

Chapter 5

Synchronous Sequential Logic

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1

Introduction

- Circuits require memory to store intermediate data
- Sequential circuits use a periodic signal to determine when to store values.
 - A **clock** signal can determine storage times
 - **Clock** signals are periodic
- Single bit storage element is a **flip flop**
- A basic type of flip flop is a **latch**
- Latches are made from logic gates
 - NAND, NOR, AND, OR, Inverter

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2

Synchronous vs. Asynchronous

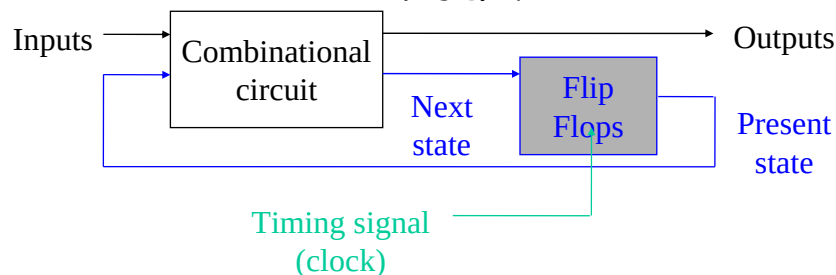
- Synchronous sequential circuit is a system whose behavior can be defined from the knowledge of its signal at discrete instants of time
- Asynchronous sequential circuit is a system whose behavior can be defined from the knowledge of its signals at any point of time

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Synchronous Sequential Circuit



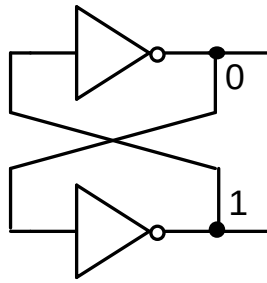
Clock

synchronizes when current state changes happen
keeps system well-behaved
makes it easier to design and build large systems

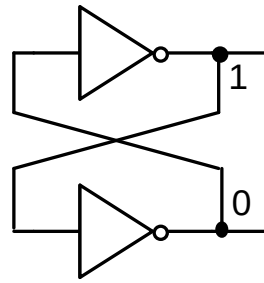
Clock

4

Cross Coupled Inverters



State 1



State 2

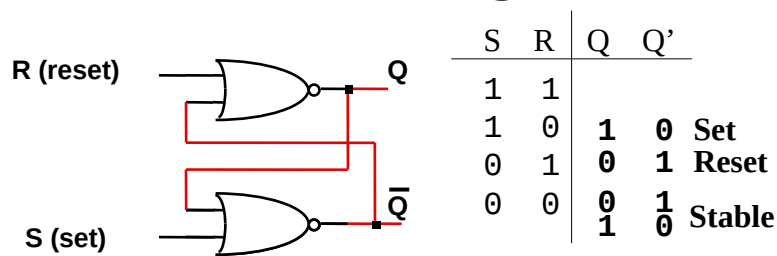
What if there is an inverter in the feedback path?

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SR Latch using NOR



°S-R latch made from **cross-coupled** NORs

°If $Q = 1$, set state

°If $Q = 0$, reset state

°Usually $S=0$ and $R=0$

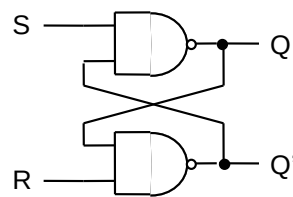
° $S=1$ and $R=1$ generates unpredictable results

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SR latch using NAND



S	R	Q	Q'	
0	0	1	1	Disallowed
0	1	1	0	Set
1	0	0	1	Reset
1	1	0	1	Store

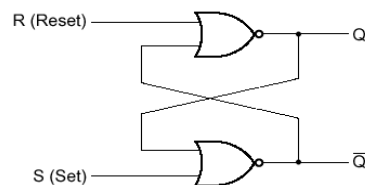
- Latch made from **cross-coupled** NANDs
- Sometimes called S'-R' latch
- Usually S=1 and R=1
- S=0 and R=0 generates unpredictable results

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7

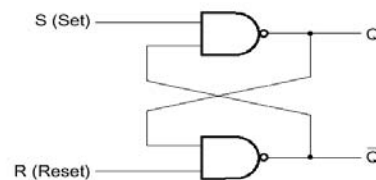
SR Latch



(a) Logic diagram

S	R	Q	$\bar{Q}$	
1	0	1	0	Set state
0	0	1	0	
0	1	0	1	Reset state
0	0	0	1	
1	1	0	0	Undefined

(b) Function table



(a) Logic diagram

S	R	Q	$\bar{Q}$	
0	1	1	0	Set state
1	1	1	0	
1	0	0	1	Reset state
1	1	0	1	
0	0	1	1	Undefined

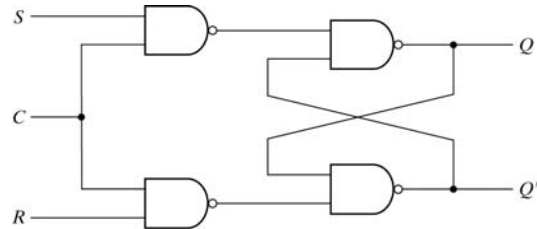
(b) Function table

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SR Latch with Control Input



(a) Logic diagram

C	S	R	Next state of Q
0	X	X	No change
1	0	0	No change
1	0	1	$Q = 0$; Reset state
1	1	0	$Q = 1$; set state
1	1	1	Indeterminate

(b) Function table

Fig. 5-5 SR Latch with Control Input

° Occasionally, desirable to avoid latch changes

° $C = 0$ disables all latch state changes

° Control signal enables data change when $C = 1$

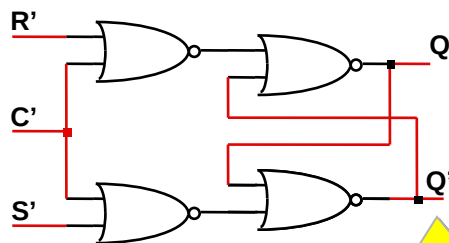
° Right side of circuit same as ordinary S-R latch.

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9

SR Latch with Control Input



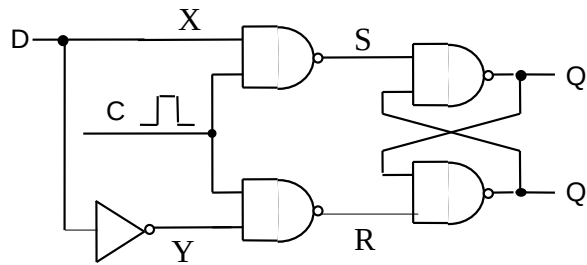
Outputs change
when C is low:
RESET and SET
Otherwise: HOLD

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D Latch



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11

D Latch

- One way to avoid the indeterminate state in the SR latch when both S and R are 1. This is done by inverting S and having the inverted S as R.
- As long as C=0, no change. If C=1 D is delivered to Q and D' to Q'.

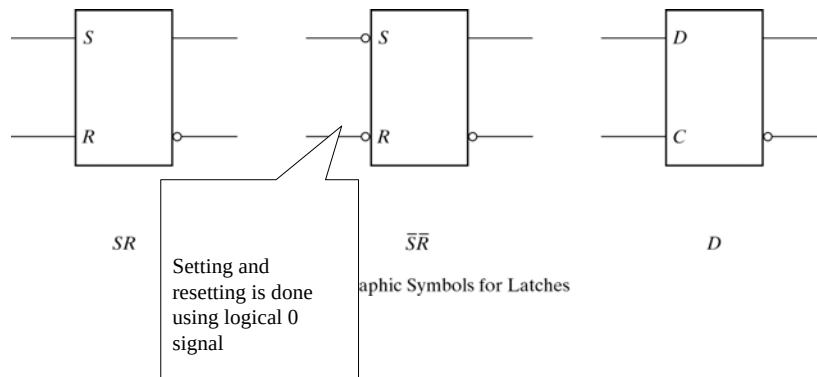
C	D	Q	Q'
0	X	Q	Q'
1	1	1	0
1	0	0	1

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12

Symbols



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Flip-Flops

- The state of the latch or flip-flop is switched by a change in the control input, this is called a *trigger*
- The D latch with pulses in its control input. As long as the pulse input is 1, any changes in the D input is transferred to the output.
- When the state of the latch changes, if the control pulse is still at logic 1, any changes to the input (possible a feedback from the output) will change the output.
- Because of this, the output of a latch can not be applied directly to the input of this or other latches

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14

Flip-Flop

- A better way is if the flip-flop is triggered during the transition of the control input.
- A clock pulse goes through 2 transitions, $1 \rightarrow 0$ and $0 \rightarrow 1$.
- The first is called –ve edge, the second is positive edge.
- There are two ways to implement this, either by using master-slave or by special design of the circuit.

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15

Edge-Triggered Flip-Flop (Master-Slave)

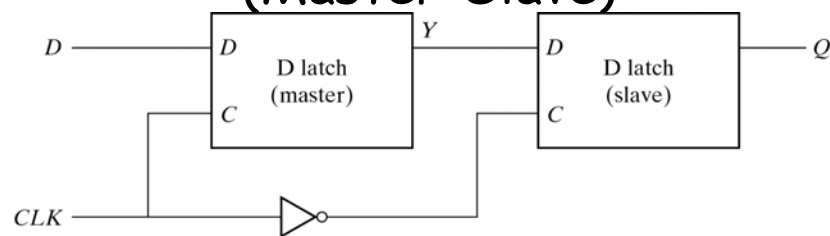


Fig. 5-9 Master-Slave *D* Flip-Flop

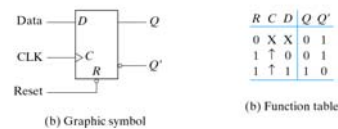
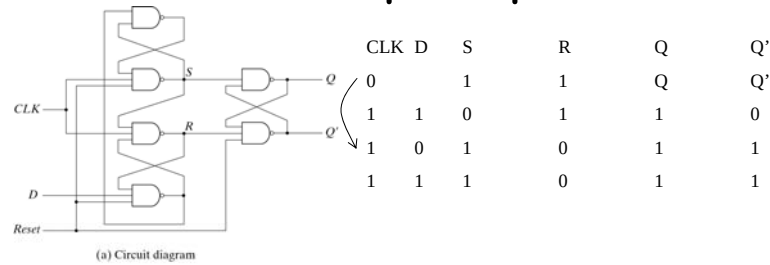
Any changes in the input can affect only Y as long as CLK=1; After CLK=0, Y propagates to Q, but the master is locked.

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16

D-Type Positive-Edge-triggered Flip-Flop



R	C	D	Q	Q'
0	X	X	0	1
1	↑	0	0	1
1	↑	1	1	0

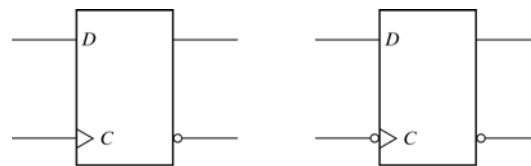
Fig. 5-14 D Flip-Flop with Asynchronous Reset

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17

Edge-triggered Flip-Flop



(a) Positive-edge

(a) Negative-edge

Fig. 5-11 Graphic Symbol for Edge-Triggered D Flip-Flop

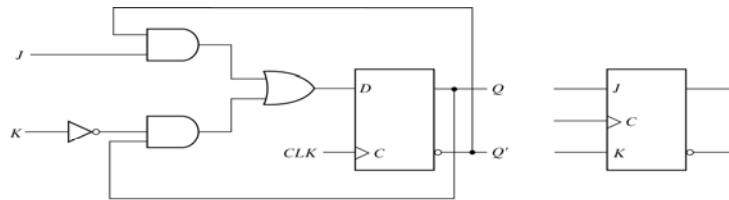


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J-K Flip-Flop



(a) Circuit diagram

(b) Graphic symbol

Fig. 5-12 JK Flip-Flop

°Created from D flop

°J sets

°K resets

°J=K=1 -> invert output

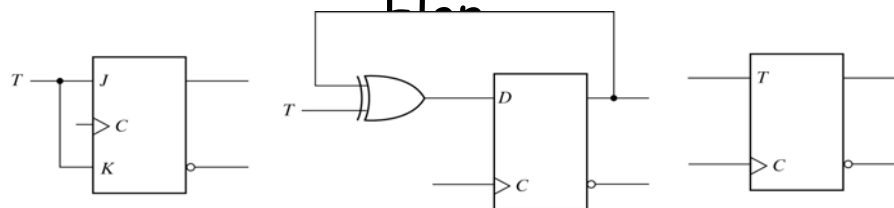
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J	K	CLK	Q	Q'
0	0	↑	Q_0	Q_0'
0	1	↑	0	1
1	0	↑	1	0
1	1	↑	TOGGLE	

19

Positive Edge Triggered T Flip-Flop



(a) From JK flip-flop

(b) From D flip-flop

(c) Graphic symbol

Fig. 5-13 T Flip-Flop

°Created from D flop

°T=0 -> keep current

°K resets

°T=1 -> invert current

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T	C	Q	Q'
	0	Q_0	Q_0'
	↑	TOGGLE	

20

Characteristic Tables

- Characteristic tables Describes the operation of the flip-flop in a tabular

JK Flip Flop			D Flip Flop		T Flip Flop	
J	K	Q(t+1)	D	Q(t+1)	T	Q(t+1)
0	0	Q(t)	0	0	0	Q(t)
0	1	0	1	1	1	Q'(t)
1	0	1				
1	1	Q'(t)				

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21

Characteristic Equation

- For D Flip-Flop

$$Q(t+1) = D$$

- For JK Flip-Flop

$$Q(t+1) = JQ' + K'Q$$

- For T Flip-Flop

$$Q(t+1) = T \oplus Q = TQ' + T'Q$$

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22

Analysis of Clocked Sequential Circuits

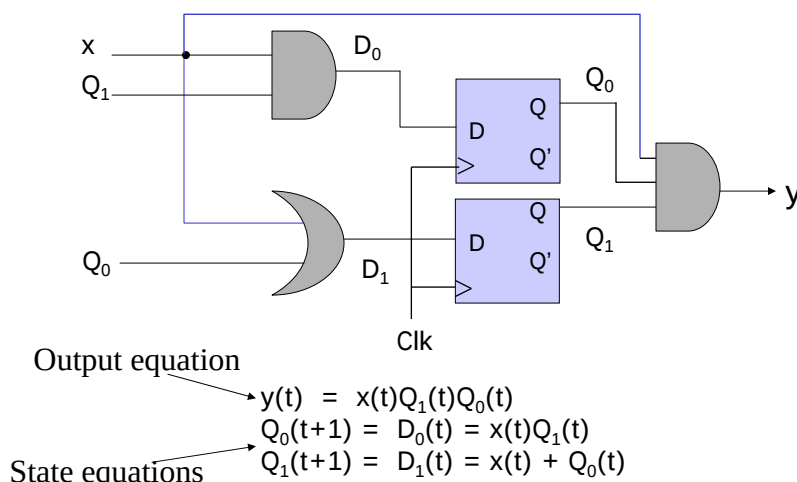
- State equation, state table
- State diagram: states are represented by circuits, transitions by arcs labeled I/O
- Flip-Flop Equations:

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Analysis



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24

State Table

- Sequence of outputs, inputs, and flip flop states enumerated in state table
- **Present state** indicates current value of flip flops
- **Next state** indicates state after next rising clock edge
- **Output** is output value on current clock edge

State Table

Present State	Next State		Output	
	x=0	x=1	x=0	x=1
0 0	00	10	0	0
0 1	10	10	0	0
1 0	00	11	0	0
1 1	10	11	0	1

$Q_1(t) \quad Q_0(t)$ $Q_1(t+1) \quad Q_0(t+1)$

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25

State Table

- All possible input combinations enumerated
- All possible state combinations enumerated
- Separate columns for each output value.
- Sometimes easier to designate a symbol for each state.

Let:

Present State	Next State		Output	
	x=0	x=1	x=0	x=1
$s_0 = 00$	s_0	s_2	0	0
$s_1 = 01$	s_1	s_2	0	0
$s_2 = 10$	s_2	s_3	0	0
$s_3 = 11$	s_3	s_2	0	1

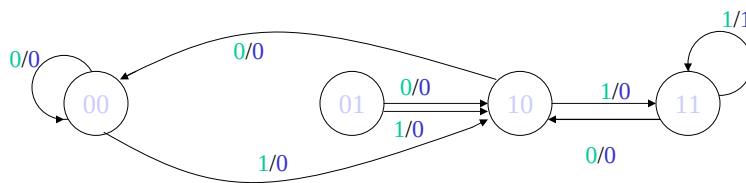
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26

State Diagram

Present State	Next State		Output	
	x=0	x=1	x=0	x=1
0 0	00	10	0	0
0 1	10	10	0	0
1 0	00	11	0	0
1 1	10	11	0	1



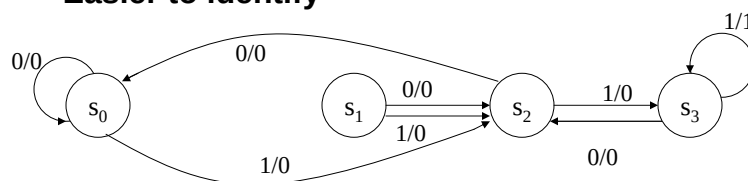
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27

State Diagram

- Each state has two arrows leaving
 - One for $x = 0$ and one for $x = 1$
- Unlimited arrows can enter a state
- Note use of state names in this example
 - Easier to identify



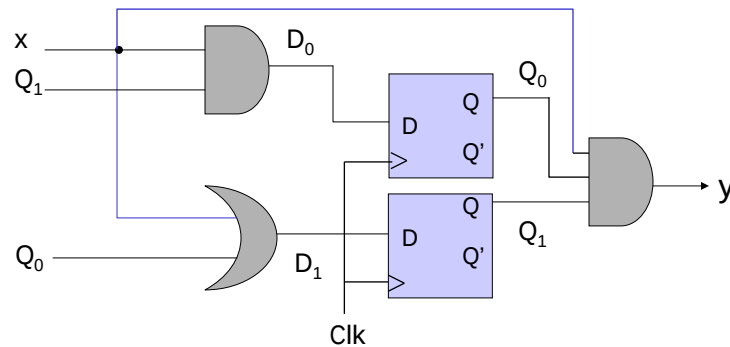
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28

Flip-Flop Input Equations

- ° Boolean expressions which indicate the input to the flip flops.



$$D_{Q0} = xQ_1$$

$$D_{Q1} = x + Q_0$$

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Format implies type of flop used

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29

Analysis with D Flip-Flop

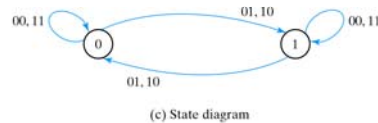
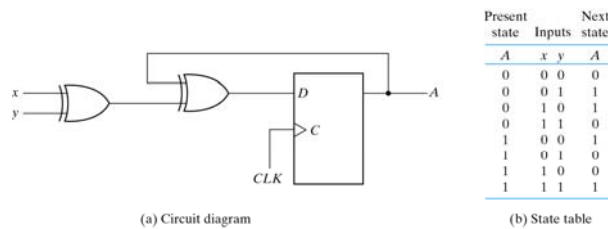


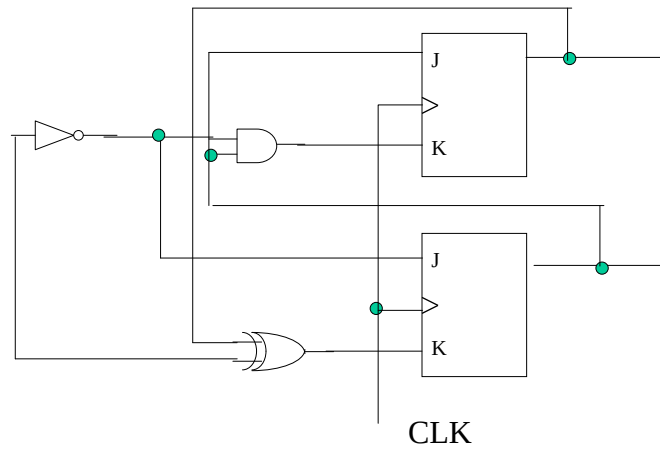
Fig. 5-17 Sequential Circuit with D Flip-Flop

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30

J-K Flip-Flop



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31

J-K Flip Flop

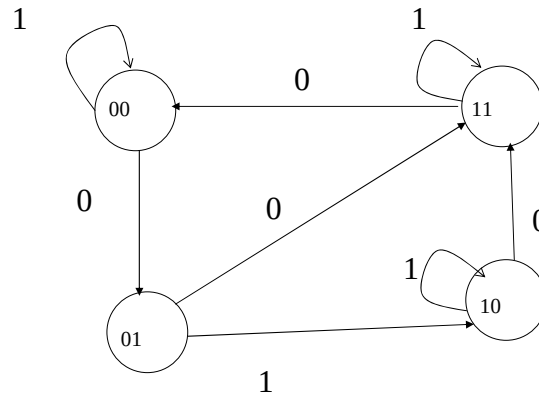
Present		Input	Next		Flip-Flop Inputs			
A	B	X	A	B	J_A	K_A	J_B	K_B
0	0	0	0	1	0	0	1	0
0	0	1	0	0	0	0	0	1
0	1	0	1	1	1	1	1	0
0	1	1	1	0	1	0	0	1
1	0	0	1	1	0	0	1	1
1	0	1	1	0	0	0	0	0
1	1	0	0	0	1	1	1	1
1	1	1	1	1	1	0	0	0

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32

J-K Flip-Flop



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33

Mealy and Moore Models

- Mealy model: the output is a function of both the present state and the input.
- Moore model: The output is a function of the present state only.
- In a Moore model, the output is synchronized with the clock (since it changes only if the state changes).
- In a Mealy model the output may change if the input changes during the clock cycle.

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34

HDL For Sequential Circuits

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35

Behavioral Modeling

```
initial  
begin  
  clock=1'b0;  
  repeat(30)  
    #10 clock = ~clock  
end
```

```
initial  
begin  
  clock = 1'b0;  
  #300 $finish;  
end;  
always  
  #10 clock=~clock;
```

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Behavioral Modeling

- One ways to use always statement

always @ (A or B or reset)

- What fellows will be done if any changes in A, B, or reset,
- Or, we can use

Always @ (posedge clock or negedge reset)

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Behavioral Modeling

- Blocking assignmnet

B=A;

C=B+1;

- A is assigned to B, and the new value is incremented
- Non-blocking assignment

B<=A; C<=B+1;

- Incrementing old value of A, because assignment is done after all the values in the block are done

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Flip-Flops and Latches

```
//Description of D latch
module D_Latch (Q,D,control);
  output Q;
  input D, control;
  reg Q;
  always @ (control or D)
  if (control) Q=D;
endmodule
```

```
//D Flip-Flop
module D_FF(Q, D, CLK);
  output Q;
  input D, CLK;
  reg Q;
  always @ (posedge CLK)
    Q=D;
endmodule
```

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39

Flip-Flops and Latches

```
//D Flip-Flop with Asynchronous reset
module DFF(Q,D,CLK,RST);
  output Q;
  input D, CLK,RST;
  reg
  always @ (posedge CLK or negedge RST);
    if (~RST) Q=1'b0;
    else Q=D;
endmodule
```

Only if RST=1 can posedge clock
event synchronously D->Q

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40

Other Types of Flip-Flop

```
//D Flip-Flop (using D)
Module TFF(Q,T,CLK,RST);
Output Q;
Input T,CLK,RST;
Wire DT;
Assign DT=Q^T;
DFF TF1(Q,DT,CLK,RST);
endmodule
```

```
//JK Flip-Flop (using D)
Module JKFF(Q,T,CLK,RST);
Output Q;
Input JK,CLK,RST;
Wire JK;
Assign JK=(J&~Q)|(~k&Q);
DFF JK1(Q,JK,CLK,RST);
endmodule
```

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41

Other Types of Flip-Flop

```
//Functional Description of JK Flip-Flop
Module JK_FF(J,K,CLK,Q,Qnot);
output Q,Qnot;
input J,K,CLK;
reg Q;
assign Qnot=~Q
always @ (posedge CLK)
    case ({J,K})
        2'b00: Q=Q;
        2'b01: Q=1'b0;
        2'b10: Q=1'b1;
        2'b11: Q=~Q;
    endcase
endmodule
```

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42

State Diagram

```
//Mealy state diagram
module Mealy_Model(x,y,CLK,RST);
  input x,CLK,RST;
  output y;
  reg y;
  reg [1:0] Prstate, Nxtstate;
  parameter S0=2'b00, s1=2'b01, s2=2'b10, S3=2'b11;
  always @ (posedge CLK or negedge RST)
    if(~RST) Prstate = S0;
    else Prstate=Nxtstate;
  always @ (Prstate or x)
    case(Prstate)
      S0: if(x) Nxtstate = S1;
           else Nxtstate = S0;
      S1: if (x) Nxtstate = S3;
           else Nxtstate = S0;

      S2: if (x) Nxtstate = S0;
           else Nxtstate = S2;

      S3: if(x) Nxtstate = S2;
           else Nxtstate = S0;
    endcase
  always @ (Prstate or x)
    case(Prstate)
      s0: y=0;
      S1: if (x) y=1'b0; else y=1'b1;
      S2: if (x) y=1/b0; else y=1'b1;
      S3: if (x) y=1'b0; else y=1'b1;
    endcsde
  endmodule
```

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43

State Diagram

```
//Moore state diagram
module Mealy_Model(x,AB,CLK,RST);
  input x,CLK,RST;
  output [:0]AB;;
  reg [1:0] State;
  parameter S0=2'b00, s1=2'b01, s2=2'b10, S3=2'b11;
  always @ (posedge CLK or negedge RST)
    if(~RST) Prstate = S0;
    else Prstate=Nxtstate;
  always @ (Prstate or x)
    case(Prstate)
      S0: if(~x) State = S1;
           else State = S0;
      S0: if (x) State = s2;
           else State = S3;

      S0: if (x) State = S3;
           else State = S2;

      S0: if(x) State = S0;
           else State = S3;
    endcase
  assign AB=State;
endmodule
```

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44

Structural Description

```
//Figure 5-20 in the text book
module TCircuit(x,y,A,B,CLK,RST);
    input x, CLK, RST;
    output y,A,B;
    wire TA,TB;
    //Flip-Flop input equation
    assign TB=x,
           TA=x & B;
    assign y = A & B;
    // Instantiate 2 ff's
    T_FF BF (B,TB,CLK,RST);
    T_FF AF (A,TA,CLK,RST);
endmodule
```

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45

Structural Description

```
//test fixture for the previous design
module testTFF;
    reg x, CLK, RST;
    wire y,A,B;
    TCircuit (x,y,A,B,CLK,RST);
    initial
        begin
            RST=0;
            CLK=0;
            #5 RST = 1;
            repeat (16);
            #5 CLK= ~CLK;
        end
    initial
        begin
            x=0;
            #15 x=1;
            repeat (8);
            #10 x=~x
        end;
endmodule
```

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46

State Reduction and Assignment

- In this part, we study some properties of the sequential circuits in order to reduce the number of gates or flip-flops.
- If we have m flip-flops, we can have up to 2^m states.
- Thus reducing the number of states, may result in reduction of the number of flip-flops.
- Sometimes, we care only about the output produced by a specific input sequence, while in others (counters) the states are important (considered as the output).

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47

State Reduction and Assignment

- There are infinite number of sequences that could be applied to the circuit, producing some output.
- Two circuits (may have different states) will produce the same output for the same input are considered equivalent (from the input output point of view).
- We want to find a way to reduce the number of states and keeping the same input-output equivalence.

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48

State Reduction

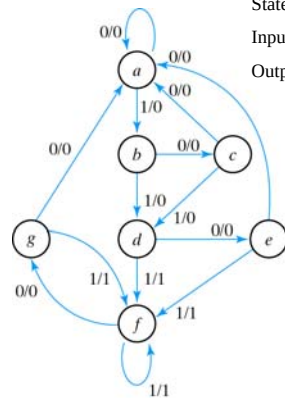


Fig. 5-22 State Diagram

State	a	a	b	c	d	e	f	g	a
Input	0	1	0	1	0	1	1	0	0
Output	0	0	0	0	0	1	1	0	0

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49

State reduction

Present State	next state		Output	
	x=0	x=1	x=0	x=1
a	a	b	0	0
b	c	d	0	0
c	a	d	0	0
d	e	f	0	1
e	a	f	0	1
f	g	f	0	1
g	a	f	0	1

look for any two state that go to the same next state and have the same output for both input combination (states g and e), remove one and replace it by the other

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50

State reduction

Present State	next state		Output	
	x=0	x=1	x=0	x=1
a	a	b	0	0
b	c	d	0	0
c	a	d	0	0
d	e	f	0	1
e	a	f	0	1
f	e	f	0	1

States d and f are equivalent

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51

State reduction

Present State	next state		Output	
	x=0	x=1	x=0	x=1
a	a	b	0	0
b	c	d	0	0
c	a	d	0	0
d	e	d	0	1
e	a	d	0	1

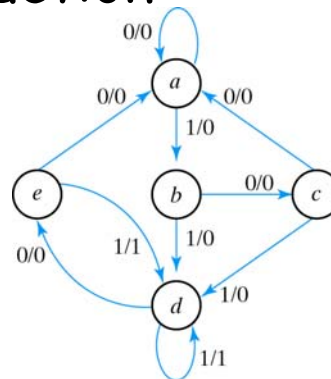


Fig. 5-23 Reduced State Diagram

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52

State Assignment

- In this stage, you have to map states to binary numbers. You can use any mapping scheme.
 - binary
 - Gray code
 - one-hot (more flip-flops)

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53

Design Procedure

- From the word description Derive the state diagram
- Reduce the number of states if necessary
- Assign Binary values to states.
- Obtain the binary-coded state table
- Choose the type of flip-flop
- Derive the simplified flip-flop input and output equations
- Draw the logic diagram

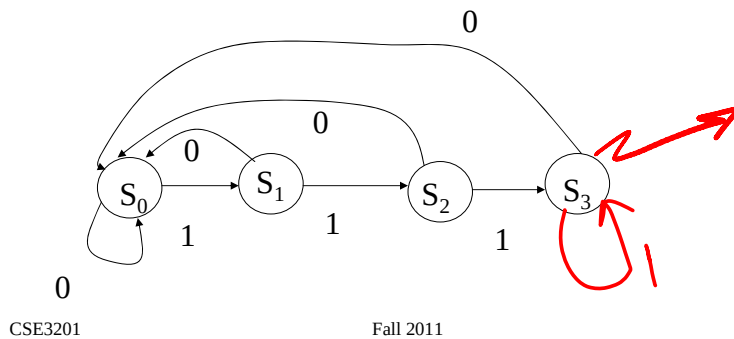
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54

Design

- Design a circuit that detects three or more consecutive ones.



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55

State table for sequence detector

Present State			Input	Next State		Output
A	B			A	B	
0	0	0	x	0	0	y
0	0	1		0	1	0
0	1	0		0	0	0
0	1	1		1	0	0
1	0	0		0	0	0
1	0	1		1	1	0
1	1	0		0	0	1
1	1	1		1	1	1



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56

Synthesis with D Flip-Flops

- Construct the state table

$$A(t+1) = D_A(A, B, X) = \sum_{ABX} (3, 5, 7)$$

$$B(t+1) = D_B(A, B, x) = \sum_{ABX} (1, 5, 7)$$

$$y(A, B, x) = \sum_{ABx} (6,7)$$

$$D_A = Ax + Bx$$

$$D_B = Ax + B'x$$

$$y = AB$$

57

Synthesis with D Flip-Flops

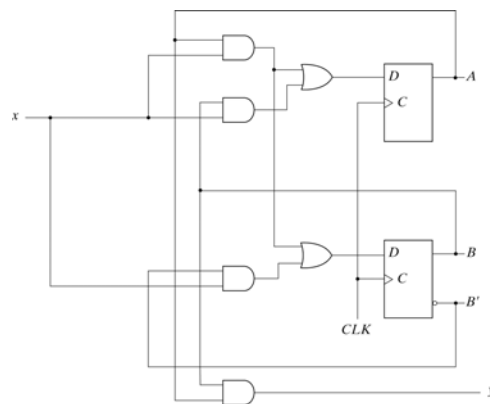


Fig. 5-26 Logic Diagram of Sequence Detector

58

Synthesis with J-K Flip-Flop

- With J-K flip-flop, it is not as easy as D, since the output is not the same as the previous input, we need an excitation table

Q(t)	Q(t+1)	J	K	Q(t)	Q(t+1)	T
0	0	0	X	0	0	0
0	1	1	X	0	1	1
1	0	X	1	1	0	1
1	1	X	0	1	1	0

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59

Synthesis with J-K Flip-Flop

Present State			Input	Next State			Output										
A	B		x	A	B		y	JA	KA	JB	KB						
0	0		0	0	0		0	0	X	0	X						
0	0		1	0	1		0	0	X	1	X						
0	1		0	0	0		0	0	X	X	1						
0	1		1	1	0		0	1	X	X	1						
1	0		0	0	0		0	X	1	0	X						
1	0		1	1	1		0	X	0	1	X						
1	1		0	0	0		1	X	1	X	1						
1	1		1	1	1		1	X	0	X	0						

T_A T_B
 0000-0-0
 0-0-0-0

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60

Synthesis with J-K Flip Flop

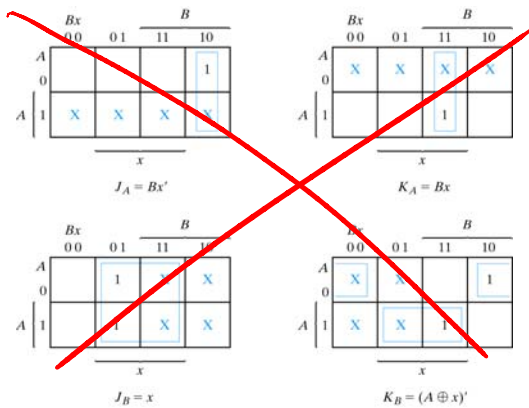


Fig. 5-27 Maps for J and K Input Equations

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61

Synthesis with J-K Flip-Flop

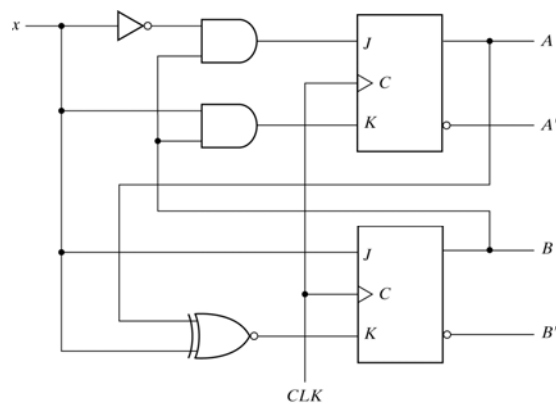


Fig. 5-28 Logic Diagram for Sequential Circuit with JK Flip-Flops

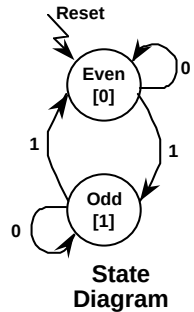
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62

Example: Odd Number of 1's

Assert output whenever input bit stream has odd # of 1's



Present State	Input	Next State	Output
0	0	0	0
0	1	1	0
1	0	1	1
1	1	0	1

- Note: Present state and output are the same value

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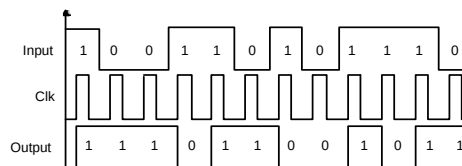
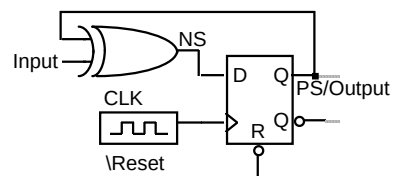
63

Odd Number of 1's

Example: Odd Parity Checker

Next State/Output Functions

$$NS = PS \text{ xor } PI; \quad OUT = PS$$



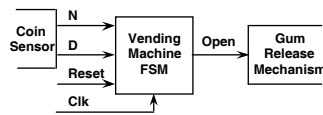
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64

Vending Machine

- ❑ Deliver package of gum after 15 cents deposited
- ❑ Single coin slot for dimes, nickels
- ❑ No change
- ❑ Design the FSM using combinational logic and flip flops

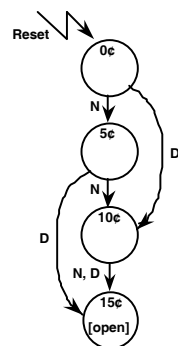


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65

Vending Machine



**Reuse states
whenever possible**

Present State	Inputs		Next State	Output Open
	D	N		
0¢	0	0	0¢	0
	0	1	5¢	0
	1	0	10¢	0
	1	1	X	X
5¢	0	0	5¢	0
	0	1	10¢	0
	1	0	15¢	0
	1	1	X	X
10¢	0	0	10¢	0
	0	1	15¢	0
	1	0	15¢	0
	1	1	X	X
15¢	X	X	15¢	1

Symbolic State Table

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66

State encoding

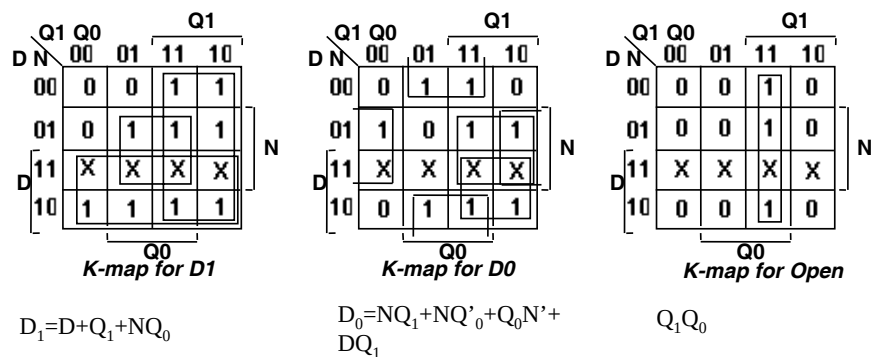
Present State Q ₁ Q ₀		Inputs D N		Next State D ₁ D ₀		Output Open
0	0	0	0	0	0	0
		0	1	0	1	0
		1	0	1	0	0
		1	1	X	X	X
0	1	0	0	0	1	0
		0	1	1	0	0
		1	0	1	1	0
		1	1	X	X	X
1	0	0	0	1	0	0
		0	1	1	1	0
		1	0	1	1	0
		1	1	X	X	X
1	1	0	0	1	1	1
		0	1	1	1	1
		1	0	1	1	1
		1	1	X	X	X

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67

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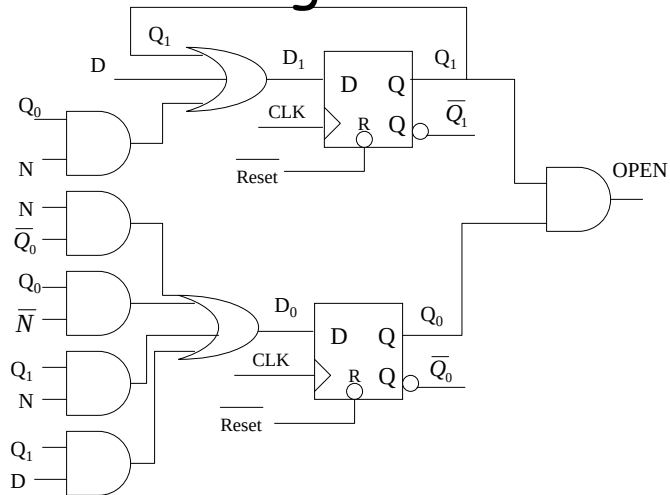


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68

Vending Machine



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69

3-bit Binary Counter

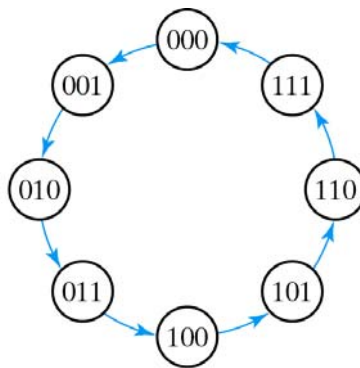


Fig. 5-29 State Diagram of 3-Bit Binary Counter

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70

3-Bit Binary Counter

Present State	Next State	T F-F Inputs
$A_2 A_1 A_0$	$A_2 A_1 A_0$	$T_{A2} T_{A1} T_{A0}$
0 0 0	0 0 1	0 0 1
0 0 1	0 1 0	0 1 1
0 1 0	0 1 1	
0 1 1	1 0 0	
1 0 0	1 0 1	
1 0 1	1 1 0	
1 1 0	1 1 1	
1 1 1	0 0 0	

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71

3-Bit Binary Counter

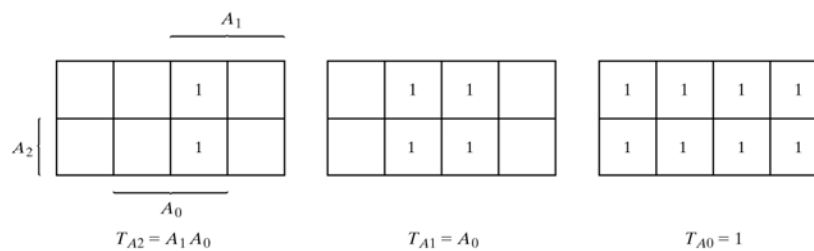


Fig. 5-30 Maps for 3-Bit Binary Counter

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72

3-Bit Binary Counter

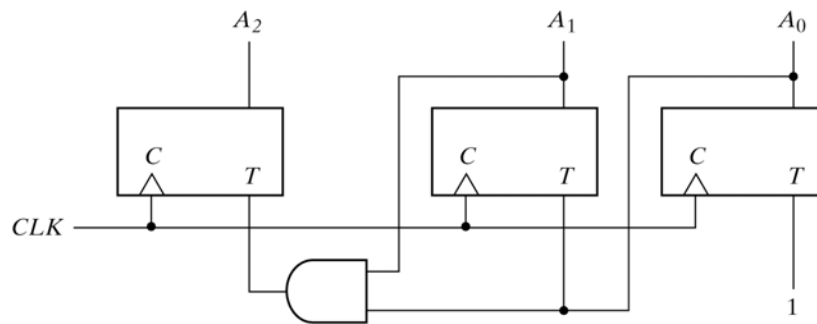


Fig. 5-31 Logic Diagram of 3-Bit Binary Counter

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73

Example (Mealy vs. Moore)

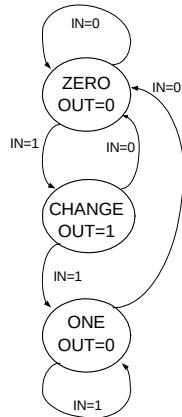
- Design a circuit that asserts its output for one cycle for every change in the input from 0 to 1
- We will try two different approaches.
- Compare between them

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74

Solution 1



	IN	PS	NS	OUT
ZERO	0	00	00	0
	1	00	01	0
CHANGE	0	01	00	1
	1	01	11	1
ONE	0	11	00	0
	1	11	11	0

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75

Solution 1

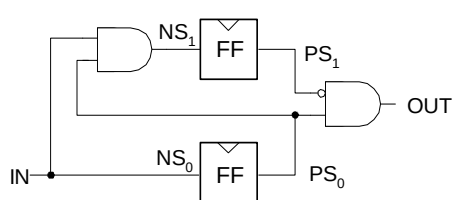
	IN	PS	NS	OUT
ZERO	0	00	00	0
	1	00	01	0
CHANGE	0	01	00	1
	1	01	11	1
ONE	0	11	00	0
	1	11	11	0

	PS
	00 01 11 10
IN	0 0 0 0 -
	1 0 1 1 -

$NS_1 = IN \cdot PS_0$

	PS
	00 01 11 10
IN	0 0 0 0 -
	1 1 1 1 -

$NS_0 = IN$



	PS
	00 01 11 10
IN	0 0 1 0 -
	1 0 1 0 -

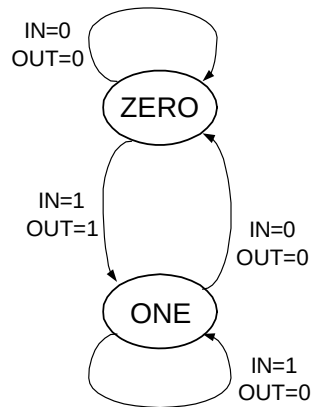
$OUT = \overline{PS_1} \cdot PS_0$

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76

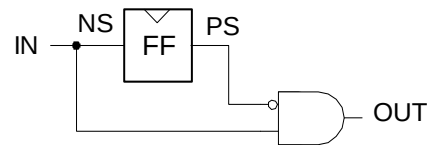
Solution 2



Let ZERO=0,
ONE=1

IN	PS	NS	OUT
0	0	0	0
0	1	0	0
1	0	1	1
1	1	1	0

NS = IN, OUT = IN PS'

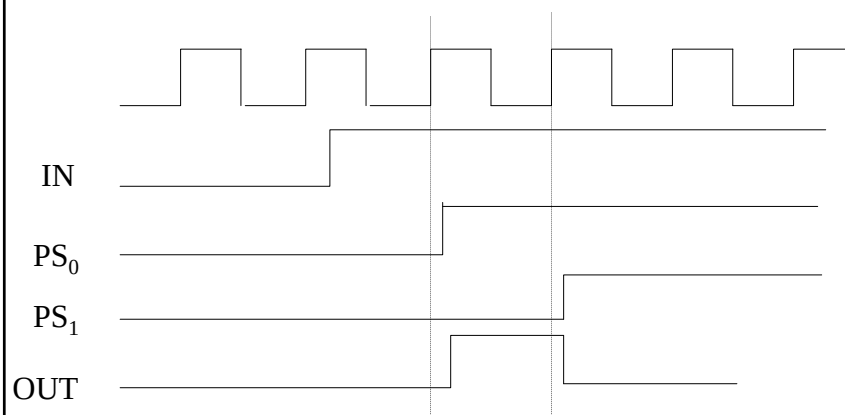


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77

Comparison

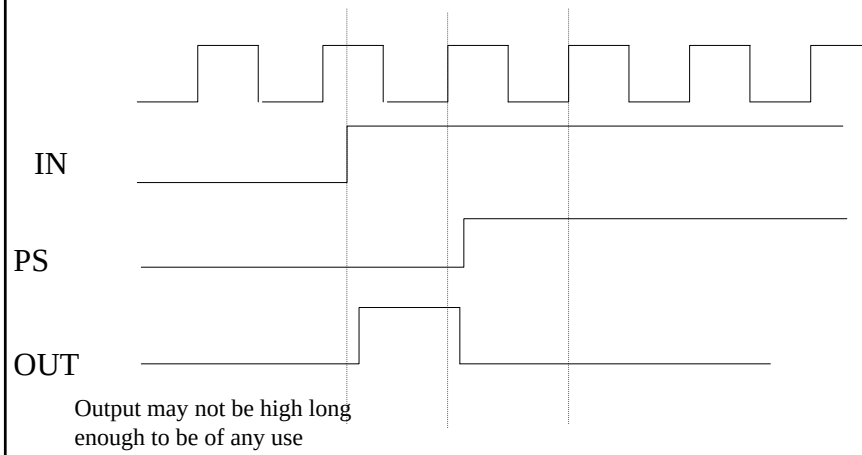


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78

Comparison

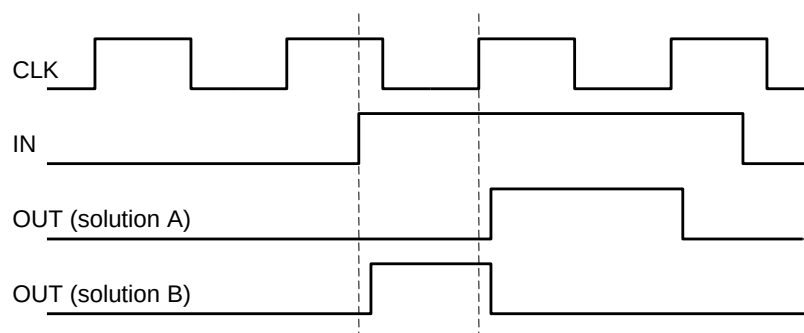


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79

Comparison



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80