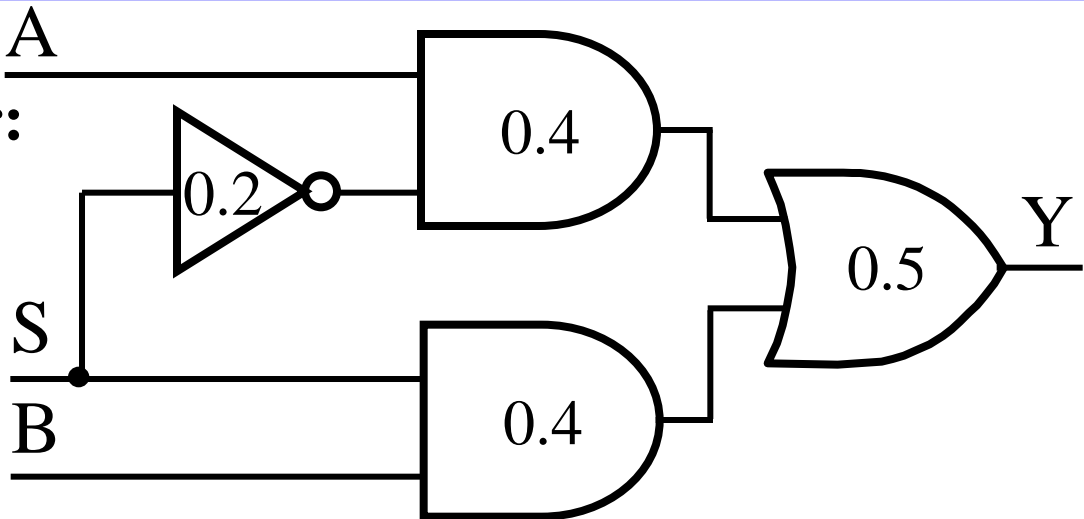


Circuit Delay Model

- Consider a simple 2-input multiplexer:

- With function:

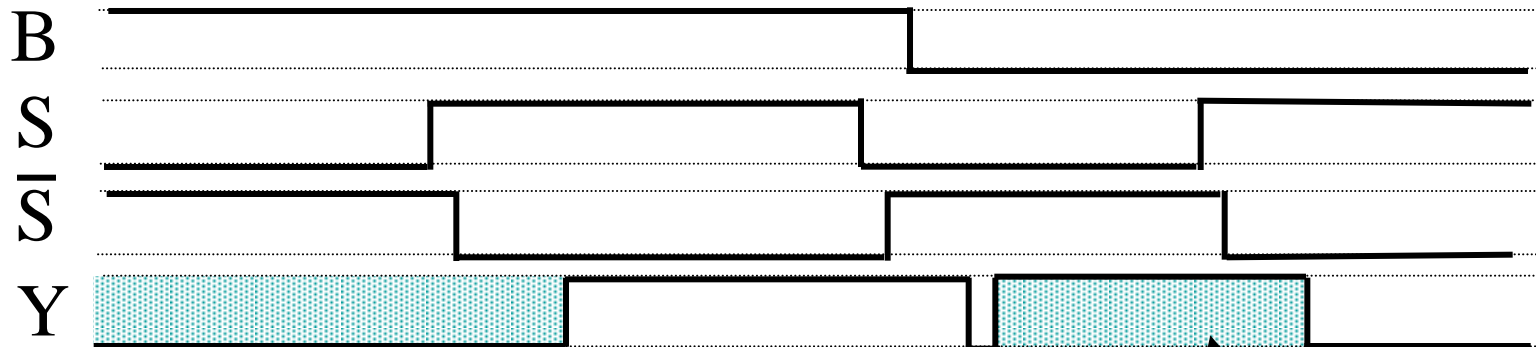
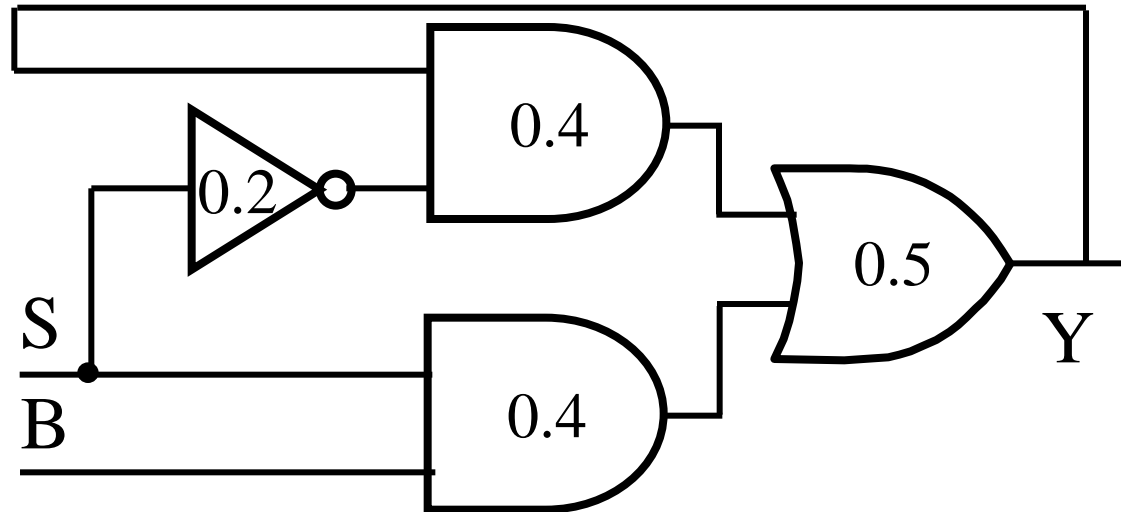
- $Y = A$ for $S = 0$
- $Y = B$ for $S = 1$



- “Glitch” is due to delay of inverter

Storing State

- What if A connected to Y?
- Circuit becomes:
- With function:
 - $Y = B$ for $S = 1$, and $Y(t)$ dependent on $Y(t - 0.9)$ for $S = 0$



- The simple combinational circuit has now become a sequential circuit because its output is a function of a time sequence of input signals!

Y is stored value in shaded area

Storing State (Continued)

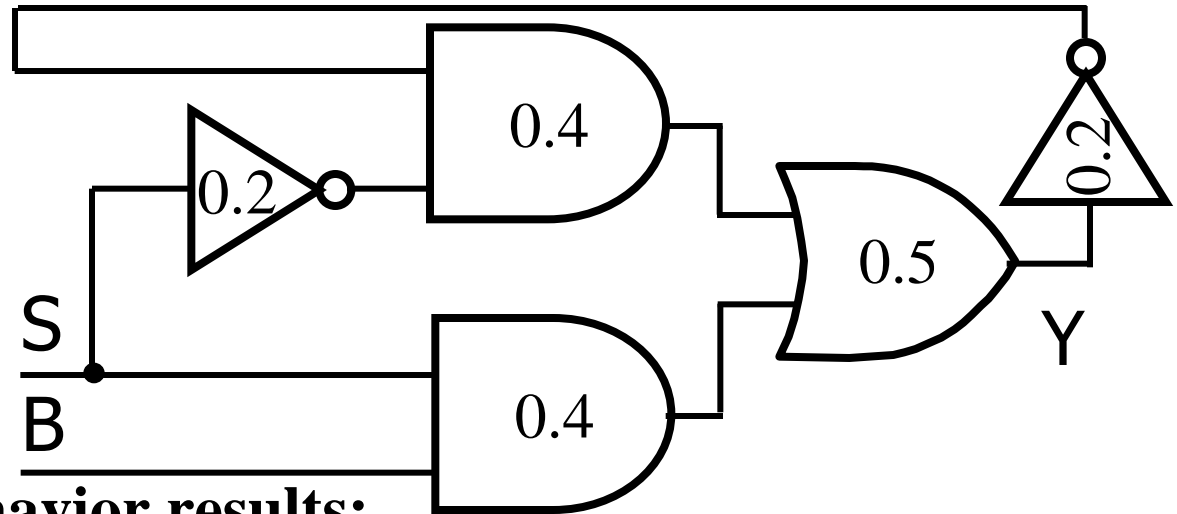
- Simulation example as input signals change with time. Changes occur every 100 ns, so that the tenths of ns delays are negligible.

Time	B	S	Y	Comment
↓	1	0	0	Y “remembers” 0
	1	1	1	Y = B when S = 1
	1	0	1	Now Y “remembers” B = 1 for S = 0
	0	0	1	No change in Y when B changes
	0	1	0	Y = B when S = 1
	0	0	0	Y “remembers” B = 0 for S = 0
	1	0	0	No change in Y when B changes

- Y represent the state of the circuit, not just an output.

Storing State (Continued)

- Suppose we place an inverter in the “feedback path.”



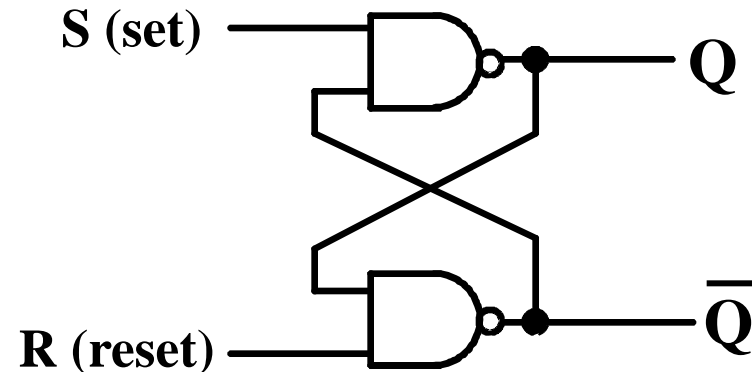
- The following behavior results:

- The circuit is said to be unstable.
- For $S = 0$, the circuit has become what is called an *oscillator*. Can be used as crude clock.

B	S	Y	Comment
0	1	0	$Y = B$ when $S = 1$
1	1	1	
1	0	1	Now Y “remembers” A
1	0	0	Y, 1.1 ns later
1	0	1	Y, 1.1 ns later
1	0	0	Y, 1.1 ns later

Basic (NAND) \bar{S} – \bar{R} Latch

- “Cross-Coupling”
two NAND gates gives
the \bar{S} - \bar{R} Latch:



- Which has the time
sequence behavior:

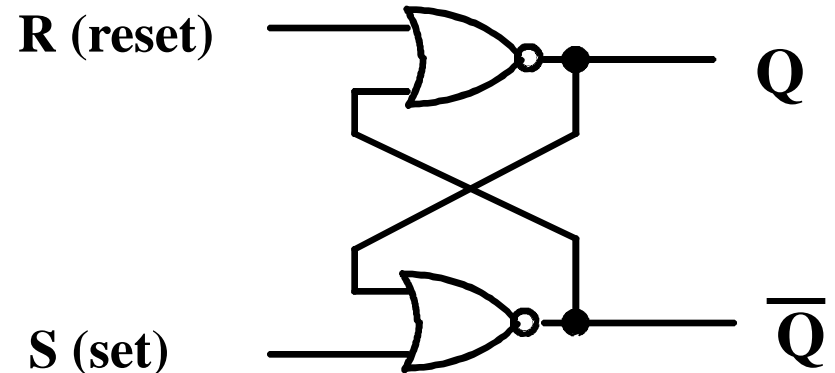
- $S = 0, R = 0$ is
forbidden as
input pattern

Time
↓

R	S	Q	\bar{Q}	Comment
1	1	?	?	Stored state unknown
1	0	1	0	“Set” Q to 1
1	1	1	0	Now Q “remembers” 1
0	1	0	1	“Reset” Q to 0
1	1	0	1	Now Q “remembers” 0
0	0	1	1	Both go high
1	1	?	?	Unstable!

Basic (NOR) S – R Latch

- Cross-coupling two NOR gates gives the S – R Latch:



- Which has the time sequence behavior:

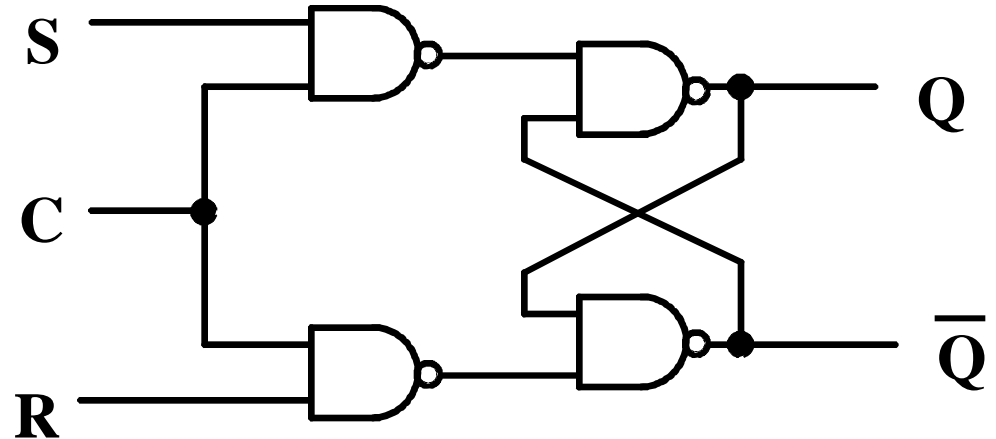
Time



R	S	Q	\bar{Q}	Comment
0	0	?	?	Stored state unknown
0	1	1	0	“Set” Q to 1
0	0	1	0	Now Q “remembers” 1
1	0	0	1	“Reset” Q to 0
0	0	0	1	Now Q “remembers” 0
1	1	0	0	Both go low
0	0	?	?	Unstable!

Clocked S - R Latch

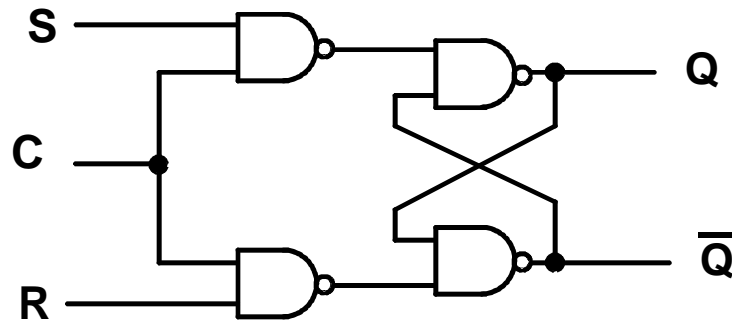
- Adding two NAND gates to the basic \overline{S} - \overline{R} NAND latch gives the clocked S - R latch:



- Has a time sequence behavior similar to the basic S-R latch except that the S and R inputs are only observed when the line C is high.
- C means “control” or “clock”.

Clocked S - R Latch (continued)

- The Clocked S-R Latch can be described by a table:



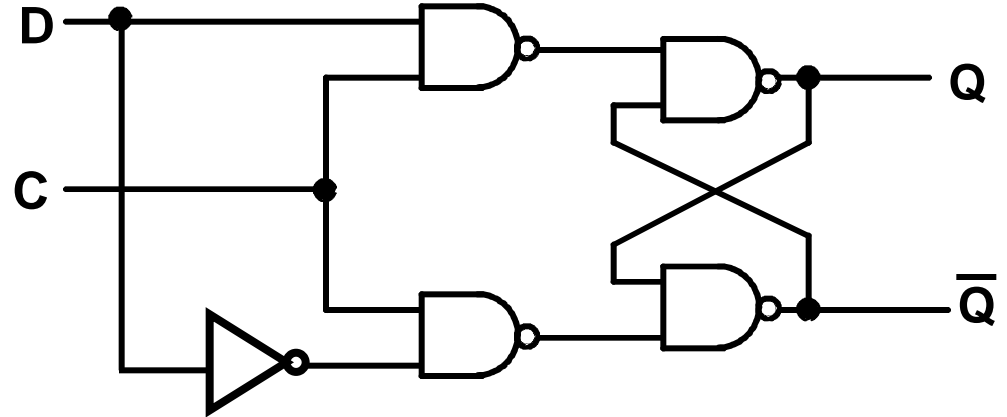
Q(t)	S	R	Q(t+1)	Comment
0	0	0	0	No change
0	0	1	0	Clear Q
0	1	0	1	Set Q
0	1	1	???	Indeterminate
1	0	0	1	No change
1	0	1	0	Clear Q
1	1	0	1	Set Q
1	1	1	???	Indeterminate

- The table describes what happens after the clock [at time (t+1)] based on:

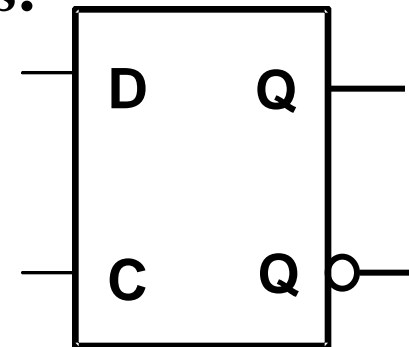
- current inputs (S,R) and
- current state Q(t).

D Latch

- Adding an inverter to the S-R Latch, gives the D Latch:
- Note that there are no “indeterminate” states!



The graphic symbol for a D Latch is:



Q	D	Q(t+1)	Comment
0	0	0	No change
0	1	1	Set Q
1	0	0	Clear Q
1	1	1	No Change

Flip-Flops

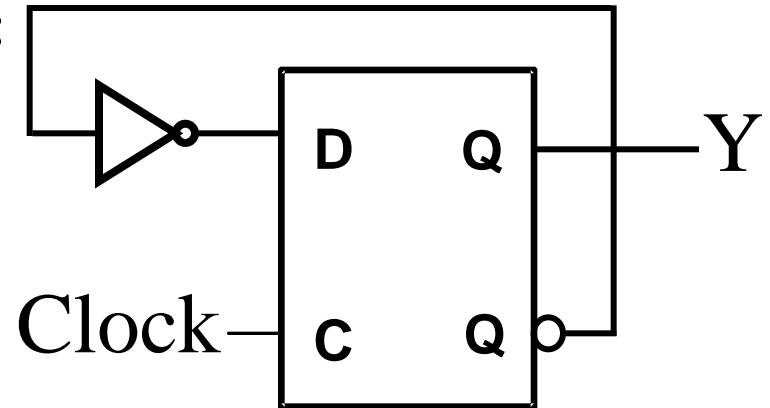
- **The latch timing problem**
- **Master-slave flip-flop**
- **Edge-triggered flip-flop**
- **Standard symbols for storage elements**
- **Direct inputs to flip-flops**

The Latch Timing Problem

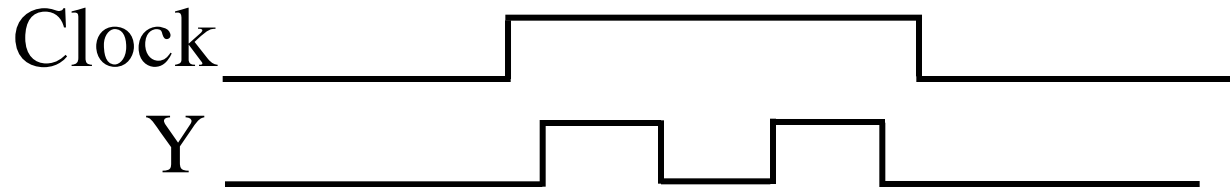
- **In a sequential circuit, paths may exist through combinational logic:**
 - From one storage element to another
 - From a storage element back to the same storage element
- **The combinational logic between a latch output and a latch input may be as simple as an interconnect**
- **For a clocked D-latch, the output Q depends on the input D whenever the clock input C has value 1**

The Latch Timing Problem (continued)

- Consider the following circuit:



- Suppose that initially $Y = 0$.



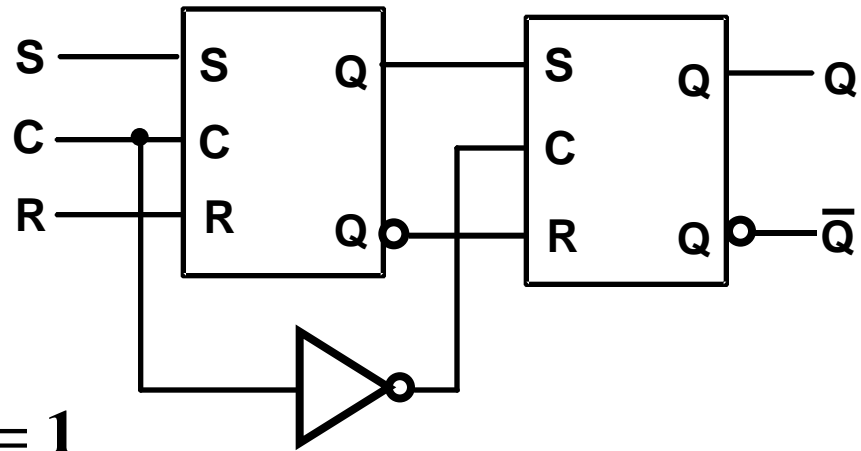
- As long as $C = 1$, the value of Y continues to change!
- The changes are based on the delay present on the loop through the connection from Y back to Y .
- This behavior is clearly unacceptable.
- Desired behavior: Y changes only once per clock pulse

The Latch Timing Problem (continued)

- A solution to the latch timing problem is to break the closed path from Y to Y within the storage element
- The commonly-used, path-breaking solutions replace the clocked D-latch with:
 - a master-slave flip-flop
 - an edge-triggered flip-flop

S-R Master-Slave Flip-Flop

- Consists of two clocked S-R latches in series with the clock on the second latch inverted
- The input is observed by the first latch with $C = 1$
- The output is changed by the second latch with $C = 0$
- The path from input to output is broken by the difference in clocking values ($C = 1$ and $C = 0$).
- The behavior demonstrated by the example with D driven by Y given previously is prevented since the clock must change from 1 to 0 before a change in Y based on D can occur.



Flip-Flop Problem

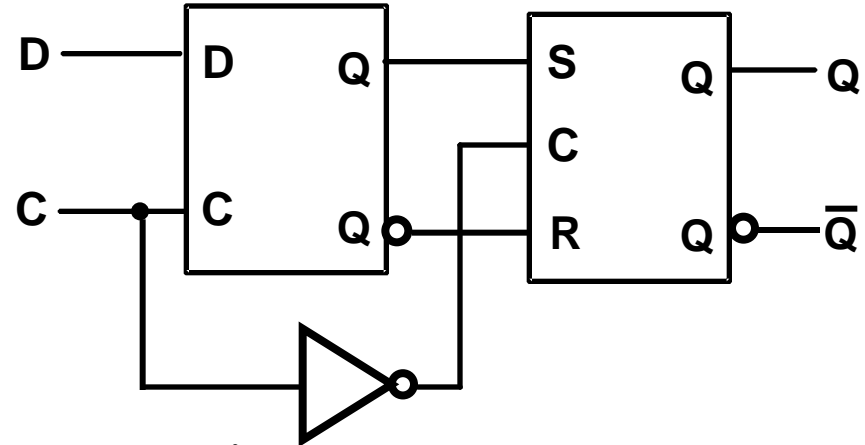
- The change in the flip-flop output is delayed by the pulse width which makes the circuit slower or
- S and/or R are permitted to change while $C = 1$
 - Suppose $Q = 0$ and S goes to 1 and then back to 0 with R remaining at 0
 - The master latch sets to 1
 - A 1 is transferred to the slave
 - Suppose $Q = 0$ and S goes to 1 and back to 0 and R goes to 1 and back to 0
 - The master latch sets and then resets
 - A 0 is transferred to the slave
 - This behavior is called *1s catching*

Flip-Flop Solution

- Use edge-triggering instead of master-slave
- An *edge-triggered* flip-flop ignores the pulse while it is at a constant level and triggers only during a transition of the clock signal
- Edge-triggered flip-flops can be built directly at the electronic circuit level, or
- A master-slave D flip-flop which also exhibits edge-triggered behavior can be used.

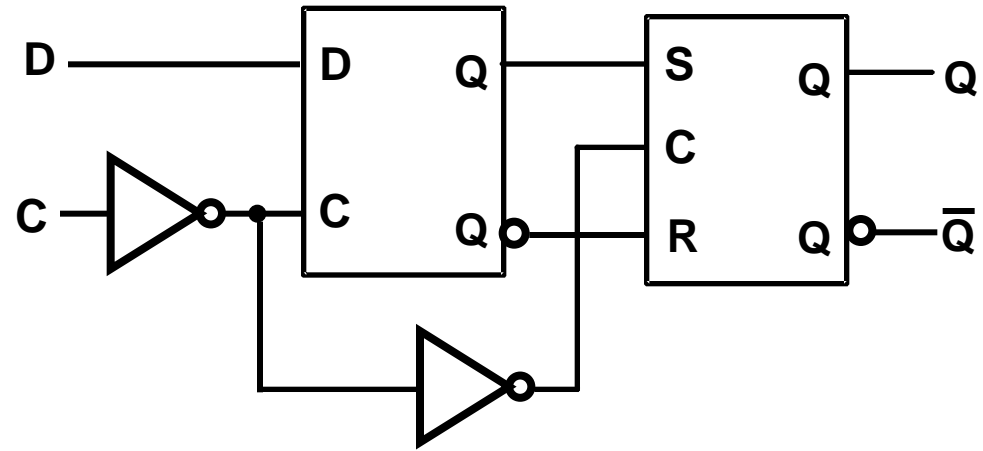
Edge-Triggered D Flip-Flop

- The edge-triggered D flip-flop is the same as the master-slave D flip-flop
- It can be formed by:
 - Replacing the first clocked S-R latch with a clocked D latch or
 - Adding a D input and inverter to a master-slave S-R flip-flop
- The delay of the S-R master-slave flip-flop can be avoided since the 1s-catching behavior is not present with D replacing S and R inputs
- The change of the D flip-flop output is associated with the negative edge at the end of the pulse
- It is called a *negative-edge triggered* flip-flop



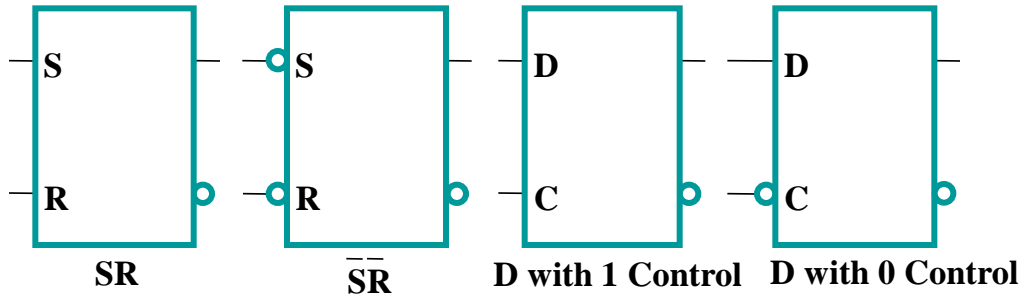
Positive-Edge Triggered D Flip-Flop

- Formed by adding inverter to clock input



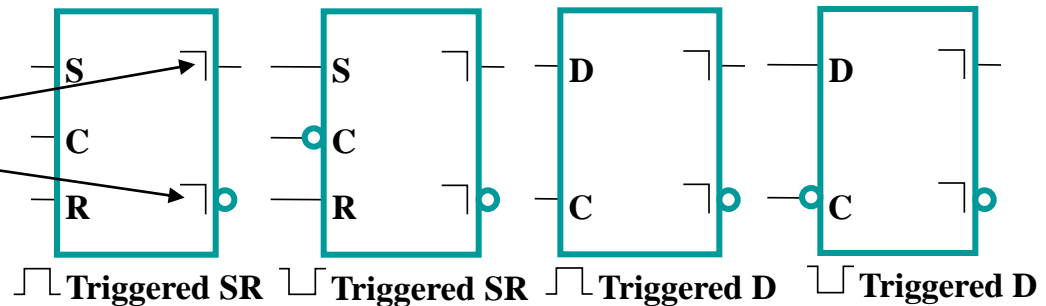
- Q changes to the value on D applied at the positive clock edge within timing constraints to be specified
- Our choice as the standard flip-flop for most sequential circuits

Standard Symbols for Storage Elements



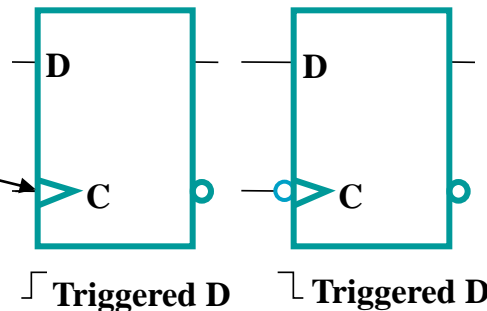
(a) Latches

- **Master-Slave:**
Postponed output
indicators



(b) Master-Slave Flip-Flops

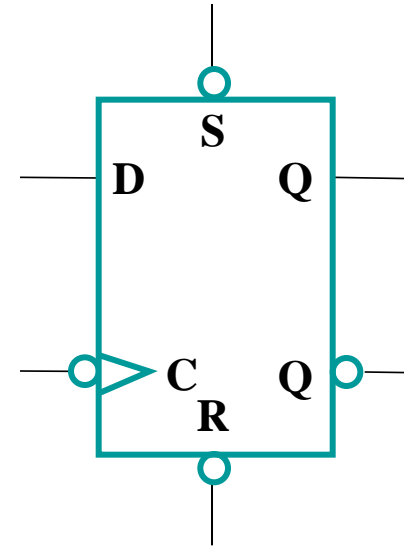
- **Edge-Triggered:**
Dynamic
indicator



(c) Edge-Triggered Flip-Flops

Direct Inputs

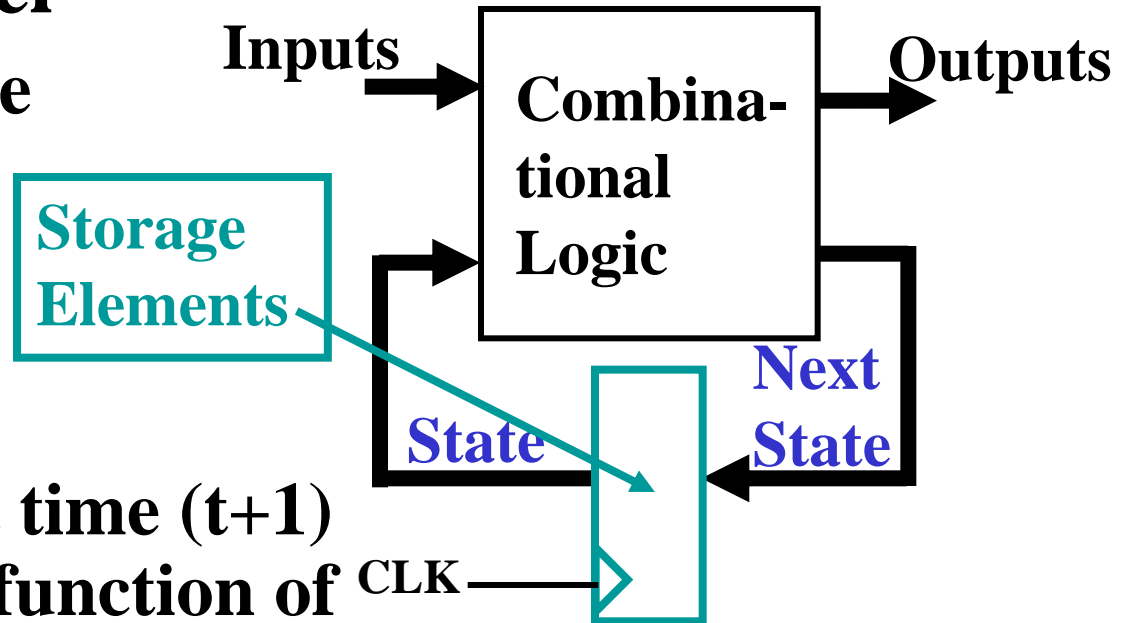
- At power up or at reset, all or part of a sequential circuit usually is initialized to a known state before it begins operation
- This initialization is often done outside of the clocked behavior of the circuit, i.e., asynchronously.
- Direct R and/or S inputs that control the state of the latches within the flip-flops are used for this initialization.
- For the example flip-flop shown
 - 0 applied to \bar{R} resets the flip-flop to the 0 state
 - 0 applied to \bar{S} sets the flip-flop to the 1 state



Sequential Circuit Analysis

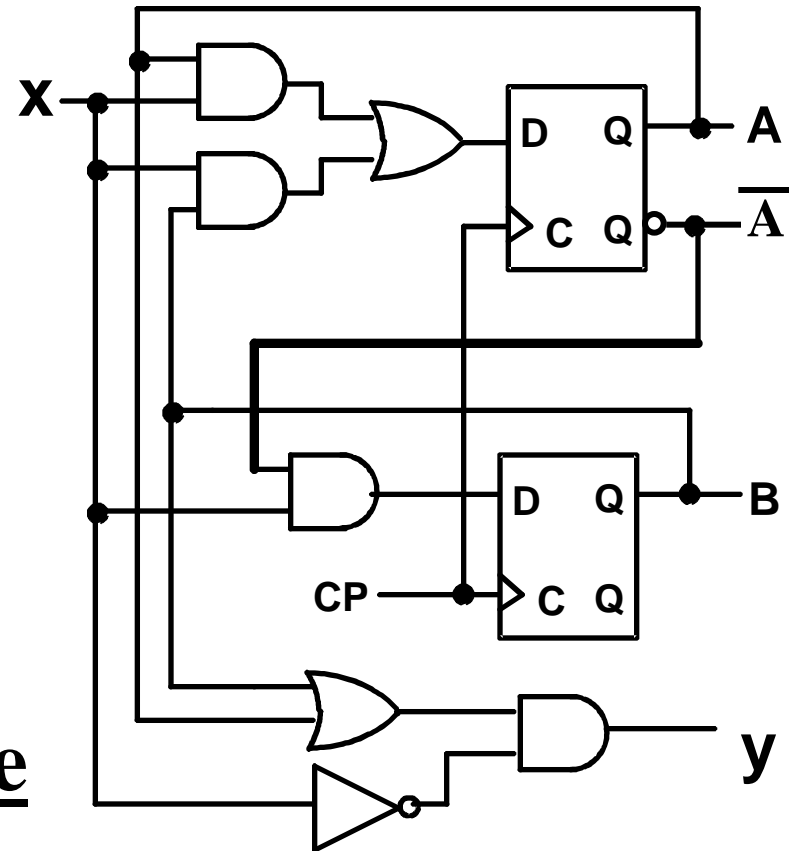
■ General Model

- **Current State** at time (t) is stored in an array of flip-flops.
- **Next State** at time (t+1) is a Boolean function of **State** and **Inputs**.
- **Outputs** at time (t) are a Boolean function of **State** (t) and (sometimes) **Inputs** (t).



Example 1 (from Fig. 5-15)

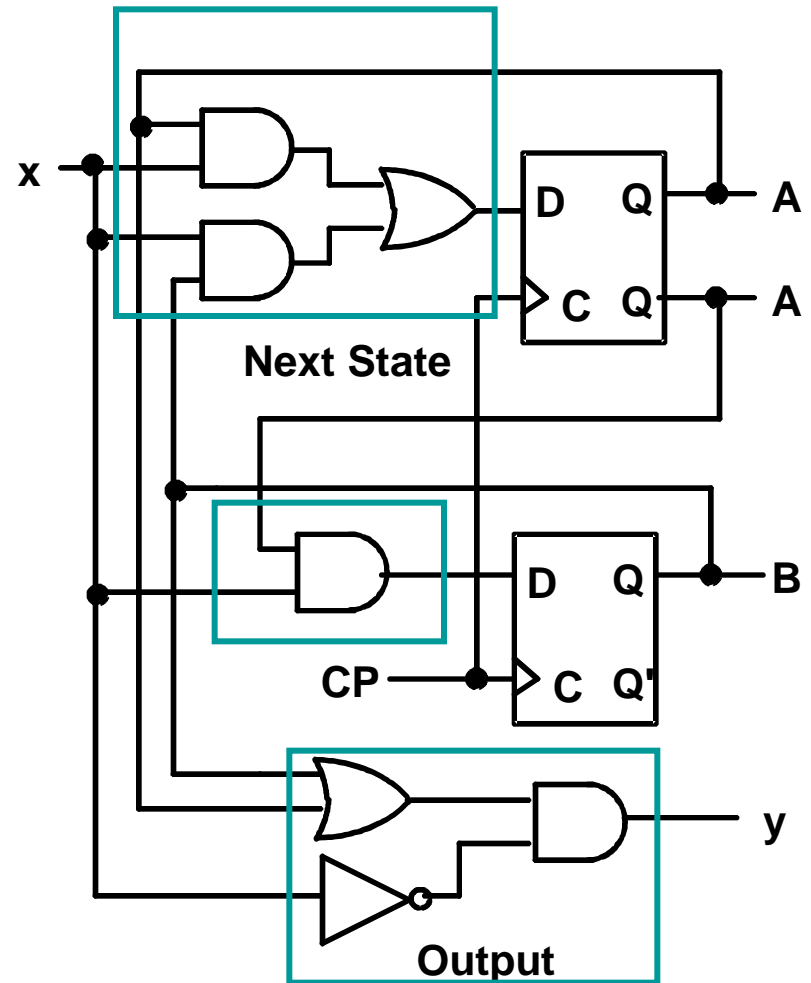
- Input: $x(t)$
- Output: $y(t)$
- State: $(A(t), B(t))$
- What is the Output Function?
- What is the Next State Function?



Example 1 (from Fig. 5-15) (continued)

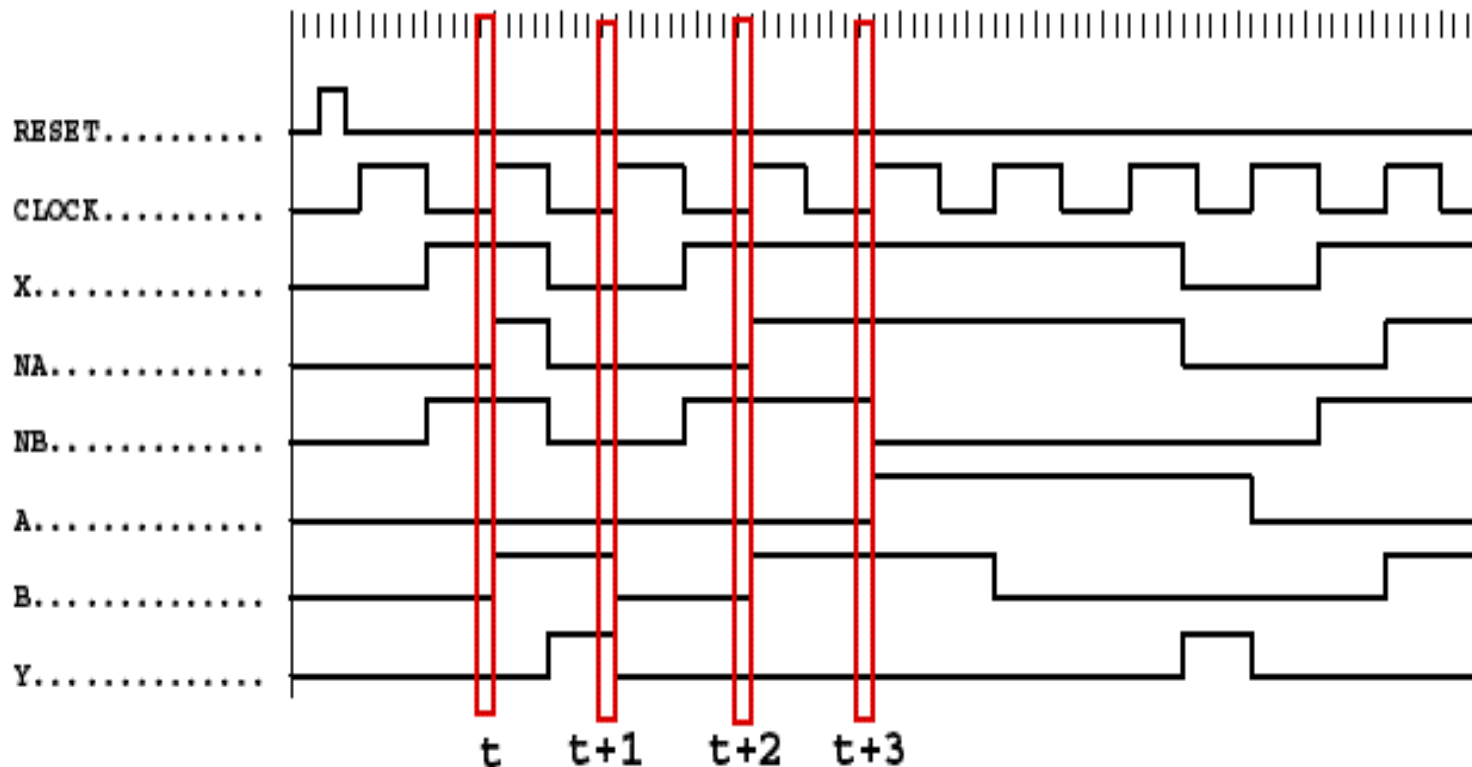
■ Boolean equations for the functions:

- $A(t+1) = A(t)x(t) + B(t)x(t)$
- $B(t+1) = \bar{A}(t)x(t)$
- $y(t) = \bar{x}(t)(B(t) + A(t))$



Example 1(from Fig. 5-15) (continued)

- Where in time are inputs, outputs and states defined?



State Table Characteristics

- ***State table*** – a multiple variable table with the following four sections:
 - ***Present State*** – the values of the state variables for each allowed state.
 - ***Input*** – the input combinations allowed.
 - ***Next-state*** – the value of the state at time $(t+1)$ based on the present state and the input.
 - ***Output*** – the value of the output as a function of the present state and (sometimes) the input.
- **From the viewpoint of a truth table:**
 - the inputs are Input, Present State
 - and the outputs are Output, Next State

Example 1: State Table (from Fig. 5-15)

- The state table can be filled in using the next state and output equations:
$$A(t+1) = A(t)x(t) + B(t)x(t)$$
$$B(t+1) = \bar{A}(t)x(t)$$
$$y(t) = \bar{x}(t)(B(t) + A(t))$$

Present State		Input	Next State		Output
A(t)	B(t)	x(t)	A(t+1)	B(t+1)	y(t)
0	0	0	0	0	0
0	0	1	0	1	0
0	1	0	0	0	1
0	1	1	1	1	0
1	0	0	0	0	1
1	0	1	1	0	0
1	1	0	0	0	1
1	1	1	1	0	0

Example 1: Alternate State Table

- 2-dimensional table that matches well to a K-map.
Present state rows and input columns in Gray code order.

- $A(t+1) = A(t)x(t) + B(t)x(t)$
- $B(t+1) = \bar{A}(t)x(t)$
- $y(t) = \bar{x}(t)(B(t) + A(t))$

Present State A(t) B(t)	Next State		Output	
	x(t)=0	x(t)=1	x(t)=0	x(t)=1
	A(t+1)B(t+1)	A(t+1)B(t+1)	y(t)	y(t)
0 0	0 0	0 1	0	0
0 1	0 0	1 1	1	0
1 0	0 0	1 0	1	0
1 1	0 0	1 0	1	0

State Diagrams

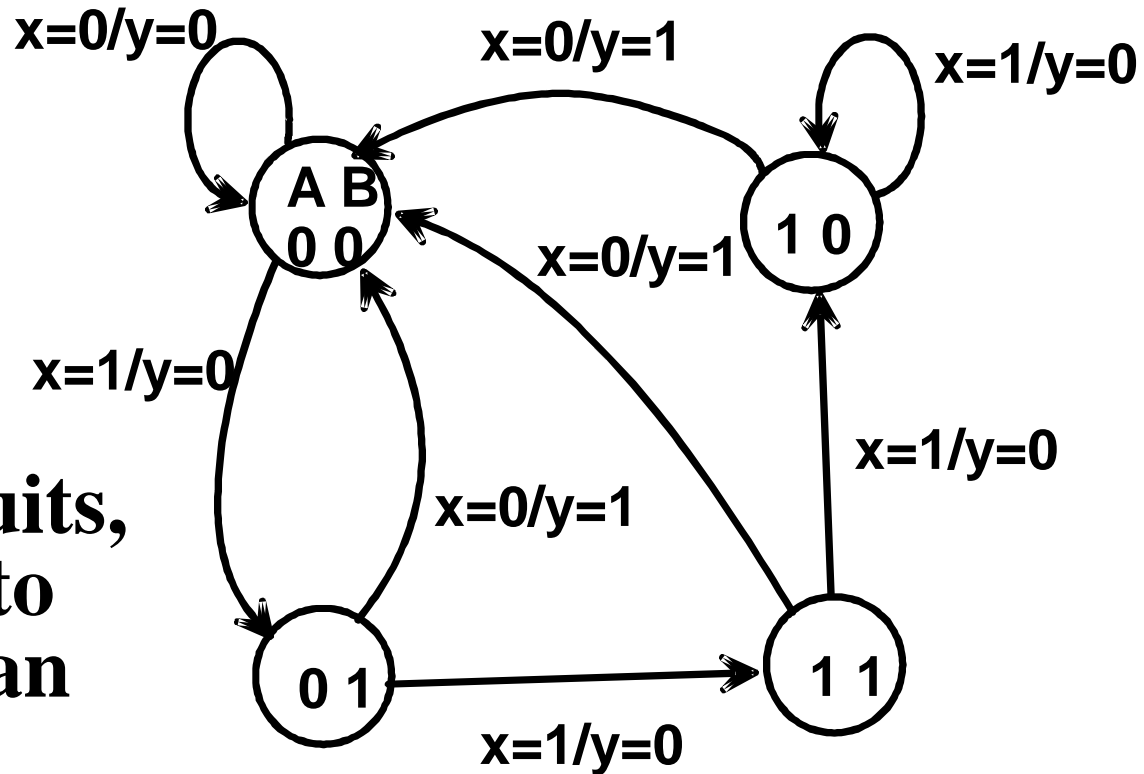
- The sequential circuit function can be represented in graphical form as a state diagram with the following components:
 - A circle with the state name in it for each state
 - A directed arc from the Present State to the Next State for each state transition
 - A label on each directed arc with the Input values which causes the state transition, and
 - A label:
 - On each circle with the output value produced, or
 - On each directed arc with the output value produced.

State Diagrams

- **Label form:**
 - **On circle with output included:**
 - **state/output**
 - **Moore type output depends only on state**
 - **On directed arc with the output included:**
 - **input/output**
 - **Mealy type output depends on state and input**

Example 1: State Diagram

- Which type?
- Diagram gets confusing for large circuits
- For small circuits, usually easier to understand than the state table



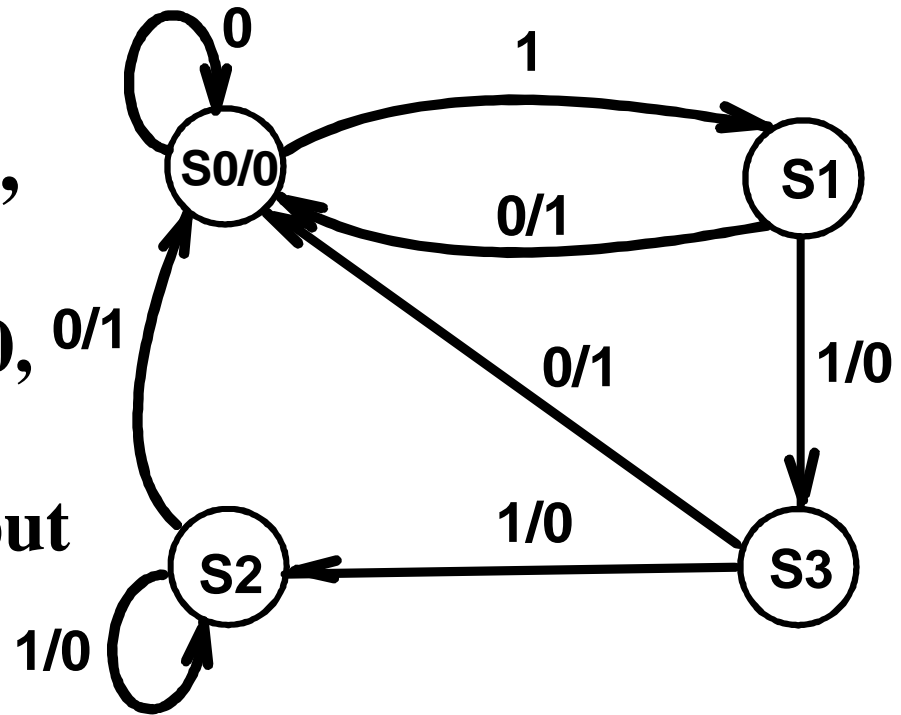
Equivalent State Definitions

- Two states are *equivalent* if their response for each possible input sequence is an identical output sequence.
- Alternatively, two states are *equivalent* if their outputs produced for each input symbol is identical and their next states for each input symbol are the same or equivalent.

Equivalent State Example

- Text Figure 5-17(a):
- For states S3 and S2,

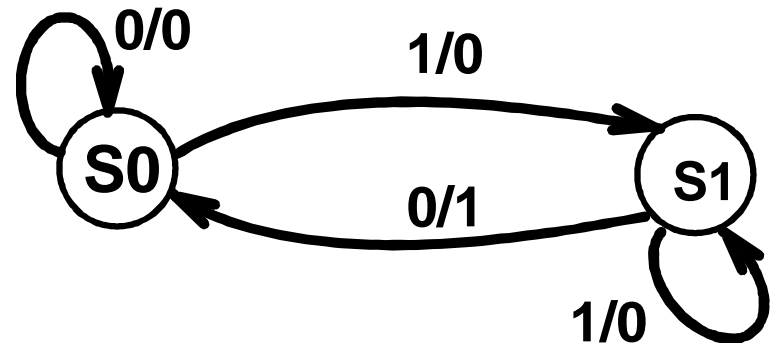
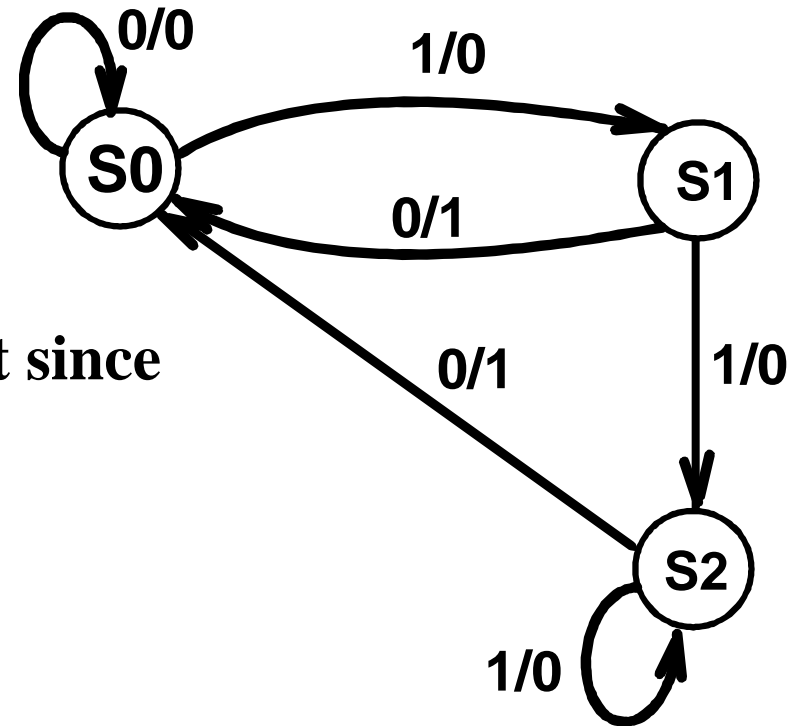
- the output for input 0 is 1 and input 1 is 0, and
- the next state for input 0 is S0 and for input 1 is S2.



- By the alternative definition, states S3 and S2 are equivalent.

Equivalent State Example

- Replacing S3 and S2 by a single state gives state diagram:
- Examining the new diagram, states S1 and S2 are equivalent since
 - their outputs for input 0 is 1 and input 1 is 0, and
 - their next state for input 0 is S0 and for input 1 is S2,
- Replacing S1 and S2 by a single state gives state diagram:



Moore and Mealy Models

- **Sequential Circuits or Sequential Machines are also called *Finite State Machines* (FSMs). Two formal models exist:**

- **Moore Model**

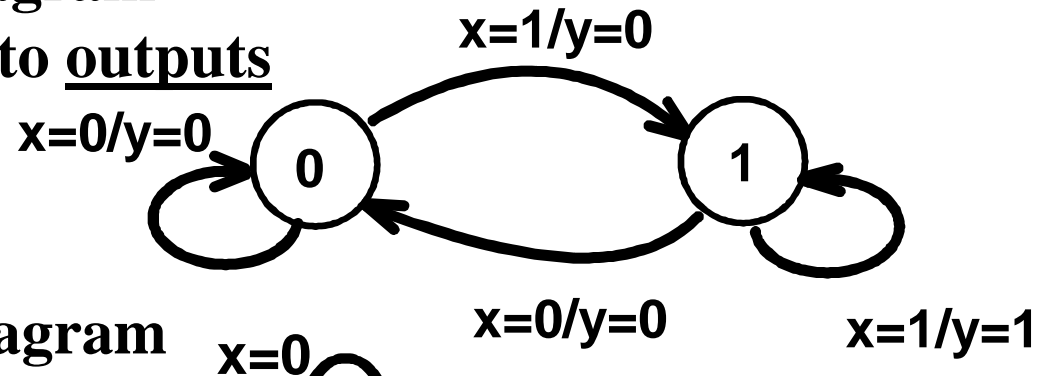
- **Named after E.F. Moore**
- **Outputs are a function ONLY of states**
- **Usually specified on the states.**

- **Mealy Model**

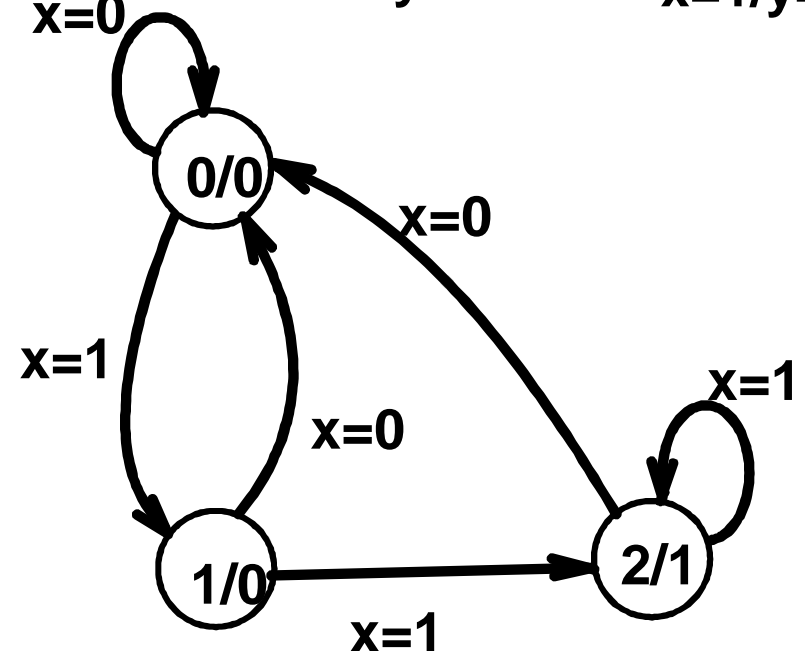
- **Named after G. Mealy**
- **Outputs are a function of inputs AND states**
- **Usually specified on the state transition arcs.**

Moore and Mealy Example Diagrams

- Mealy Model State Diagram
maps inputs and state to outputs



- Moore Model State Diagram
maps states to outputs



Moore and Mealy Example Tables

- **Moore Model state table maps state to outputs**

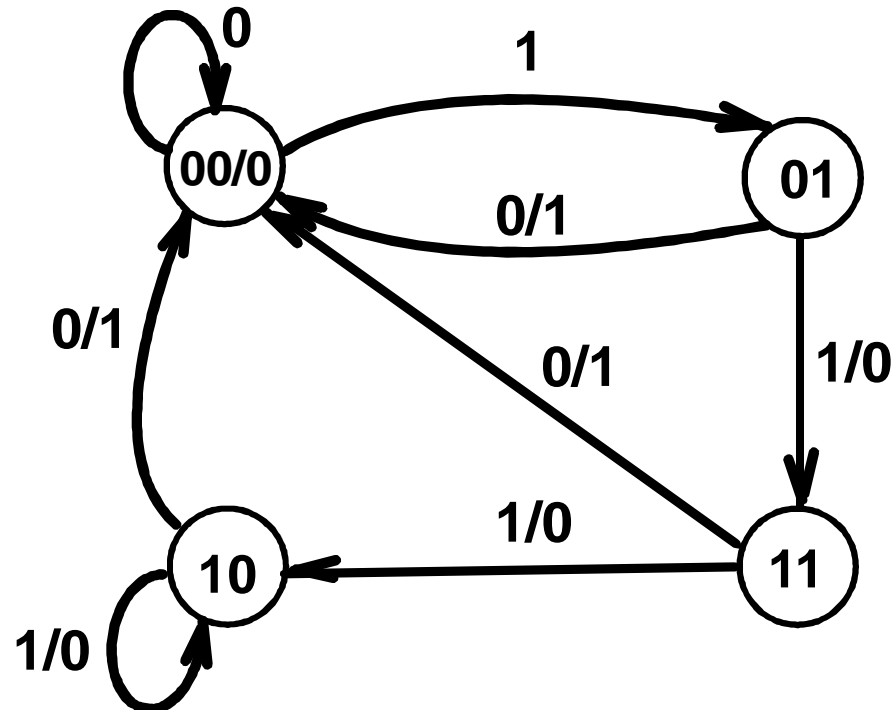
Present State	Next State		Output
	x=0	x=1	
0	0	1	0
1	0	2	0
2	0	2	1

- **Mealy Model state table maps inputs and state to outputs**

Present State	Next State		Output	
	x=0	x=1	x=0	x=1
0	0	1	0	0
1	0	1	0	1

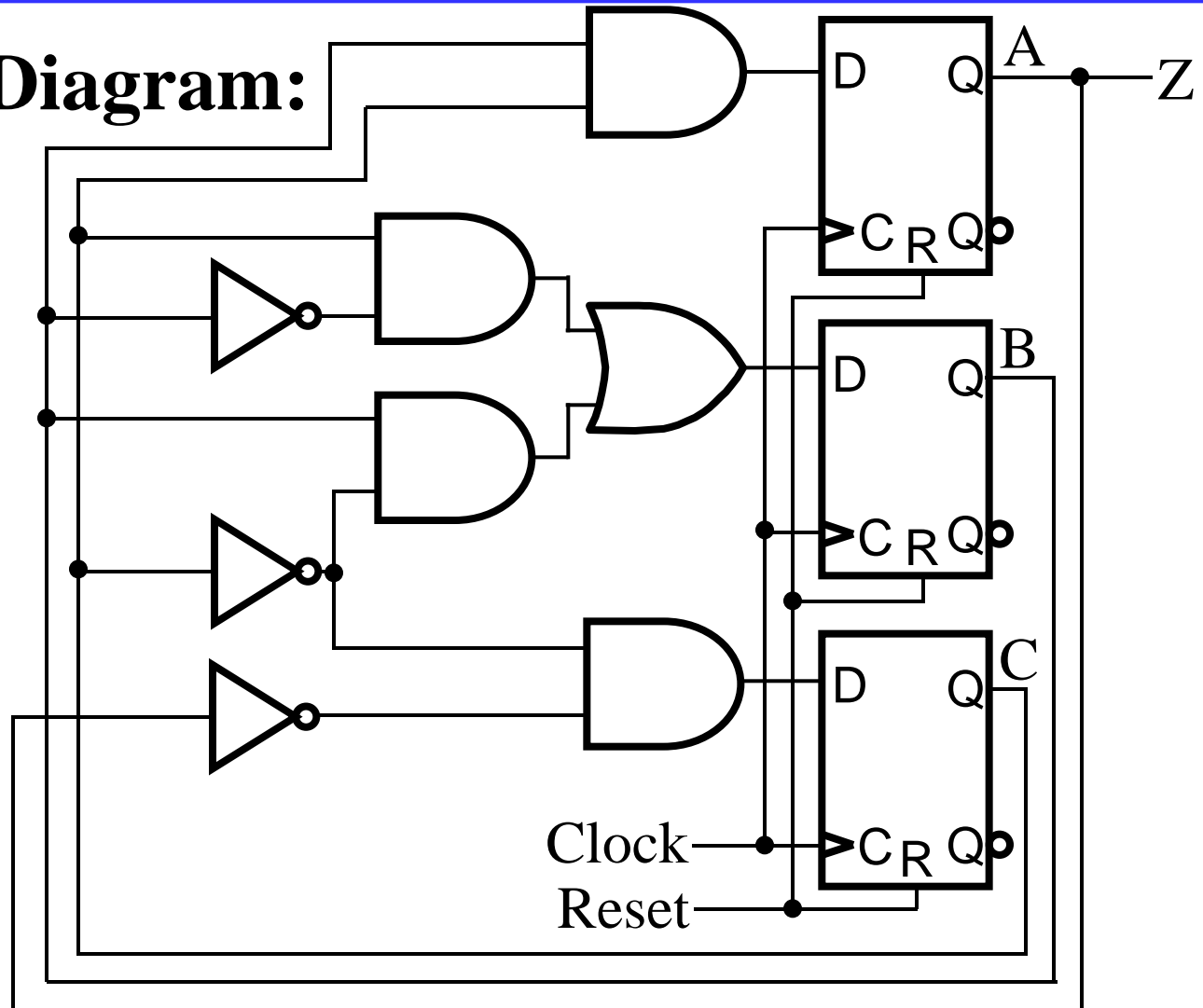
Mixed Moore and Mealy Outputs

- In real designs, some outputs may be Moore type and other outputs may be Mealy type.
- Example: Figure 5-17(a) can be modified to illustrate this
 - State 00: Moore
 - States 01, 10, and 11: Mealy
- Simplifies output specification



Example 2: Sequential Circuit Analysis

- **Logic Diagram:**



Example 2: Flip-Flop Input Equations

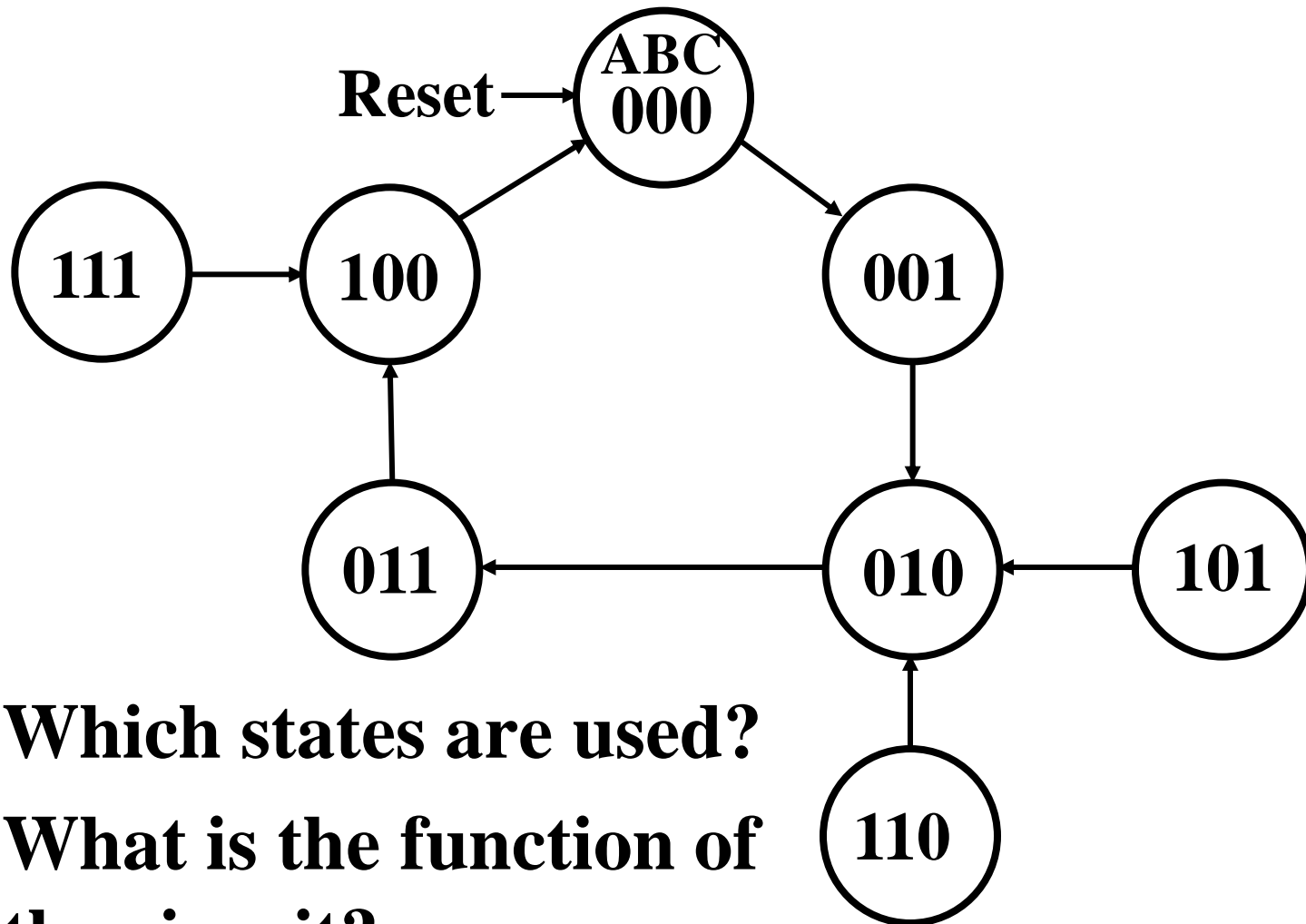
- **Variables**
 - **Inputs: None**
 - **Outputs: Z**
 - **State Variables: A, B, C**
- **Initialization: Reset to (0,0,0)**
- **Equations**
 - $A(t+1) =$ $Z =$
 - $B(t+1) =$
 - $C(t+1) =$

Example 2: State Table

$X' = X(t+1)$

A B C	A'B'C'	Z
0 0 0		
0 0 1		
0 1 0		
0 1 1		
1 0 0		
1 0 1		
1 1 0		
1 1 1		

Example 2: State Diagram



- Which states are used?
- What is the function of the circuit?

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