



# **CprE 281: Digital Logic**

**Instructor: Alexander Stoytchev**

**<http://www.ece.iastate.edu/~alexs/classes/>**

# State Assignment Problem

*CprE 281: Digital Logic*  
*Iowa State University, Ames, IA*  
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# **Administrative Stuff**

- **Homework 9 is due on Monday**

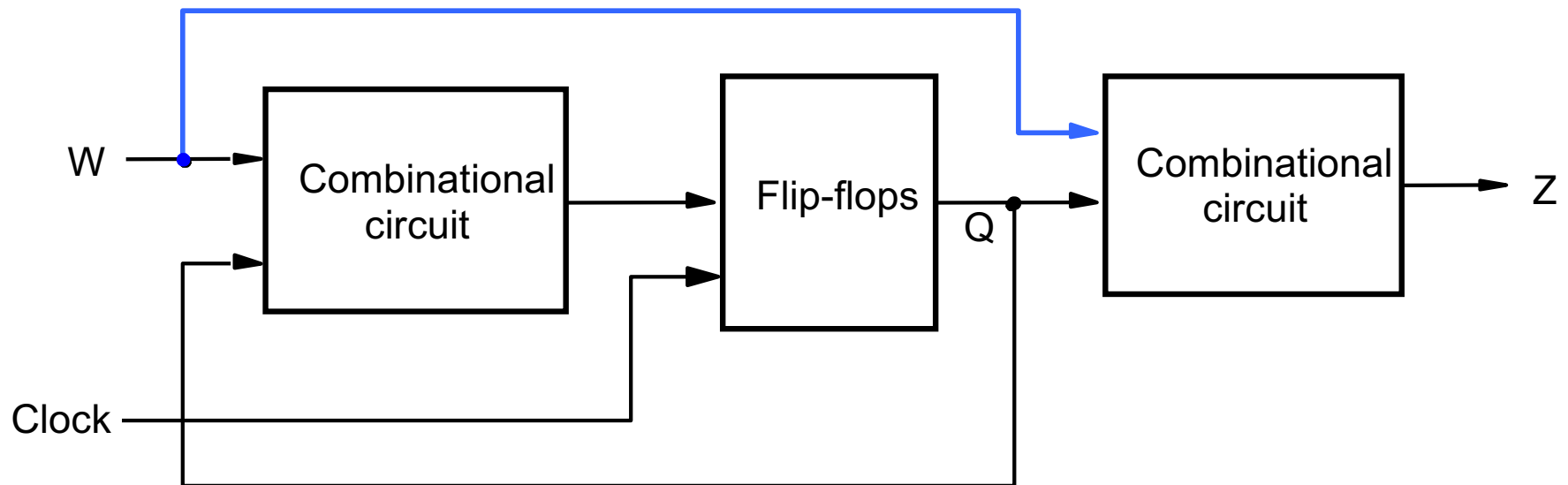
# **Administrative Stuff**

- **Homework 10 is out**
- **It is due on Monday Nov 12 @ 4pm**

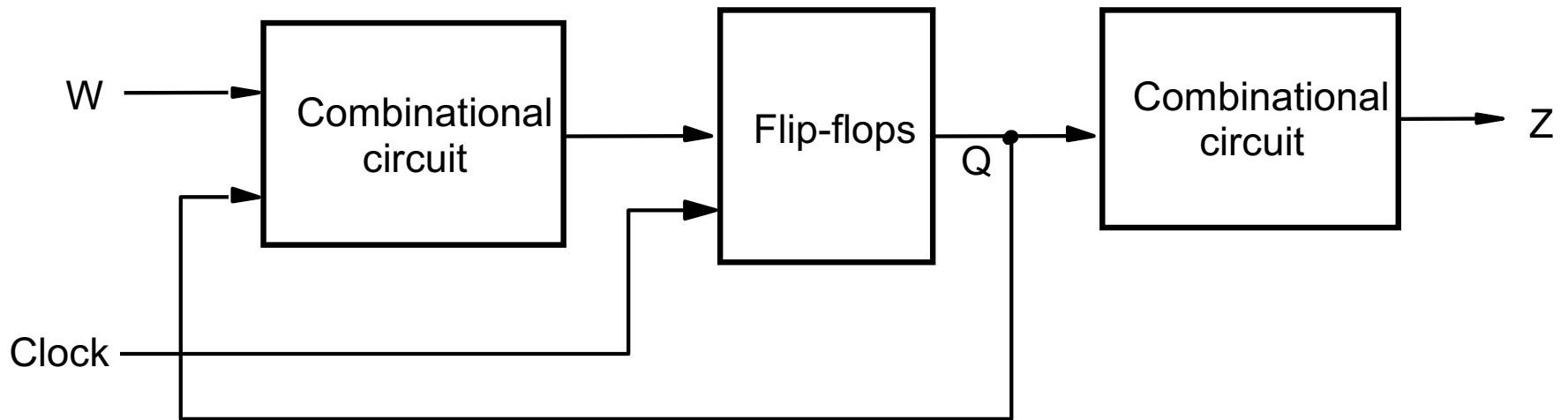


# Quick Review

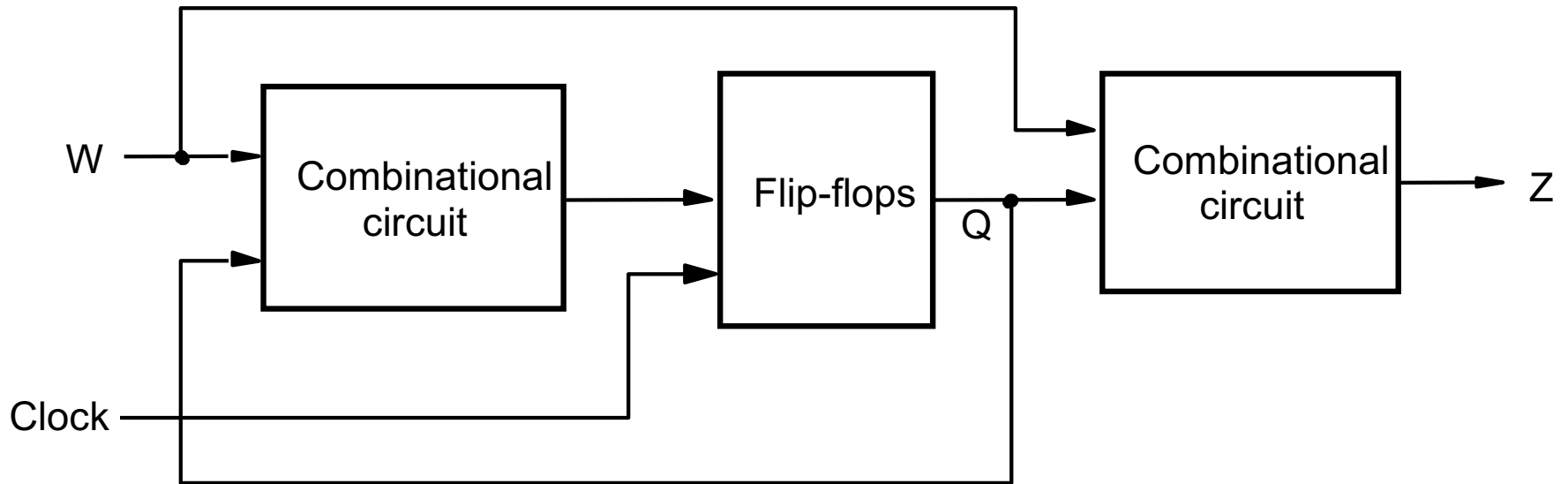
# The general form of a synchronous sequential circuit



# Moore Type



# Mealy Type



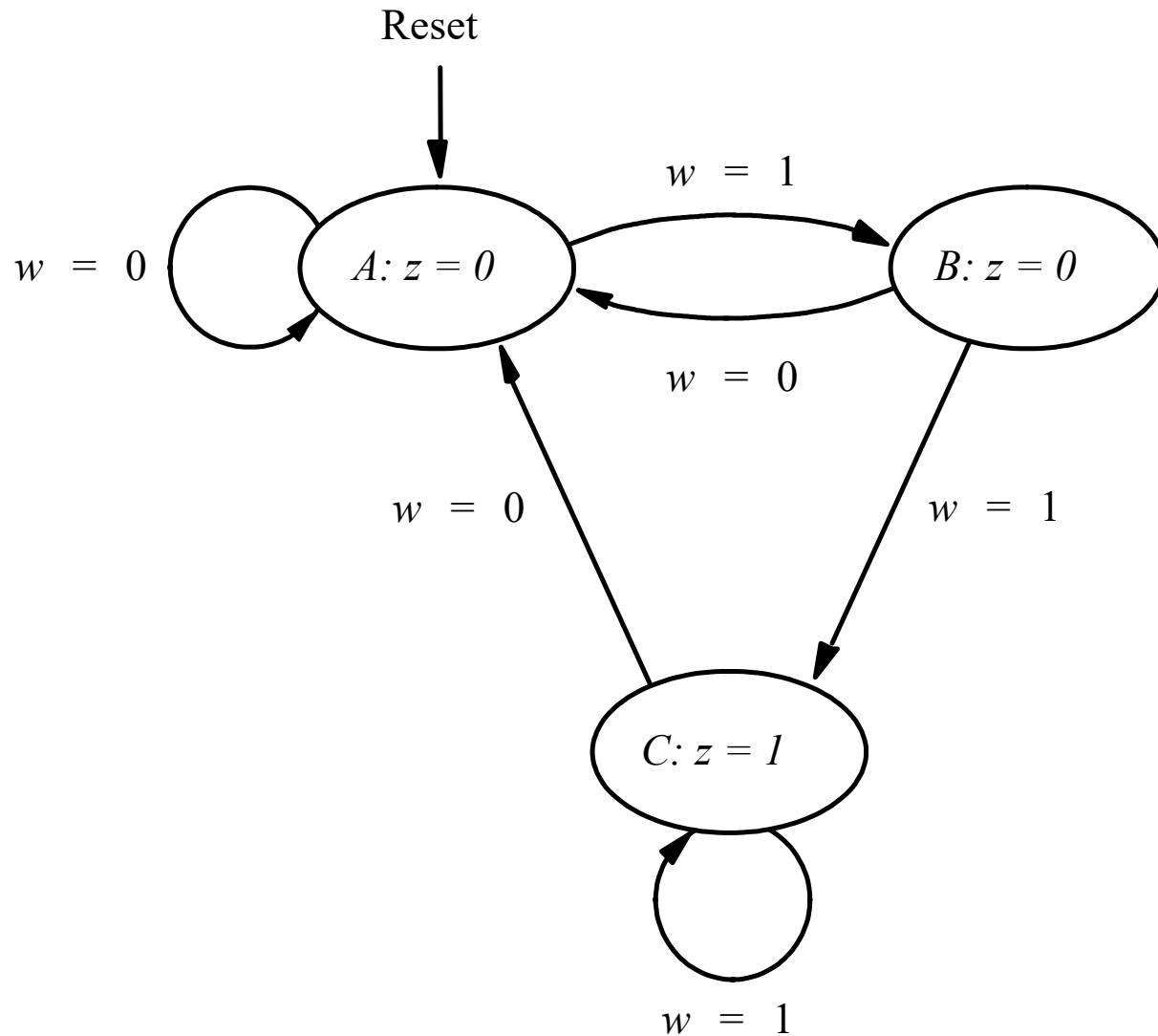
# Moore Machine

- **The machine's current state and current inputs are used to decide which next state to transition into.**
- **The machine's current state decides the current output.**
- **Named after Edward Moore (1925-2003) who published the idea in 1956.**
- **Moore, E. (1956). "Gedanken-experiments on Sequential Machines". Automata Studies, Annals of Math. Studies. Princeton Univ. Press (34): 129–153.**

# Mealy Machine

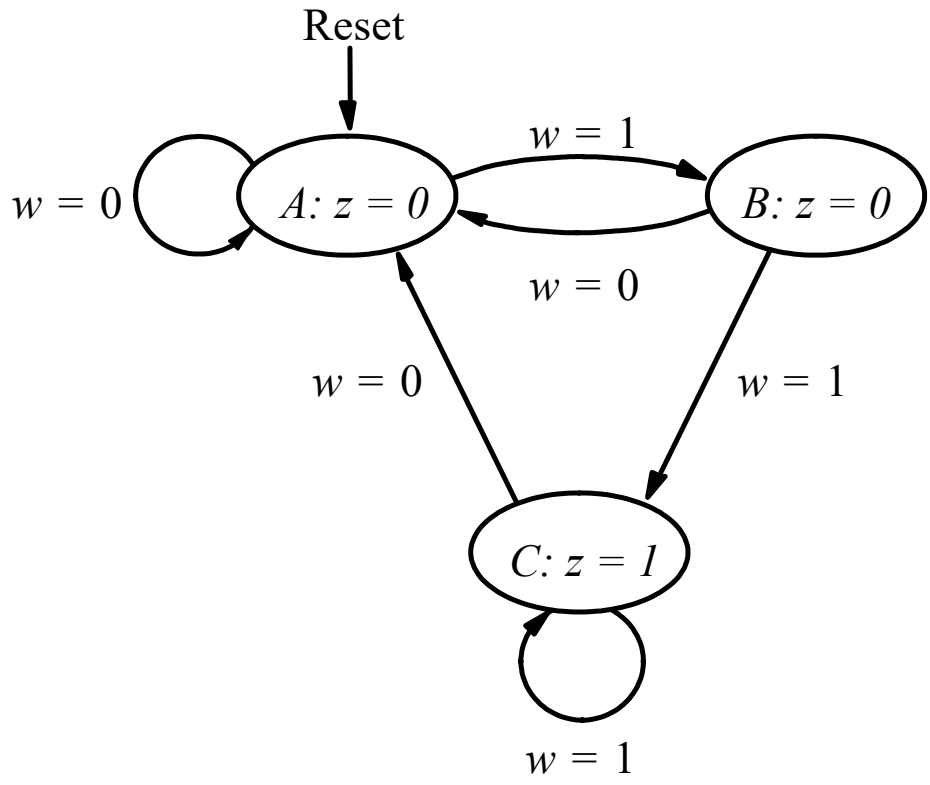
- The machine's current state and current inputs are used to decide which next state to transition into.
- The machine's current state **and current input values** decide the current output.
- Named after George Mealy (1927 – 2010) who published the idea in 1955.
- Mealy, G. (1955). "A method for synthesizing sequential circuits" The Bell System Technical Journal, Volume: 34, Issue: 5, Sept. 1955.

# **Example #1**

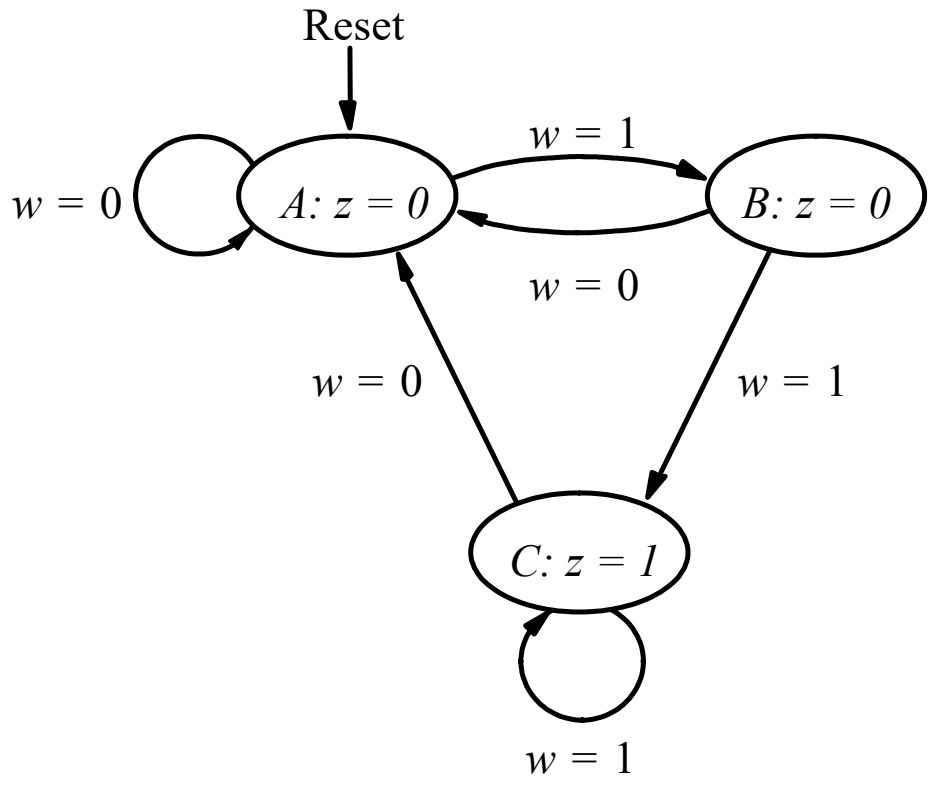


We need to find both the *next state logic* and the *output logic* implied by this machine.





Present state	Next state		Output $z$
	$w = 0$	$w = 1$	
A			
B			
C			



Present state	Next state		Output $z$
	$w = 0$	$w = 1$	
A	A	B	0
B	A	C	0
C	A	C	1

[ Figure 6.4 from the textbook ]

**State Encoding for Example #1:**

**A=00, B=01, C=10**

**(Uses Two Flip-Flops)**

# How to represent the states?

One way is to encode each state with a 2-bit binary number

**A = 00**

**B = 01**

**C = 10**

# How to represent the states?

One way is to encode each state with a 2-bit binary number

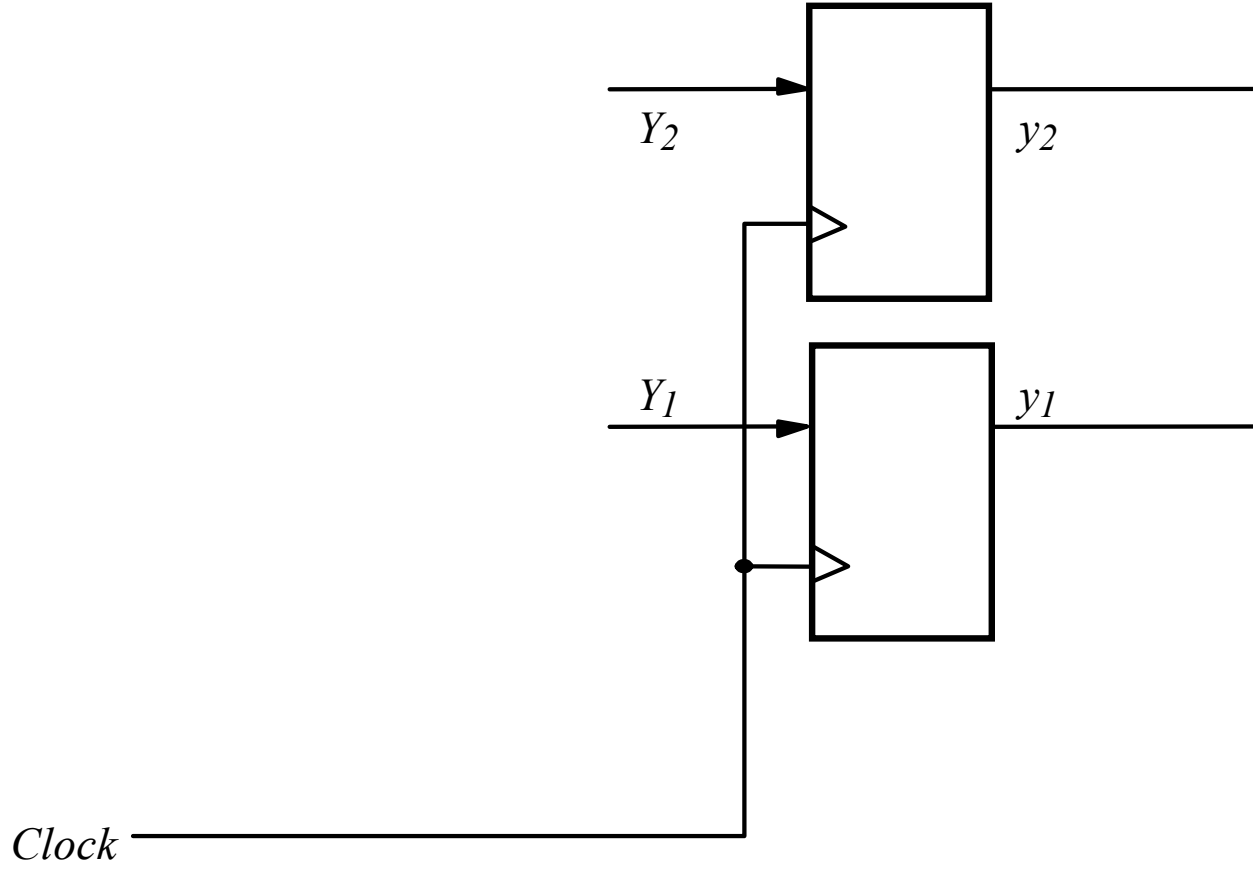
**A = 00**

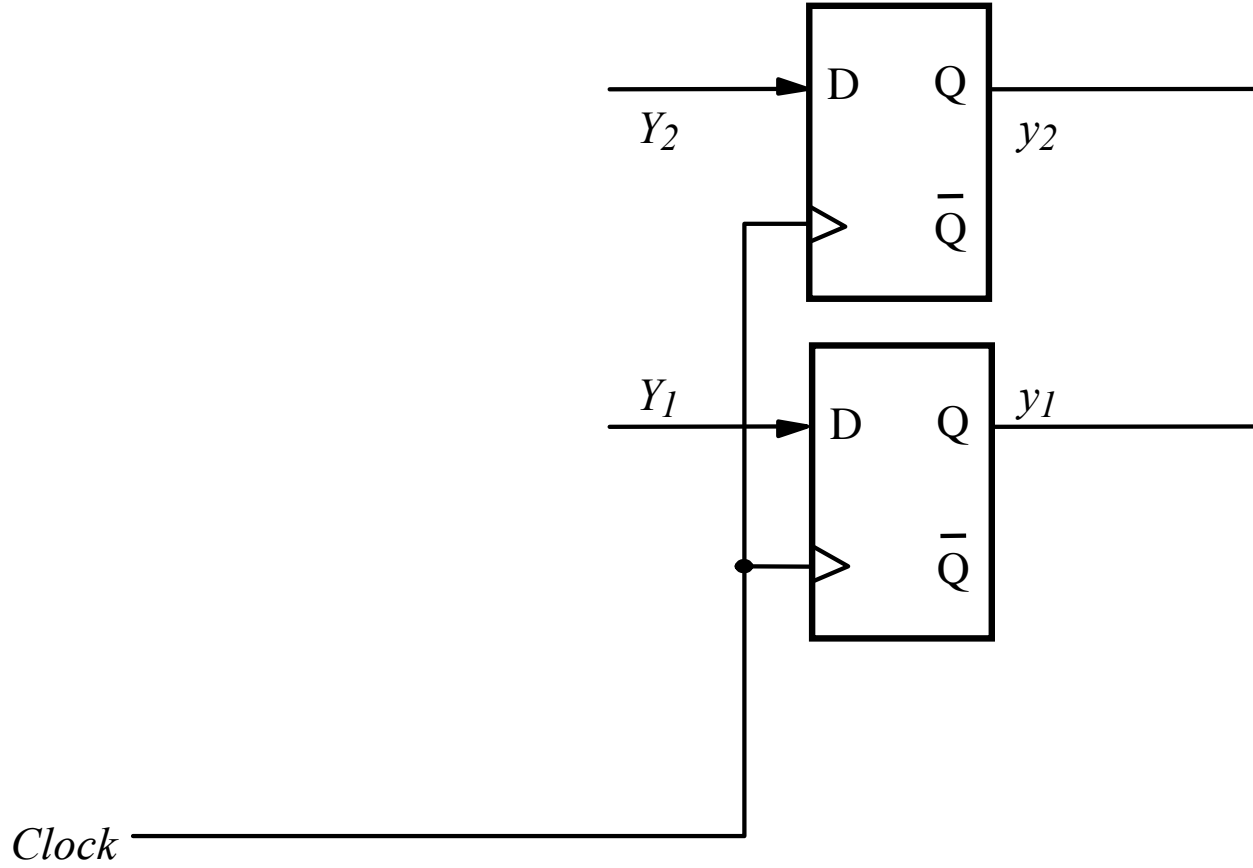
**B = 01**

**C = 10**

How many flip-flops do we need?

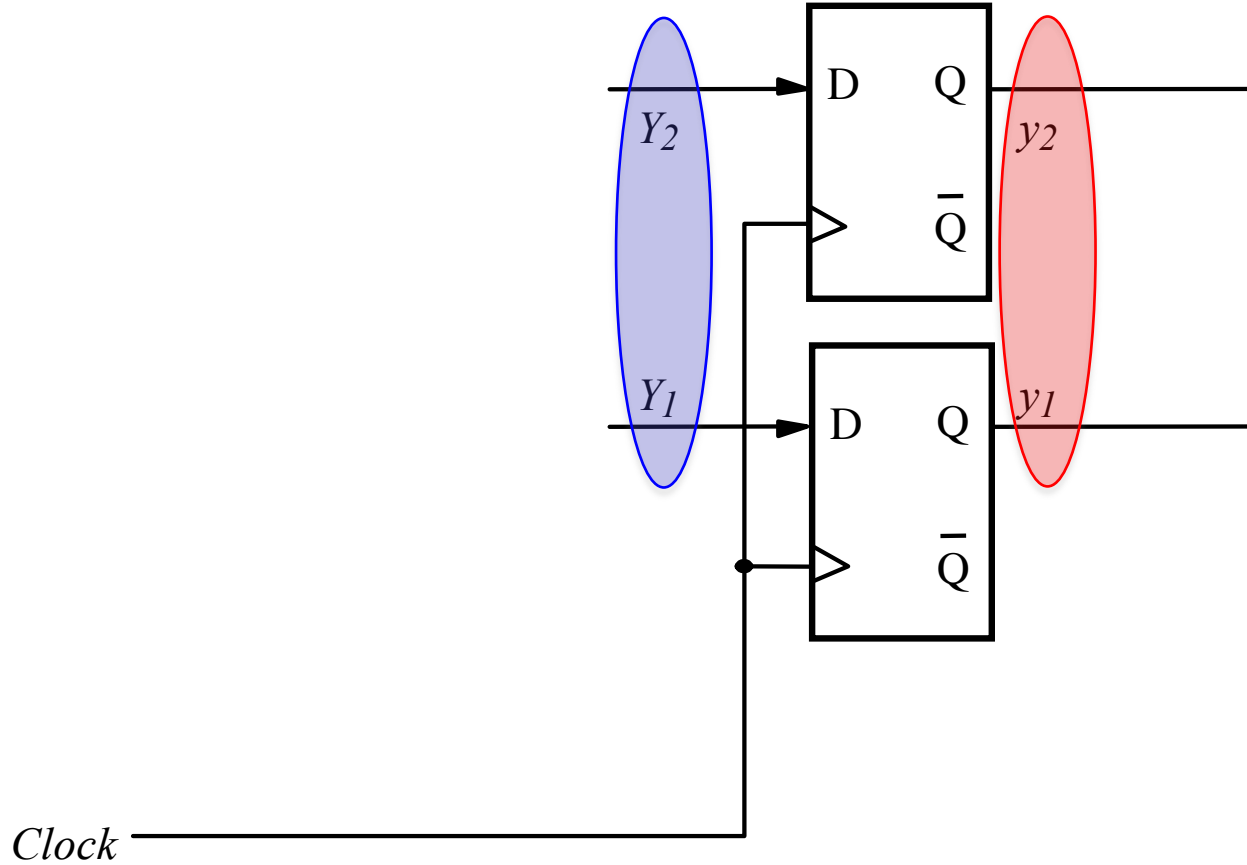
**Let's use two flip flops  
to hold the state of this machine**





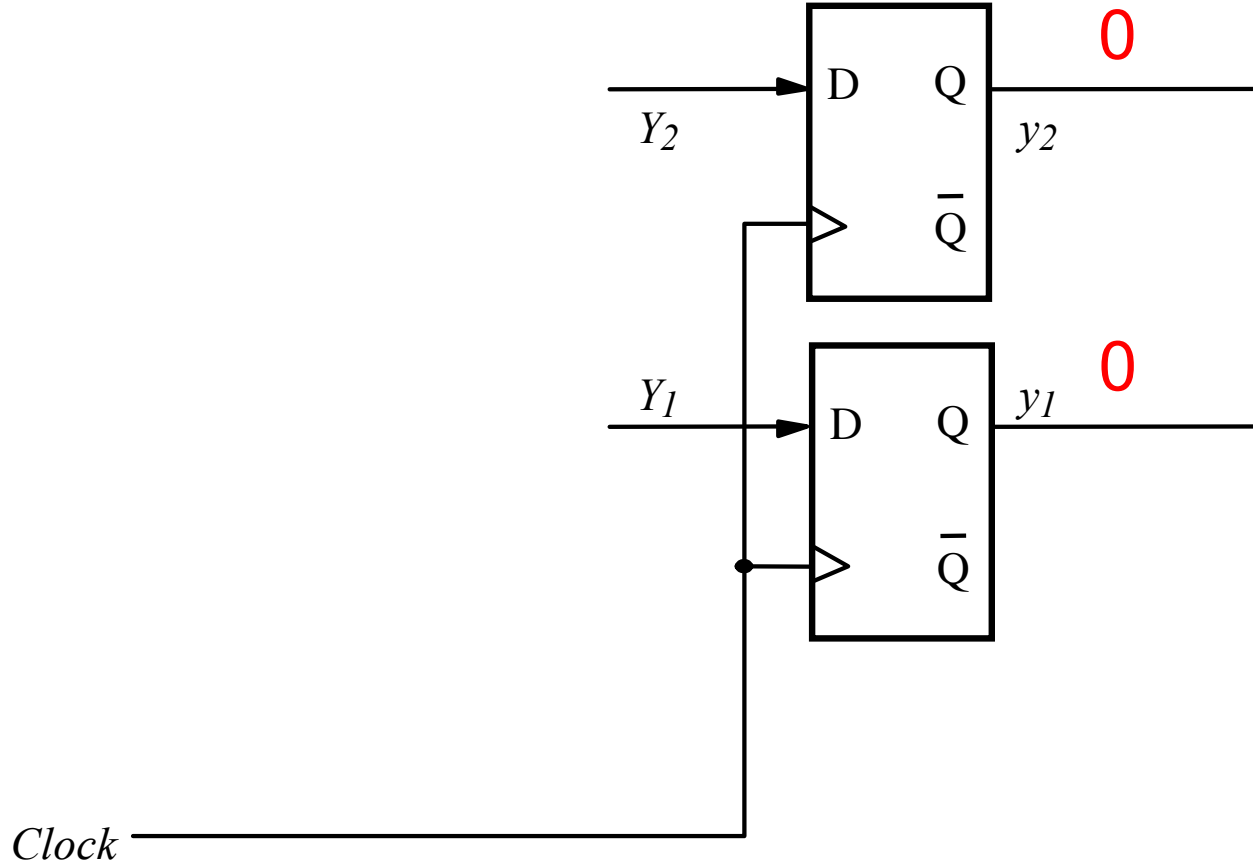
Let's pick D Flip-Flops.



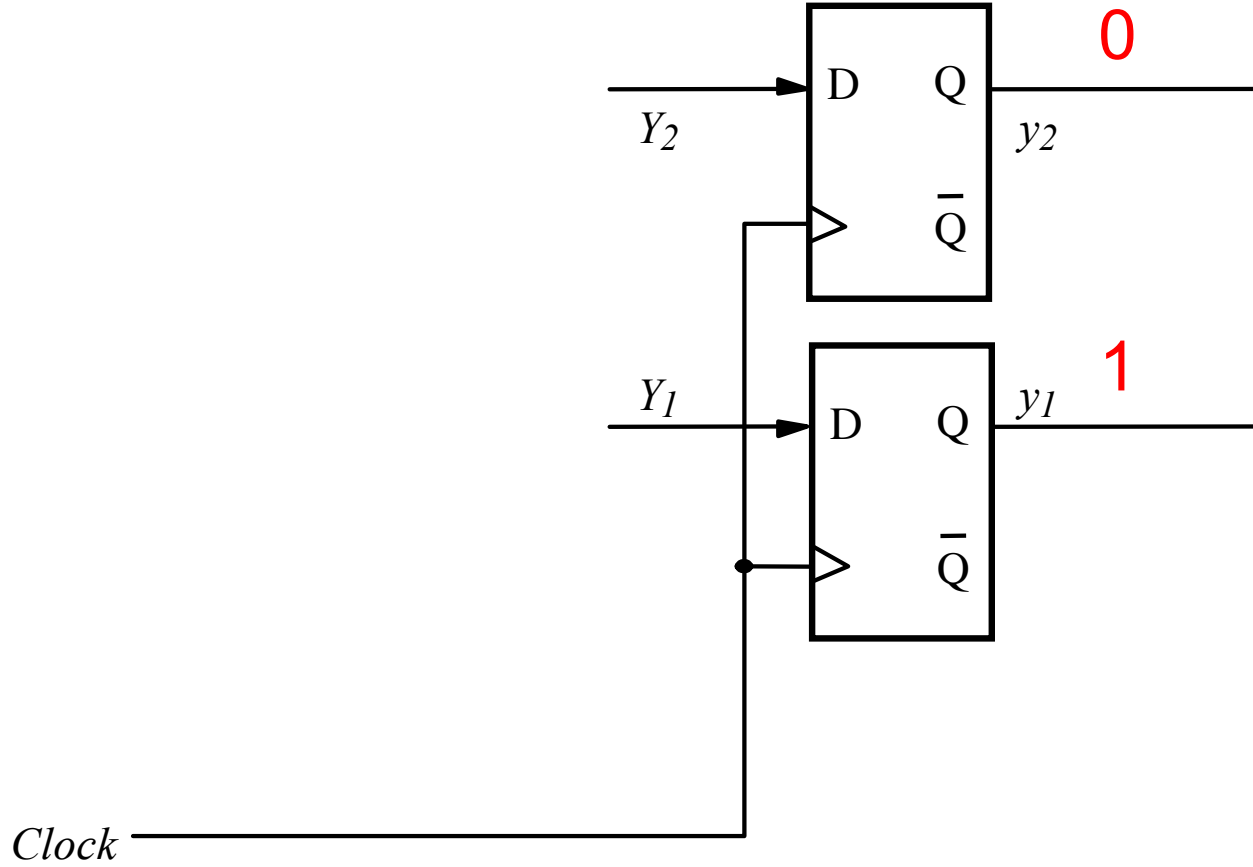


We will call  $y_1$  and  $y_2$  the *present state variables*.

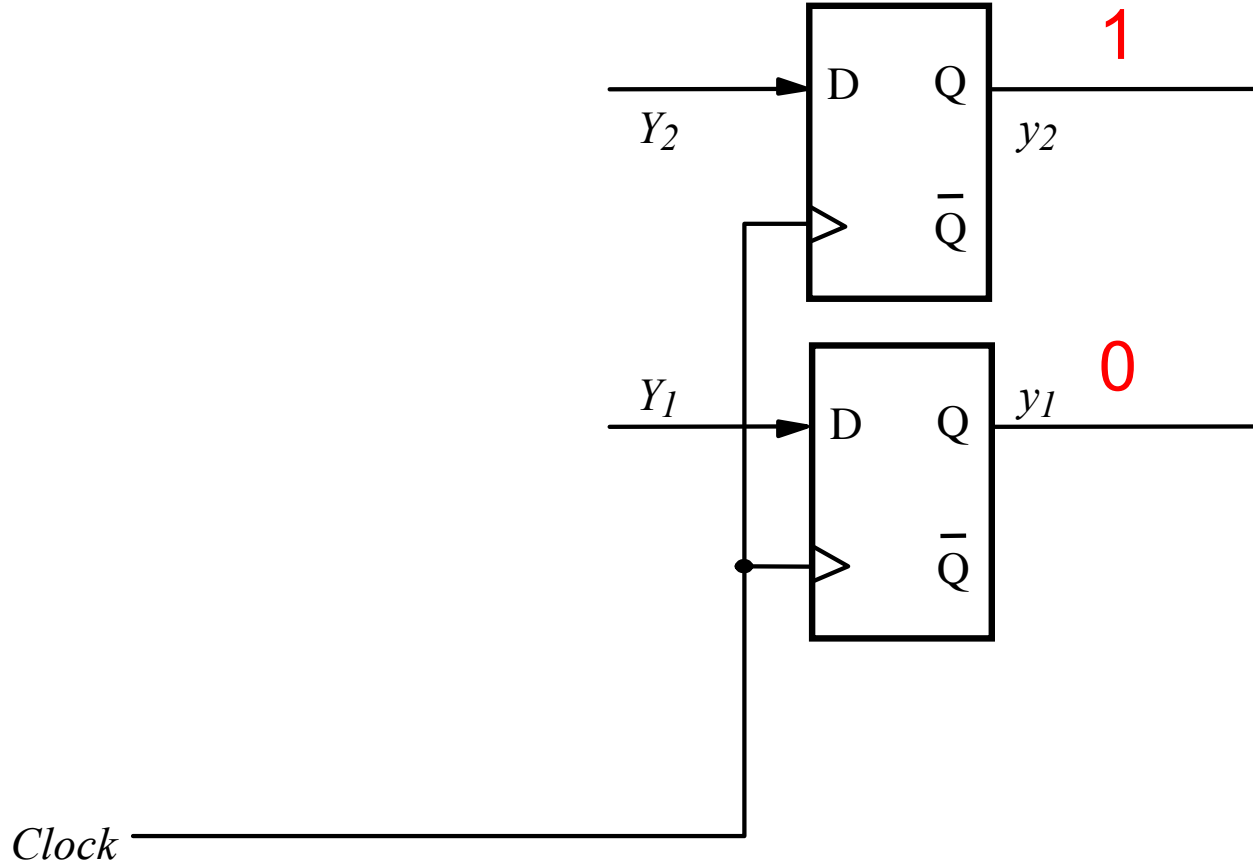
We will call  $Y_1$  and  $Y_2$  the *next state variables*.



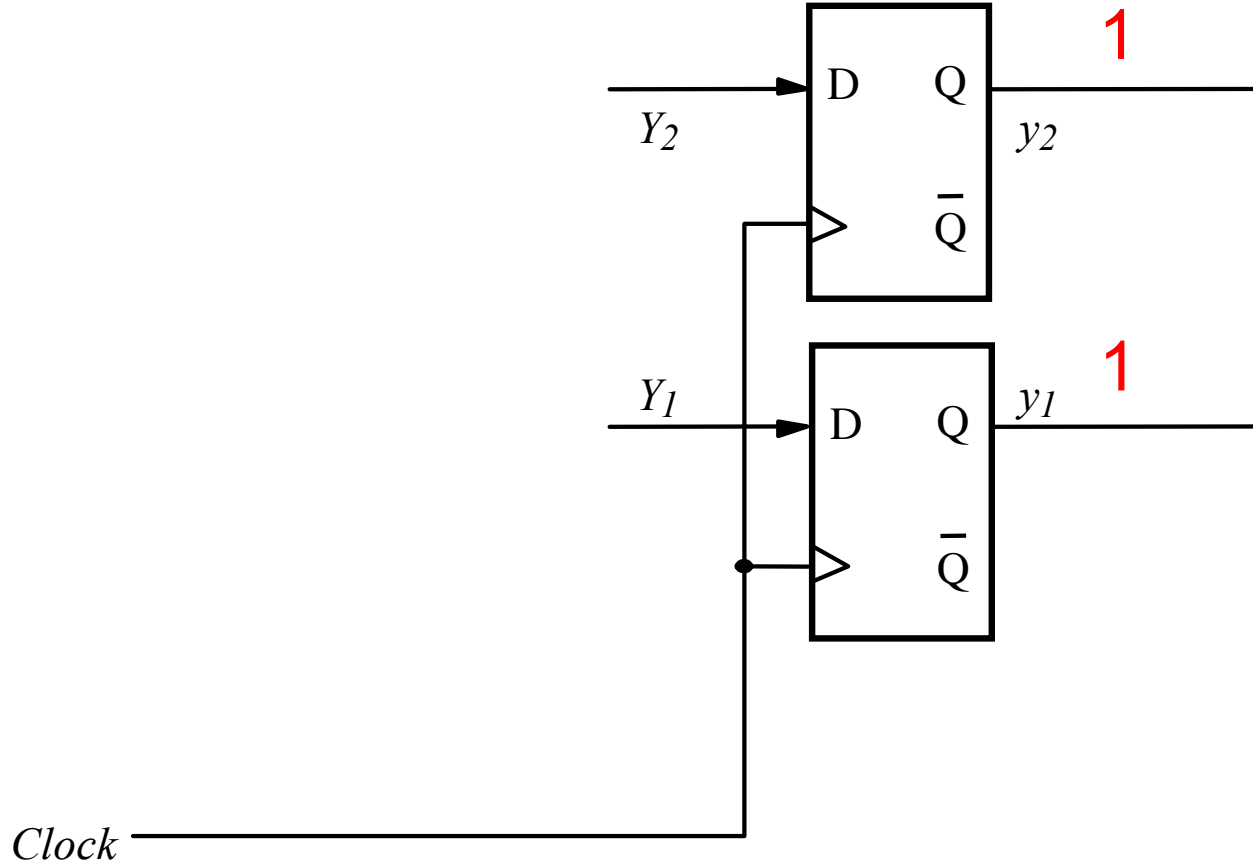
Two zeros on the output JOINTLY represent state A.



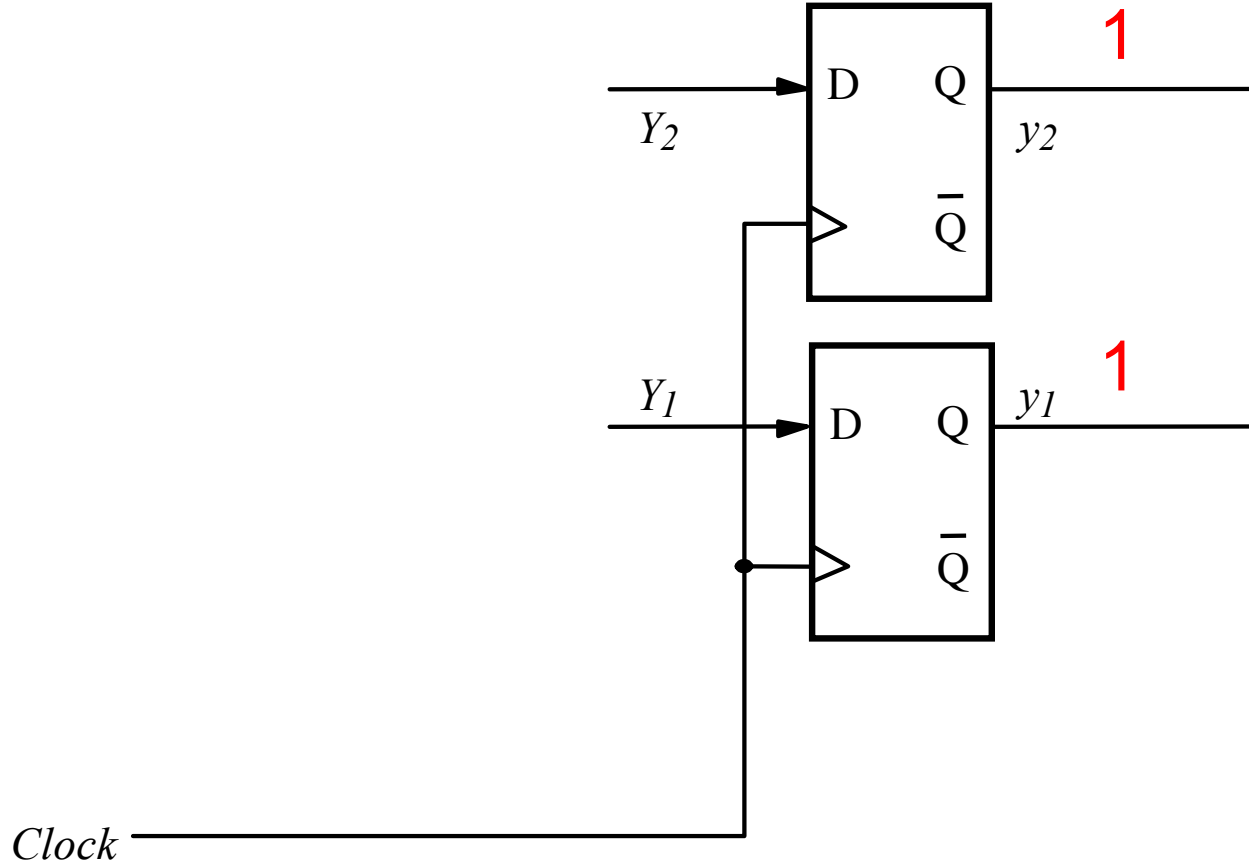
This flip-flop output pattern represents state B.



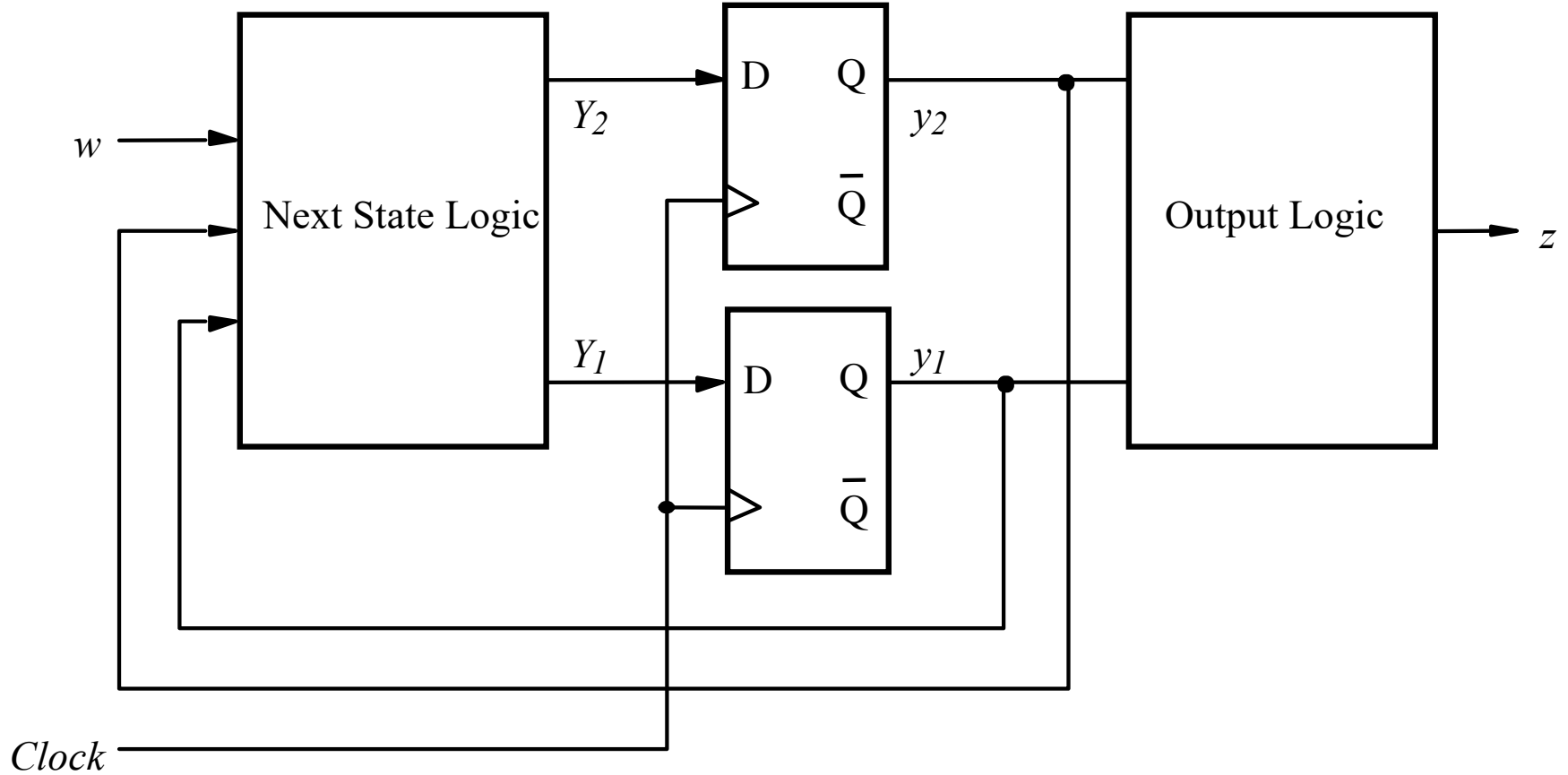
This flip-flop output pattern represents state C.



What does this flip-flop output pattern represent?

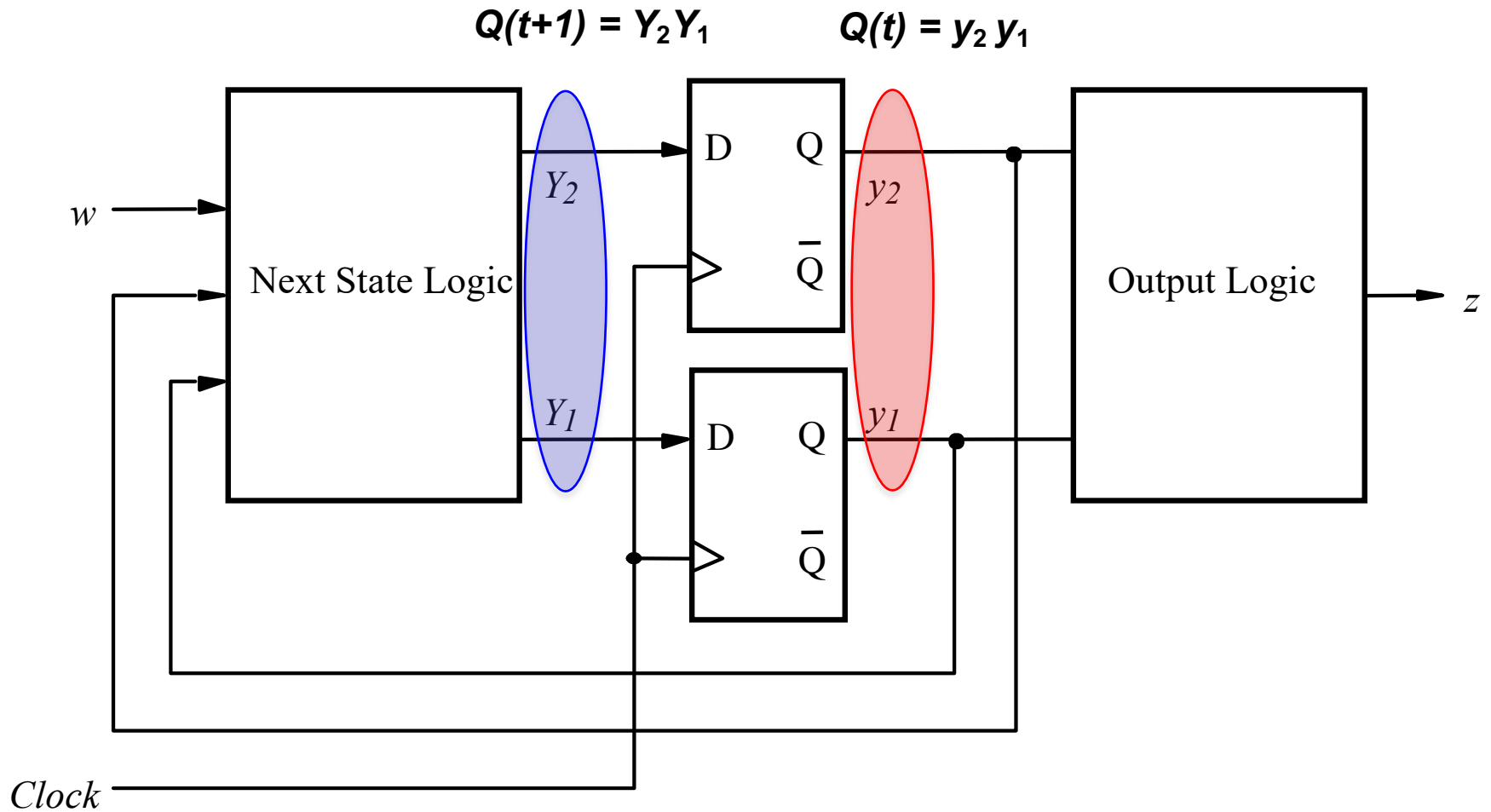


This would be state D, but we don't have one in this example. So this is an impossible state.



We will call  $y_1$  and  $y_2$  the *present state variables*.

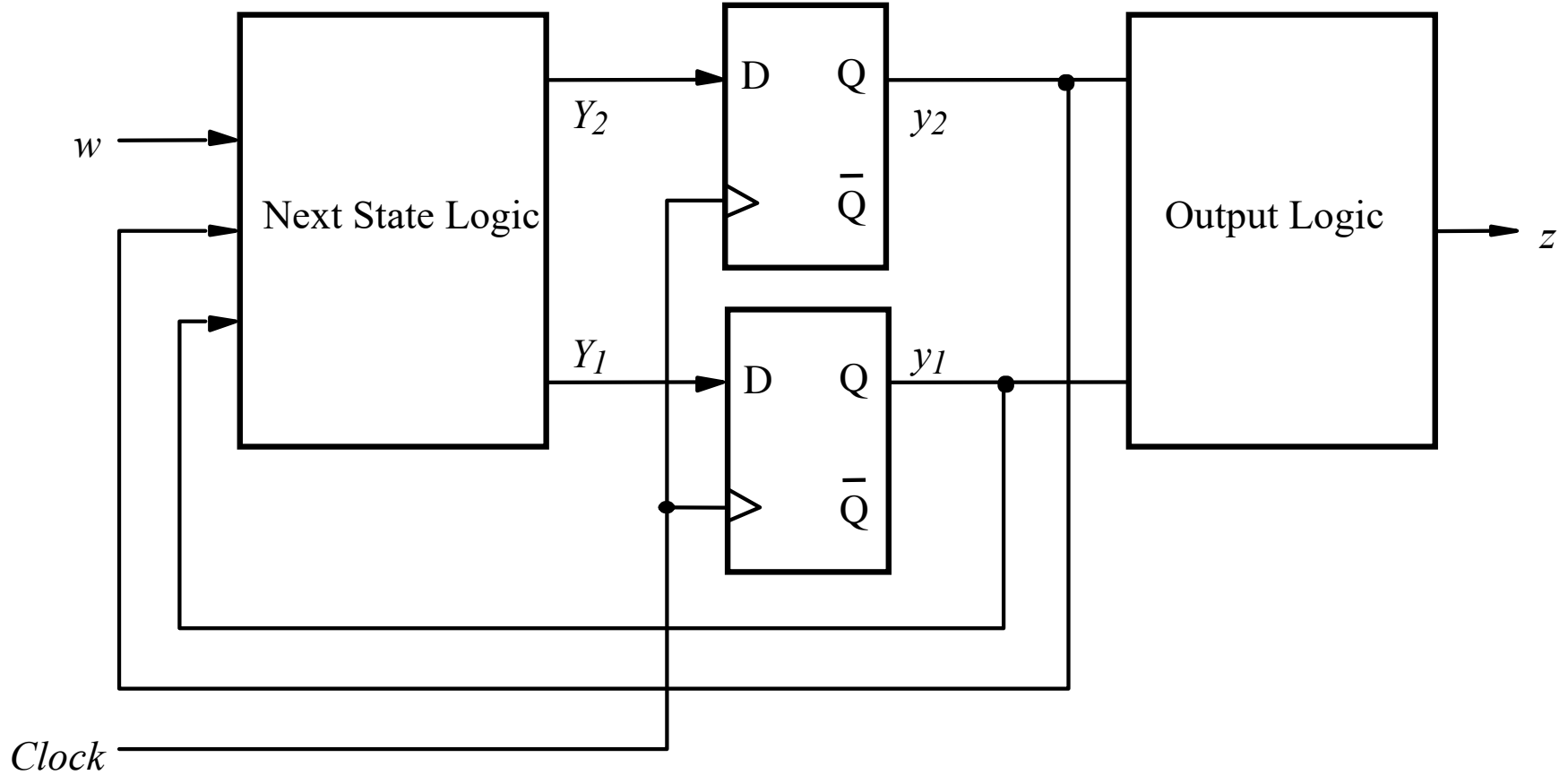
We will call  $Y_1$  and  $Y_2$  the *next state variables*.



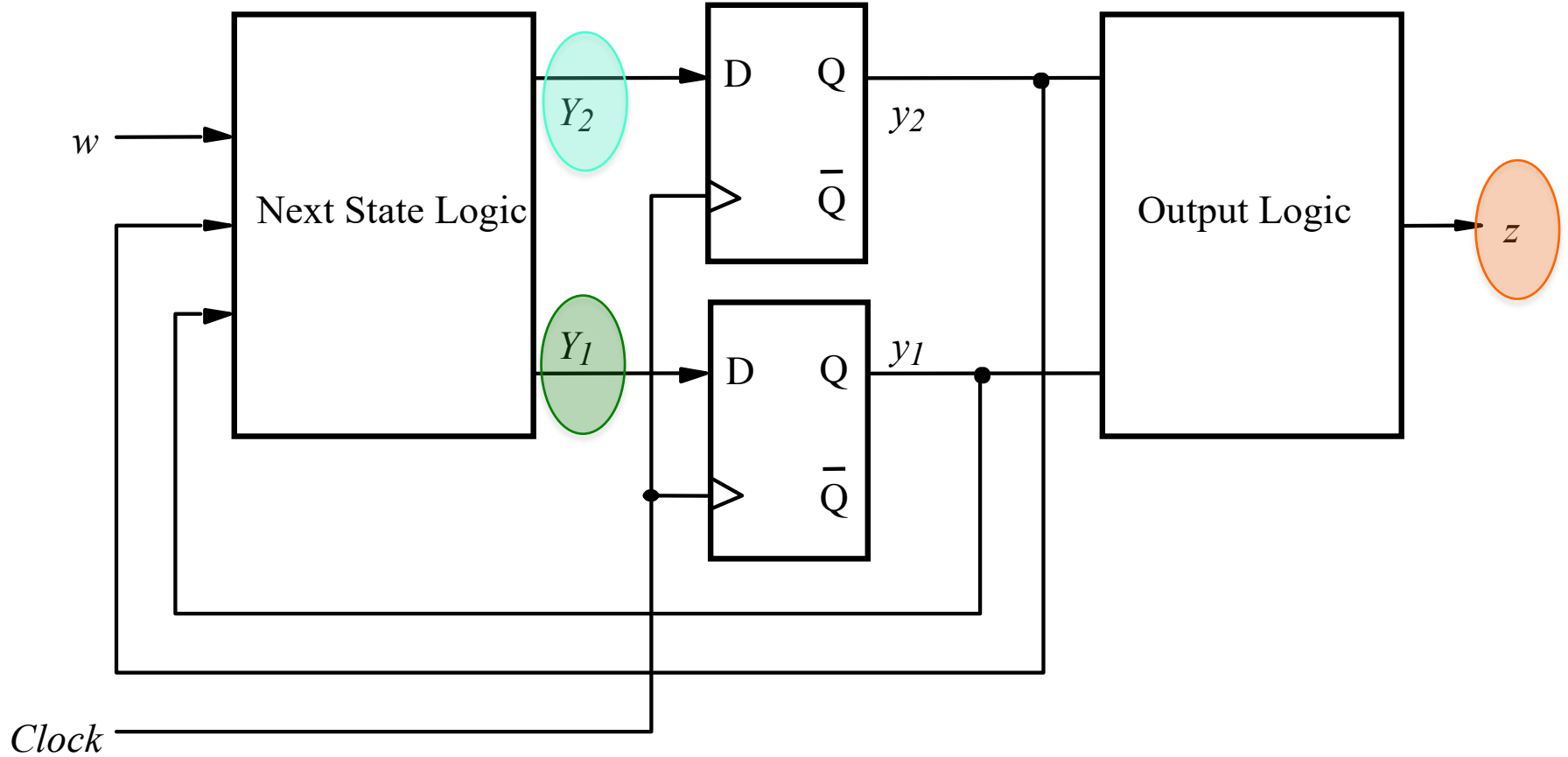
We will call  $y_1$  and  $y_2$  the *present state variables*.

We will call  $Y_1$  and  $Y_2$  the *next state variables*.





We need to find logic expressions for  $Y_1(w, y_1, y_2)$ ,  $Y_2(w, y_1, y_2)$ , and  $z(y_1, y_2)$ .



We need to find logic expressions for  $Y_1(w, y_1, y_2)$ ,  $Y_2(w, y_1, y_2)$ , and  $z(y_1, y_2)$ .

[ Figure 6.5 from the textbook ]

Present state	Next state		Output $z$
	$w = 0$	$w = 1$	
A	A	B	0
B	A	C	0
C	A	C	1

Suppose we encoded our states in the same order in which they were labeled:

A ~ 00

B ~ 01

C ~ 10

Present state	Next state		Output $z$
	$w = 0$	$w = 1$	
A	A	B	0
B	A	C	0
C	A	C	1

	Present state	Next state		Output $z$
		$w = 0$	$w = 1$	
A	00			
B	01			
C	10			
	11			

The finite state machine will never reach a state encoded as 11.

[ Figure 6.6 from the textbook ]

Present state	Next state		Output $z$
	$w = 0$	$w = 1$	
A	A	B	0
B	A	C	0
C	A	C	1

	Present state	Next state		Output $z$
		$w = 0$	$w = 1$	
	$y_2 y_1$	$Y_2 Y_1$	$Y_2 Y_1$	
A	00	00	01	0
B	01	00	10	0
C	10	00	10	1
	11	<i>dd</i>	<i>dd</i>	<i>d</i>

We arbitrarily chose these as our state encodings. We could have used others.

[ Figure 6.6 from the textbook ]

$$Q(t) = y_2y_1 \text{ and } Q(t+1) = Y_2Y_1$$

Present state $y_2y_1$	Next state		Output $z$
	$w = 0$	$w = 1$	
	$Y_2Y_1$	$Y_2Y_1$	
00	00	01	0
01	00	10	0
10	00	10	1
11	<i>dd</i>	<i>dd</i>	<i>d</i>

$w$	$y_2$	$y_1$	$Y_2$	$Y_1$
0	0	0		
0	0	1		
0	1	0		
0	1	1		
1	0	0		
1	0	1		
1	1	0		
1	1	1		

$y_2$	$y_1$	$z$
0	0	
0	1	
1	0	
1	1	

[ Figure 6.6 from the textbook ]

$$Q(t) = y_2y_1 \text{ and } Q(t+1) = Y_2Y_1$$

Present state $y_2y_1$	Next state		Output $z$
	$w = 0$	$w = 1$	
	$Y_2Y_1$	$Y_2Y_1$	
00	00	01	0
01	00	10	0
10	00	10	1
11	<i>dd</i>	<i>dd</i>	<i>d</i>

$w$	$y_2$	$y_1$	$Y_2$	$Y_1$
0	0	0		
0	0	1		
0	1	0		
0	1	1		
1	0	0		
1	0	1		
1	1	0		
1	1	1		

$y_2$	$y_1$	$z$
0	0	0
0	1	0
1	0	1
1	1	<i>d</i>

[ Figure 6.6 from the textbook ]

$$Q(t) = y_2y_1 \text{ and } Q(t+1) = Y_2Y_1$$

Present state $y_2y_1$	Next state		Output $z$
	$w = 0$	$w = 1$	
	$Y_2Y_1$	$Y_2Y_1$	
00	00	01	0
01	00	10	0
10	00	10	1
11	<i>dd</i>	<i>dd</i>	<i>d</i>

$w$	$y_2$	$y_1$	$Y_2$	$Y_1$
0	0	0		
0	0	1		
0	1	0		
0	1	1		
1	0	0		
1	0	1		
1	1	0		
1	1	1		

$y_2$	$y_1$	$z$
0	0	0
0	1	0
1	0	1
1	1	<i>d</i>

[ Figure 6.6 from the textbook ]



$$Q(t) = y_2y_1 \text{ and } Q(t+1) = Y_2Y_1$$

Present state $y_2y_1$	Next state		Output $z$
	$w = 0$	$w = 1$	
	$Y_2Y_1$	$Y_2Y_1$	
00	00	01	0
01	00	10	0
10	00	10	1
11	dd	dd	d

$w$	$y_2$	$y_1$	$Y_2$	$Y_1$
0	0	0	0	
0	0	1	0	
0	1	0	0	
0	1	1	d	
1	0	0		
1	0	1		
1	1	0		
1	1	1		

$y_2$	$y_1$	$z$
0	0	0
0	1	0
1	0	1
1	1	d

[ Figure 6.6 from the textbook ]

$$Q(t) = y_2y_1 \text{ and } Q(t+1) = Y_2Y_1$$

Present state $y_2y_1$	Next state		Output $z$
	$w = 0$	$w = 1$	
	$Y_2Y_1$	$Y_2Y_1$	
00	00	01	0
01	00	10	0
10	00	10	1
11	$dd$	$dd$	$d$

$w$	$y_2$	$y_1$	$Y_2$	$Y_1$
0	0	0	0	
0	0	1	0	
0	1	0	0	
0	1	1	d	
1	0	0	0	
1	0	1	1	
1	1	0	1	
1	1	1	d	

$y_2$	$y_1$	$z$
0	0	0
0	1	0
1	0	1
1	1	d

[ Figure 6.6 from the textbook ]

$$Q(t) = y_2y_1 \text{ and } Q(t+1) = Y_2Y_1$$

Present state $y_2y_1$	Next state		Output $z$
	$w = 0$	$w = 1$	
	$Y_2Y_1$	$Y_2Y_1$	
00	00	01	0
01	00	10	0
10	00	10	1
11	<i>dd</i>	<i>dd</i>	<i>d</i>

$w$	$y_2$	$y_1$	$Y_2$	$Y_1$
0	0	0	0	
0	0	1	0	
0	1	0	0	
0	1	1	d	
1	0	0	0	
1	0	1	1	
1	1	0	1	
1	1	1	d	

$y_2$	$y_1$	$z$
0	0	0
0	1	0
1	0	1
1	1	d

[ Figure 6.6 from the textbook ]

$$Q(t) = y_2y_1 \text{ and } Q(t+1) = Y_2Y_1$$

Present state $y_2y_1$	Next state		Output $z$
	$w = 0$	$w = 1$	
	$Y_2Y_1$	$Y_2Y_1$	
00	00	01	0
01	00	10	0
10	00	10	1
11	$dd$	$dd$	$d$

$w$	$y_2$	$y_1$	$Y_2$	$Y_1$
0	0	0	0	0
0	0	1	0	0
0	1	0	0	0
0	1	1	d	d
1	0	0	0	
1	0	1	1	
1	1	0	1	
1	1	1	d	

$y_2$	$y_1$	$z$
0	0	0
0	1	0
1	0	1
1	1	d

[ Figure 6.6 from the textbook ]

$$Q(t) = y_2y_1 \text{ and } Q(t+1) = Y_2Y_1$$

Present state $y_2y_1$	Next state		Output $z$
	$w = 0$	$w = 1$	
	$Y_2Y_1$	$Y_2Y_1$	
00	00	01	0
01	00	10	0
10	00	10	1
11	<i>dd</i>	<i>dd</i>	<i>d</i>

$w$	$y_2$	$y_1$	$Y_2$	$Y_1$
0	0	0	0	0
0	0	1	0	0
0	1	0	0	0
0	1	1	d	d
1	0	0	0	1
1	0	1	1	0
1	1	0	1	0
1	1	1	d	d

$y_2$	$y_1$	$z$
0	0	0
0	1	0
1	0	1
1	1	d

[ Figure 6.6 from the textbook ]

$$Q(t) = y_2y_1 \text{ and } Q(t+1) = Y_2Y_1$$

Present state $y_2y_1$	Next state		Output $z$
	$w = 0$	$w = 1$	
	$Y_2Y_1$	$Y_2Y_1$	
00	00	01	0
01	00	10	0
10	00	10	1
11	<i>dd</i>	<i>dd</i>	<i>d</i>

$w$	$y_2$	$y_1$	$Y_2$	$Y_1$
0	0	0	0	0
0	0	1	0	0
0	1	0	0	0
0	1	1	d	d
1	0	0	0	1
1	0	1	1	0
1	1	0	1	0
1	1	1	d	d

$y_2$	$y_1$	$z$
0	0	0
0	1	0
1	0	1
1	1	d

[ Figure 6.6 from the textbook ]

Note that the textbook draws these K-Maps differently from all previous K-maps (the least significant bits index the columns, instead of the most significant bits).

$Y_1$

$w$	$y_2 y_1$	00	01	11	10
0		0	0	d	0
1		1	0	d	0

$Y_2$

$w$	$y_2 y_1$	00	01	11	10
0		0	0	d	0
1		0	1	d	1

$z$

$y_2$	$y_1$	0	1
0		0	0
1		1	d

$$Q(t) = y_2 y_1 \text{ and } Q(t+1) = Y_2 Y_1$$

$w$	$y_2$	$y_1$	$Y_2$	$Y_1$
0	0	0	0	0
0	0	1	0	0
0	1	0	0	0
0	1	1	d	d
1	0	0	0	1
1	0	1	1	0
1	1	0	1	0
1	1	1	d	d

$y_2$	$y_1$	$z$
0	0	0
0	1	0
1	0	1
1	1	d

# Don't care conditions simplify the combinatorial logic

$Y_1$

	$y_2 y_1$	00	01	11	10
$w$					
0		0	0	d	0
1		1	0	d	0

$Y_2$

	$y_2 y_1$	00	01	11	10
$w$					
0		0	0	d	0
1		0	1	d	1

$z$

	$y_1$	0	1
$y_2$			
0		0	0
1		1	d

Ignoring don't cares

$$Y_1 = w\bar{y}_1\bar{y}_2$$

$$Y_2 = wy_1\bar{y}_2 + \bar{w}y_1y_2$$

$$z = \bar{y}_1y_2$$

Using don't cares

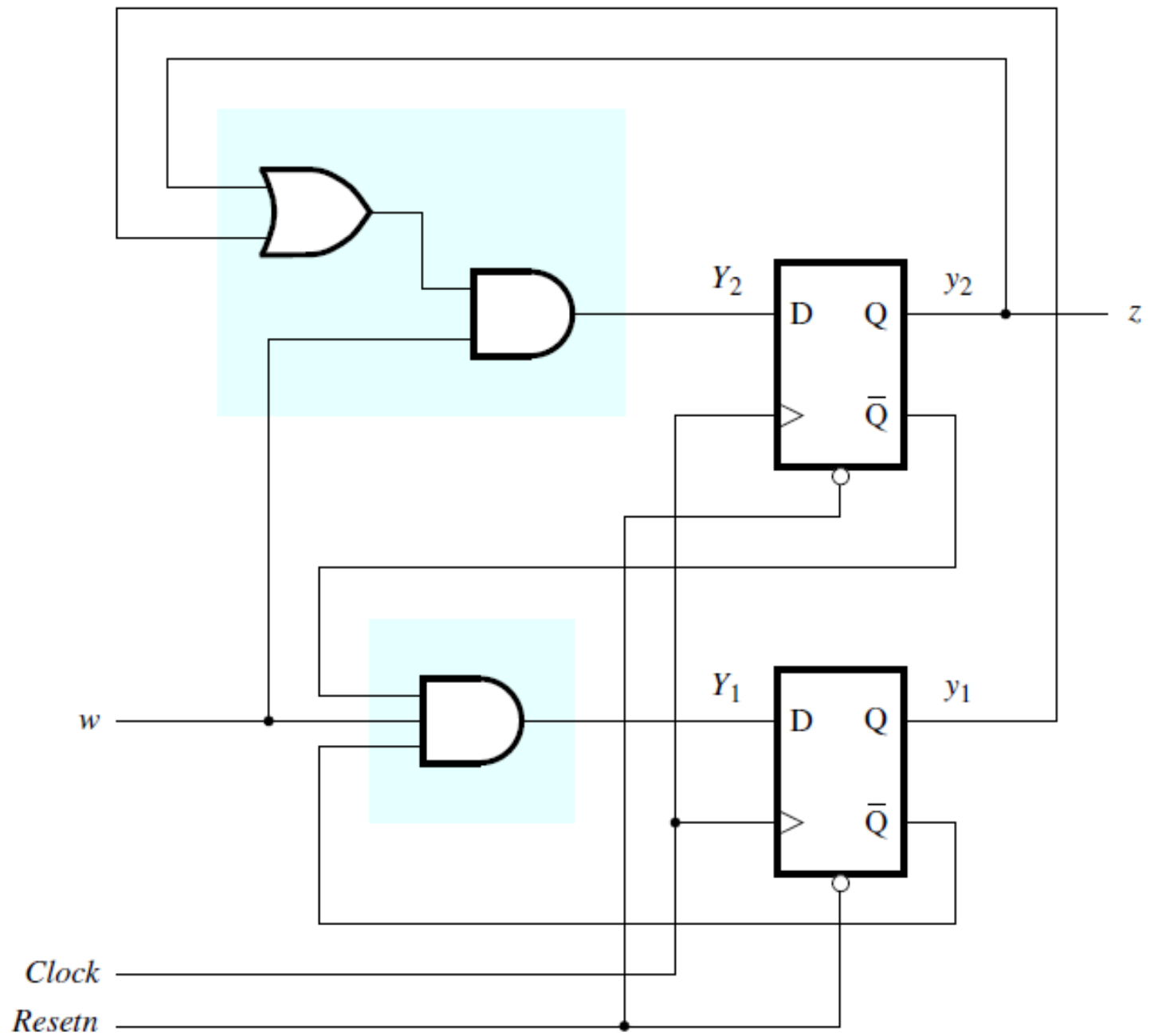
$$Y_1 = w\bar{y}_1\bar{y}_2$$

$$\begin{aligned} Y_2 &= wy_1 + wy_2 \\ &= w(y_1 + y_2) \end{aligned}$$

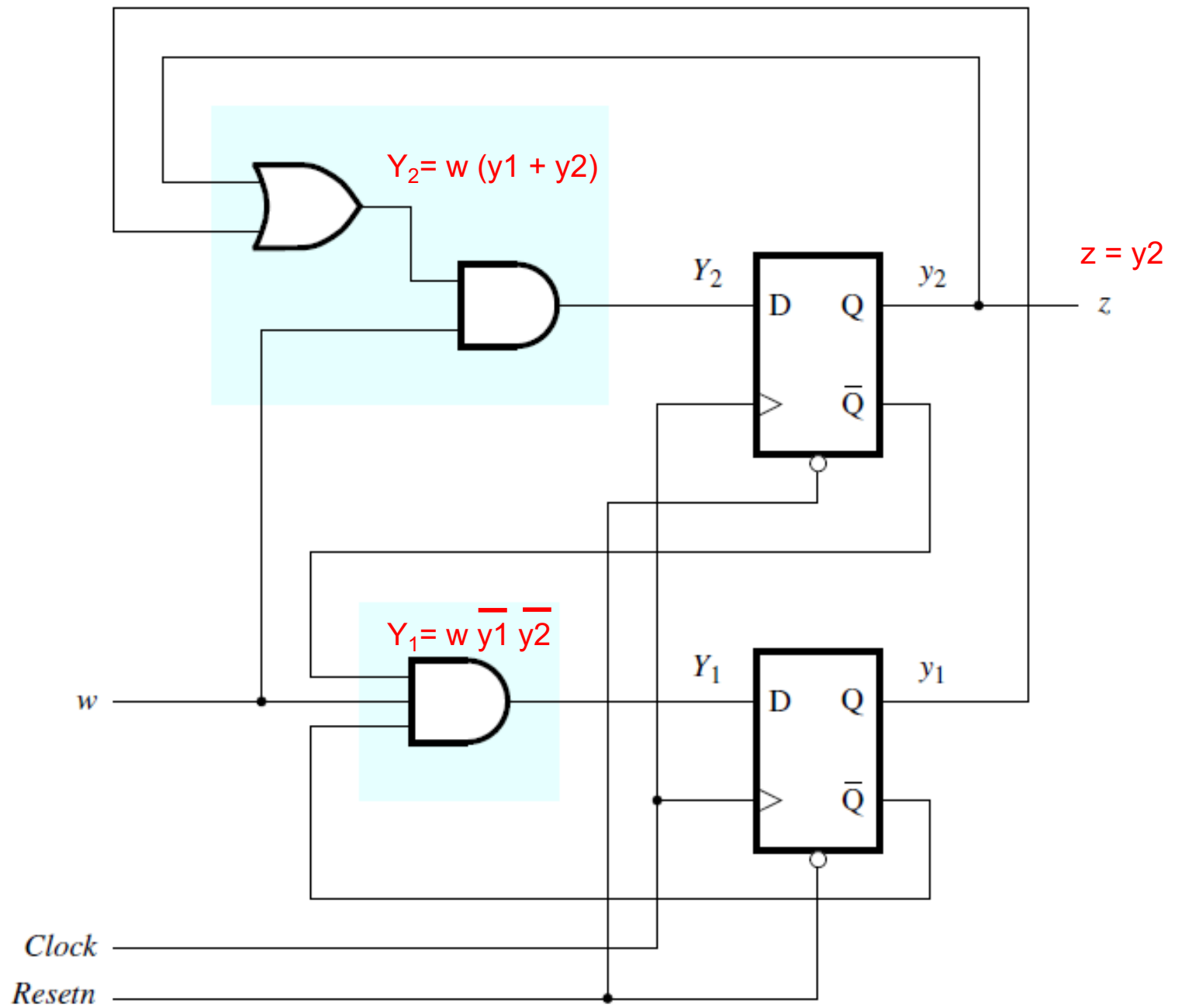
$$z = y_2$$

[ Figure 6.7 from the textbook ]



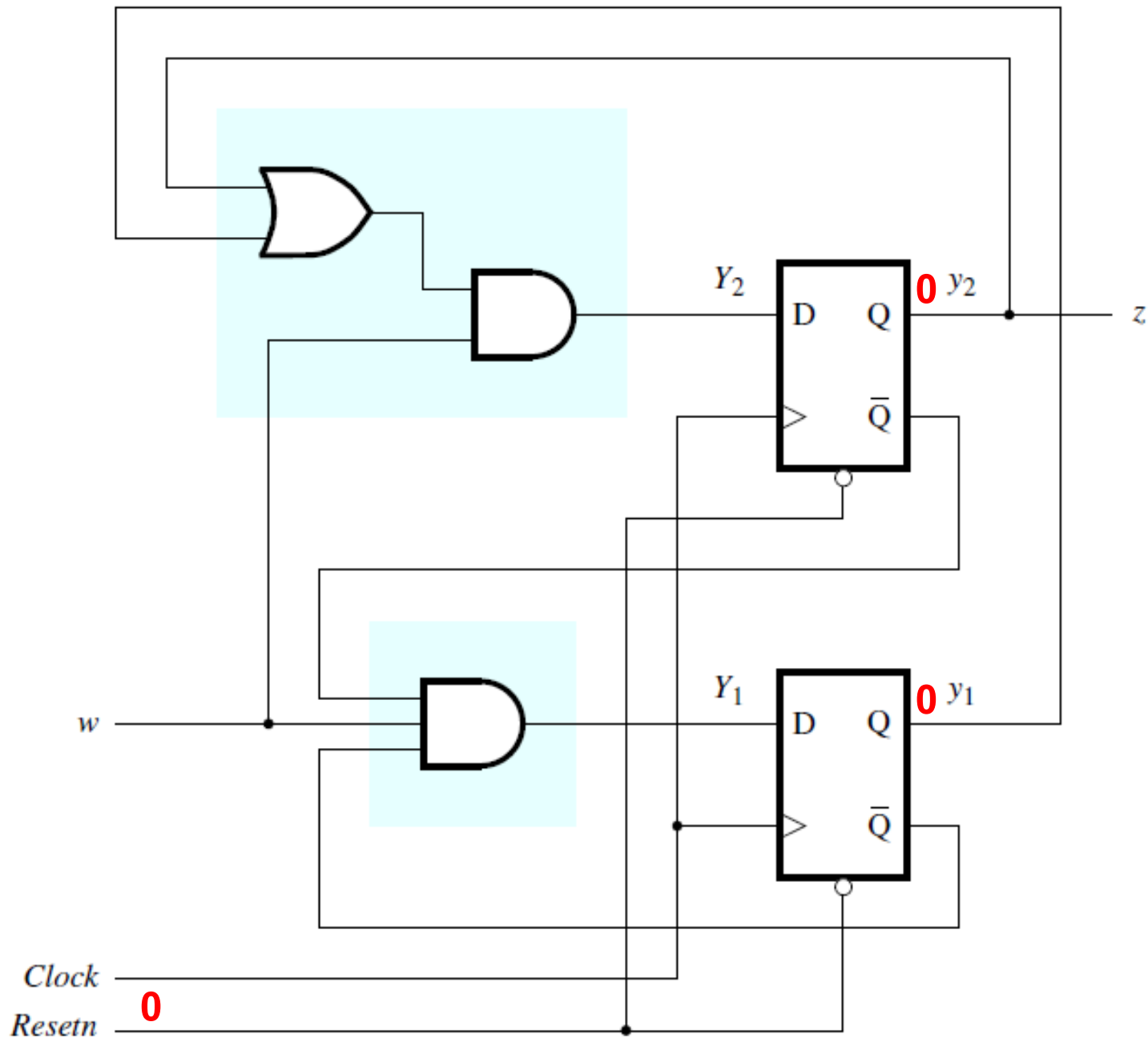


[ Figure 6.8 from the textbook ]



[ Figure 6.8 from the textbook ]

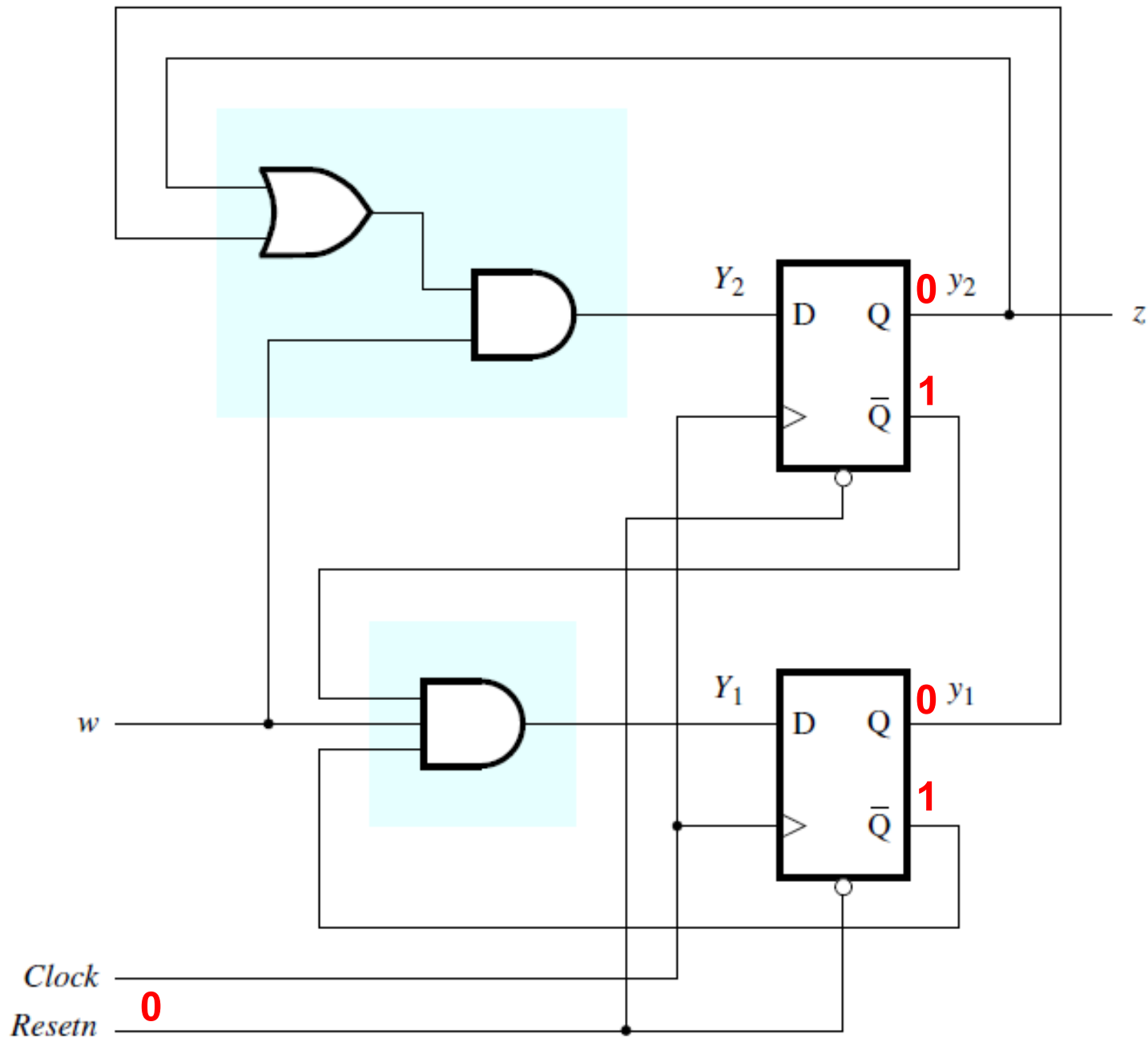
State A=00



Finally, we add a reset signal. When it is equal to zero it puts the machine back to its start state, which is state  $00$  in this case.

[ Figure 6.8 from the textbook ]

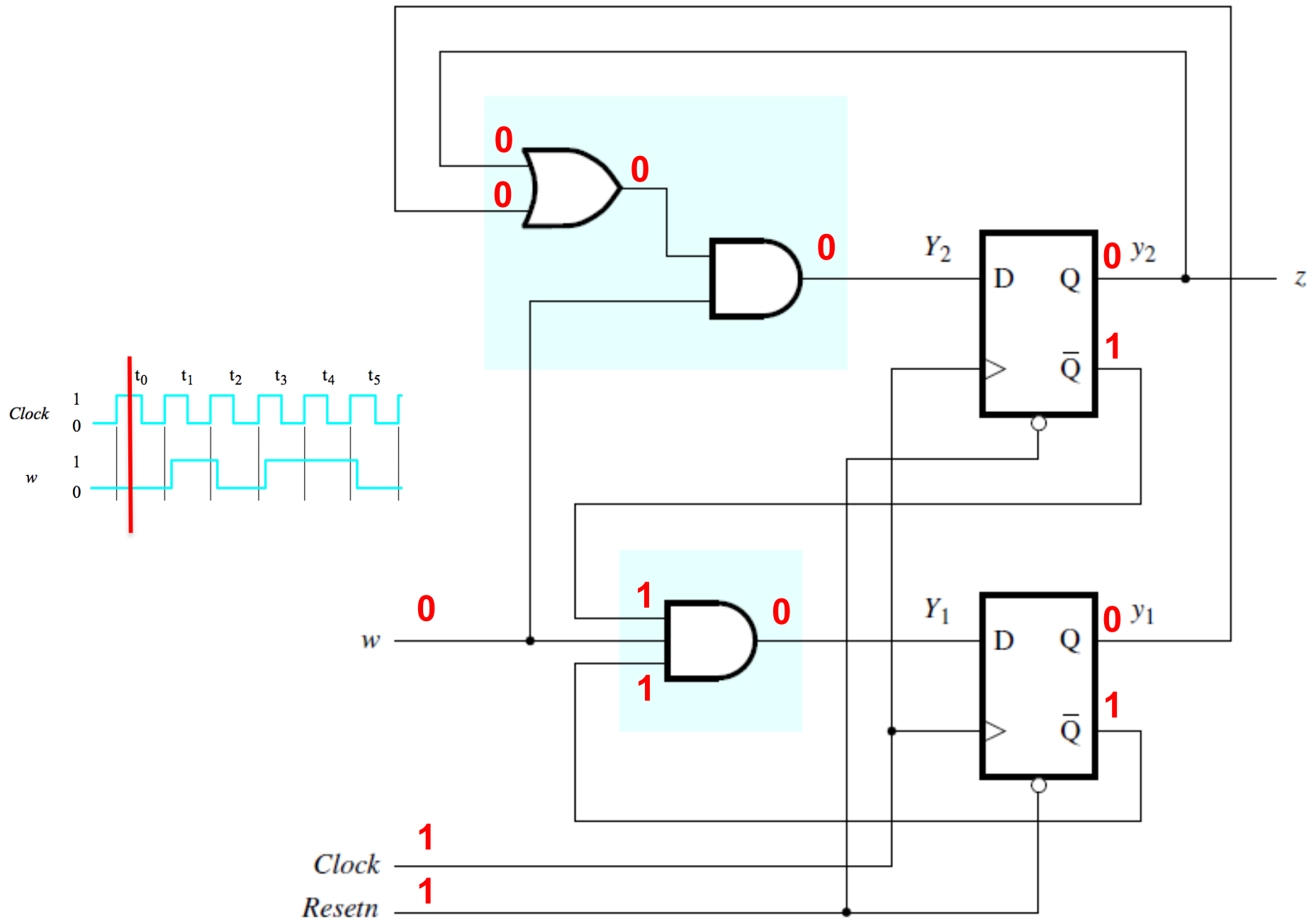
State A=00



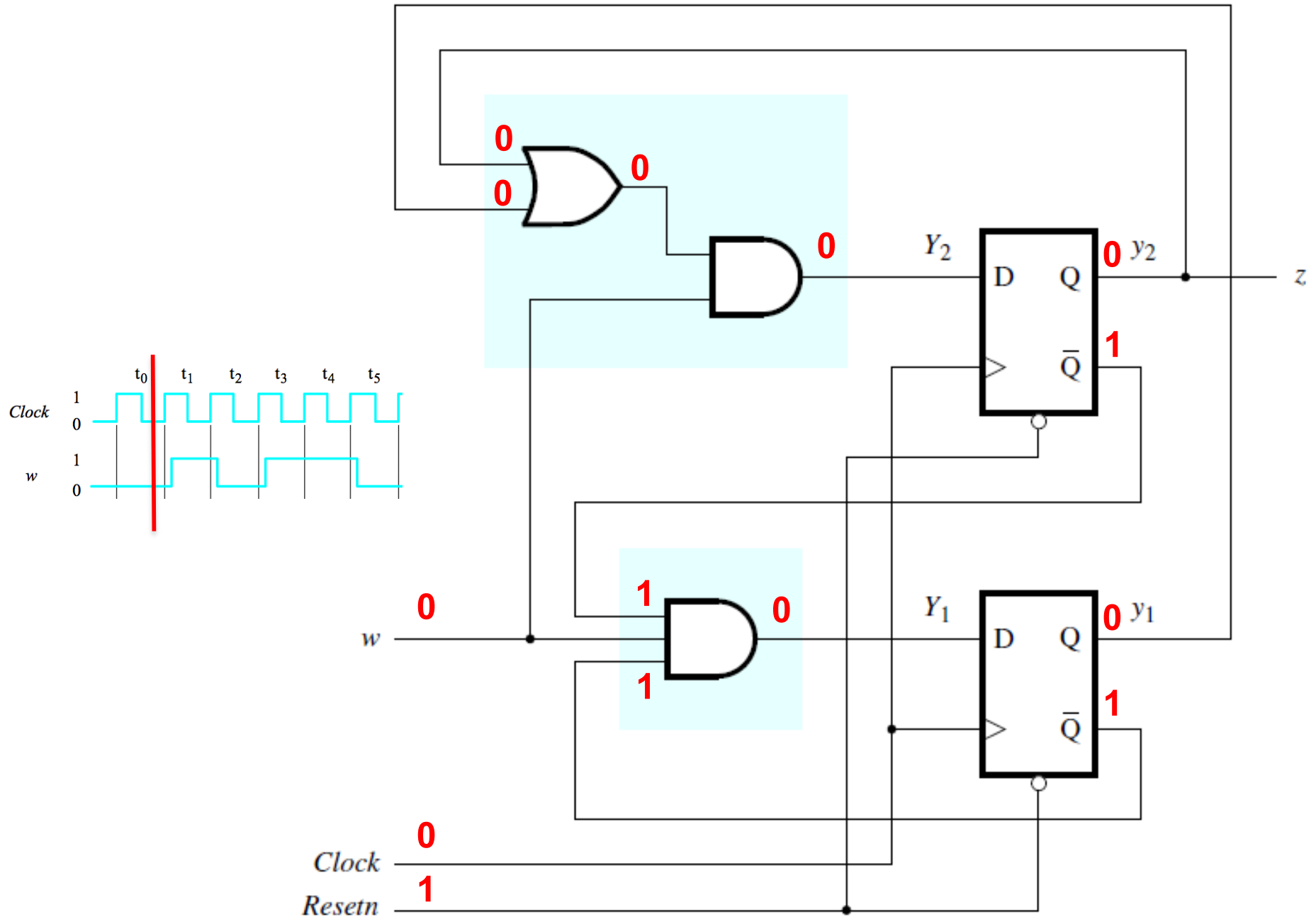
Finally, we add a reset signal. When it is equal to zero it puts the machine back to its start state, which is state 00 in this case.

[ Figure 6.8 from the textbook ]

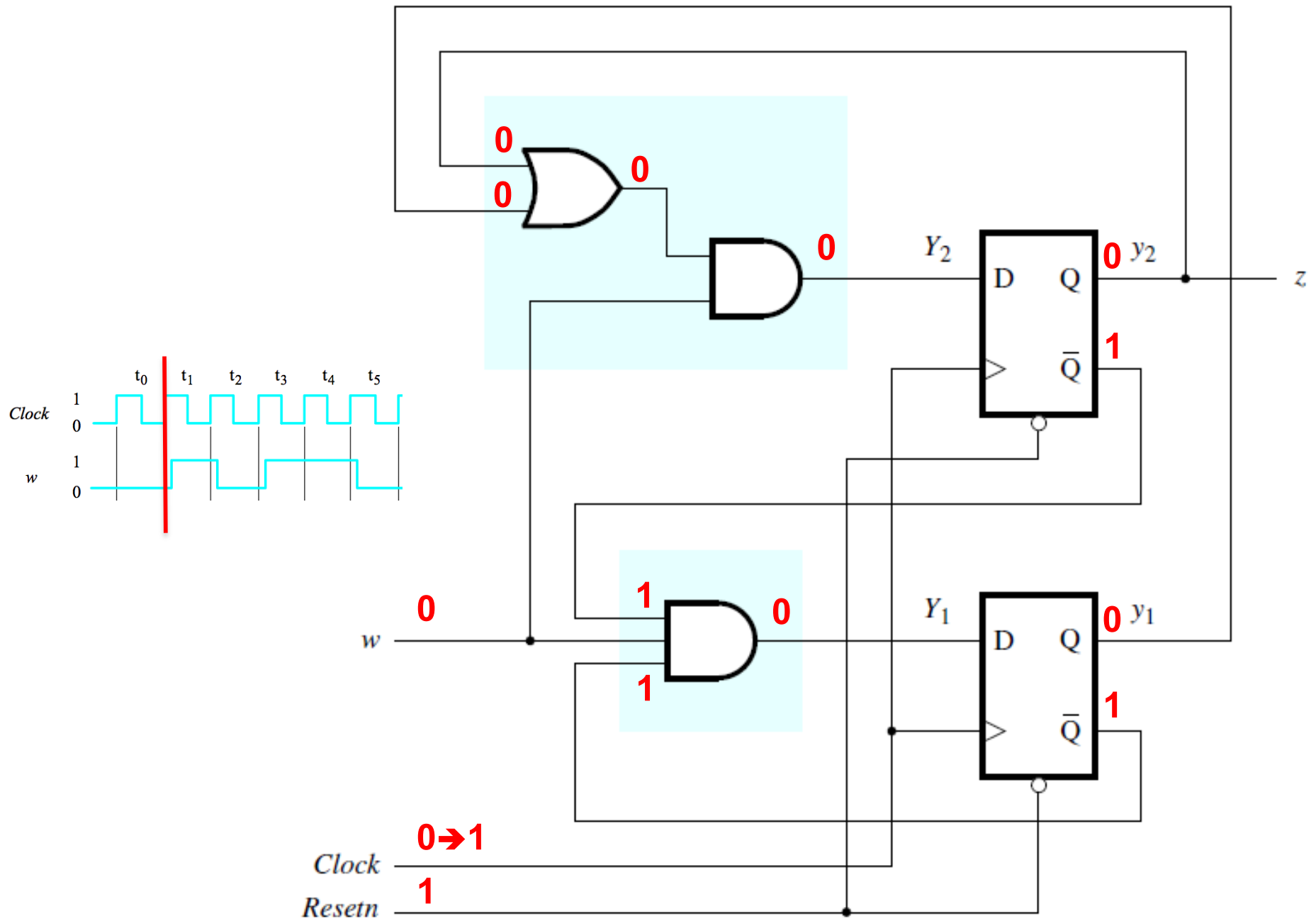
State A=00



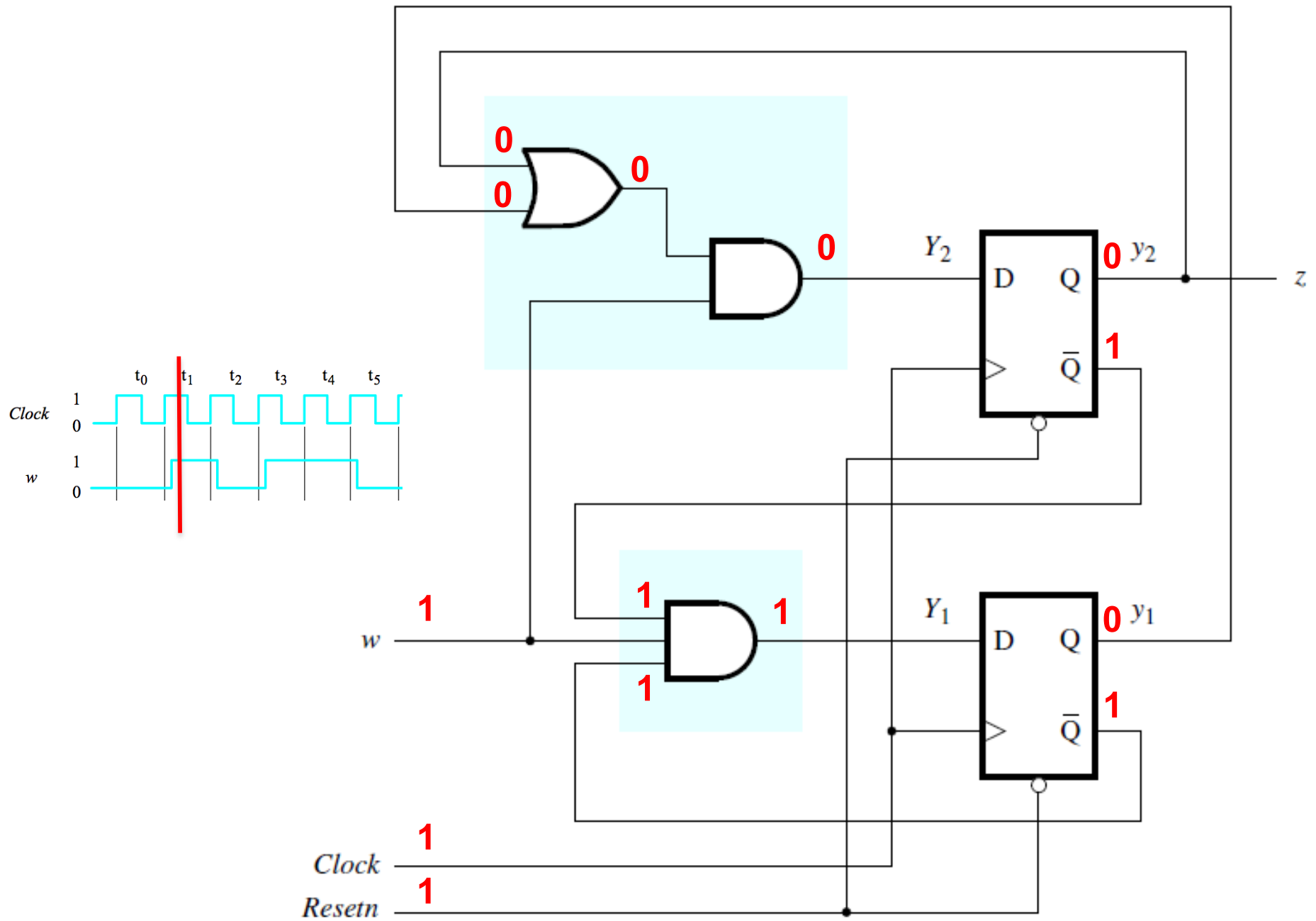
State A=00



State A=00

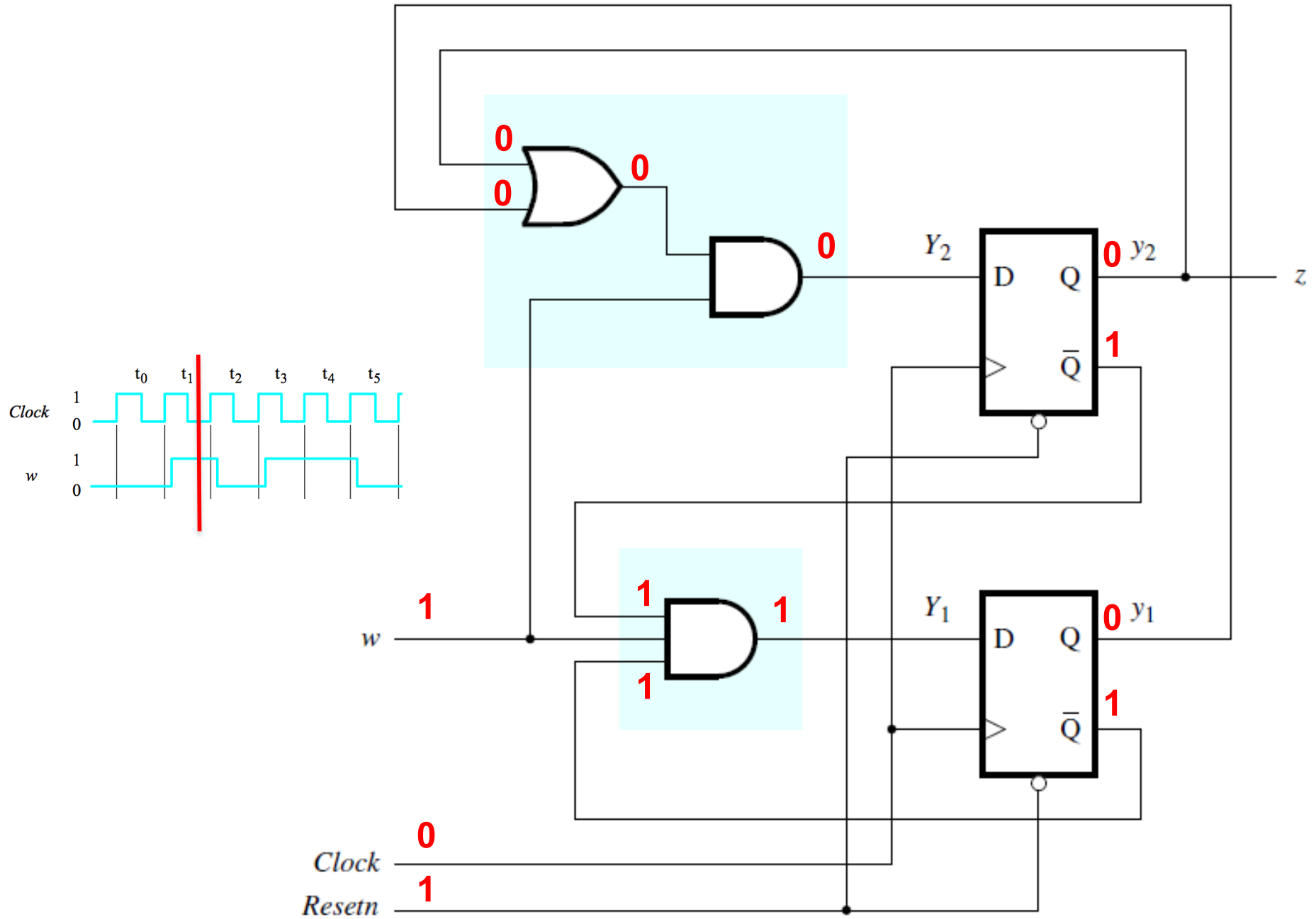


State A=00

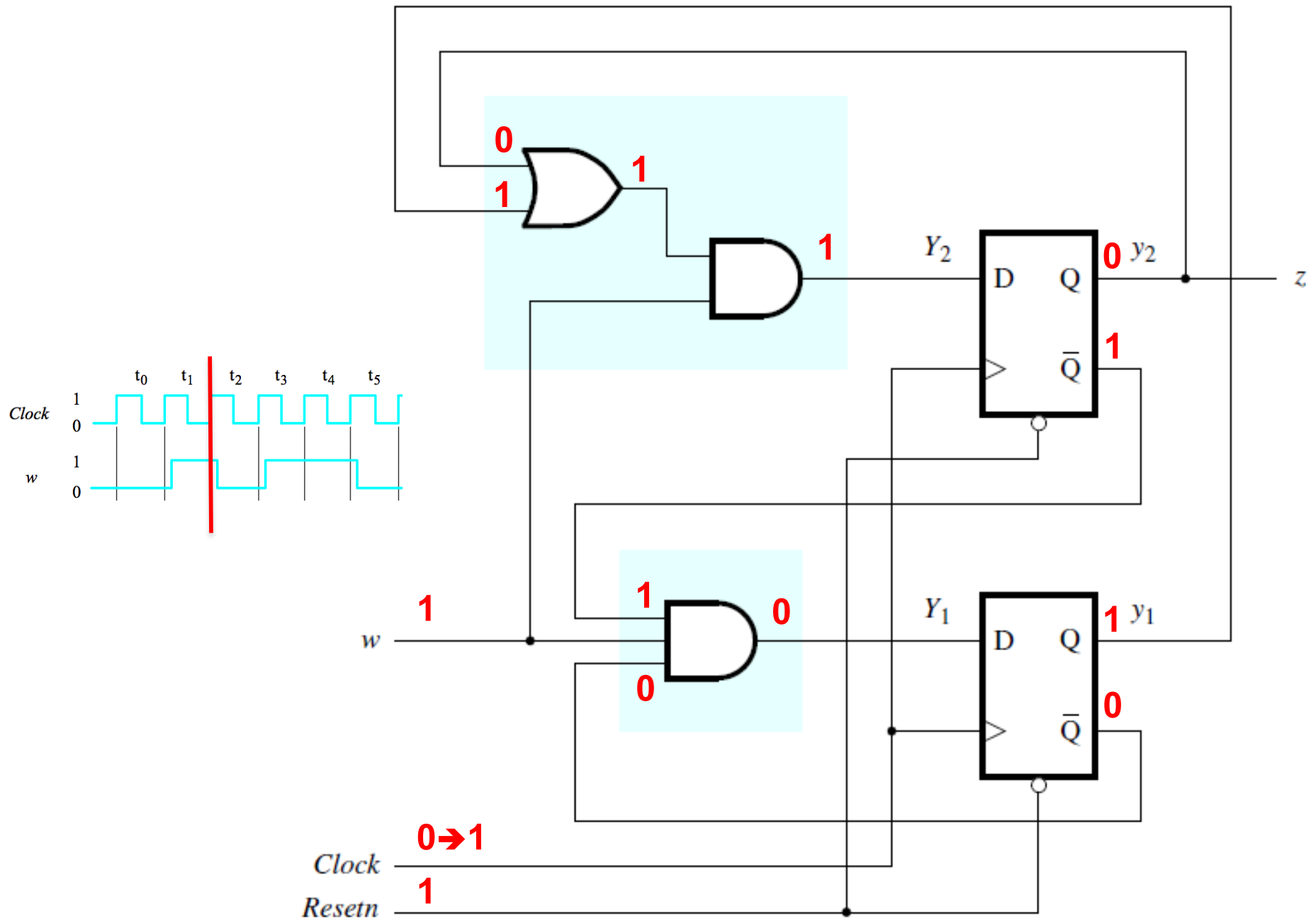




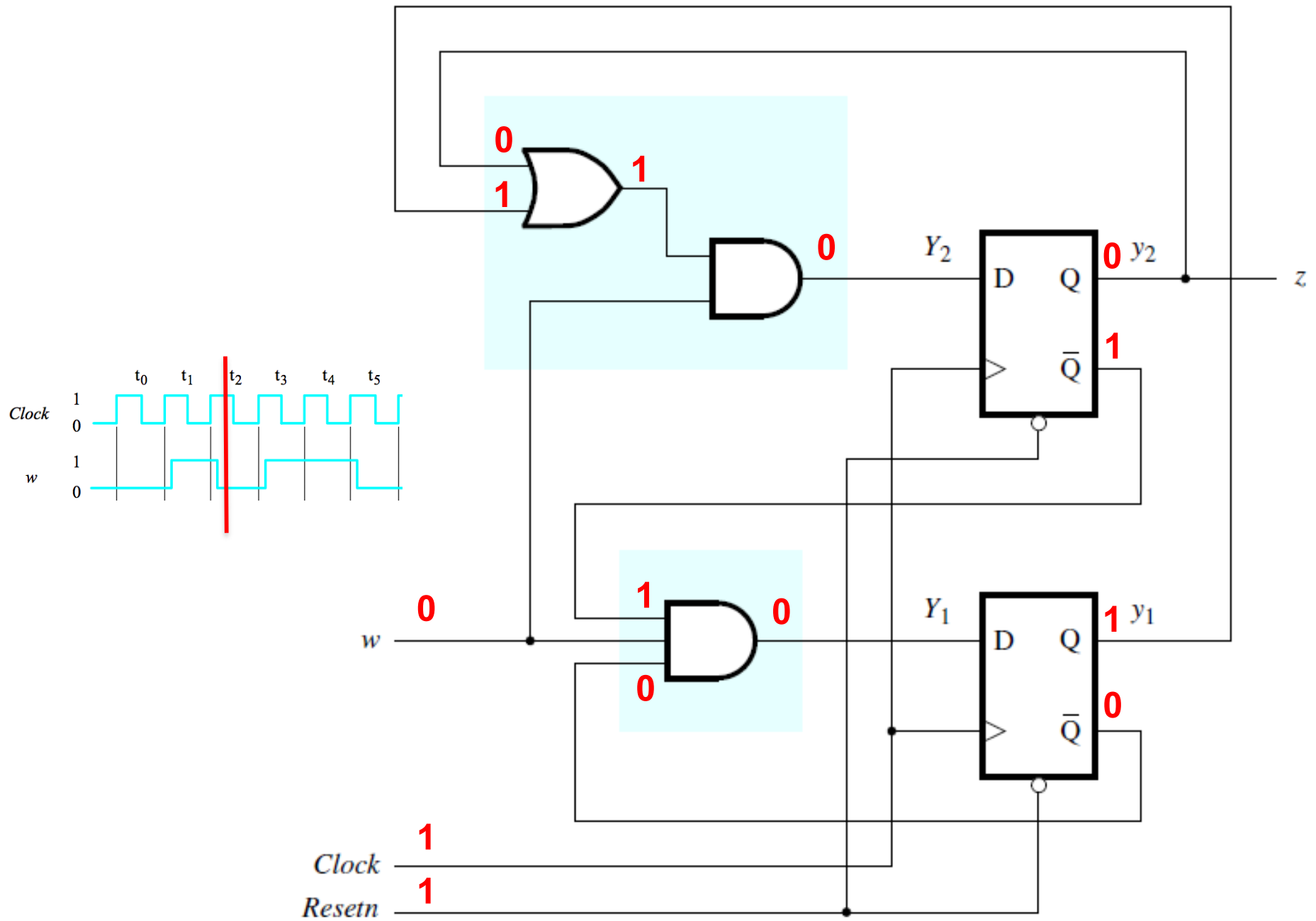
State A=00



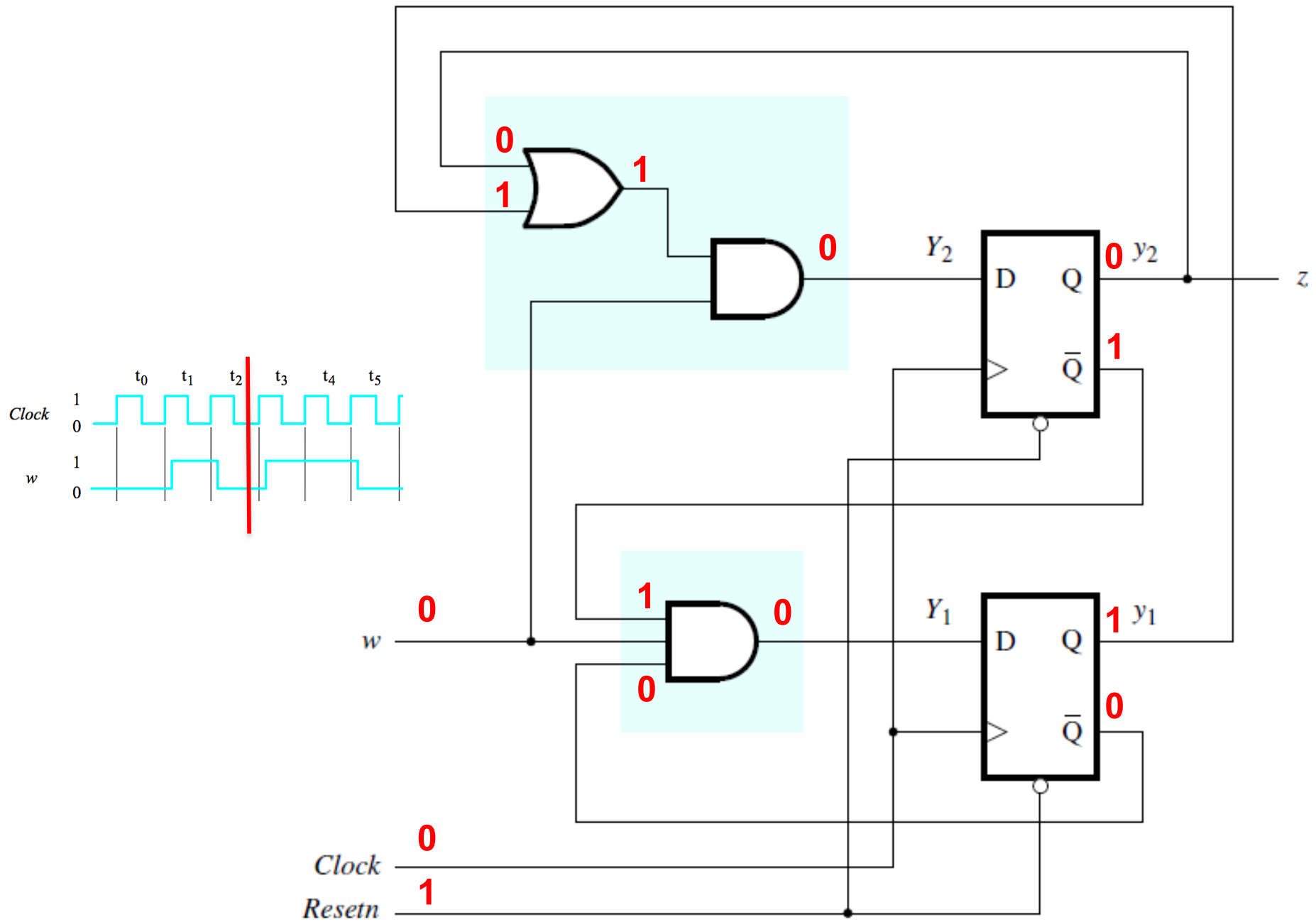
State B=01



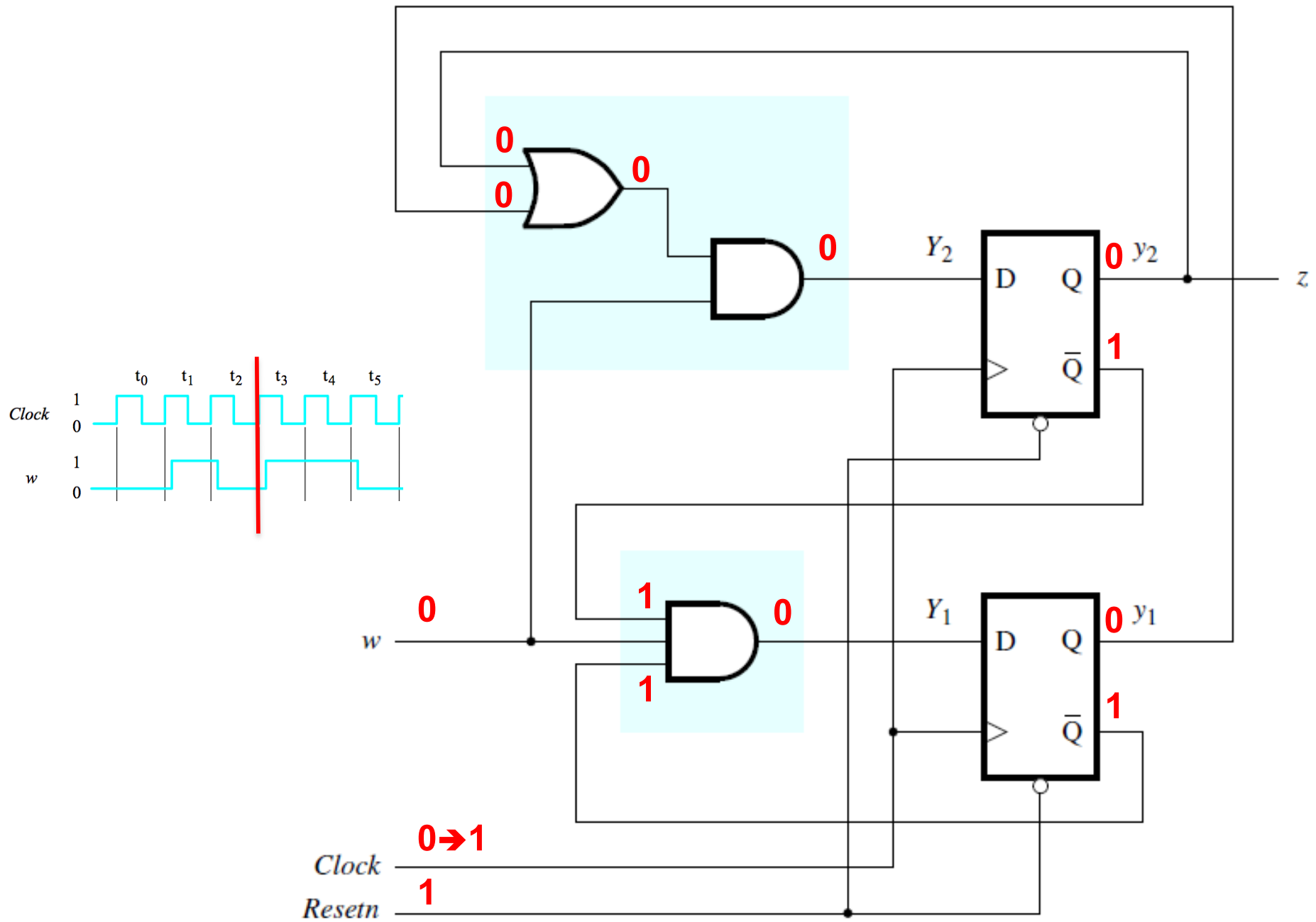
State B=01



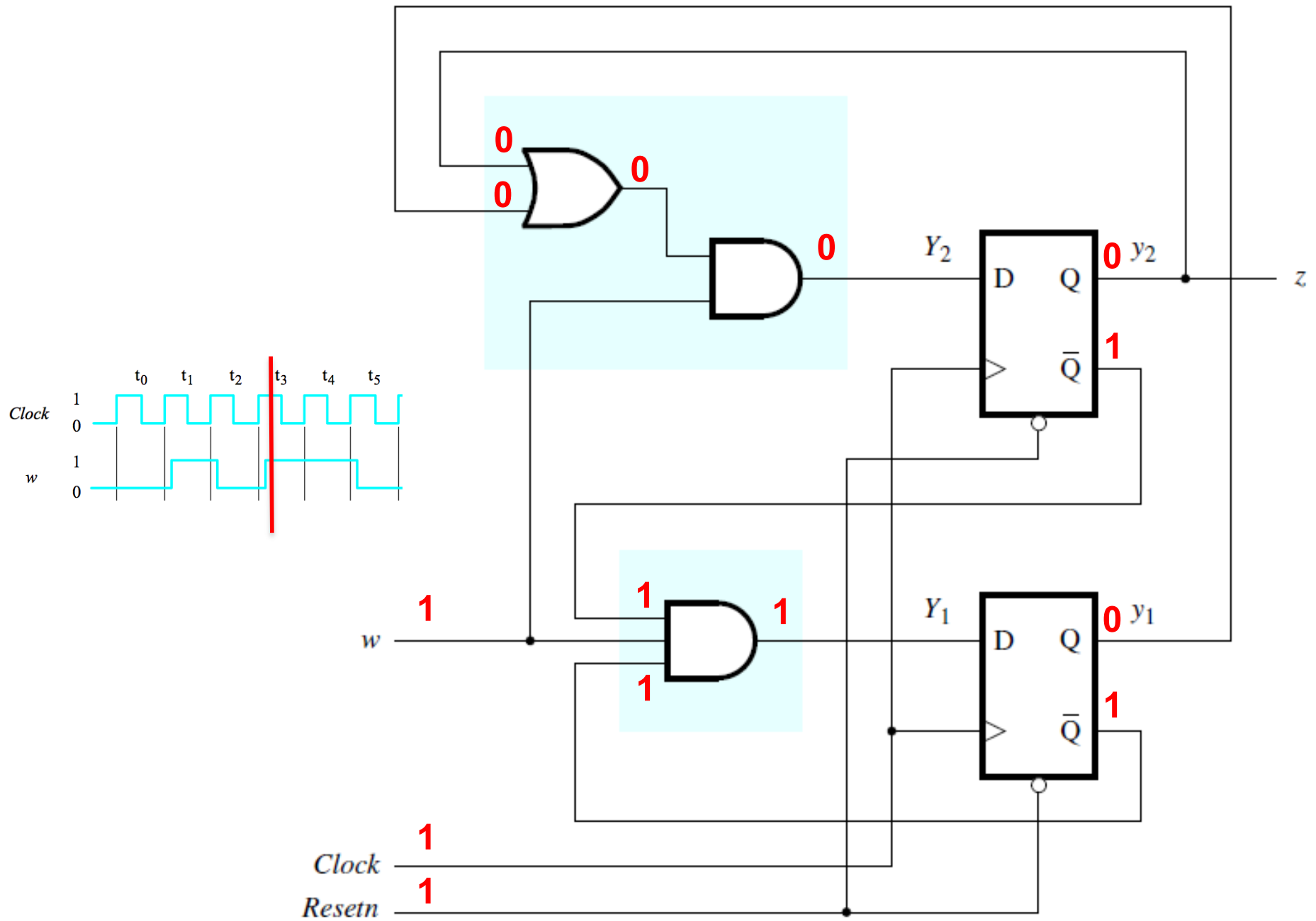
State B=01



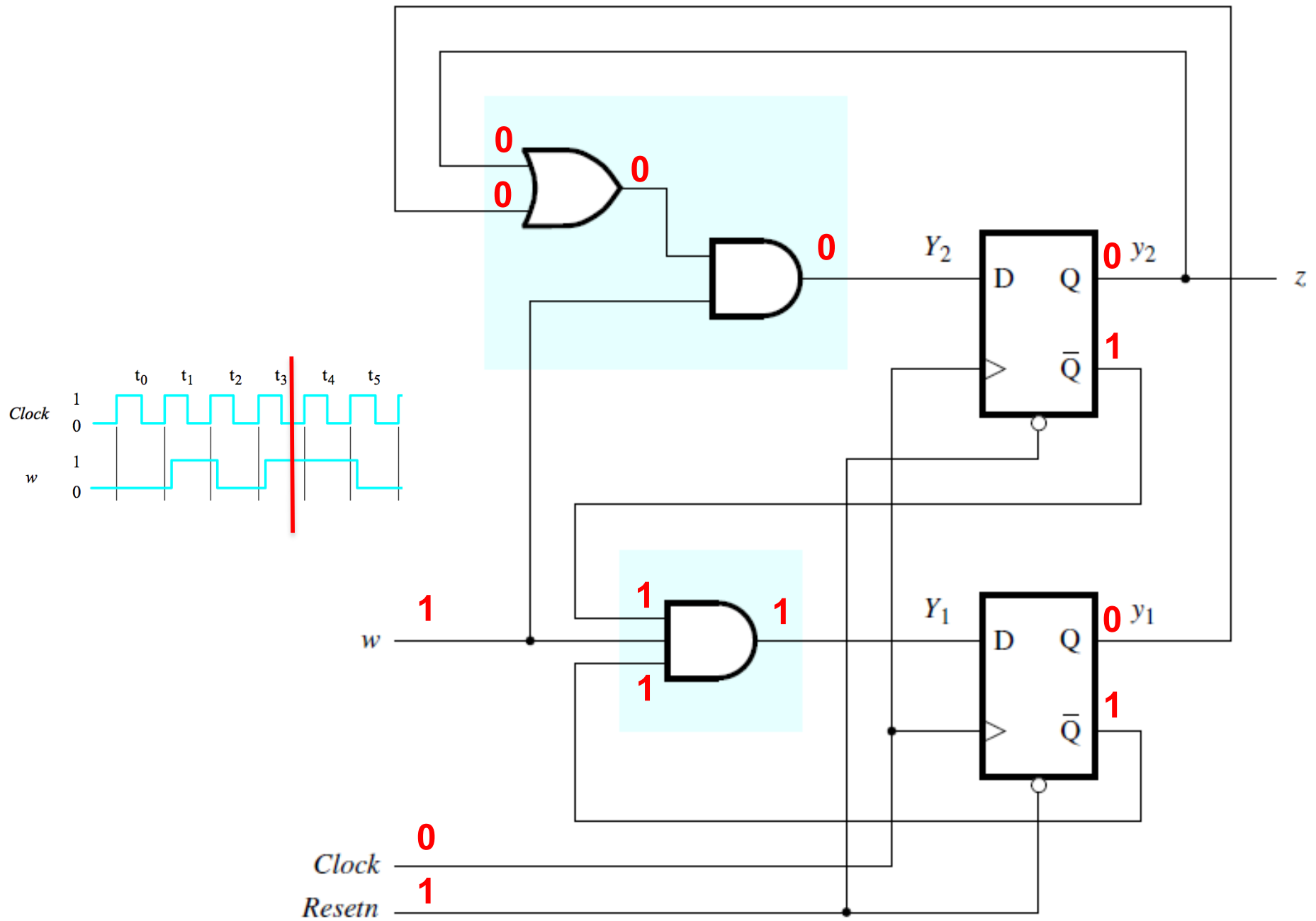
State A=00



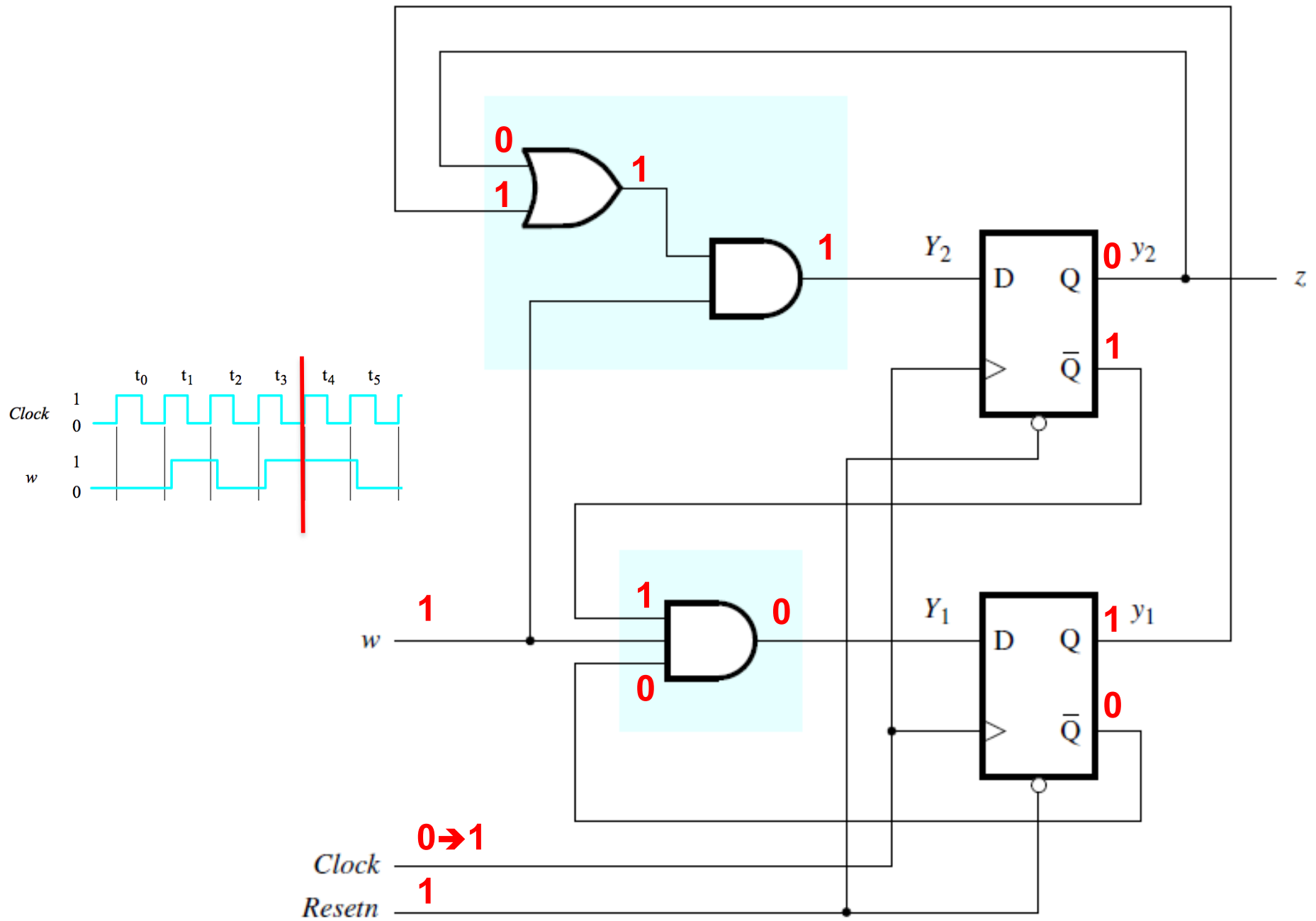
State A=00



State A=00

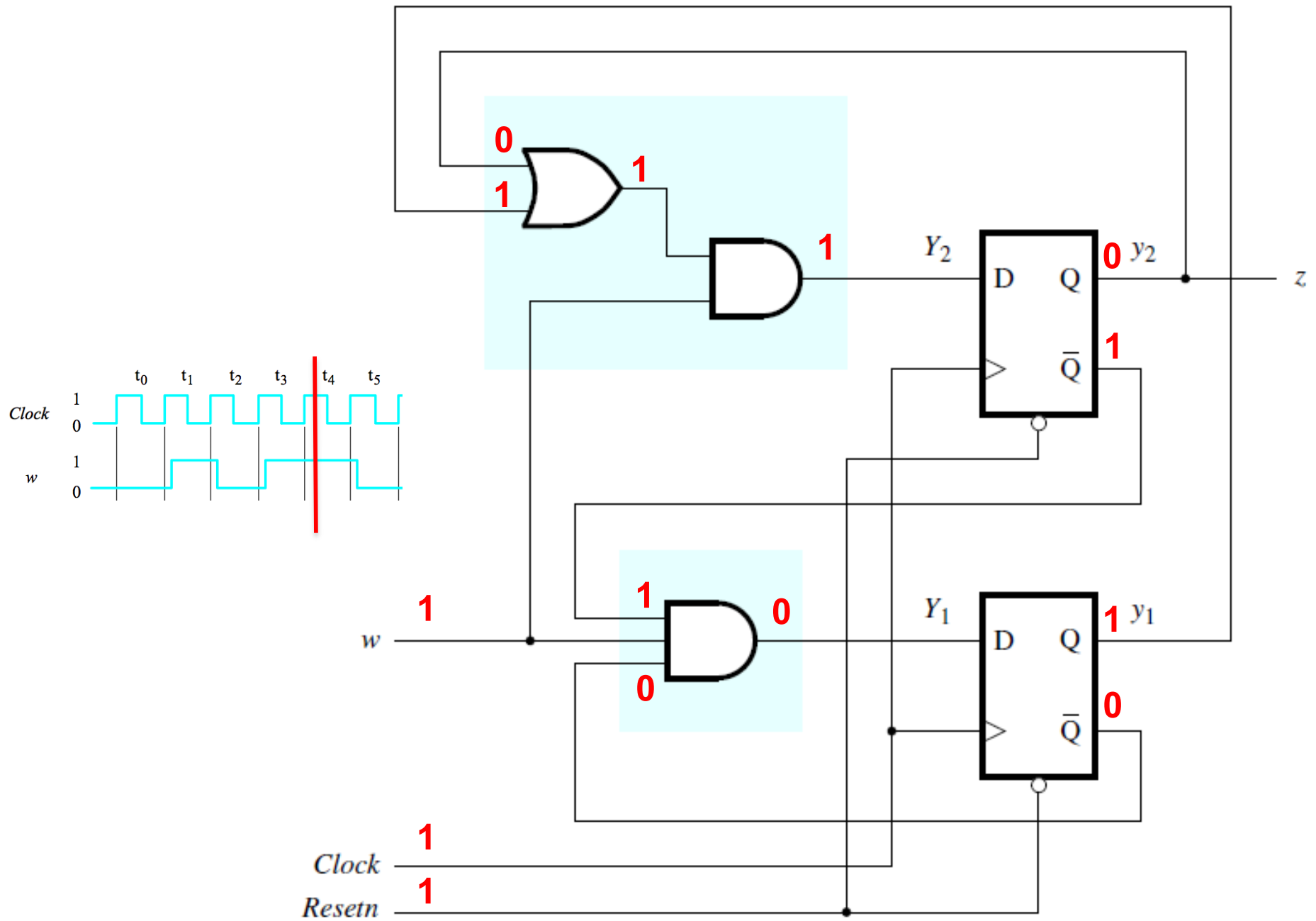


State B=01

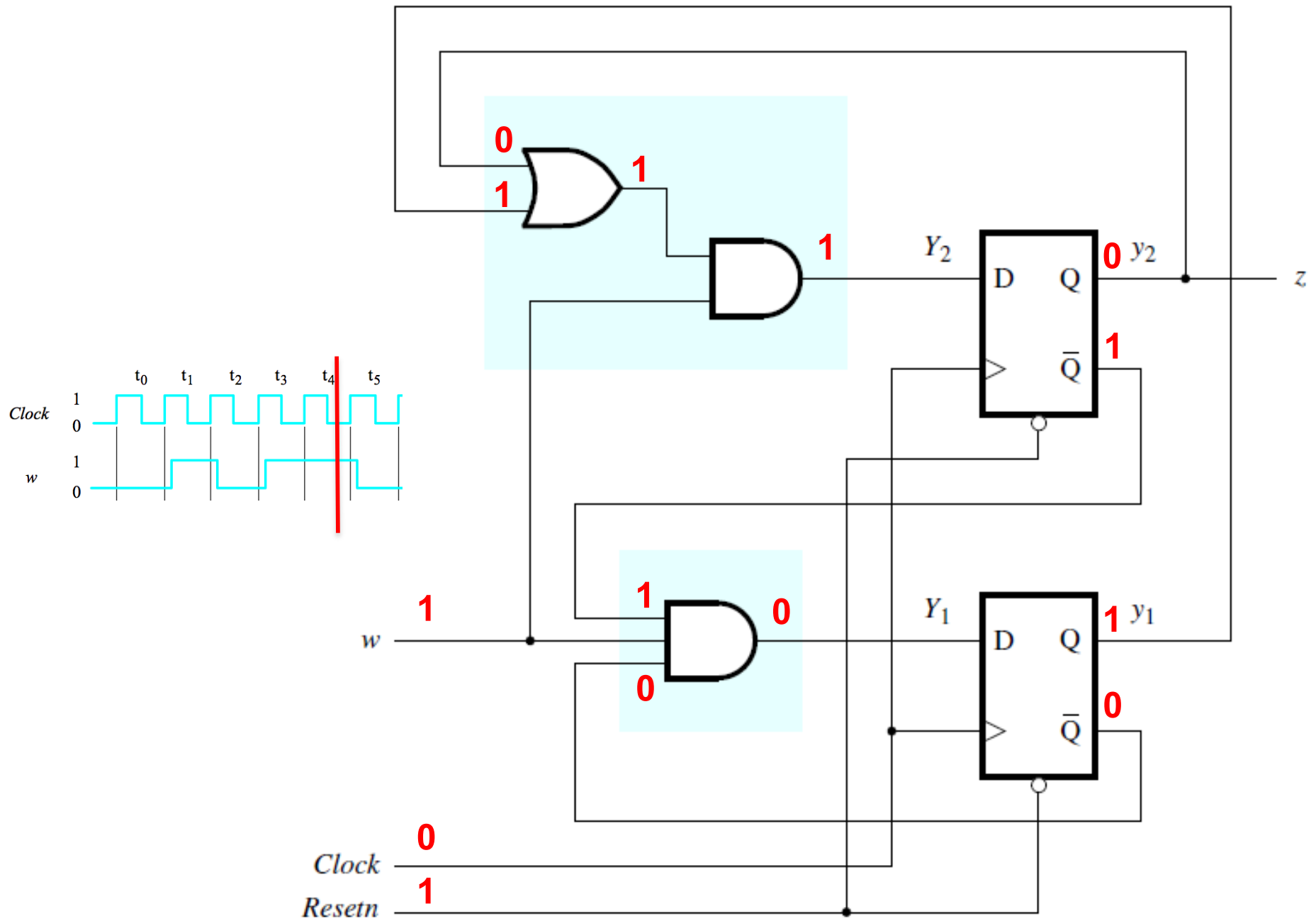




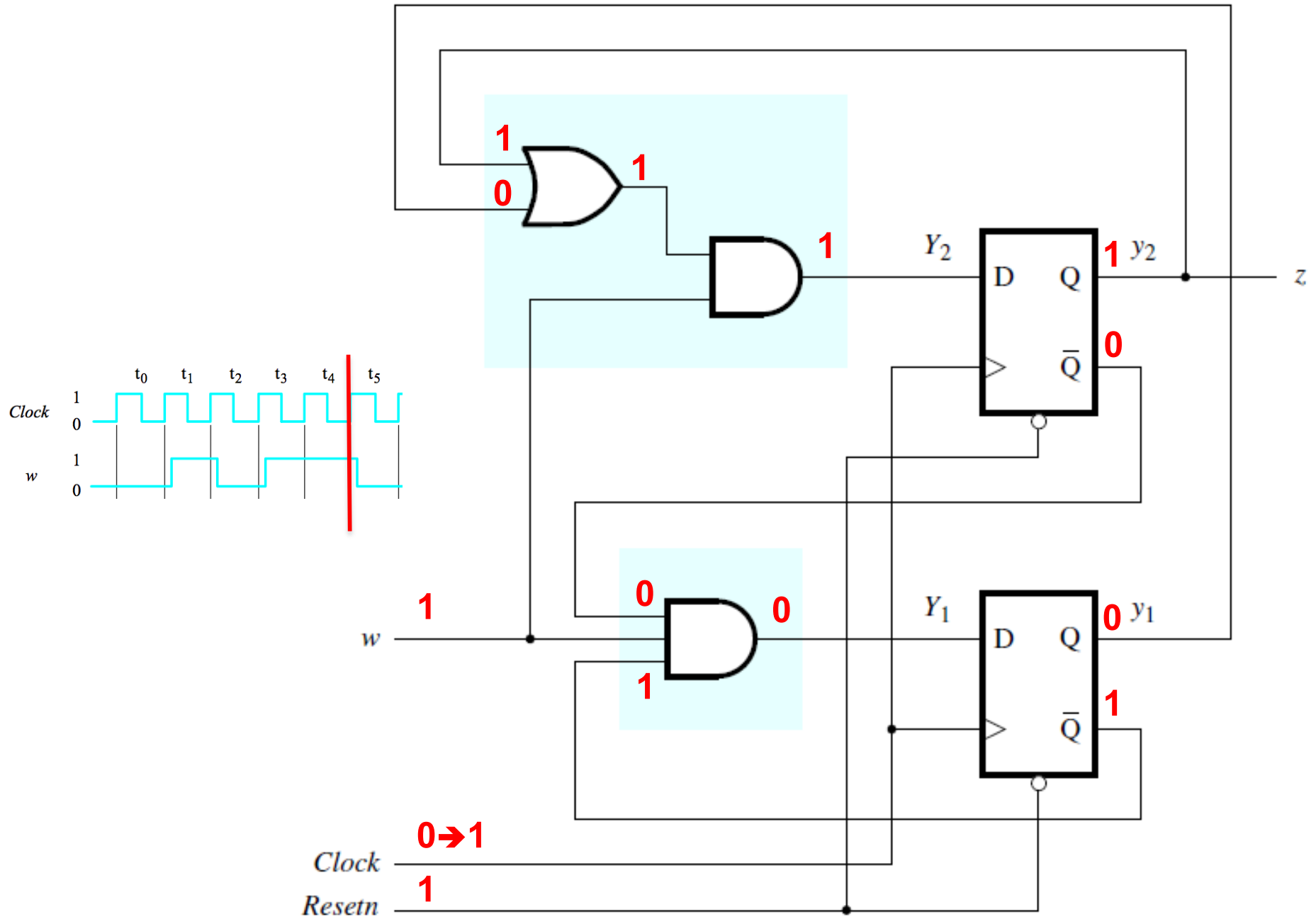
State B=01



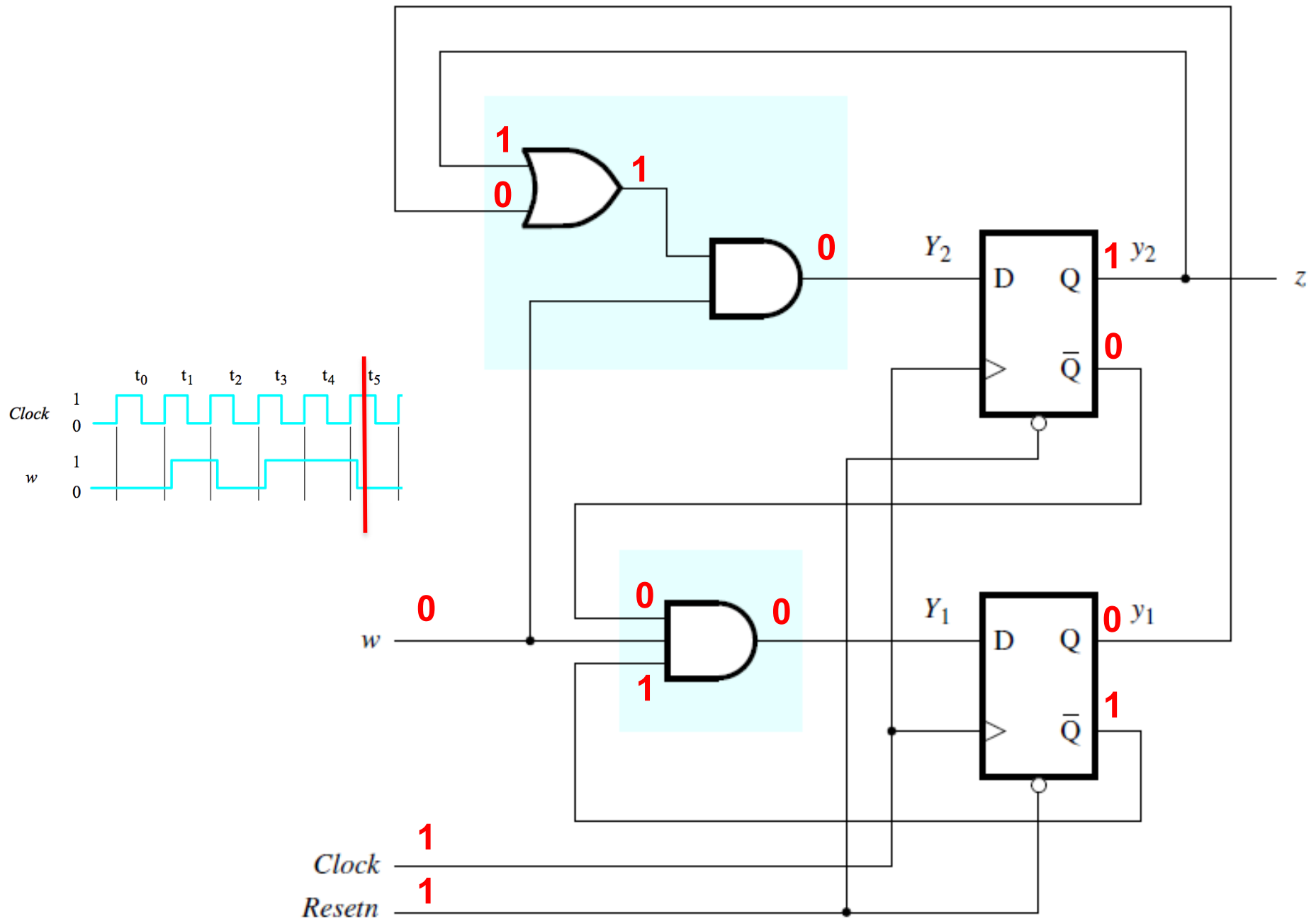
State B=01



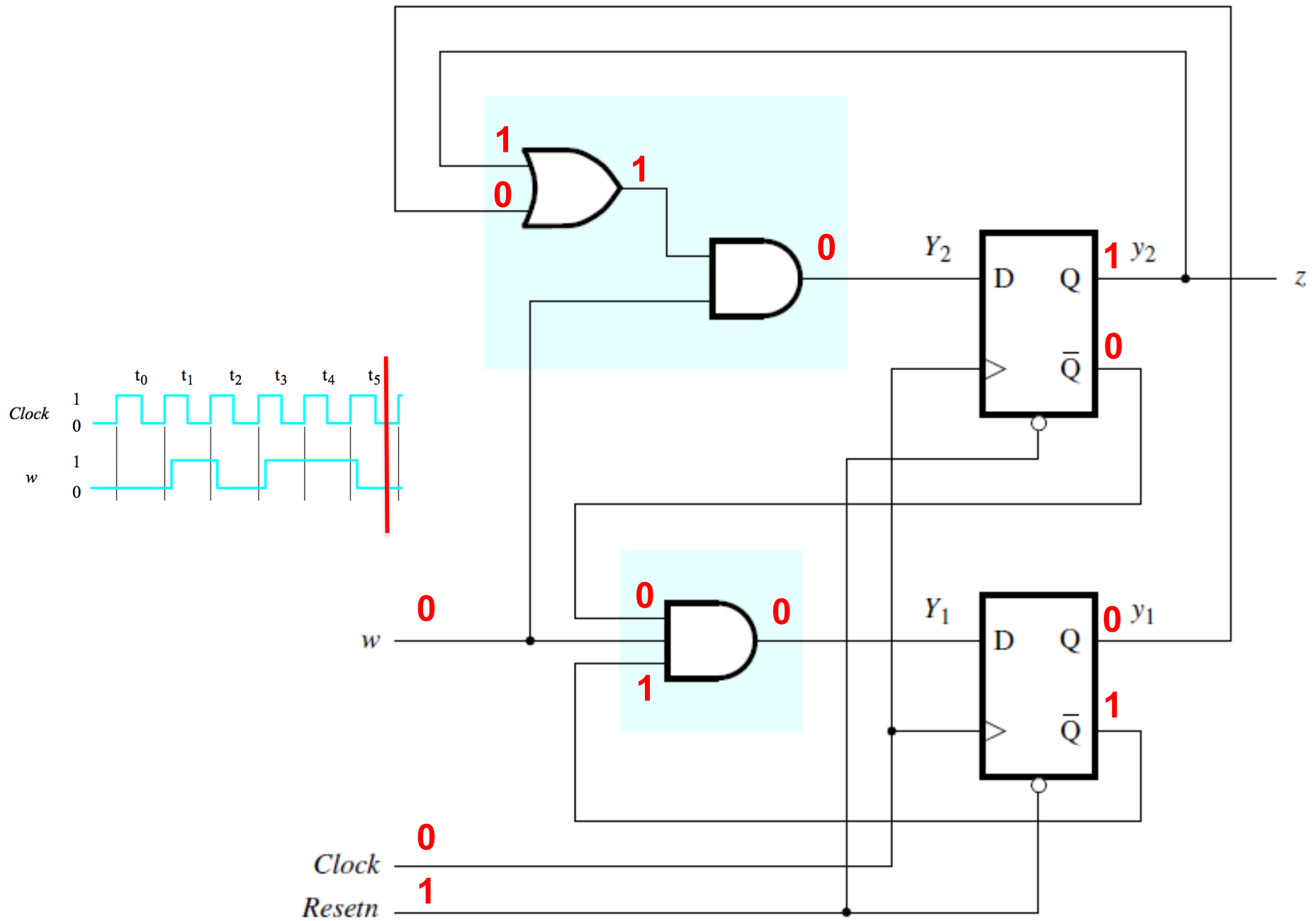
State C=10



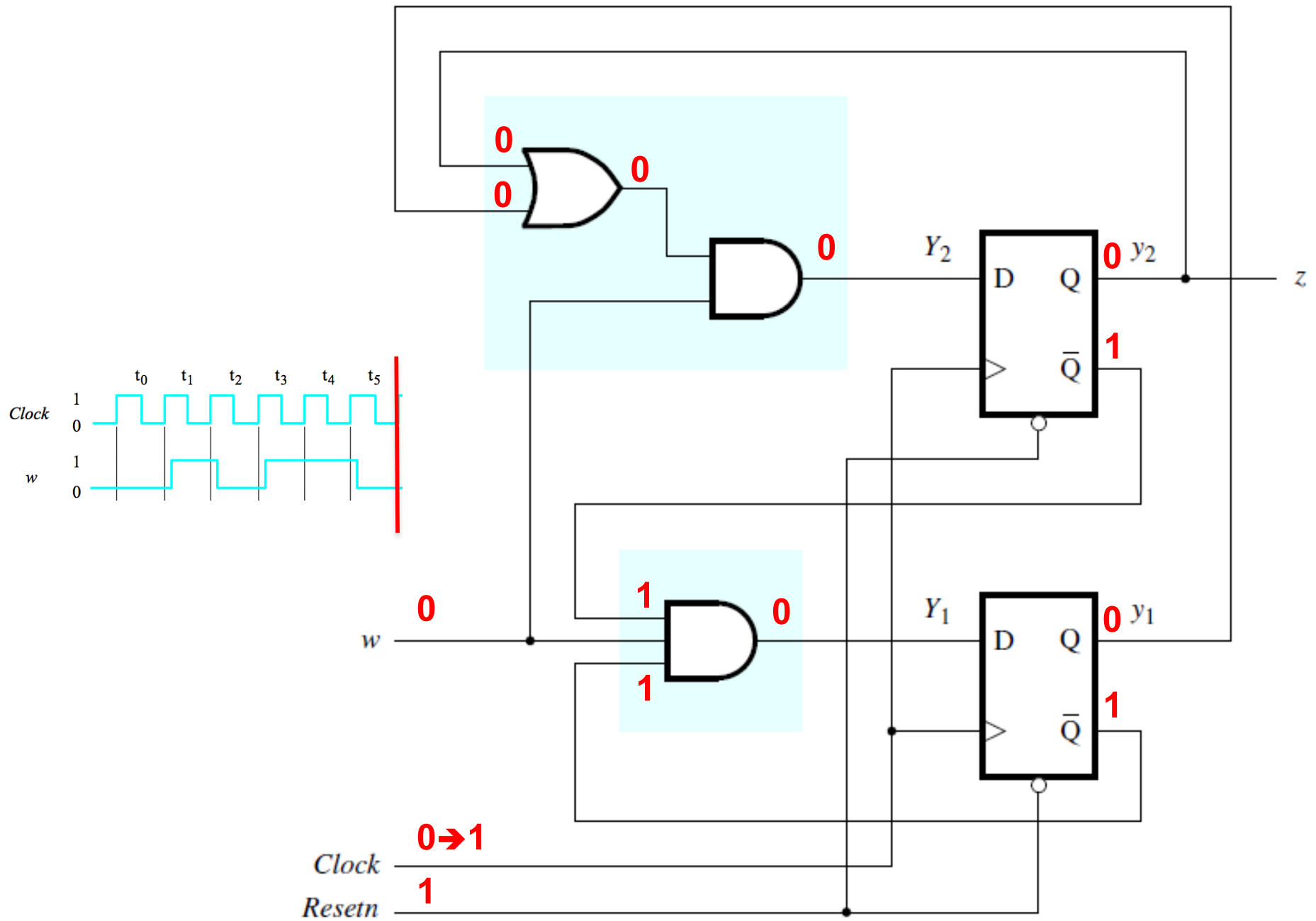
State C=10



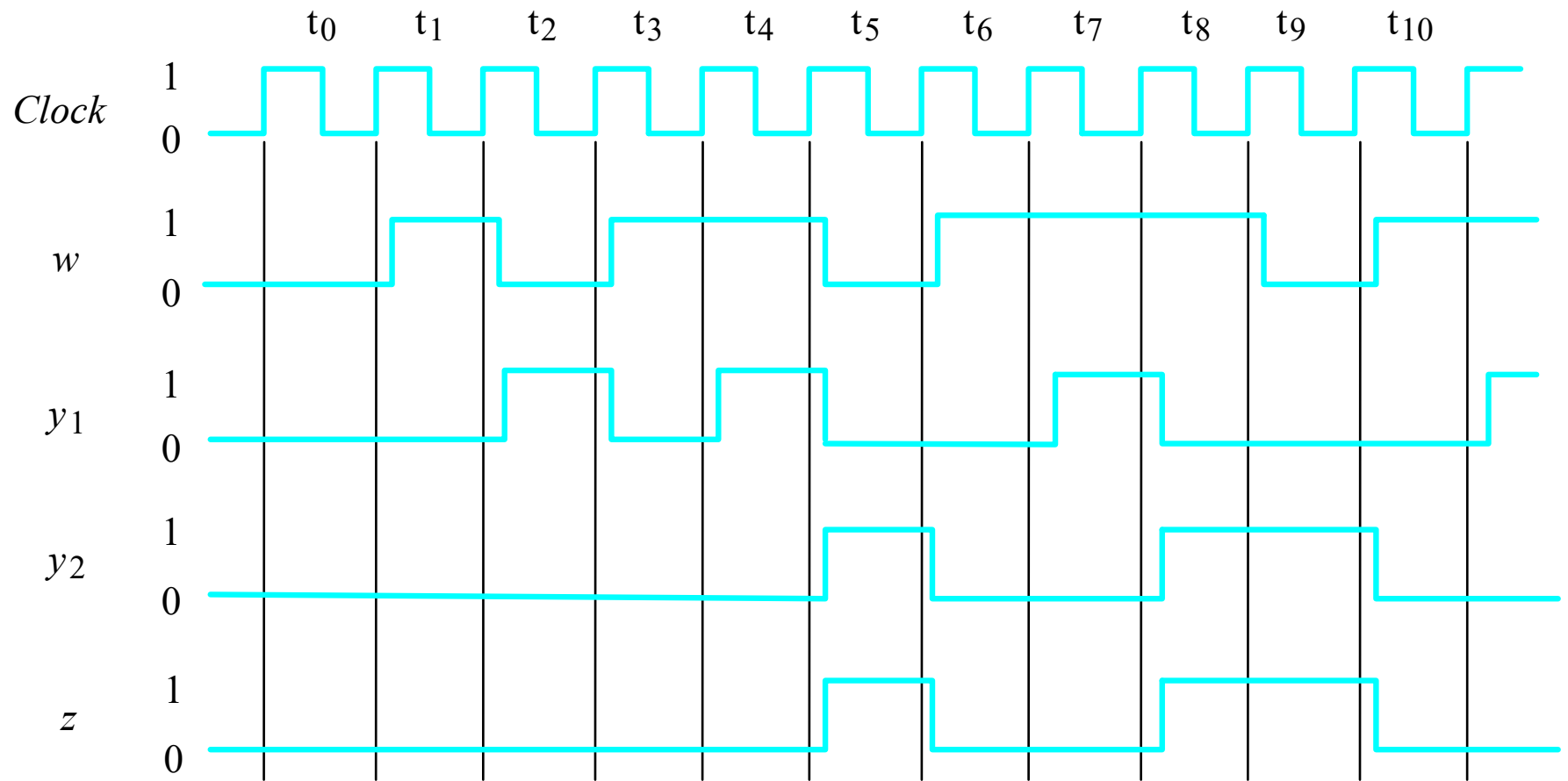
State C=10



State A=00

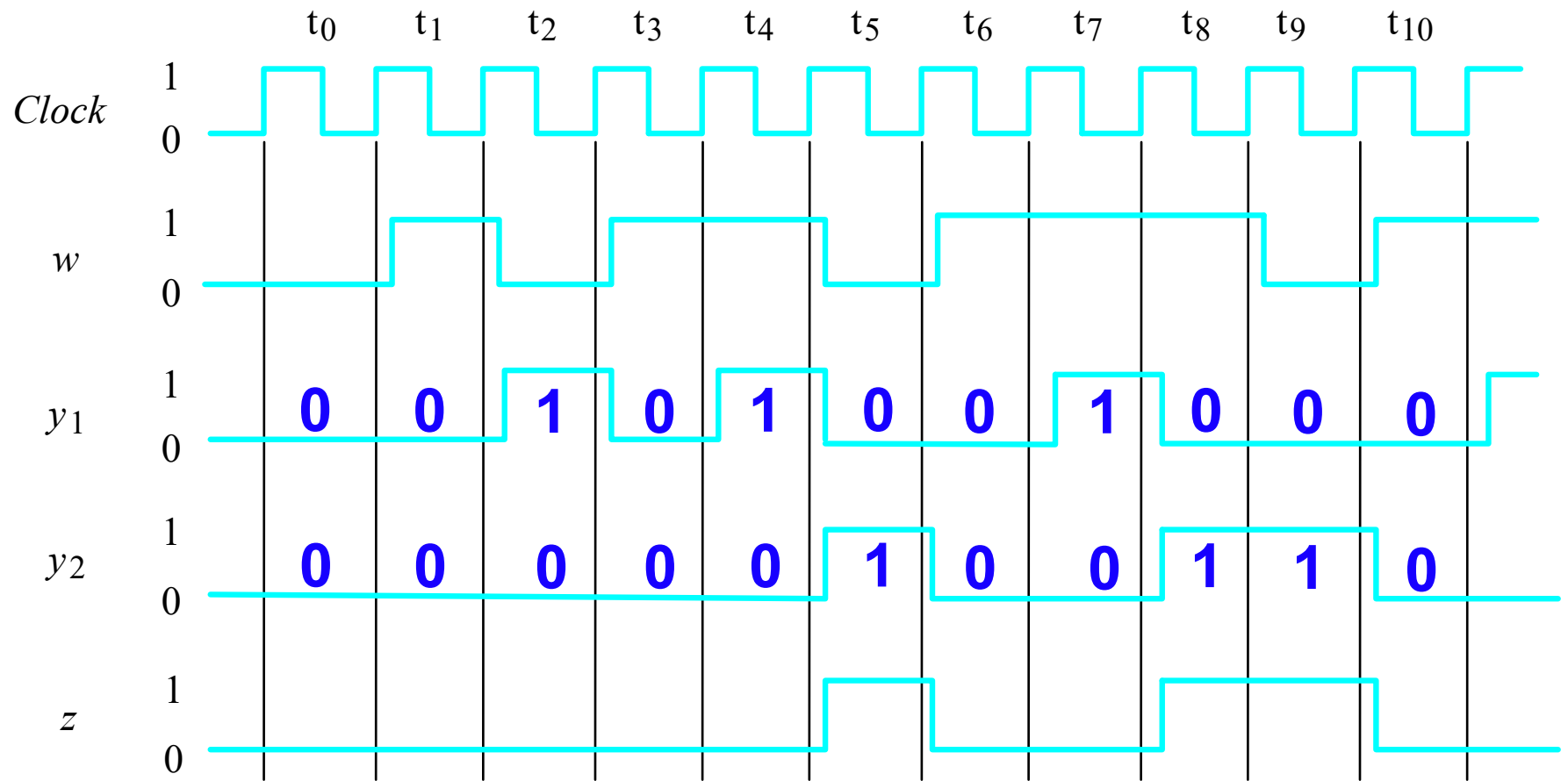


Clockcycle:	$t_0$	$t_1$	$t_2$	$t_3$	$t_4$	$t_5$	$t_6$	$t_7$	$t_8$	$t_9$	$t_{10}$
$w$ :	0	1	0	1	1	0	1	1	1	0	1
$z$ :	0	0	0	0	0	1	0	0	1	1	0



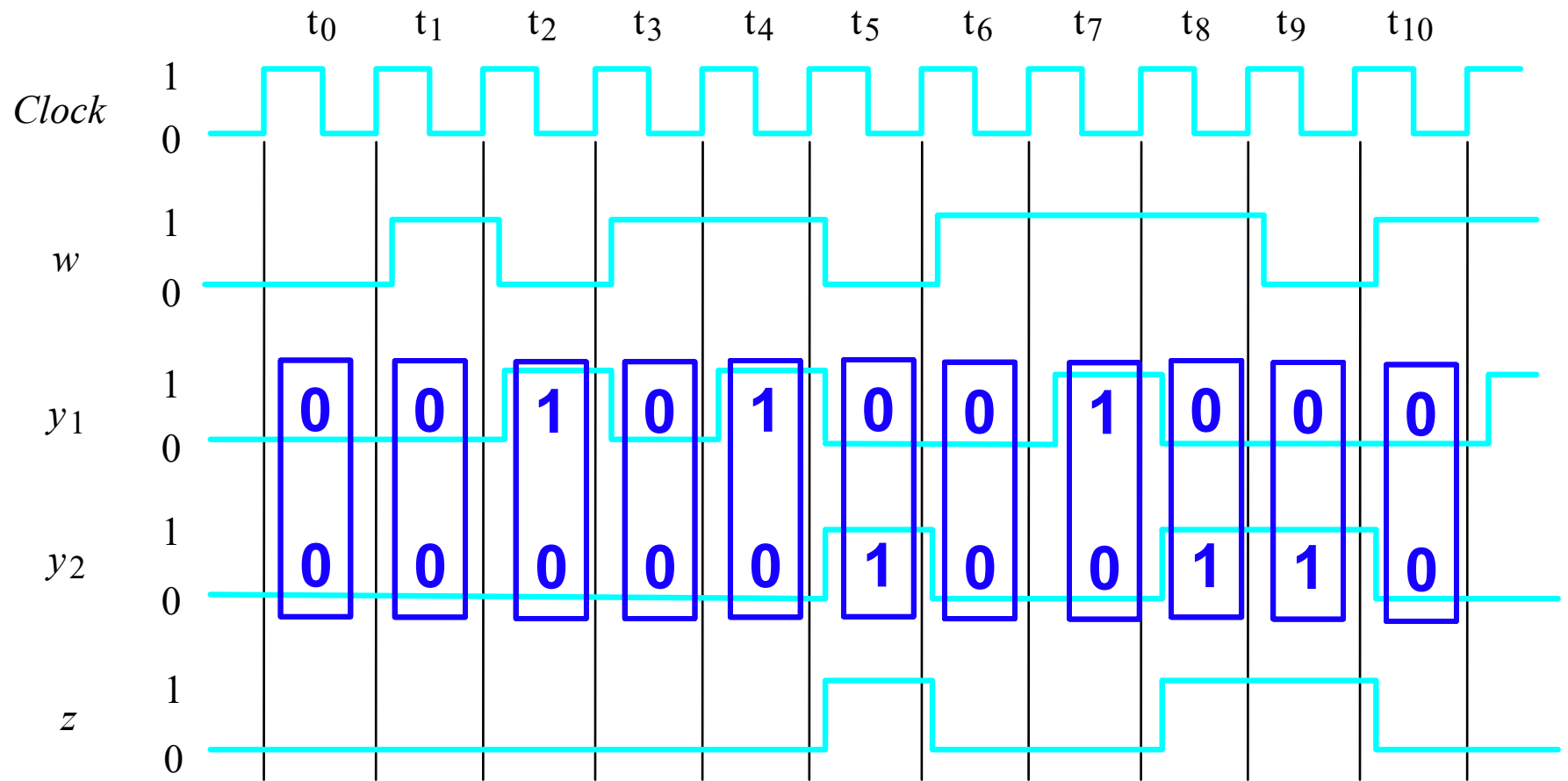
[ Figure 6.9 from the textbook ]

Clockcycle:	$t_0$	$t_1$	$t_2$	$t_3$	$t_4$	$t_5$	$t_6$	$t_7$	$t_8$	$t_9$	$t_{10}$
$w$ :	0	1	0	1	1	0	1	1	1	0	1
$z$ :	0	0	0	0	0	1	0	0	1	1	0

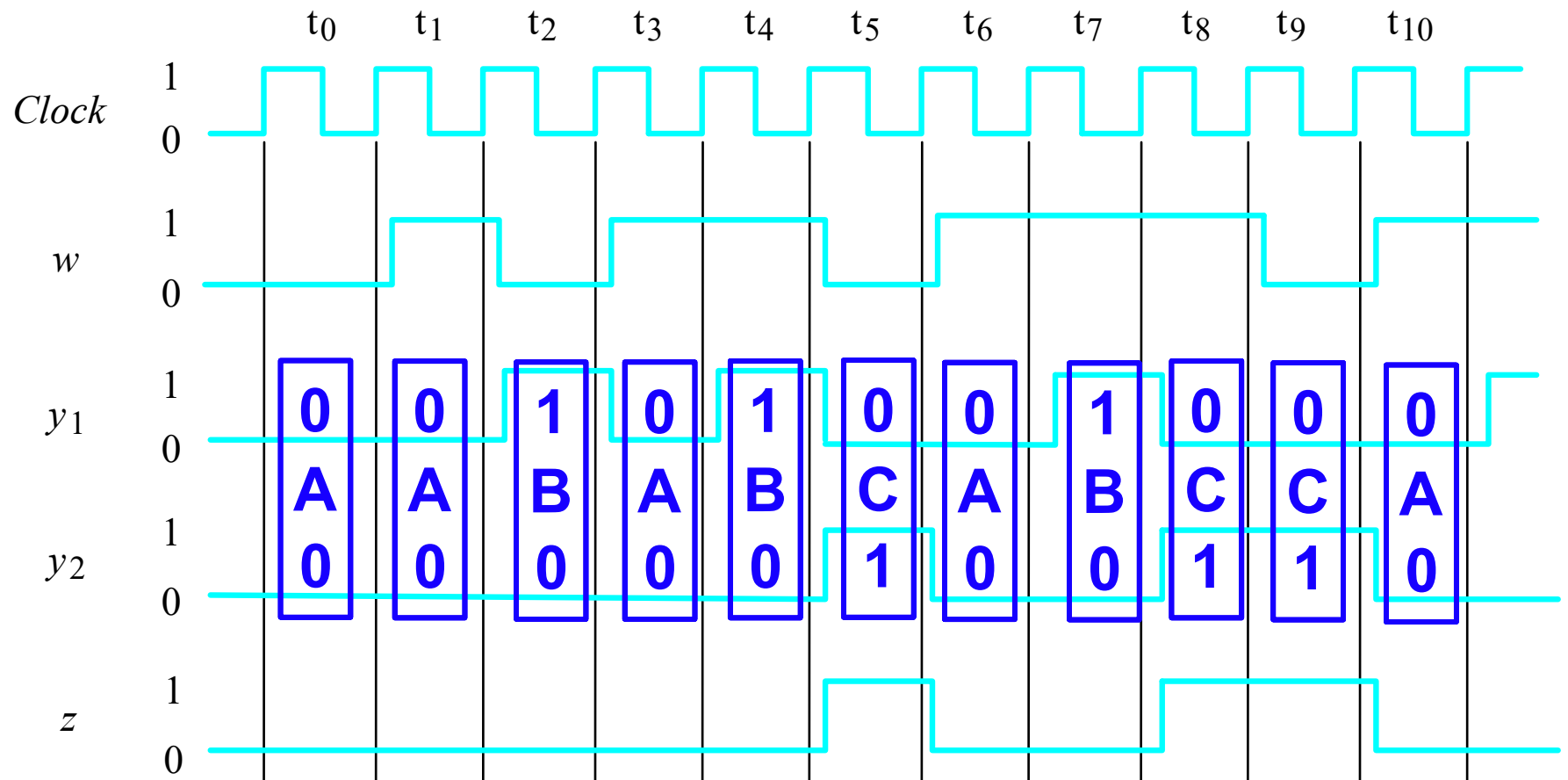




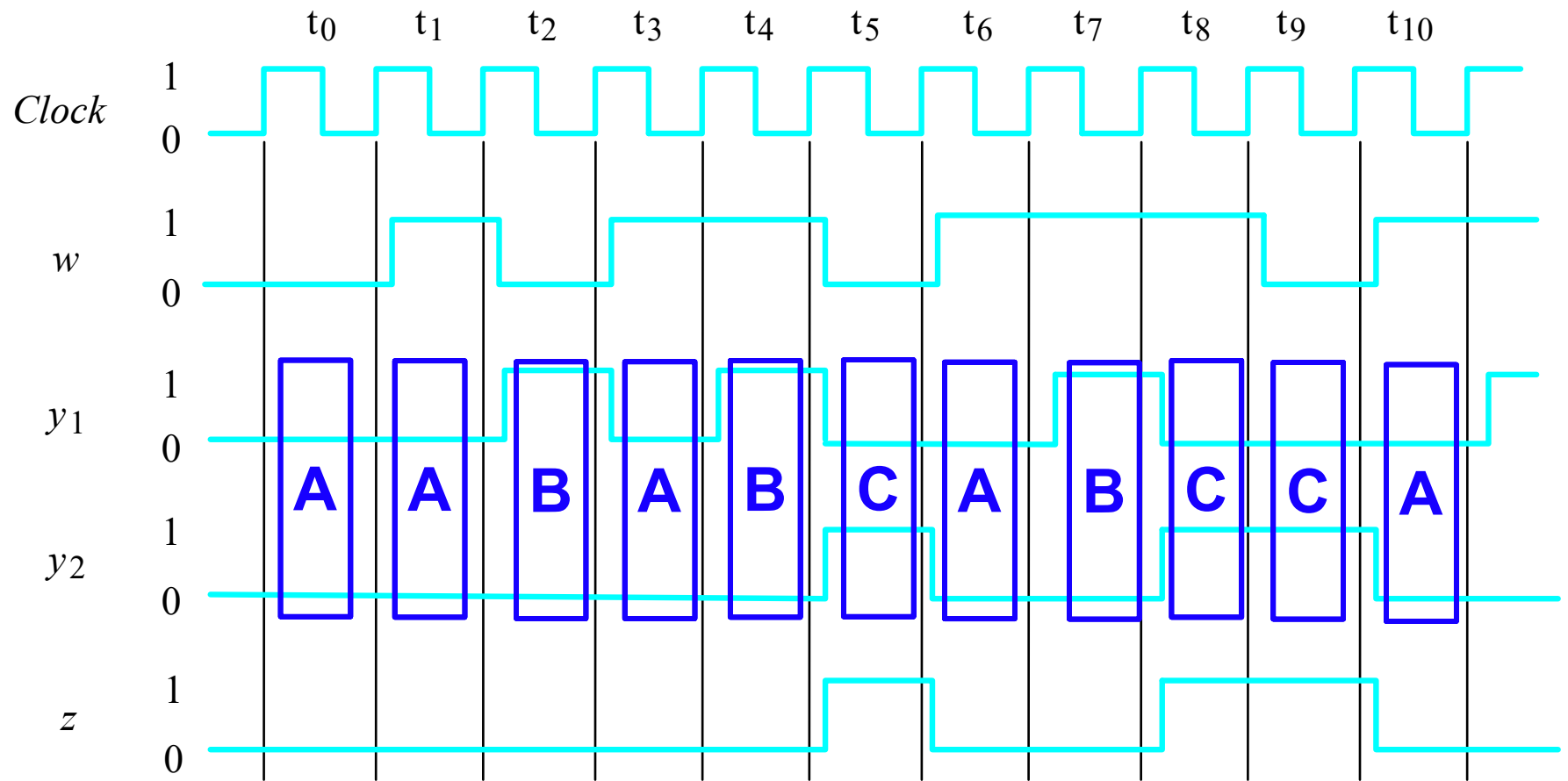
Clockcycle:	$t_0$	$t_1$	$t_2$	$t_3$	$t_4$	$t_5$	$t_6$	$t_7$	$t_8$	$t_9$	$t_{10}$
$w$ :	0	1	0	1	1	0	1	1	1	0	1
$z$ :	0	0	0	0	0	1	0	0	1	1	0



Clockcycle:	$t_0$	$t_1$	$t_2$	$t_3$	$t_4$	$t_5$	$t_6$	$t_7$	$t_8$	$t_9$	$t_{10}$
$w$ :	0	1	0	1	1	0	1	1	1	0	1
$z$ :	0	0	0	0	0	1	0	0	1	1	0



Clockcycle:	$t_0$	$t_1$	$t_2$	$t_3$	$t_4$	$t_5$	$t_6$	$t_7$	$t_8$	$t_9$	$t_{10}$
$w$ :	0	1	0	1	1	0	1	1	1	0	1
$z$ :	0	0	0	0	0	1	0	0	1	1	0



# Summary: Designing a Moore Machine

- Obtain the circuit specification
- Derive a state diagram
- Derive the state table
- Decide on a state encoding
- Encode the state table
- Derive the output logic and next-state logic
- Draw the Circuit Diagram
- Add a reset signal

**Alternative State Encoding for Example #1:**

**A=00, B=01, C=11**

**(Also Uses Two Flip-Flops)**

# A Better State Encoding

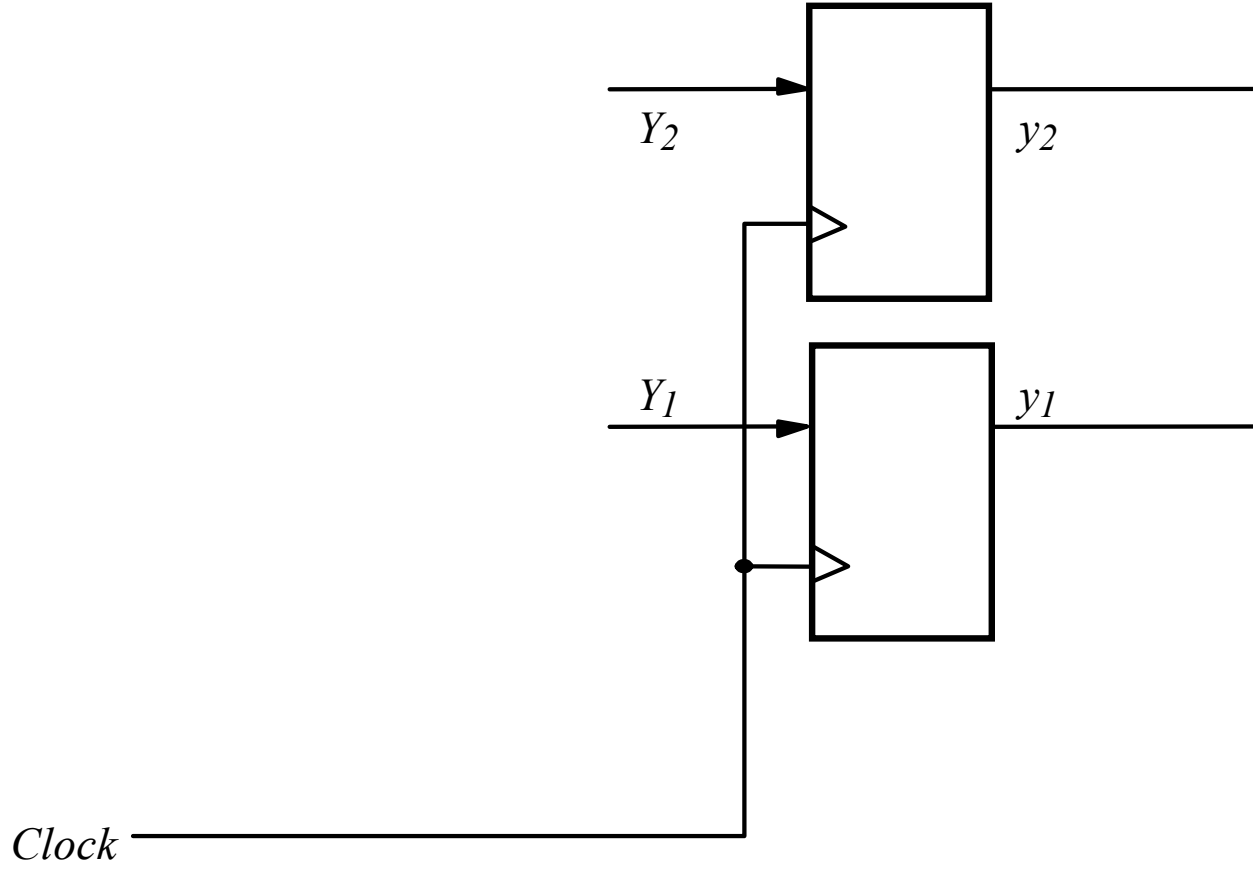
Present state	Next state		Output $z$
	$w = 0$	$w = 1$	
A	A	B	0
B	A	C	0
C	A	C	1

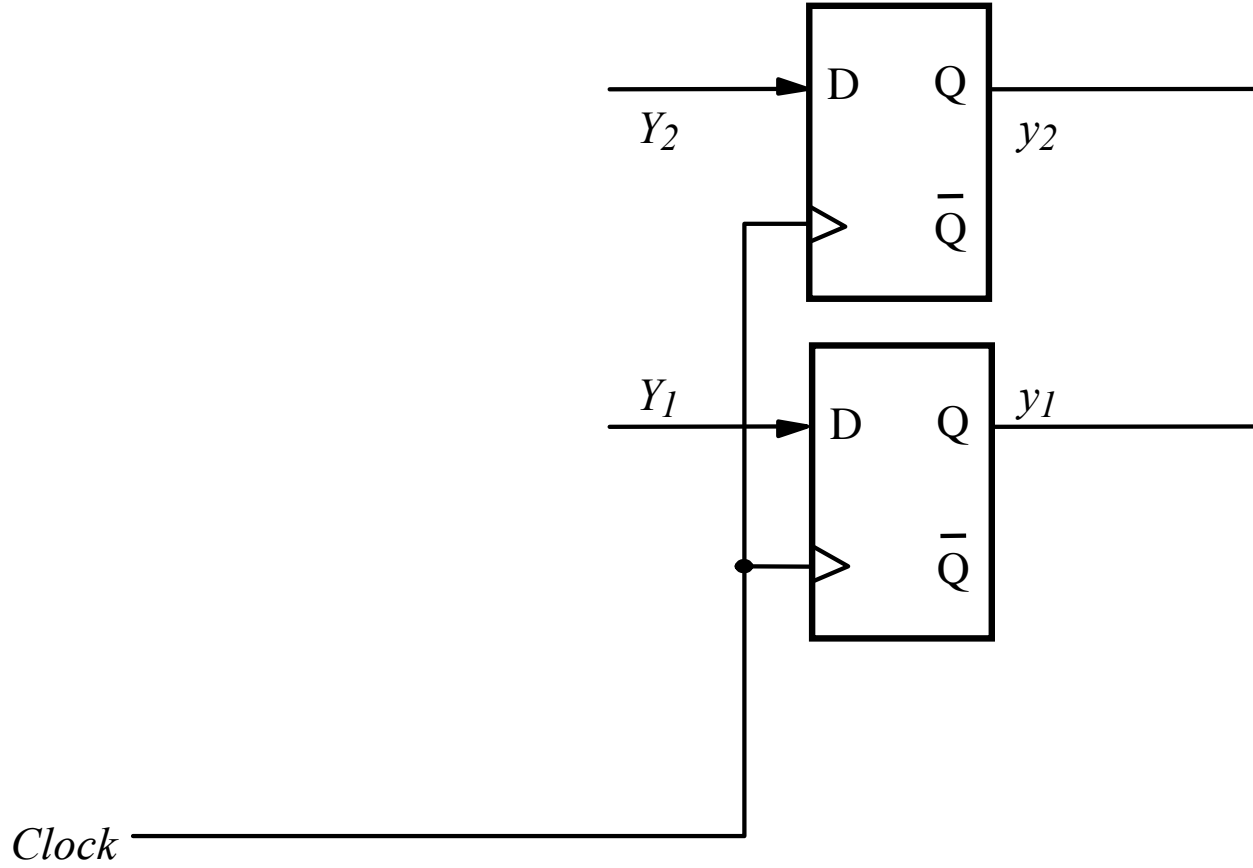
Suppose we encoded our states another way:

$$A = 00$$

$$B = 01$$

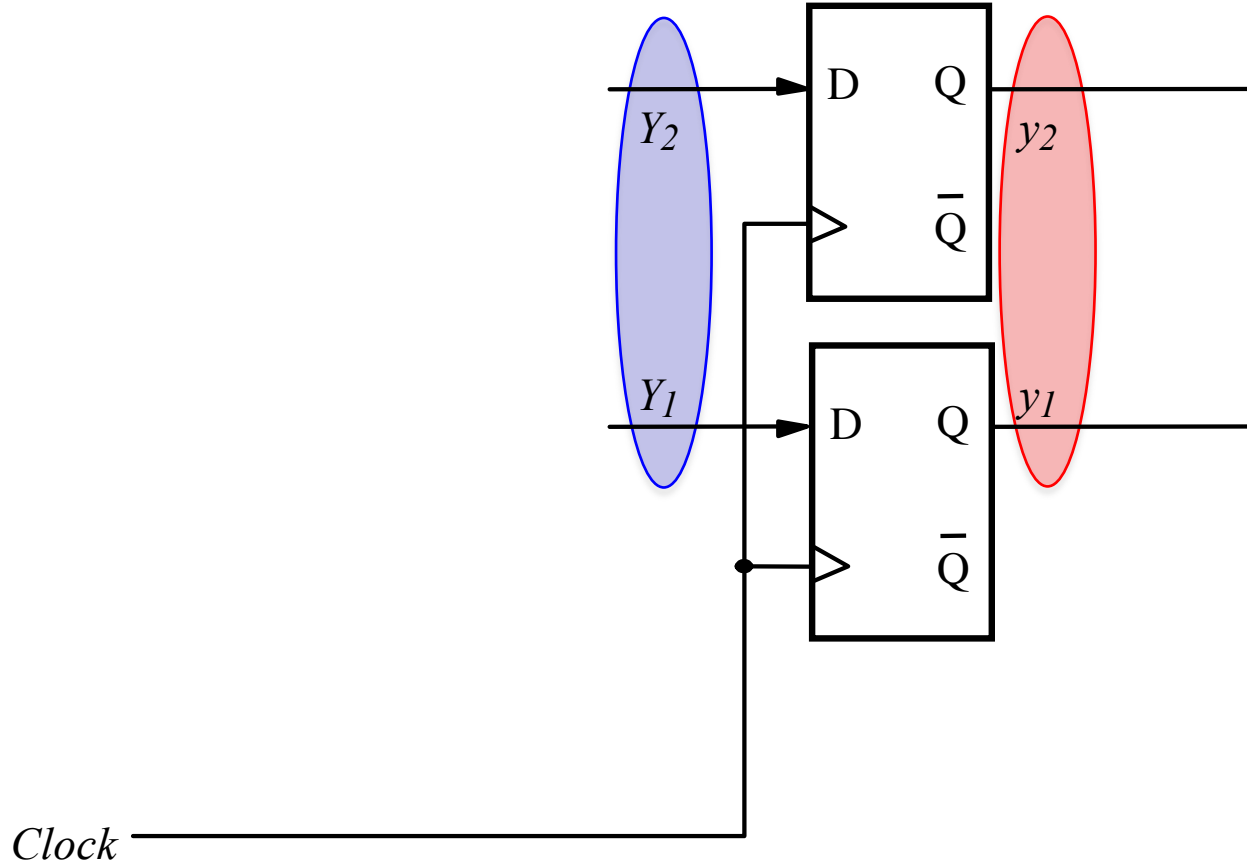
$$C = 11$$





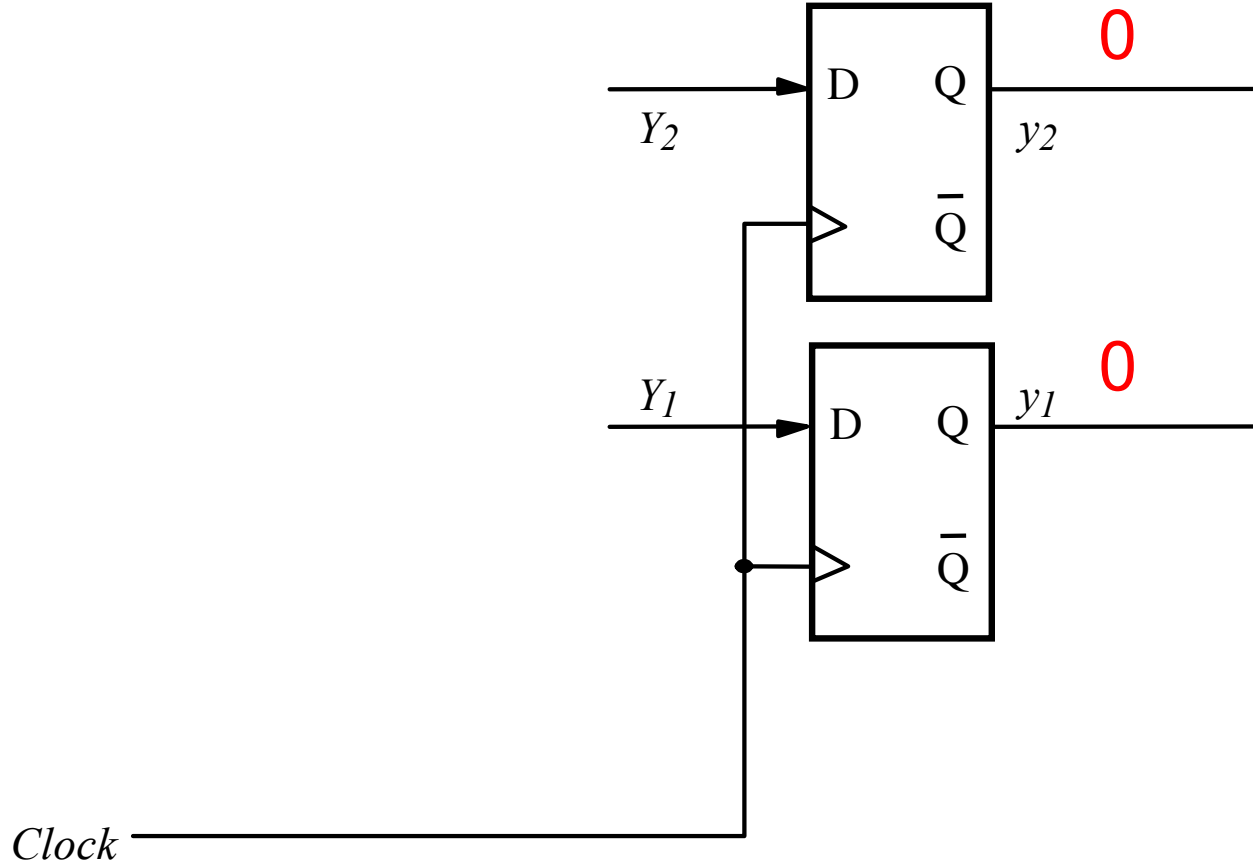
Let's pick D Flip-Flops.



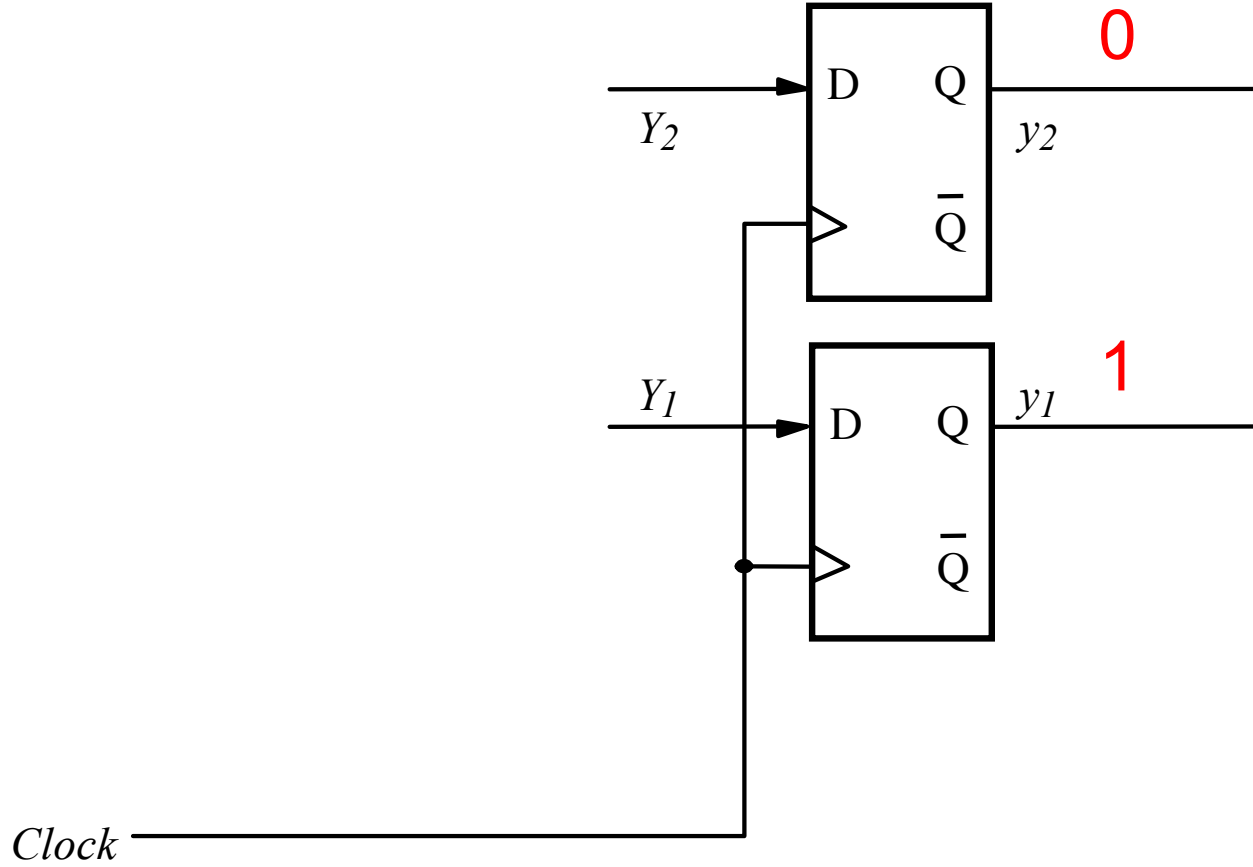


We will call  $y_1$  and  $y_2$  the *present state variables*.

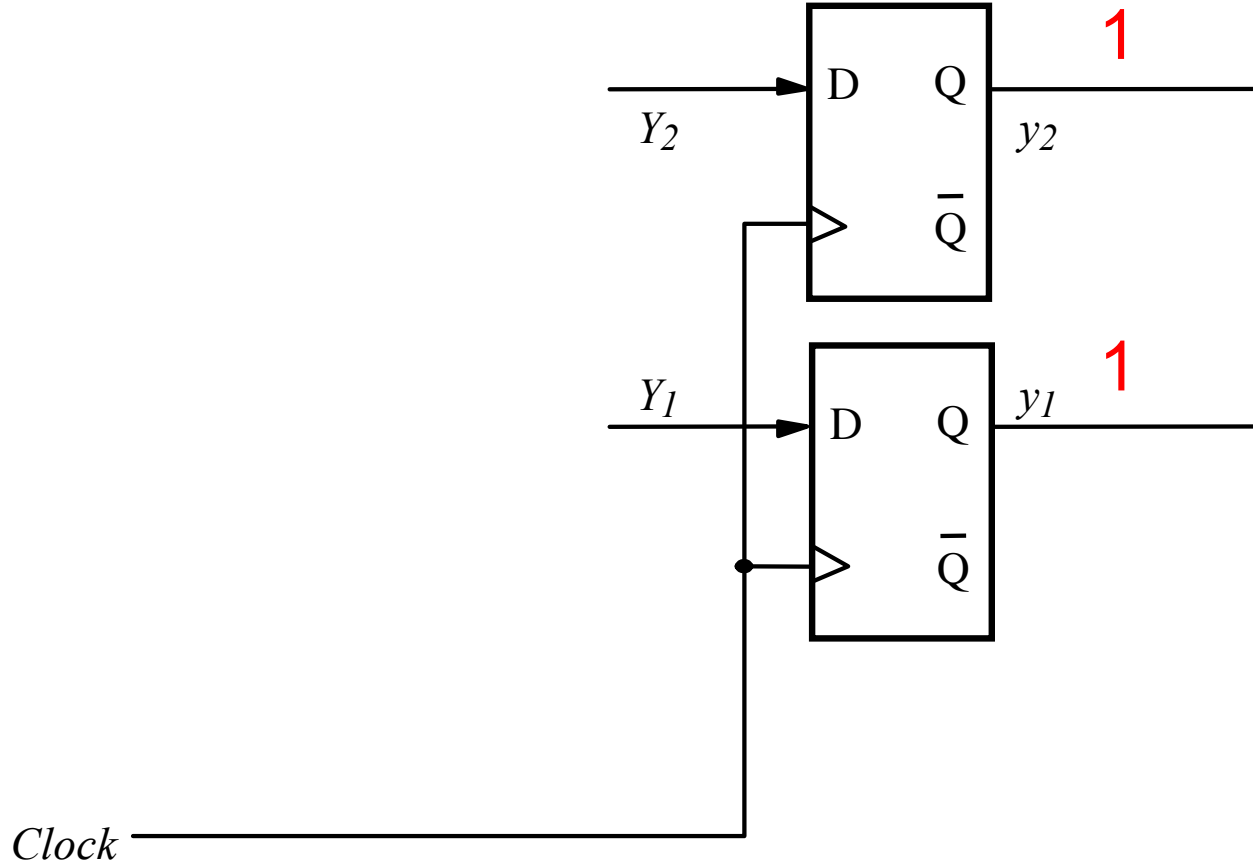
We will call  $Y_1$  and  $Y_2$  the *next state variables*.



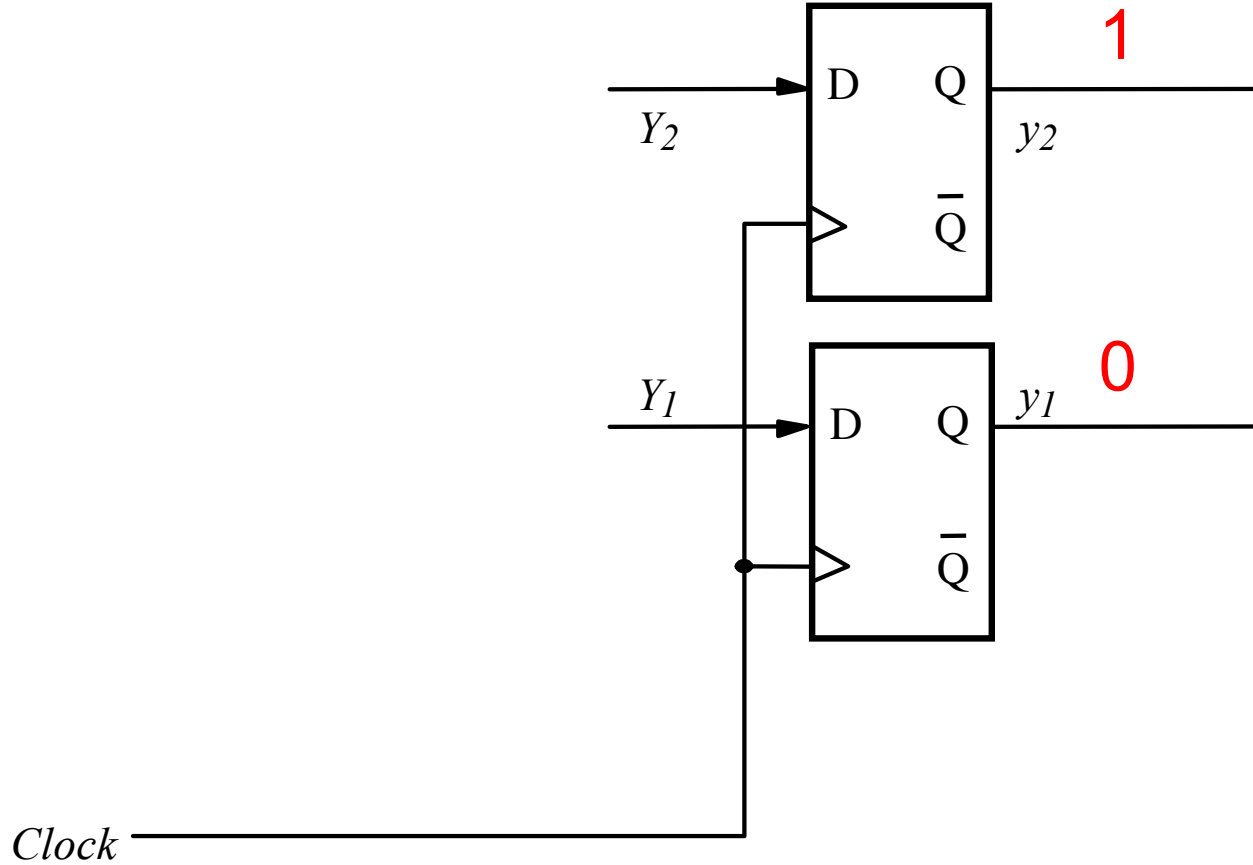
Two zeros on the output JOINTLY represent state A.



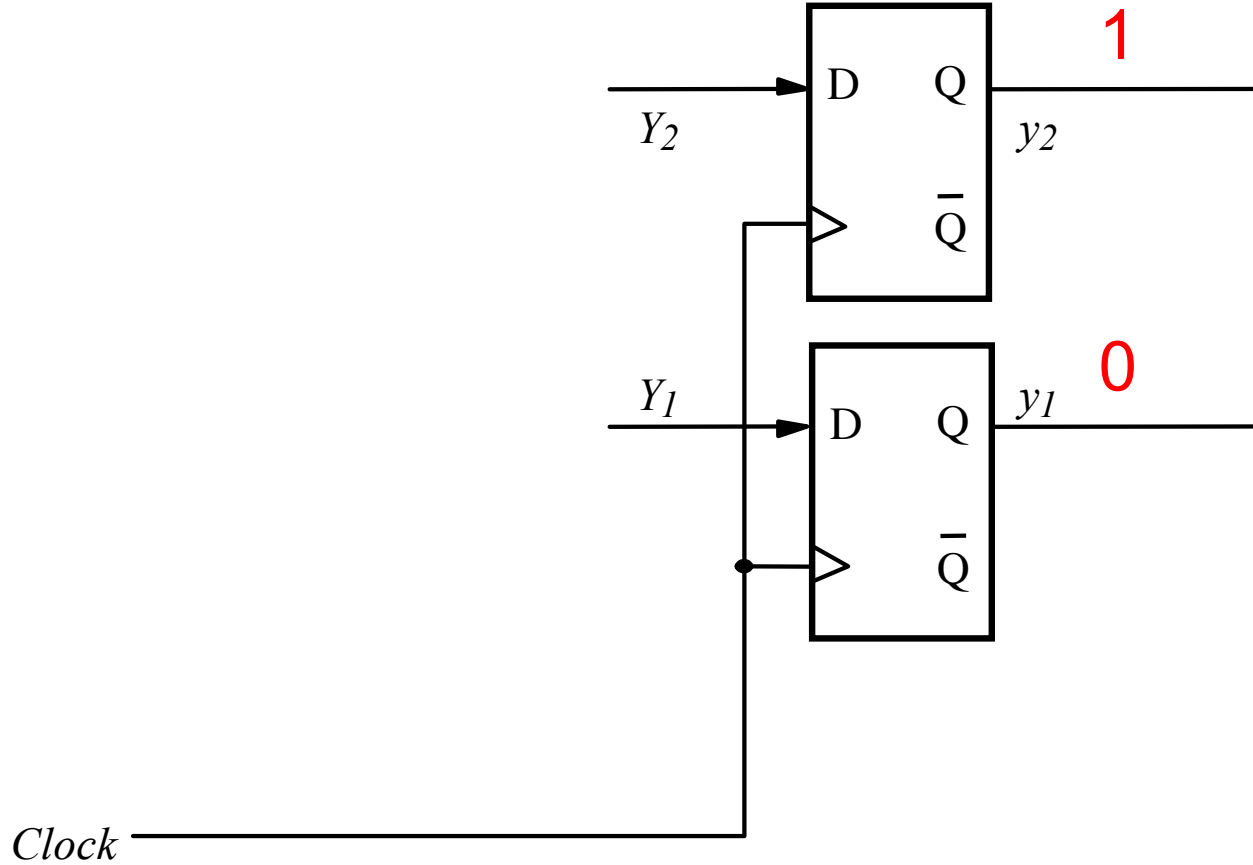
This flip-flop output pattern represents state B.



This flip-flop output pattern represents state C.



What does this flip-flop output pattern represent?



This would be state D, but we don't have one in this example. So this is an impossible state.

# A Better State Encoding

Present state	Next state		Output $z$
	$w = 0$	$w = 1$	
A	A	B	0
B	A	C	0
C	A	C	1

Suppose we encoded our states another way:

$$A = 00$$

$$B = 01$$

$$C = 11$$

# A Better State Encoding

Present state	Next state		Output $z$
	$w = 0$	$w = 1$	
A	A	B	0
B	A	C	0
C	A	C	1

Present state	Next state		Output $z$
	$w = 0$	$w = 1$	

A = 00

B = 01

C = 11



# A Better State Encoding

Present state	Next state		Output $z$
	$w = 0$	$w = 1$	
A	A	B	0
B	A	C	0
C	A	C	1

	Present state	Next state		Output $z$
		$w = 0$	$w = 1$	
	$y_2y_1$	$Y_2Y_1$	$Y_2Y_1$	
A	00	00	01	0
B	01	00	11	0
C	11	00	11	1
	10	$dd$	$dd$	$d$

A = 00

B = 01

C = 11

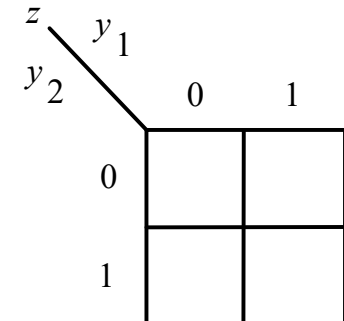
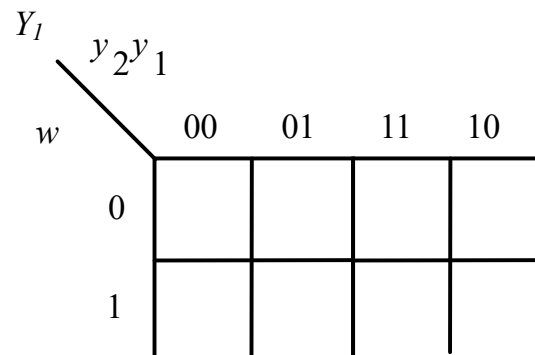
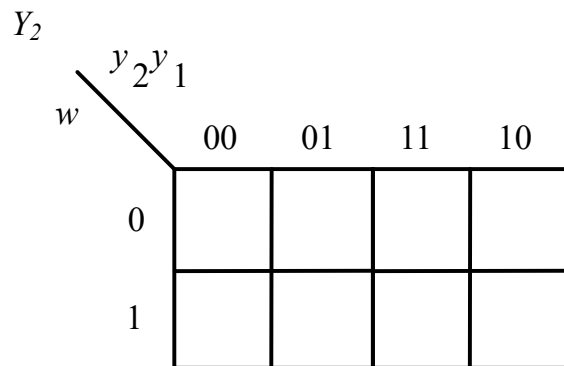
# Let's Derive the Logic Expressions

	Present state	Next state		Output $z$
		$w = 0$	$w = 1$	
	$y_2y_1$	$Y_2Y_1$	$Y_2Y_1$	
A	00	00	01	0
B	01	00	11	0
C	11	00	11	1
	10	<i>dd</i>	<i>dd</i>	<i>d</i>

# Let's Derive the Logic Expressions

Warning:  
This table does not enumerate  $y_2y_1$ , in the standard way, so be careful when filling out the K-Map.

	Present state	Next state		Output
		$w = 0$	$w = 1$	
	$y_2y_1$	$Y_2Y_1$	$Y_2Y_1$	$z$
A	00	00	01	0
B	01	00	11	0
C	11	00	11	1
	10	<i>dd</i>	<i>dd</i>	<i>d</i>



# Let's Derive the Logic Expressions

Warning:  
This table does not enumerate  $y_2y_1$ , in the standard way, so be careful when filling out the K-Map.

	Present state $y_2y_1$	Next state		Output $z$
		$w = 0$	$w = 1$	
		$Y_2Y_1$	$Y_2Y_1$	
A	00	00	01	0
B	01	00	11	0
C	11	00	11	1
	10	$dd$	$dd$	$d$

$Y_2$	$w$	$y_2y_1$	00	01	11	10
	0		0	0	0	d
	1		0	1	1	d

$$Y_2(w, y_2, y_1) = wy_1$$

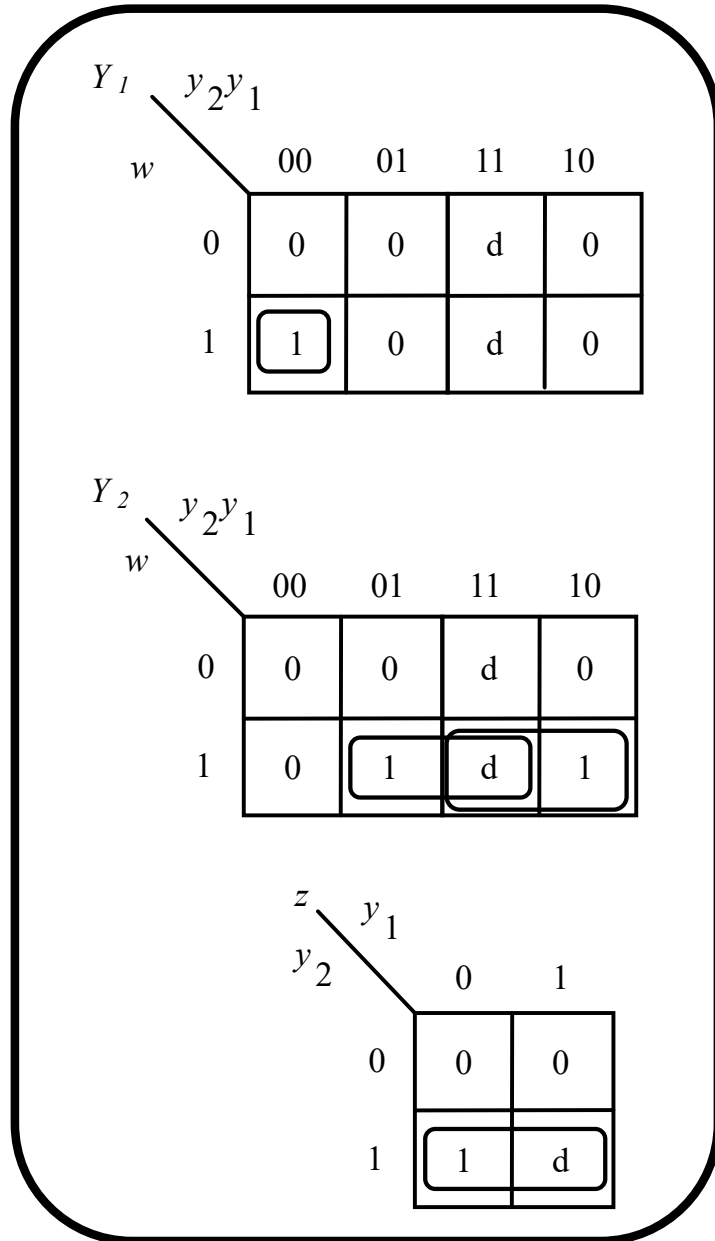
$Y_1$	$w$	$y_2y_1$	00	01	11	10
	0		0	0	0	d
	1		1	1	1	d

$$Y_1(w, y_2, y_1) = w$$

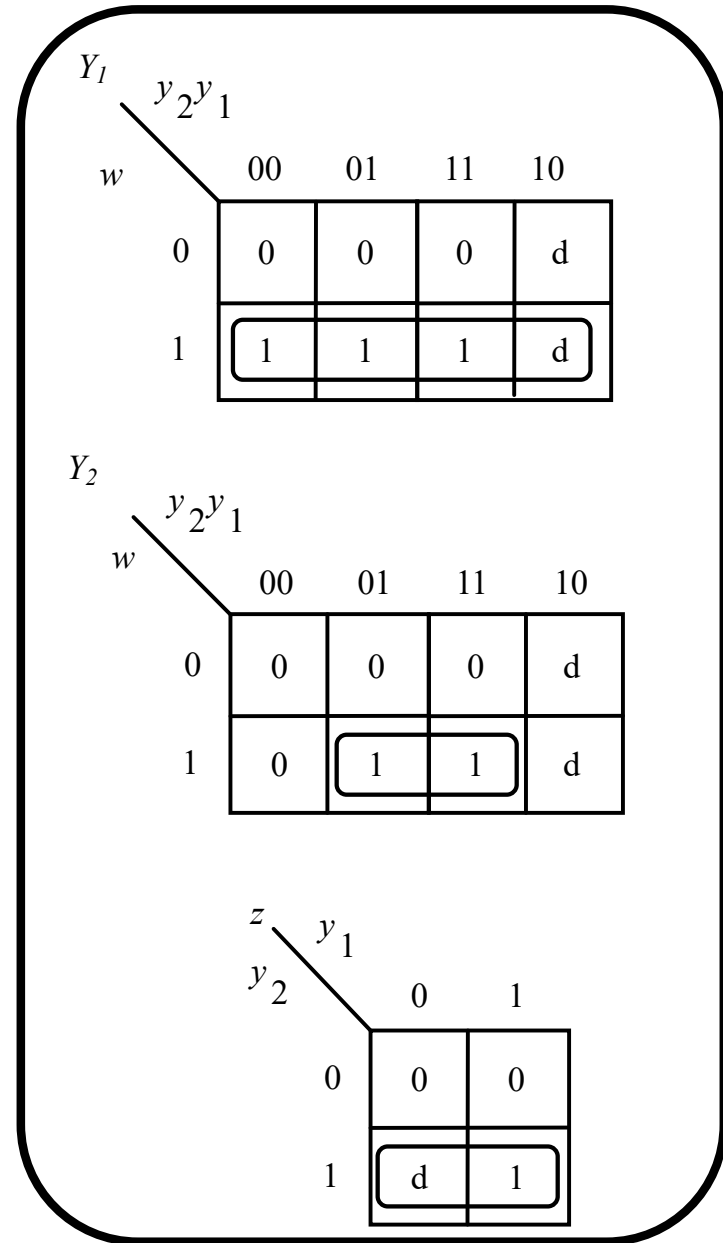
$z$	$y_2$	$y_1$	0	1
	0		0	0
	1		d	1

$$z(y_2, y_1) = y_2$$

## Original State Encodings



## New State Encodings

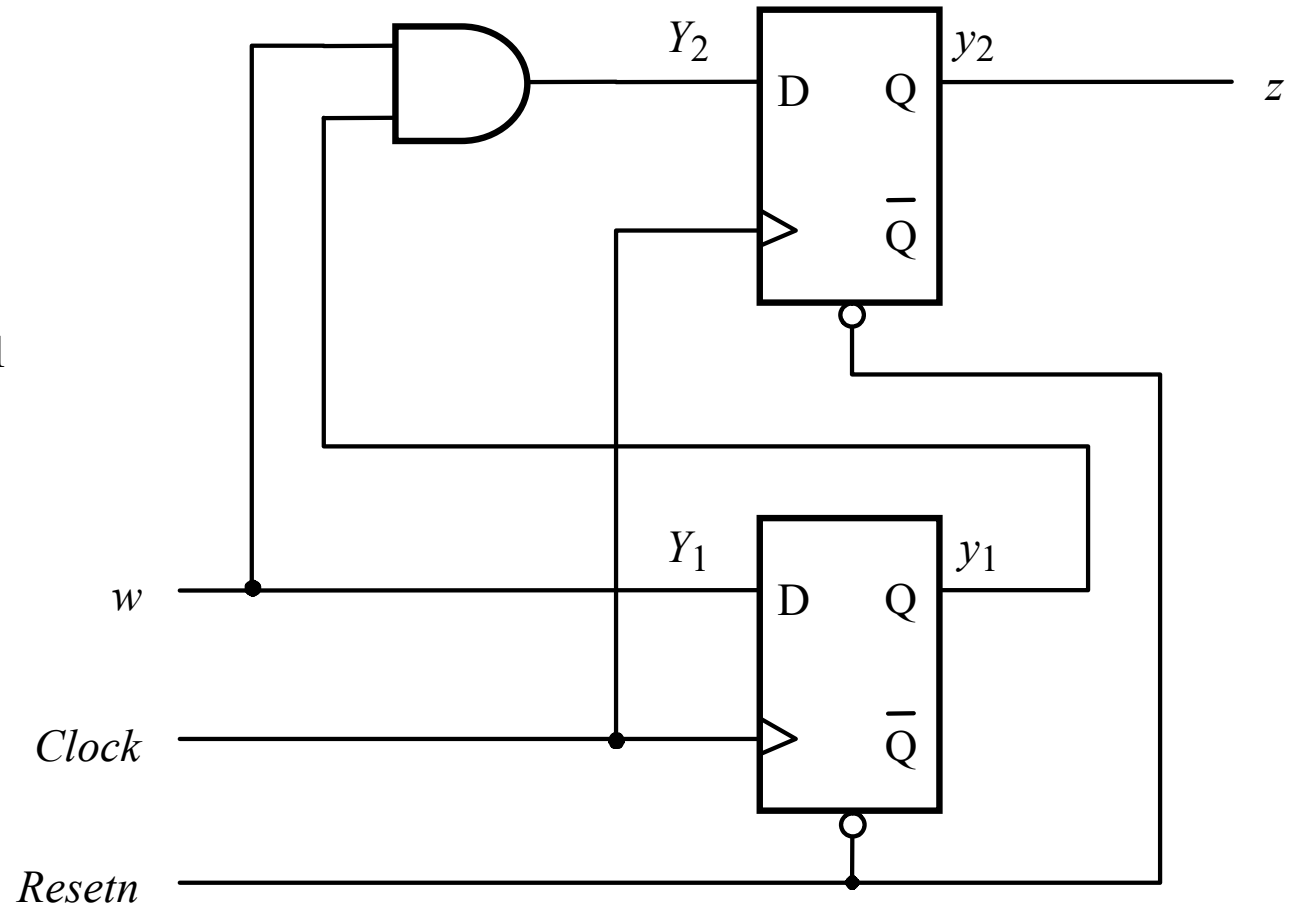


# The New and Improved Circuit Diagram

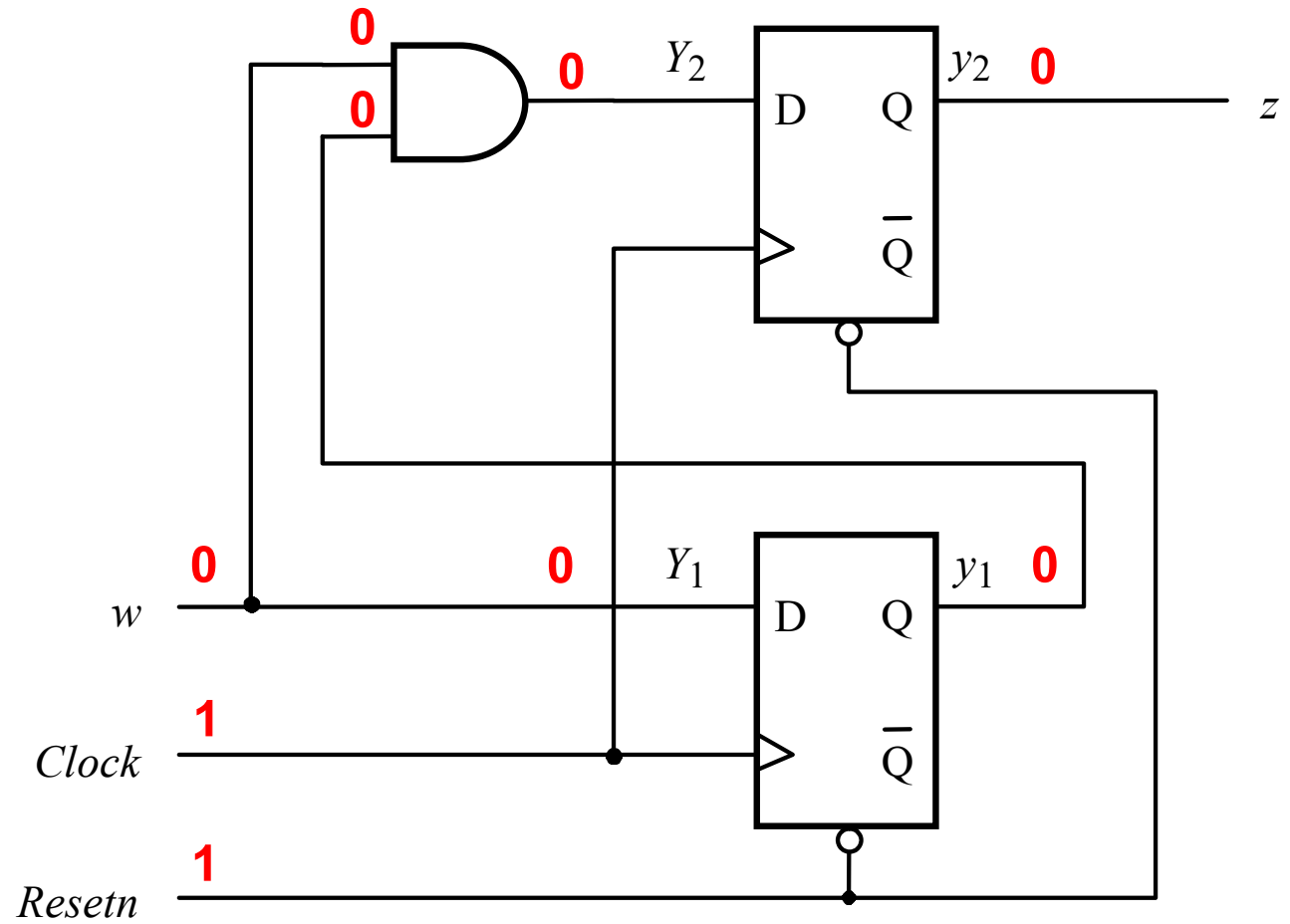
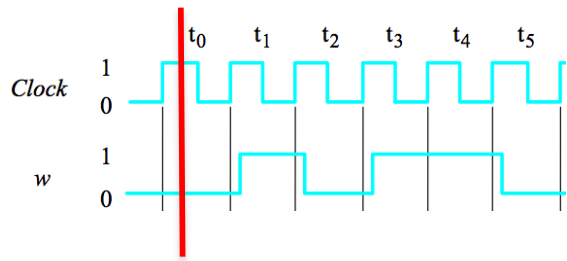
$$Y_1(w, y_2, y_1) = w$$

$$Y_2(w, y_2, y_1) = wy_1$$

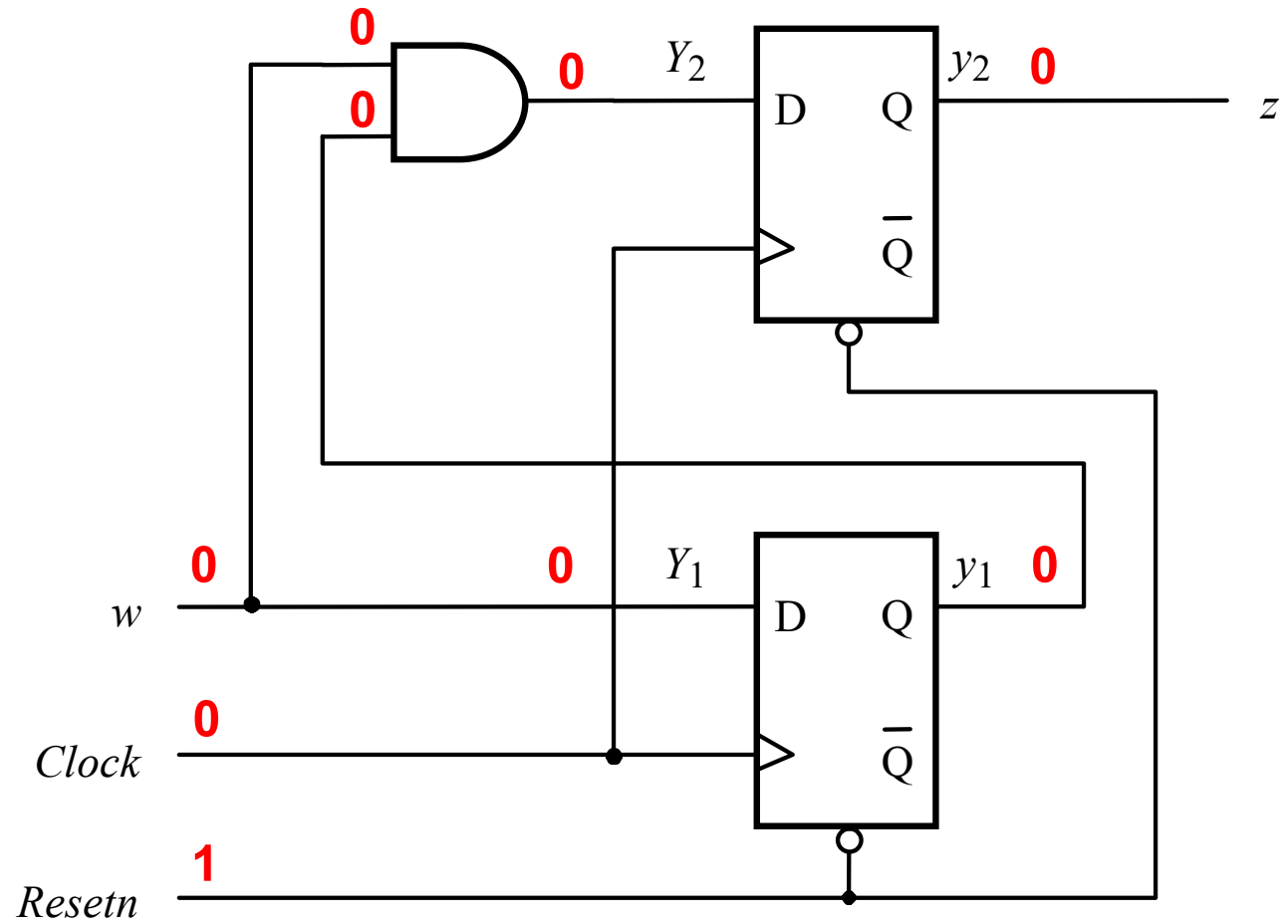
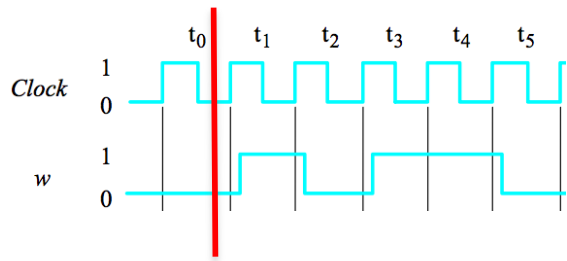
$$z(y_2, y_1) = y_2$$



State A=00

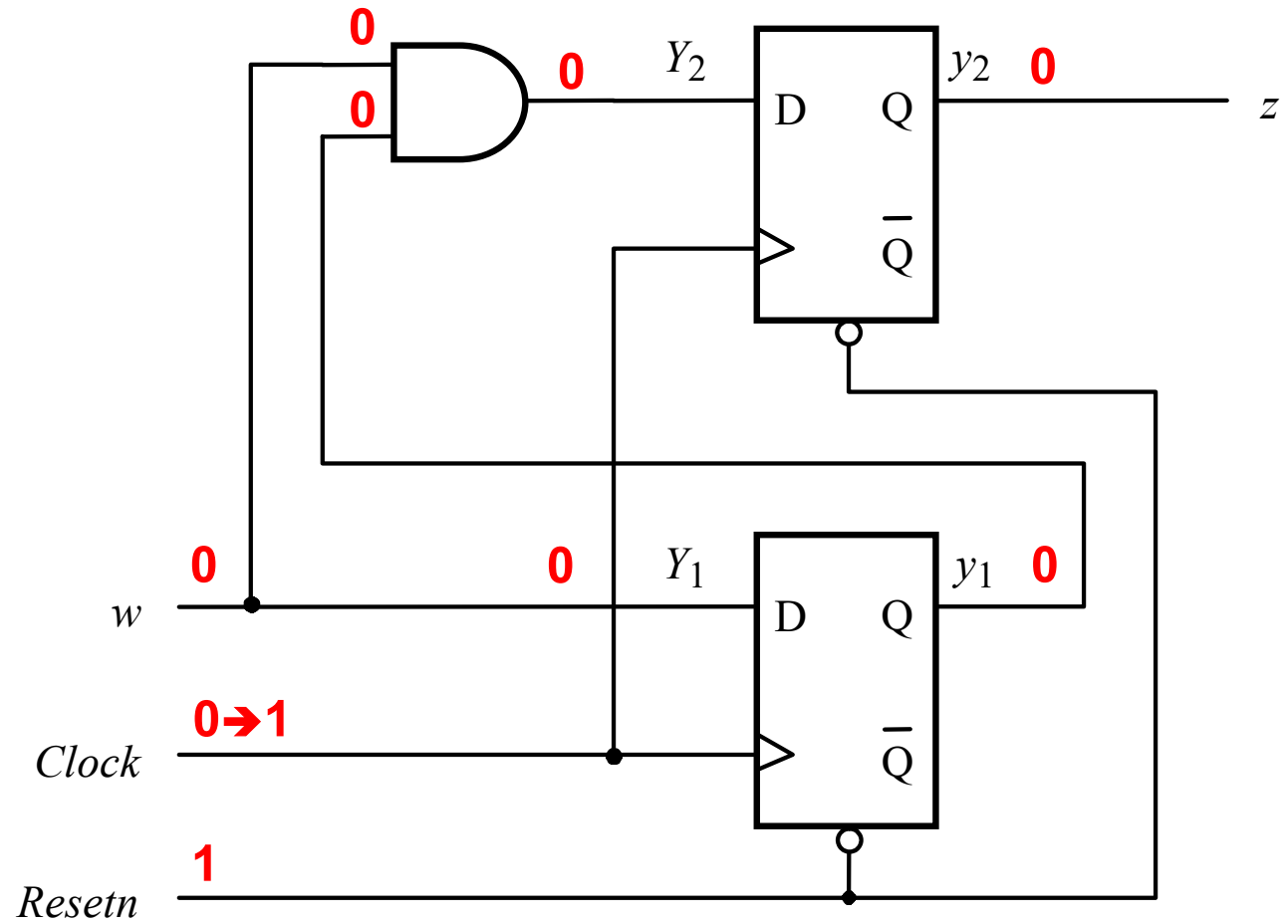
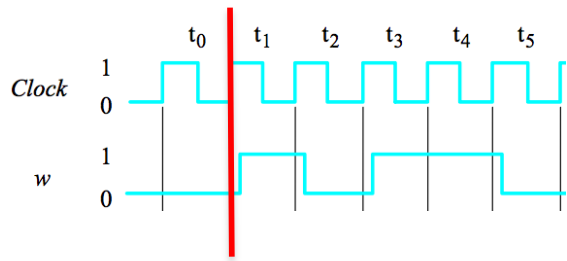


State A=00

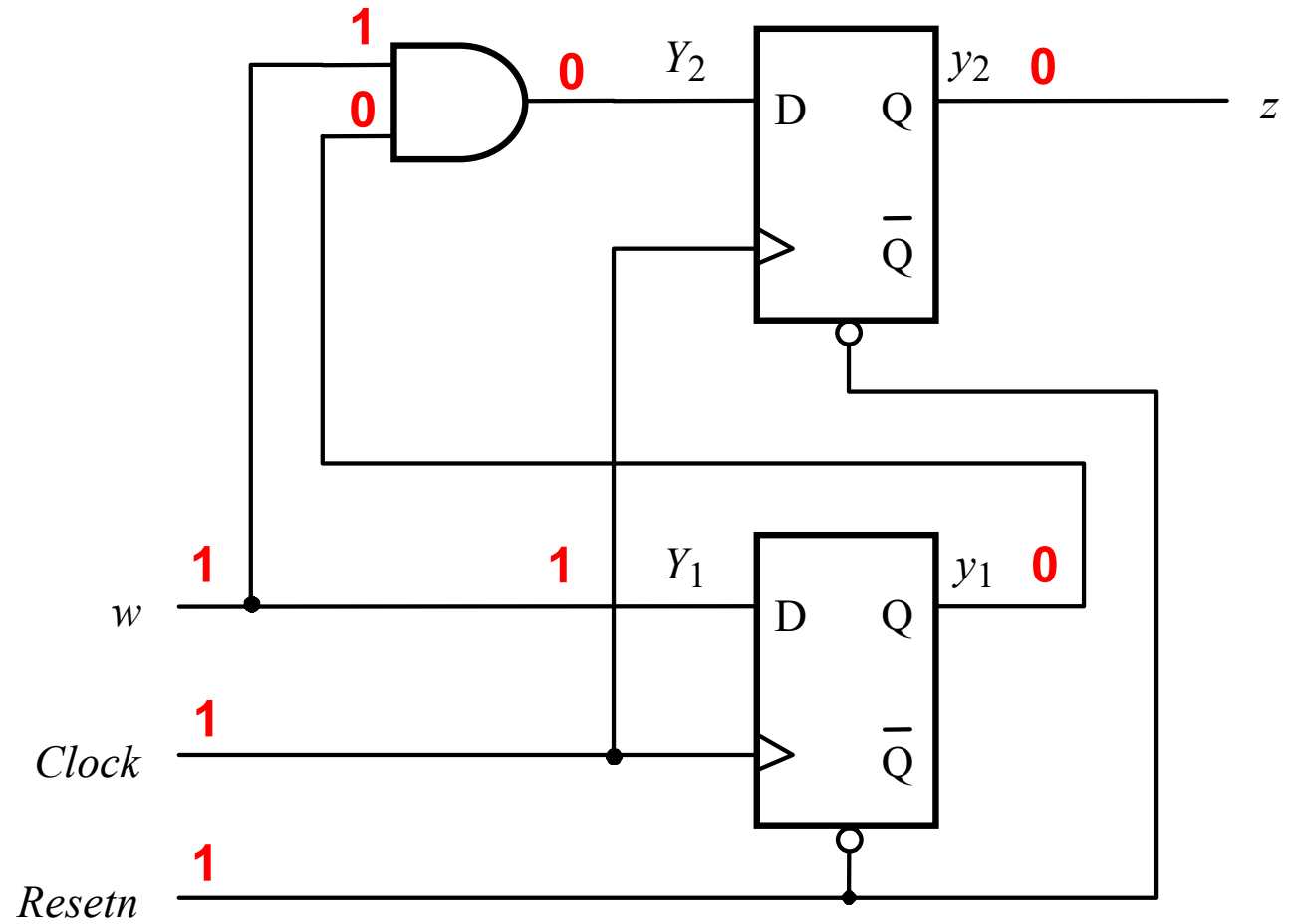
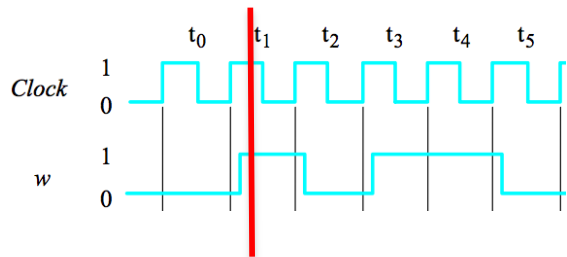




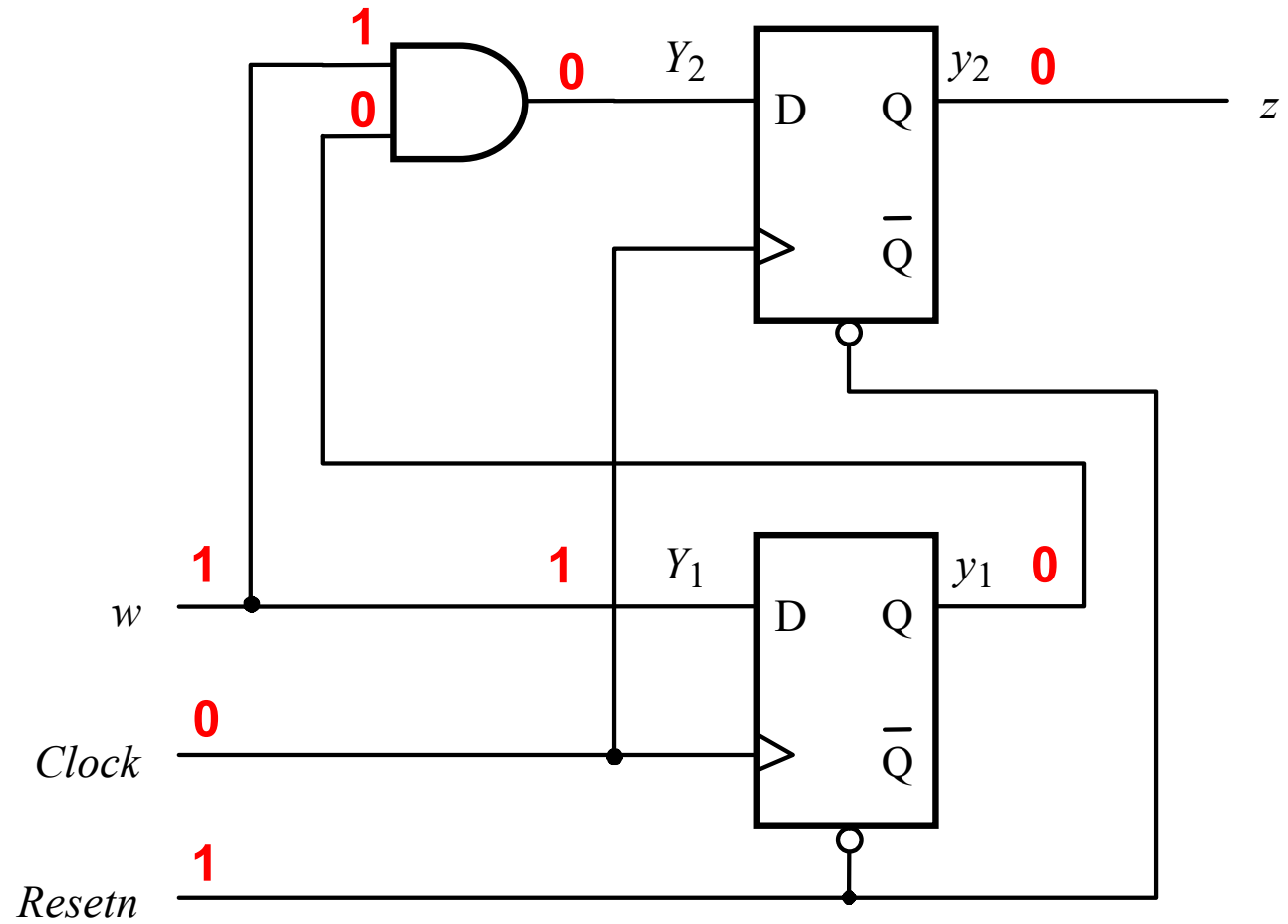
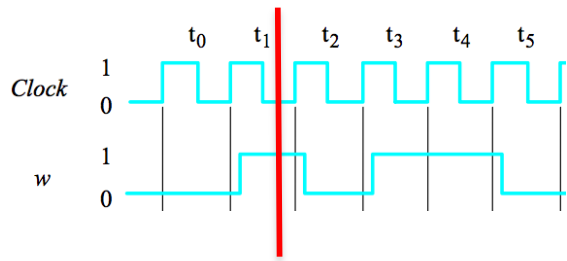
State A=00



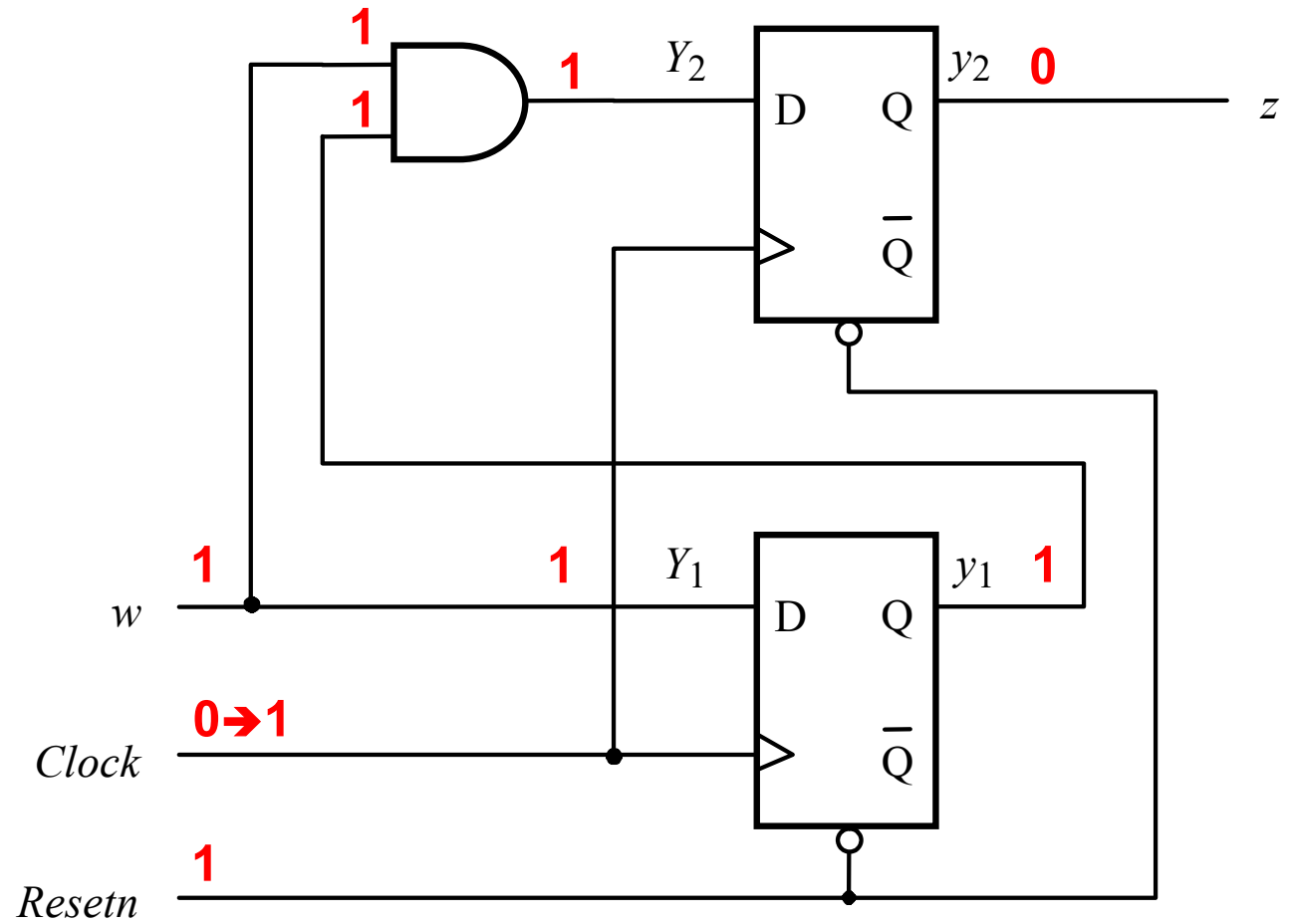
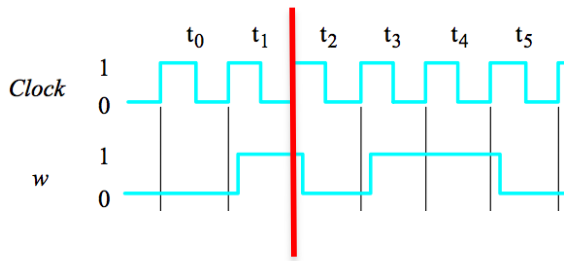
State A=00



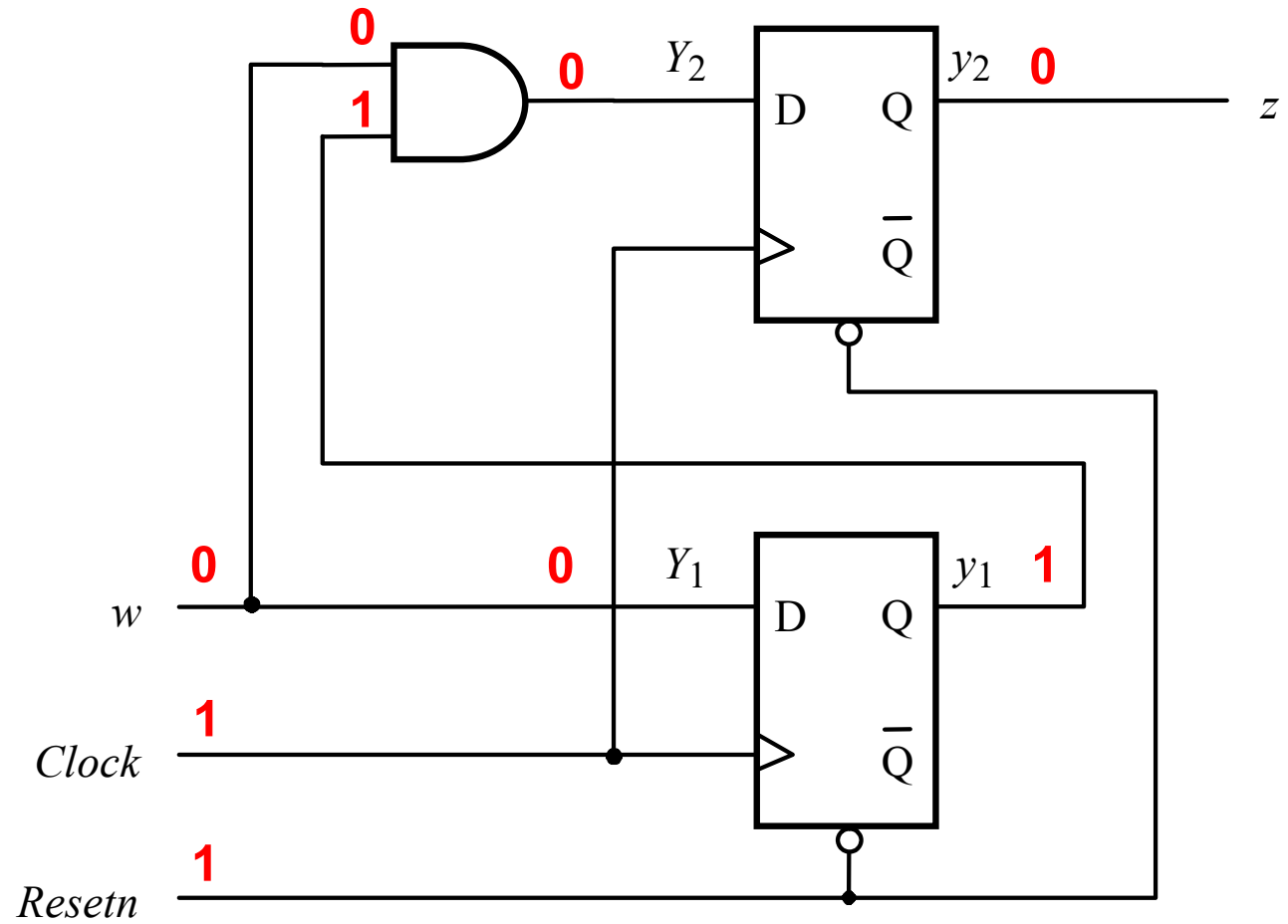
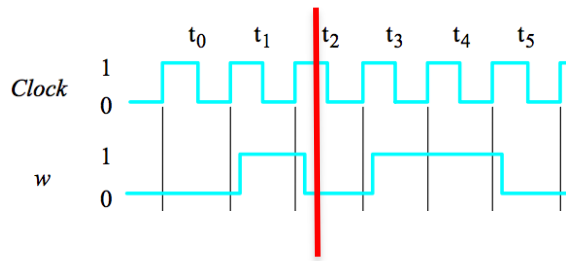
State A=00



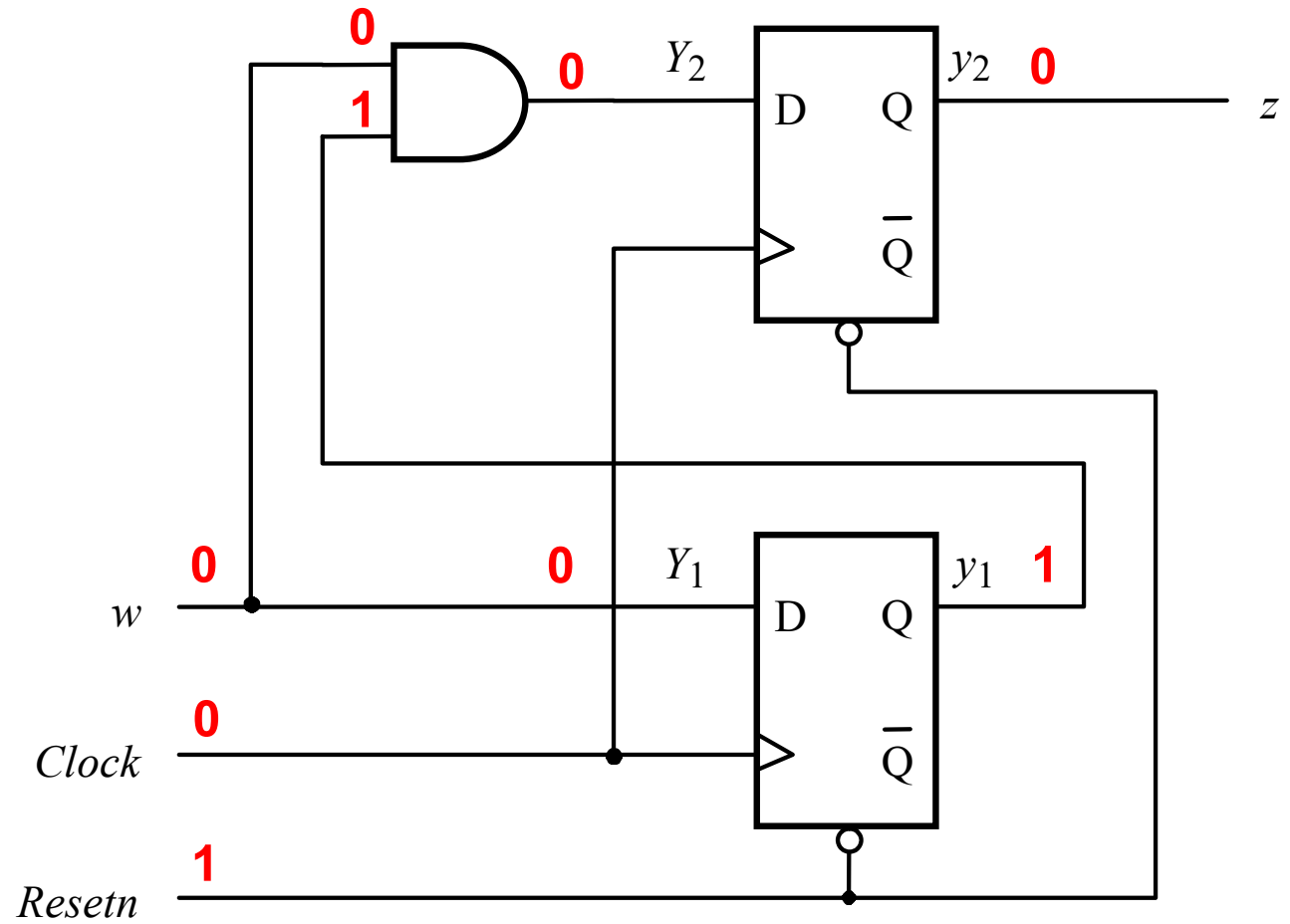
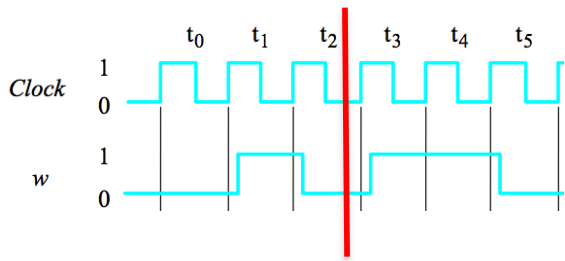
State B=01



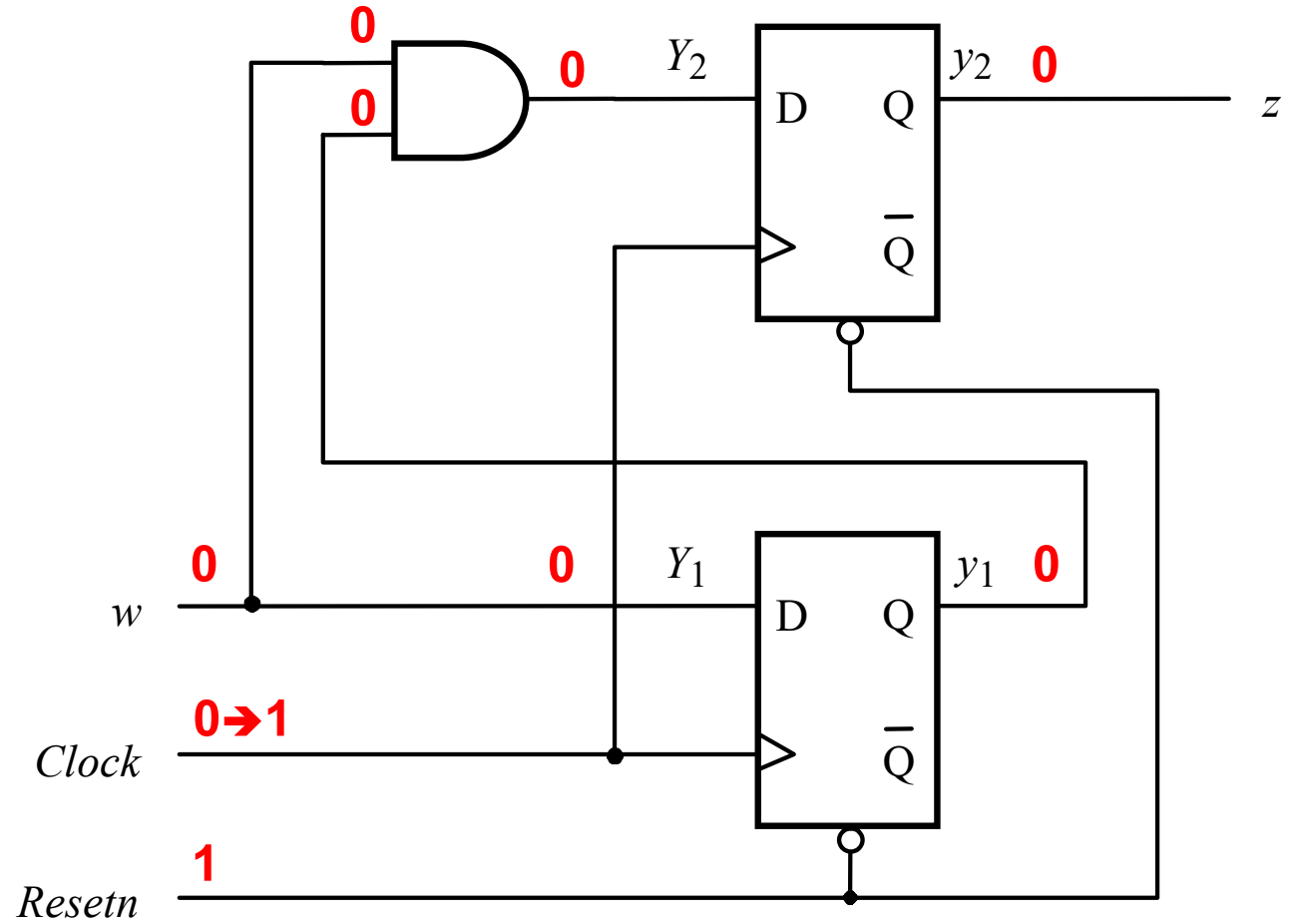
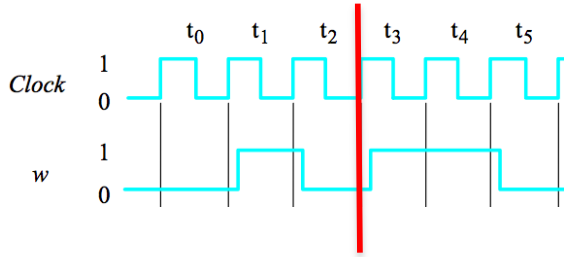
State B=01



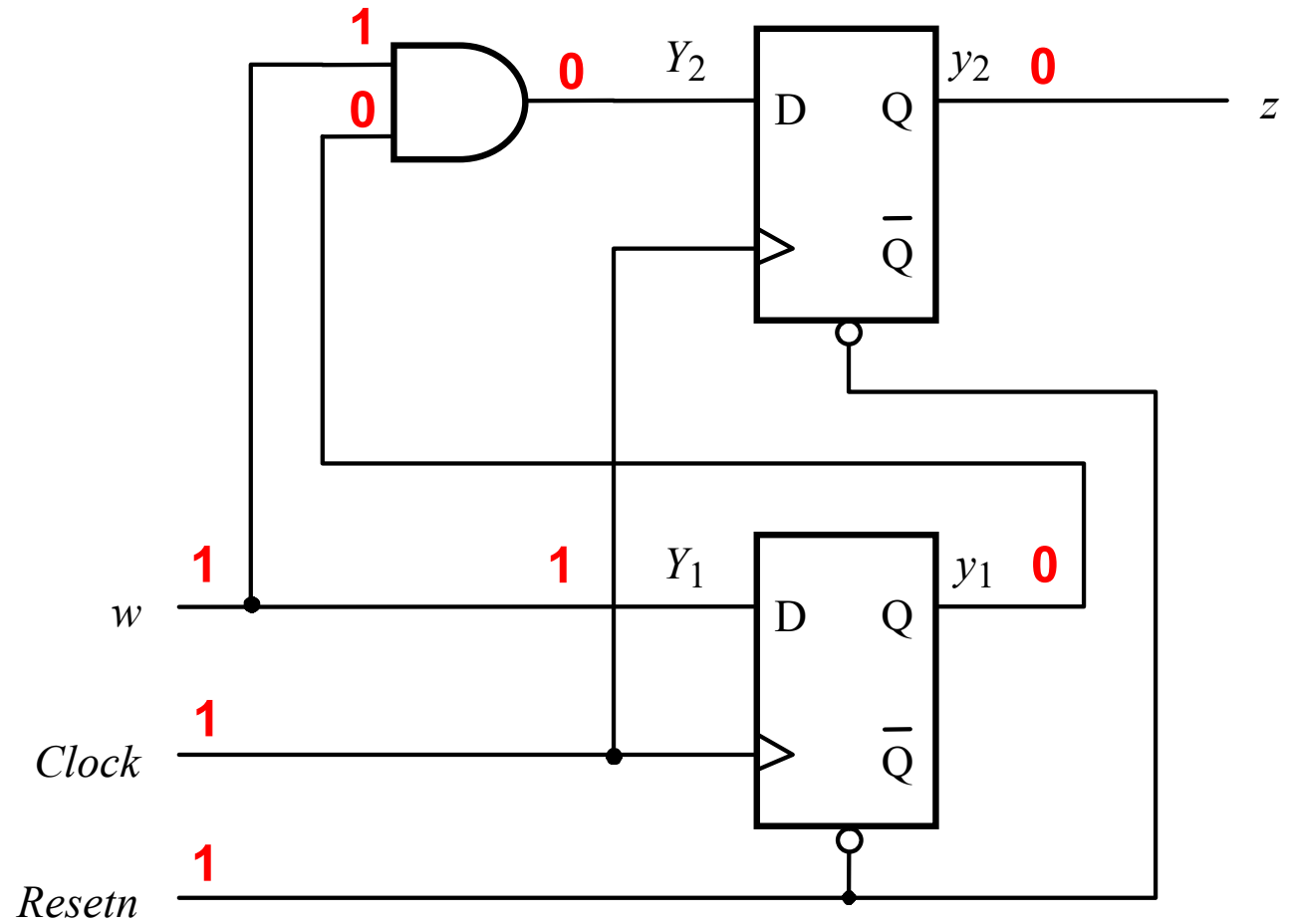
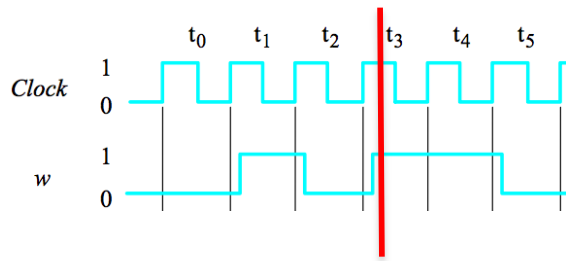
State B=01



State A=00

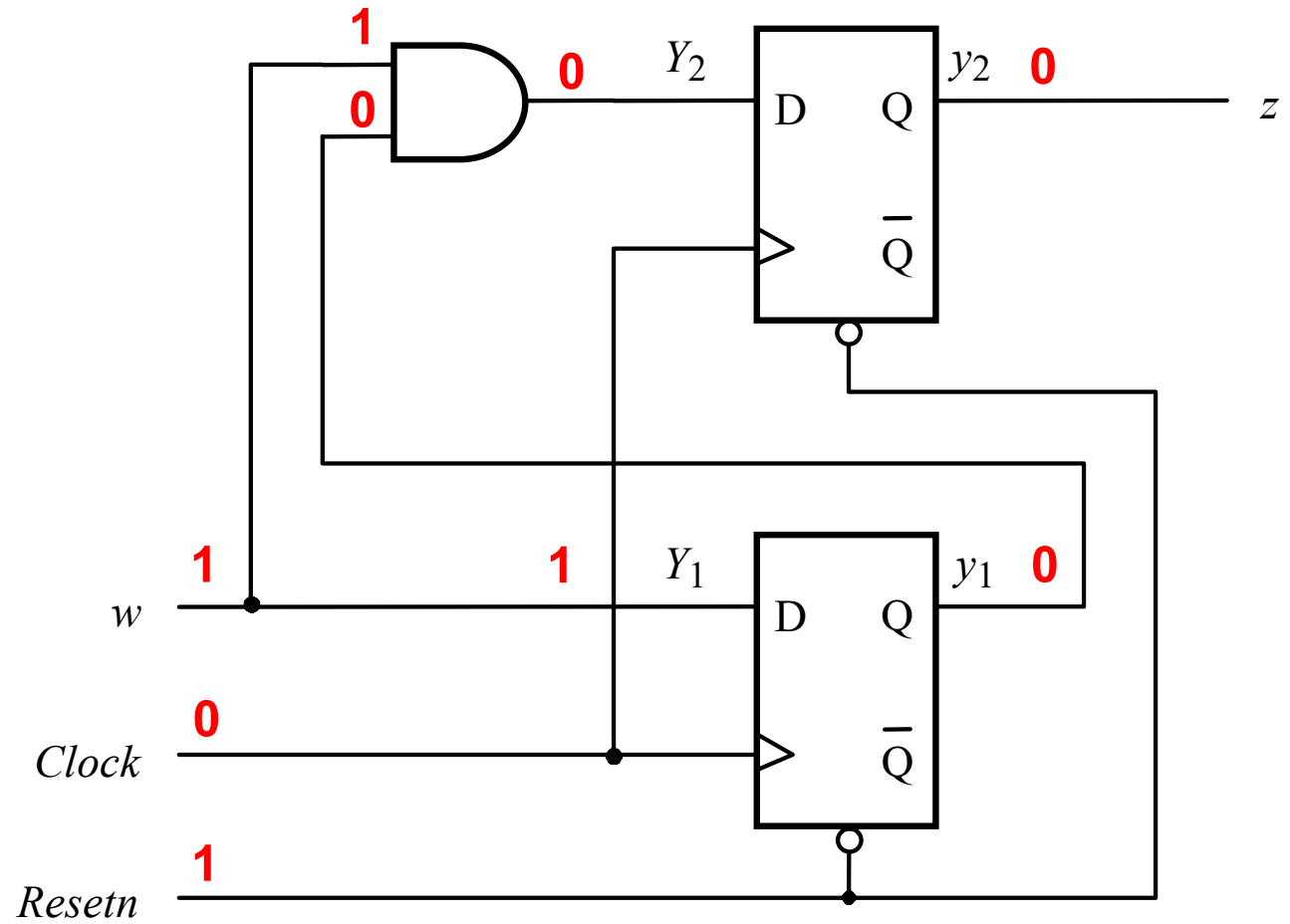
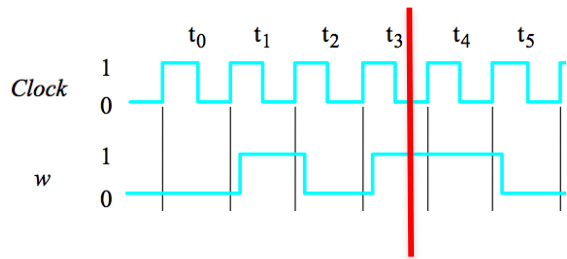


State A=00

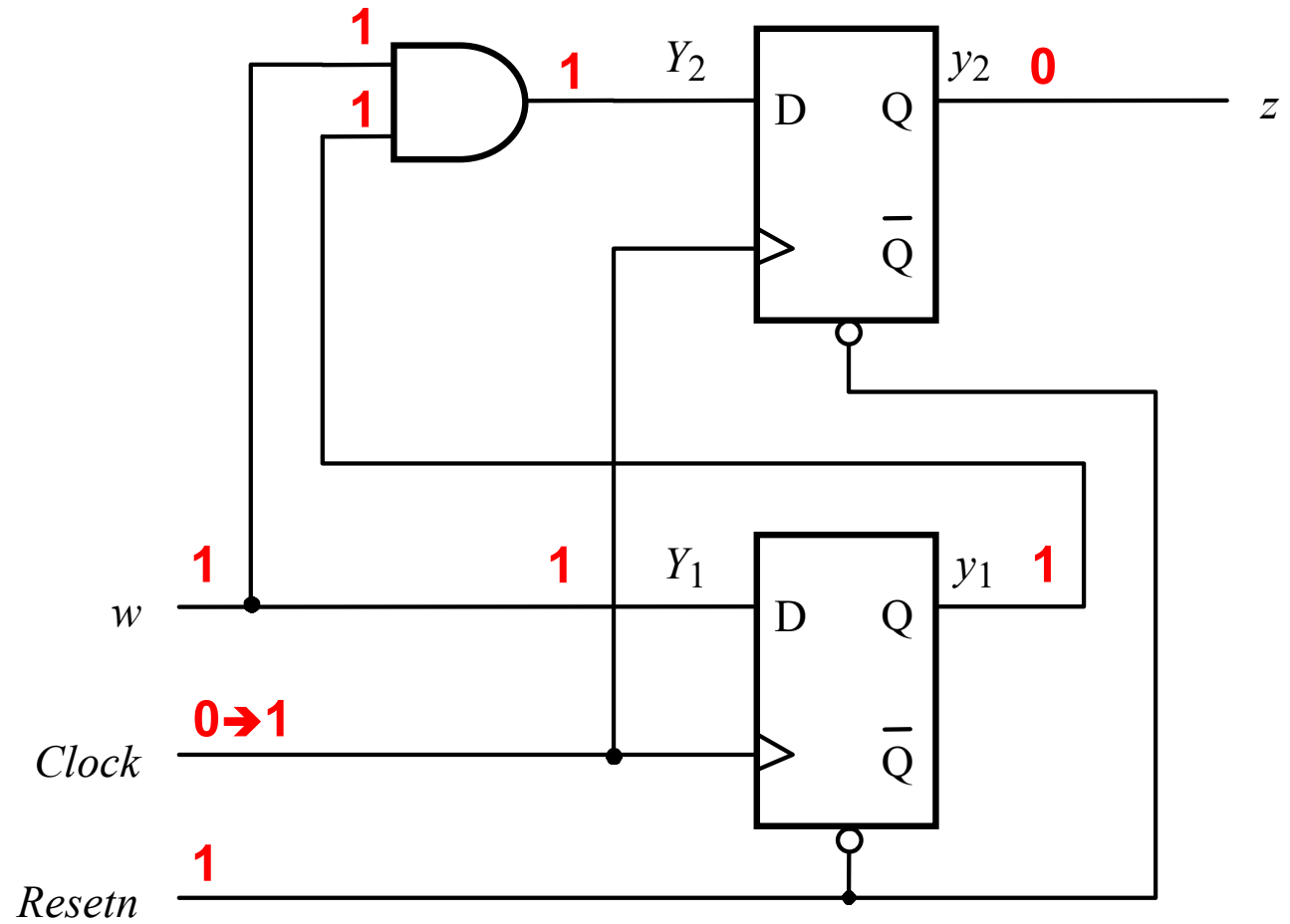
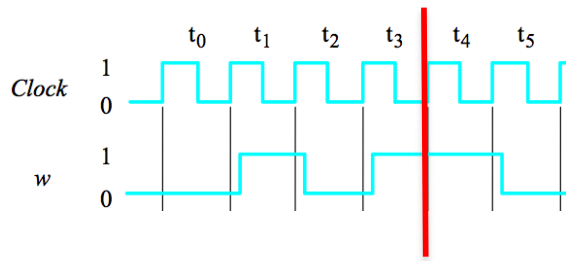




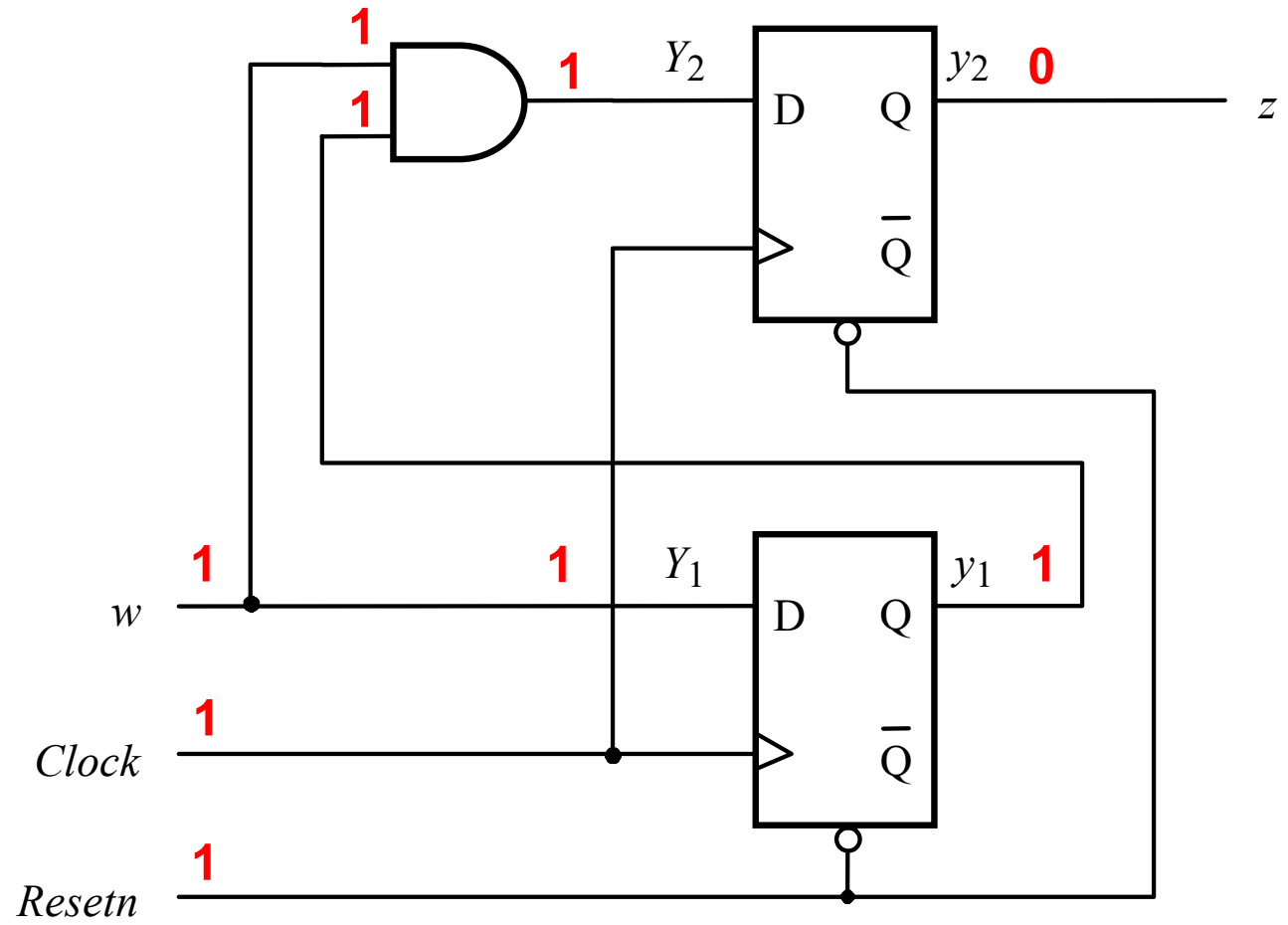
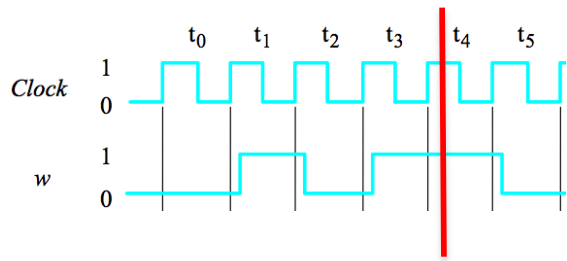
State A=00



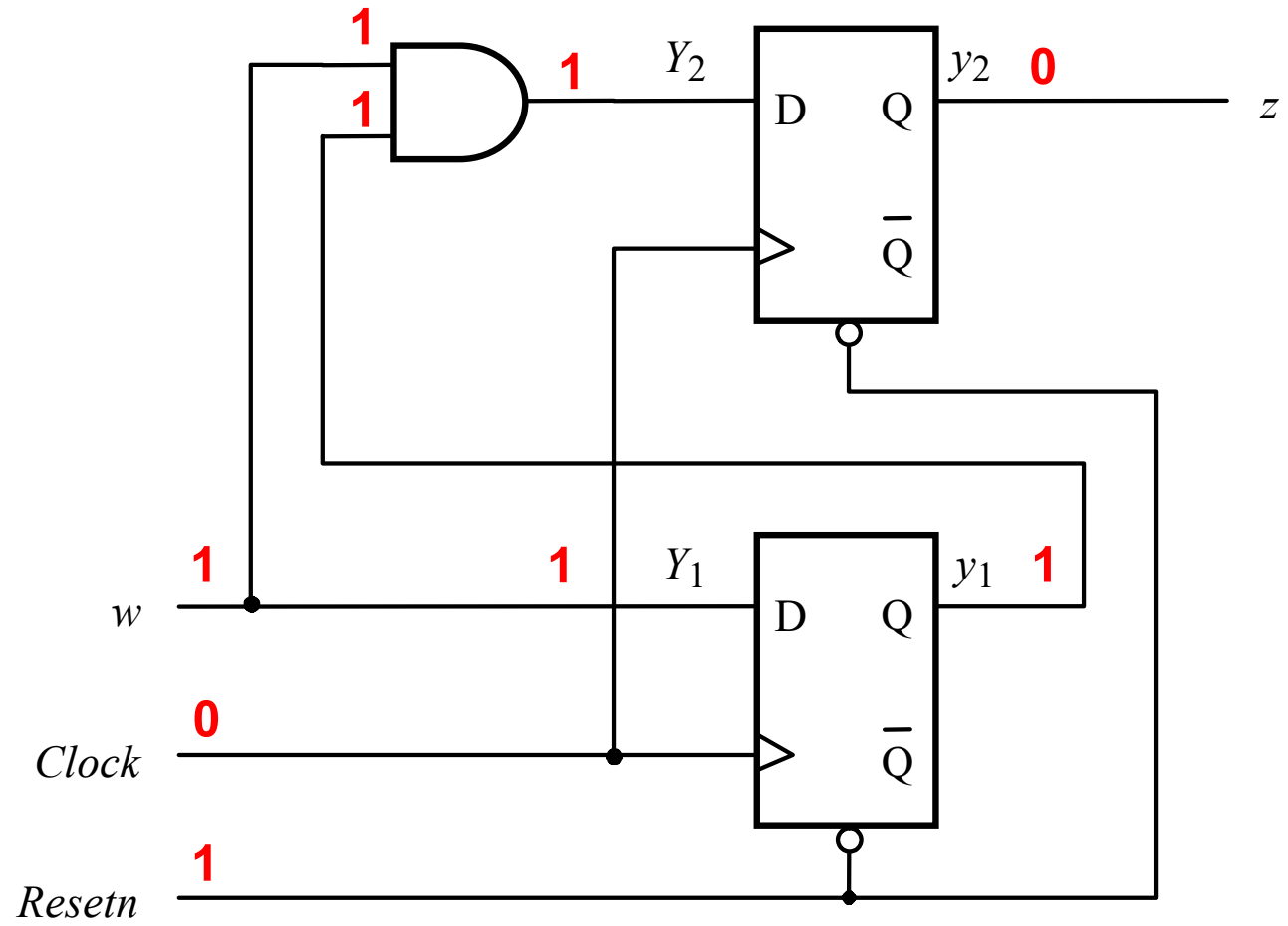
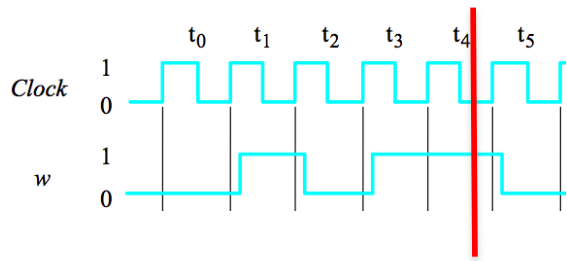
State B=01



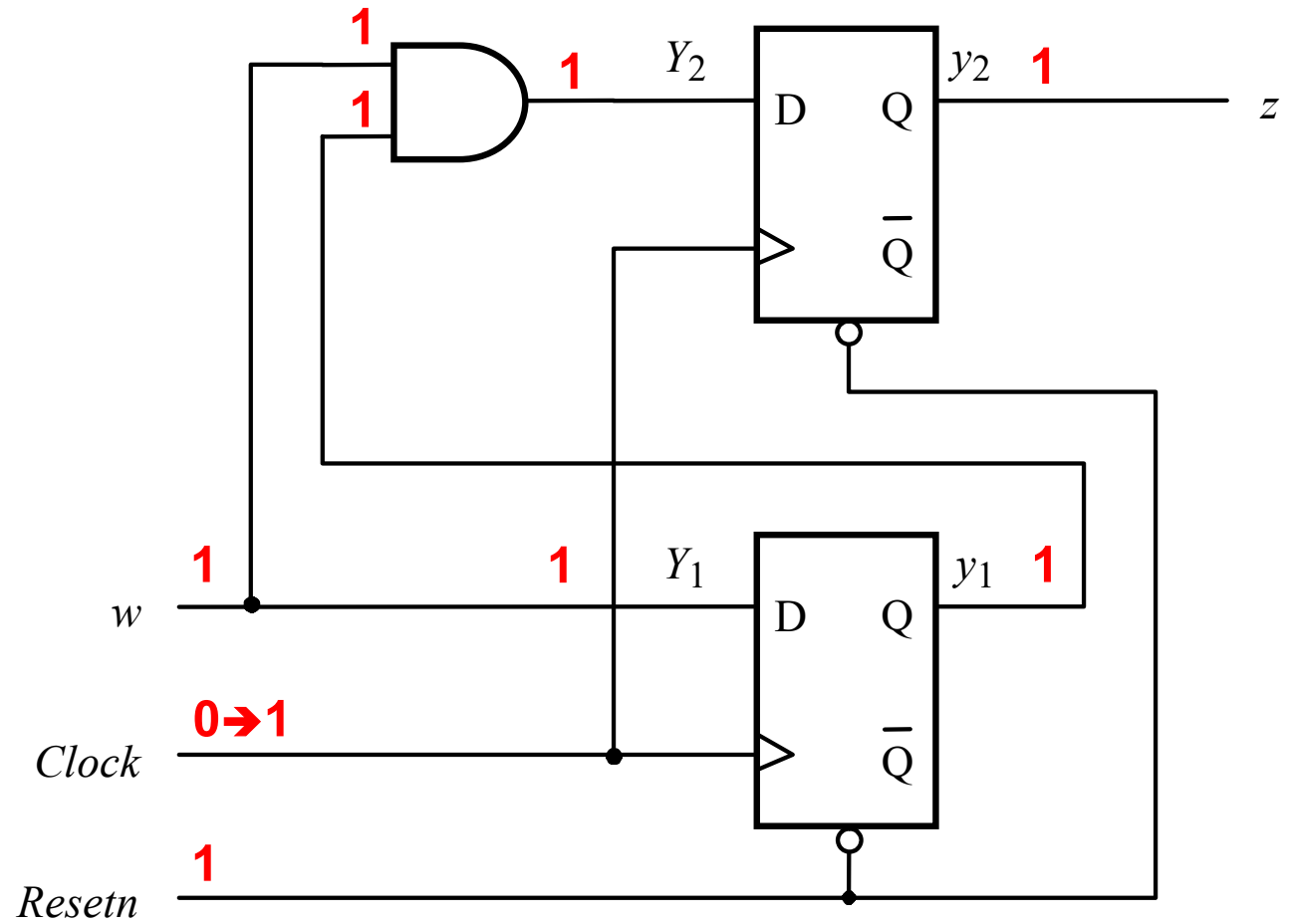
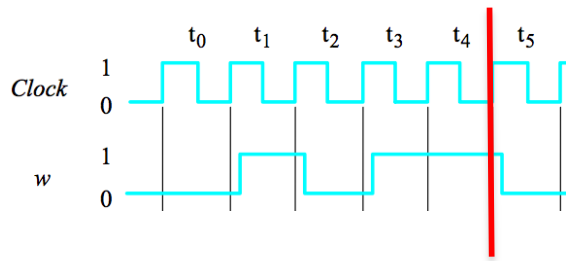
State B=01



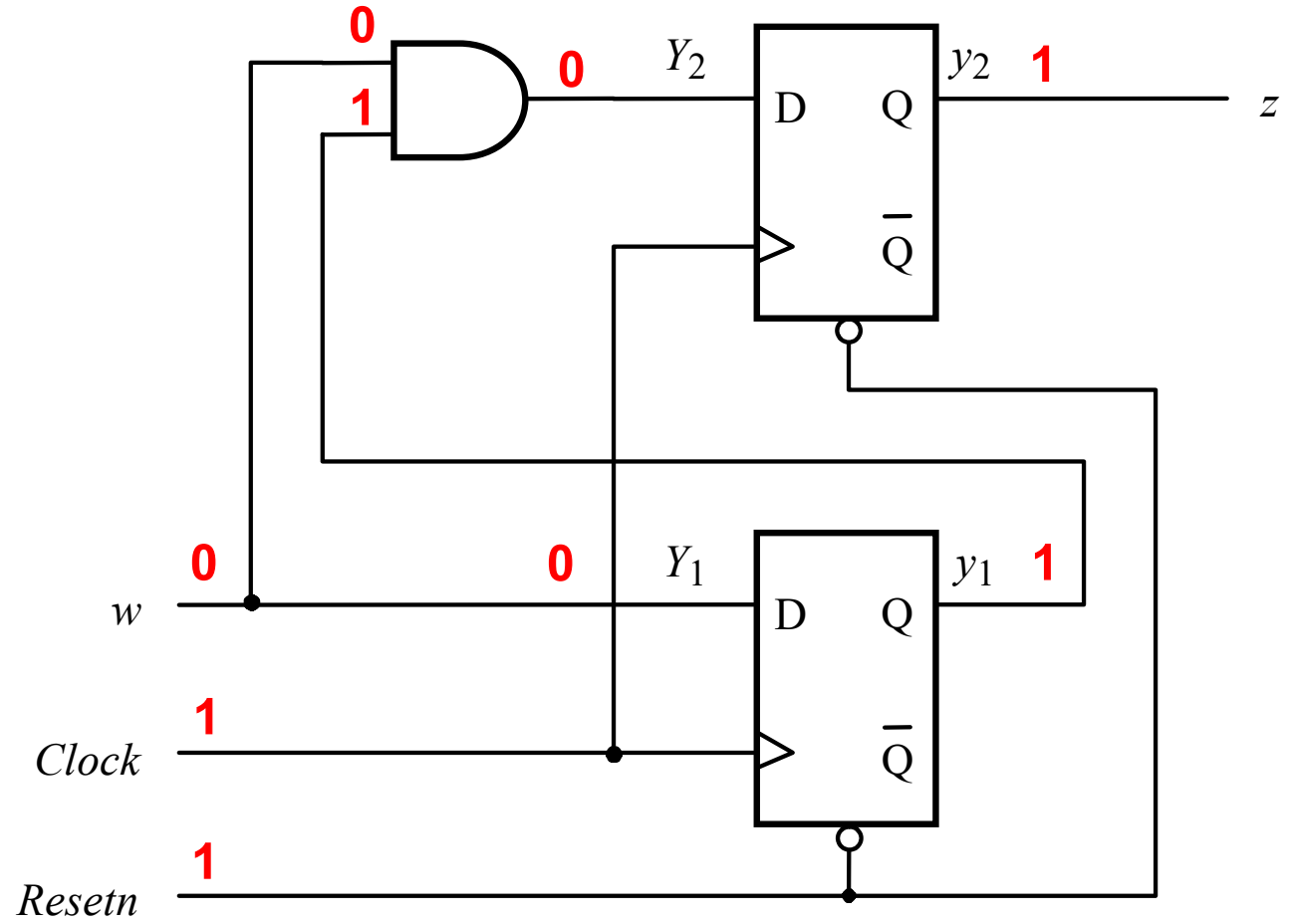
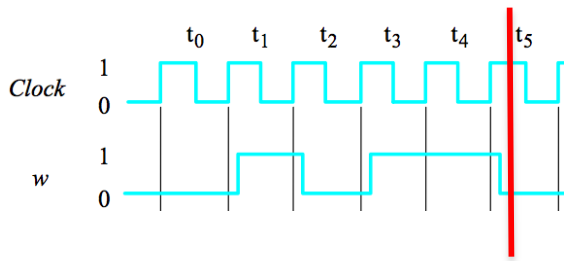
State B=01



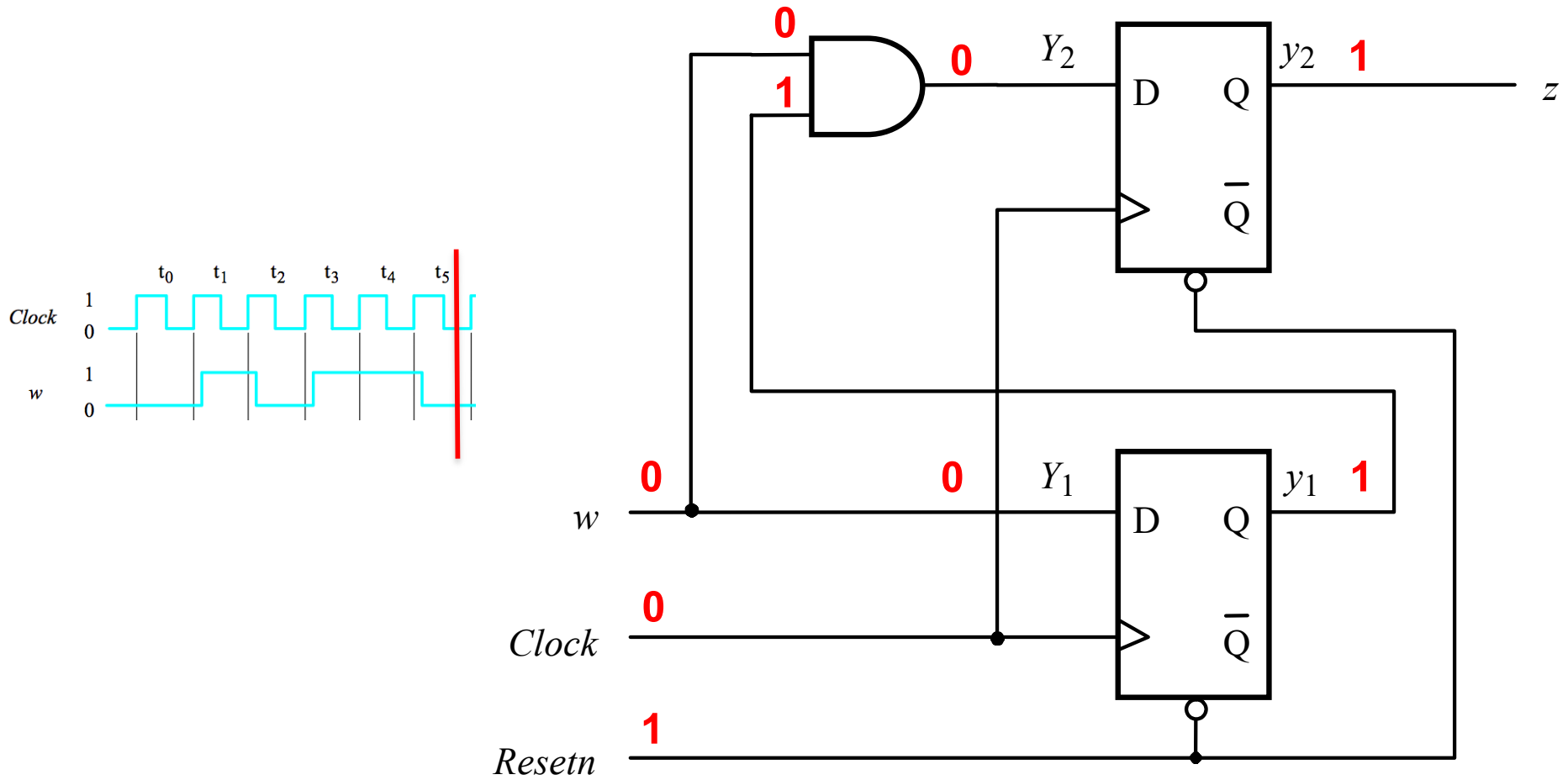
# State C=11



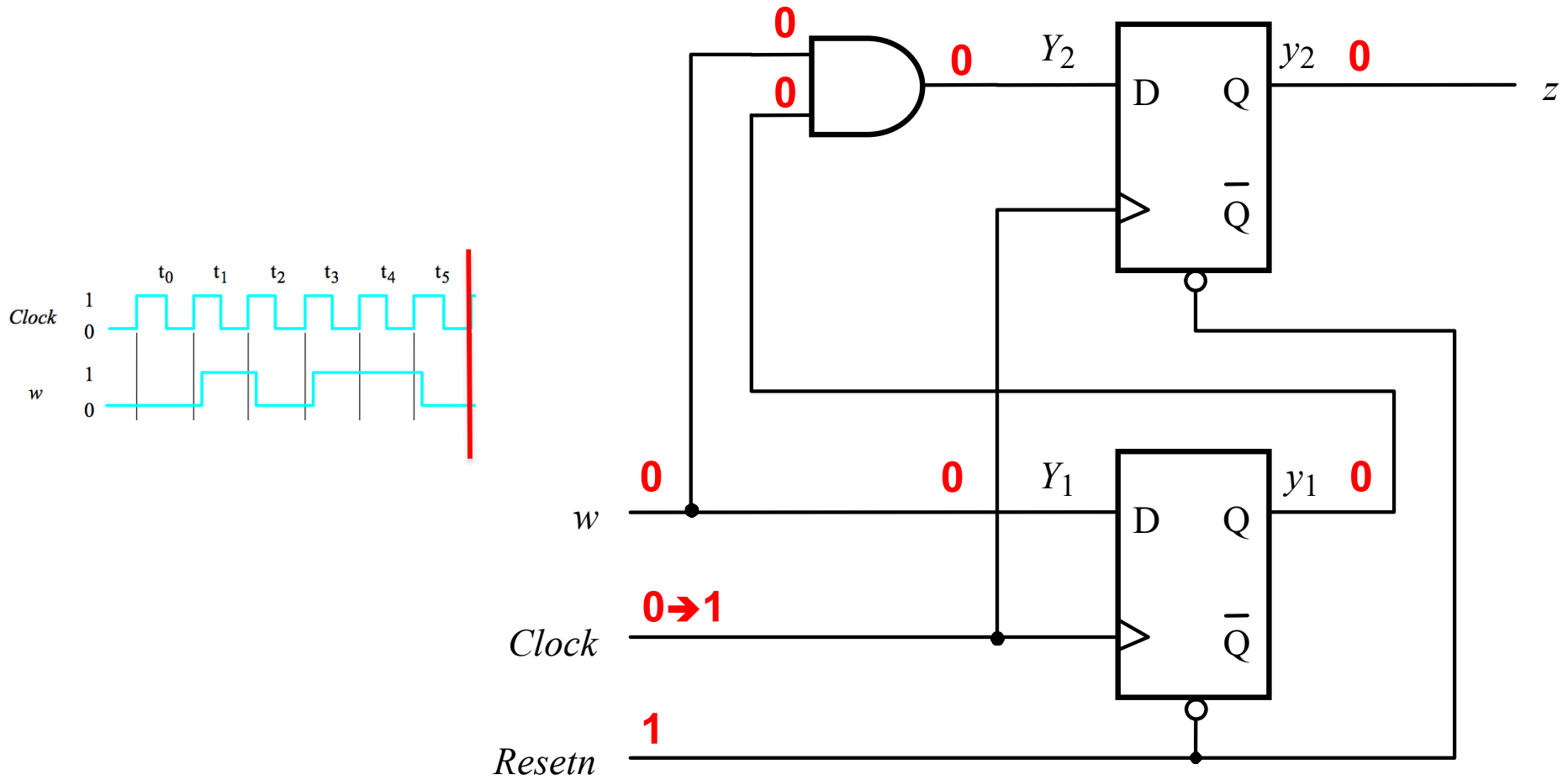
# State C=11



# State C=11

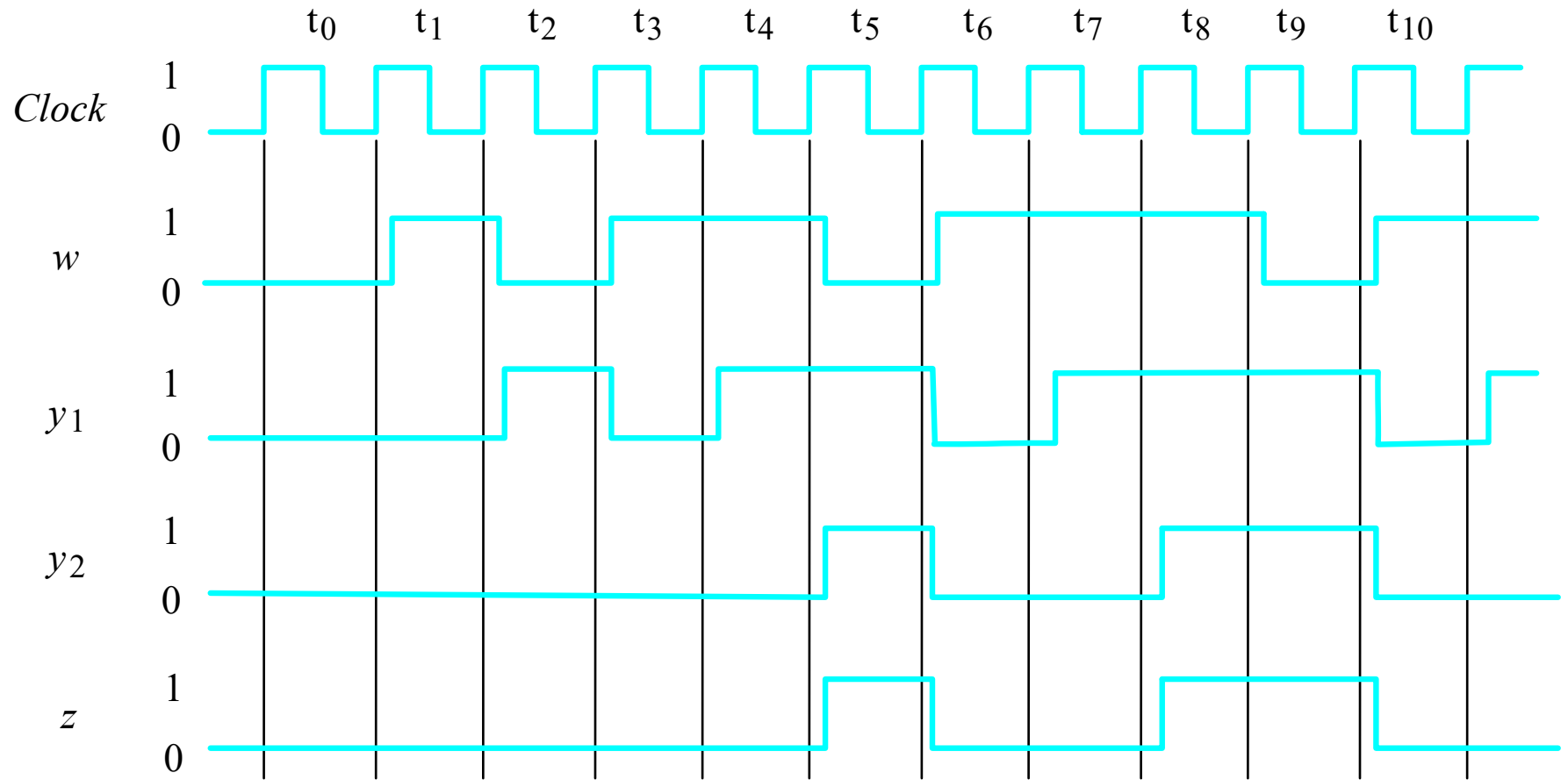


State A=00

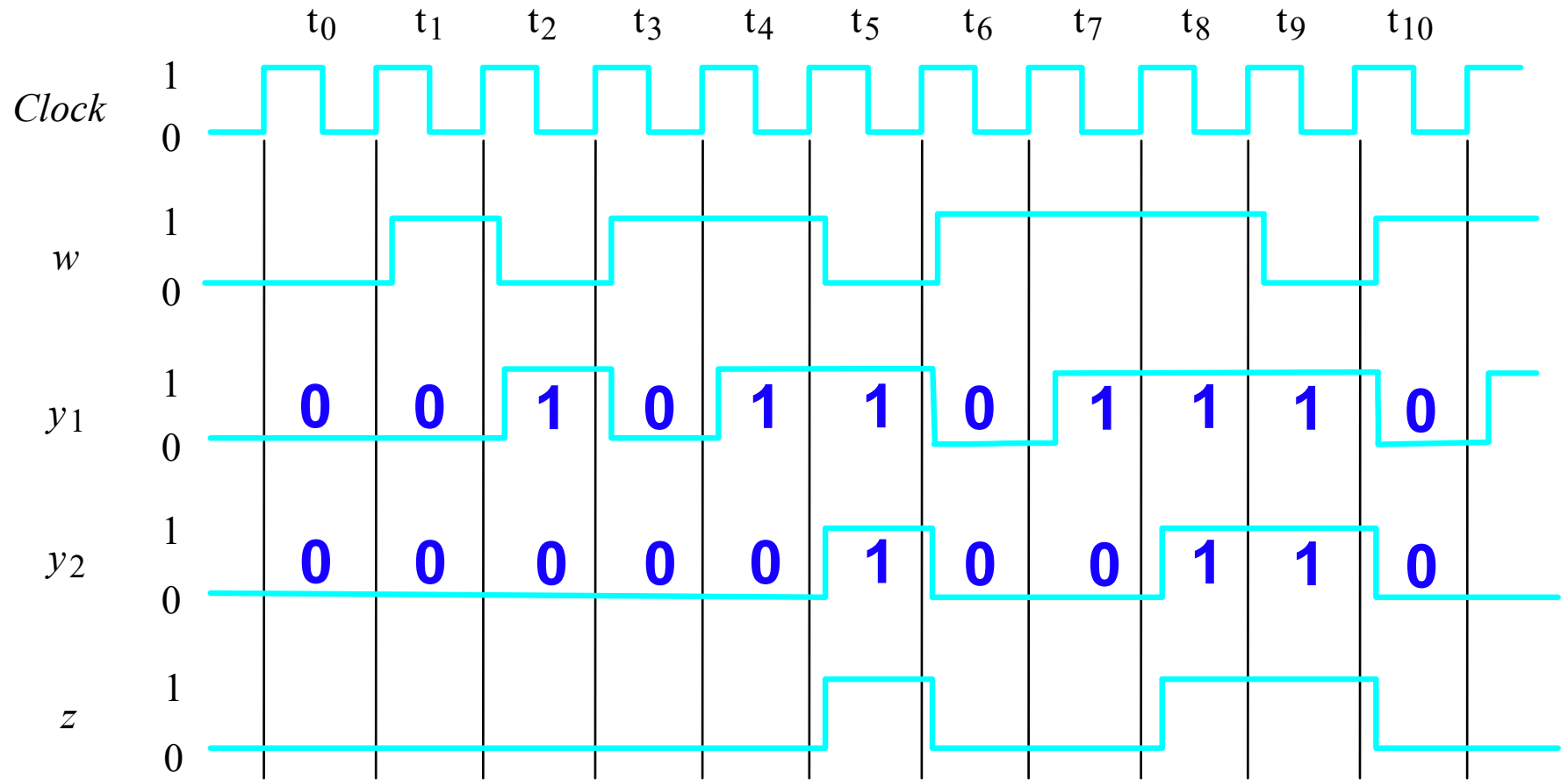




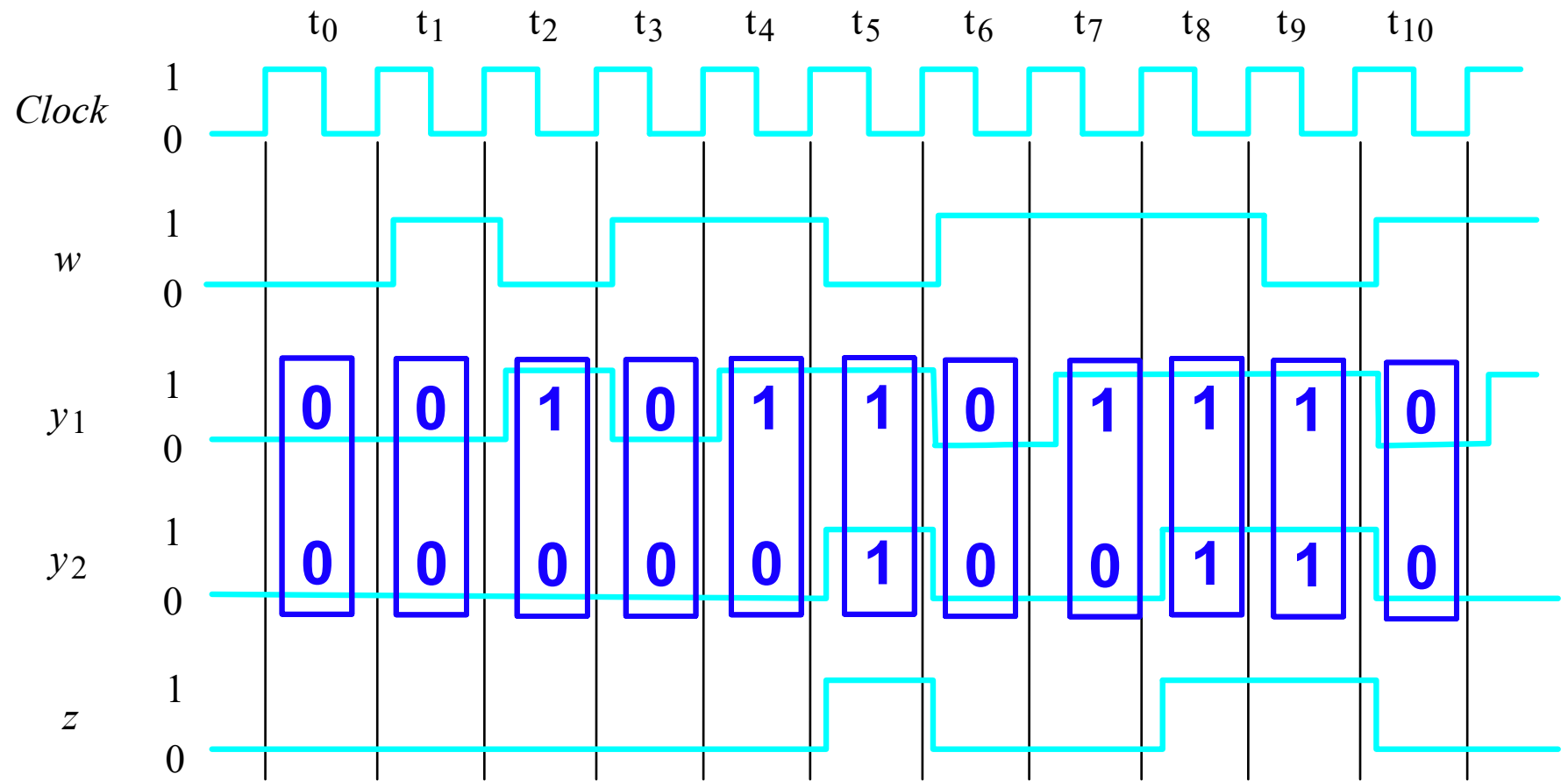
Clockcycle:	$t_0$	$t_1$	$t_2$	$t_3$	$t_4$	$t_5$	$t_6$	$t_7$	$t_8$	$t_9$	$t_{10}$
$w$ :	0	1	0	1	1	0	1	1	1	0	1
$z$ :	0	0	0	0	0	1	0	0	1	1	0



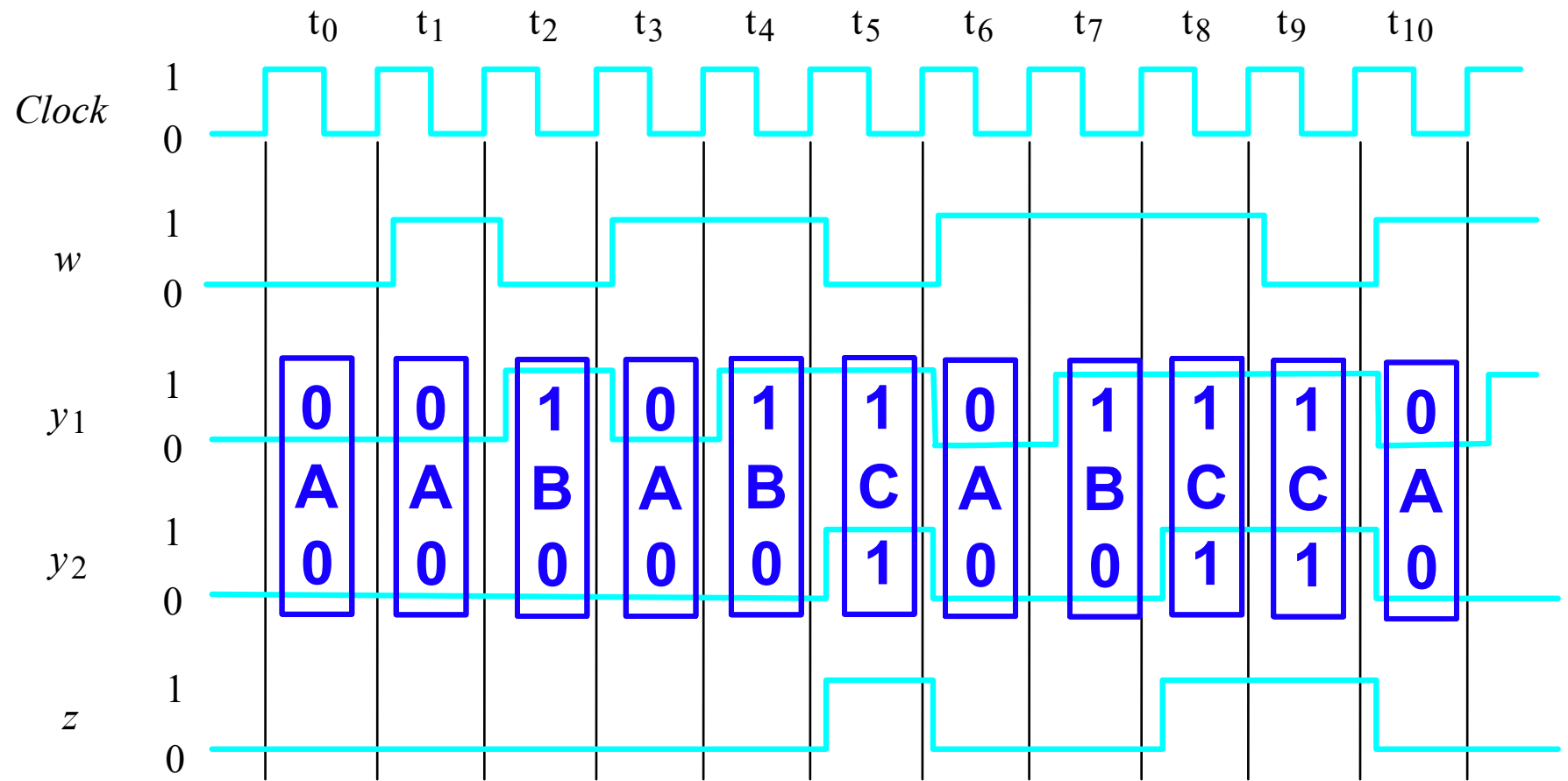
Clockcycle:	$t_0$	$t_1$	$t_2$	$t_3$	$t_4$	$t_5$	$t_6$	$t_7$	$t_8$	$t_9$	$t_{10}$
$w$ :	0	1	0	1	1	0	1	1	1	0	1
$z$ :	0	0	0	0	0	1	0	0	1	1	0



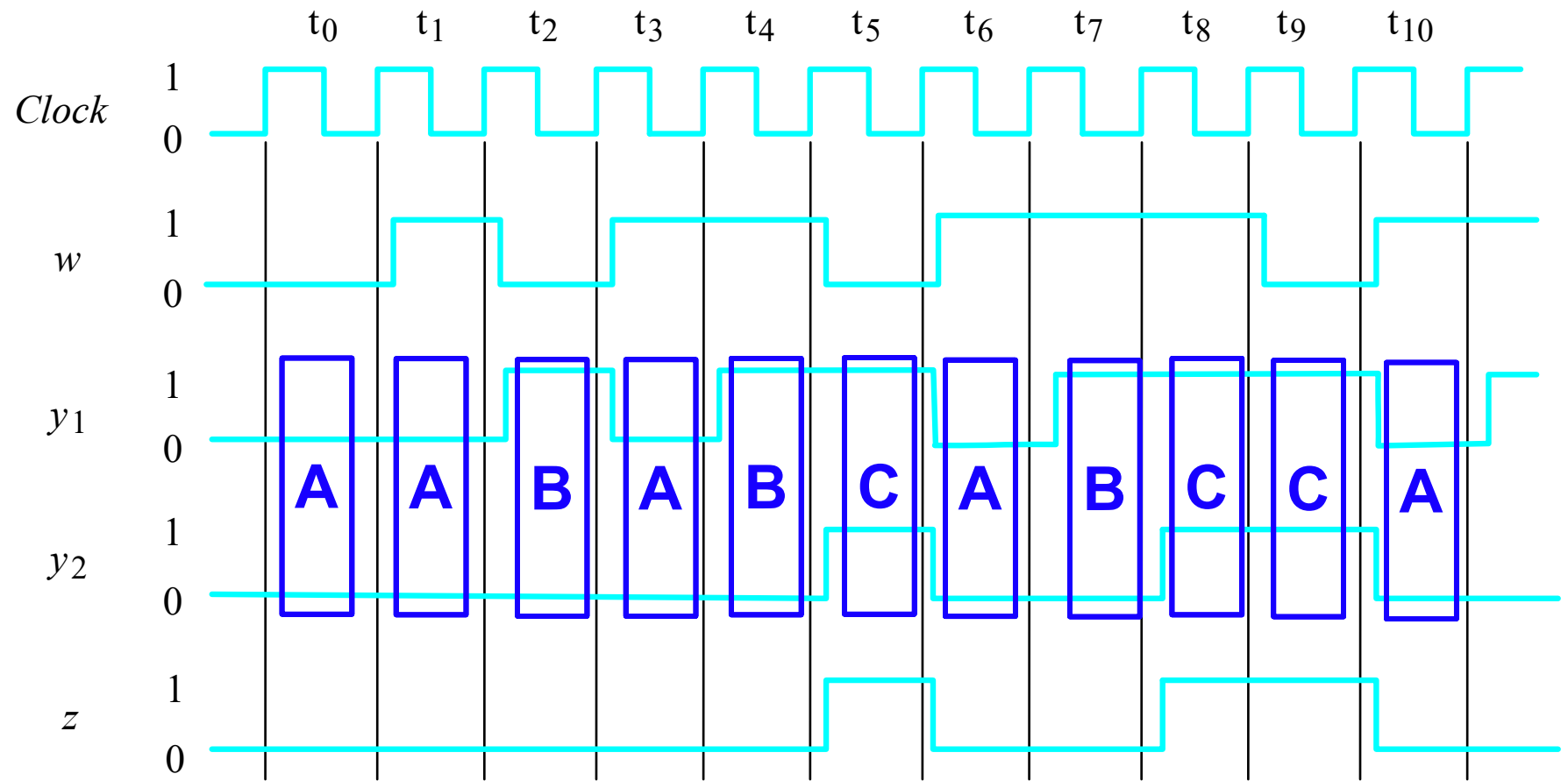
Clockcycle:	$t_0$	$t_1$	$t_2$	$t_3$	$t_4$	$t_5$	$t_6$	$t_7$	$t_8$	$t_9$	$t_{10}$
$w$ :	0	1	0	1	1	0	1	1	1	0	1
$z$ :	0	0	0	0	0	1	0	0	1	1	0



Clockcycle:	$t_0$	$t_1$	$t_2$	$t_3$	$t_4$	$t_5$	$t_6$	$t_7$	$t_8$	$t_9$	$t_{10}$
$w$ :	0	1	0	1	1	0	1	1	1	0	1
$z$ :	0	0	0	0	0	1	0	0	1	1	0



Clockcycle:	$t_0$	$t_1$	$t_2$	$t_3$	$t_4$	$t_5$	$t_6$	$t_7$	$t_8$	$t_9$	$t_{10}$
$w$ :	0	1	0	1	1	0	1	1	1	0	1
$z$ :	0	0	0	0	0	1	0	0	1	1	0



# Main Idea

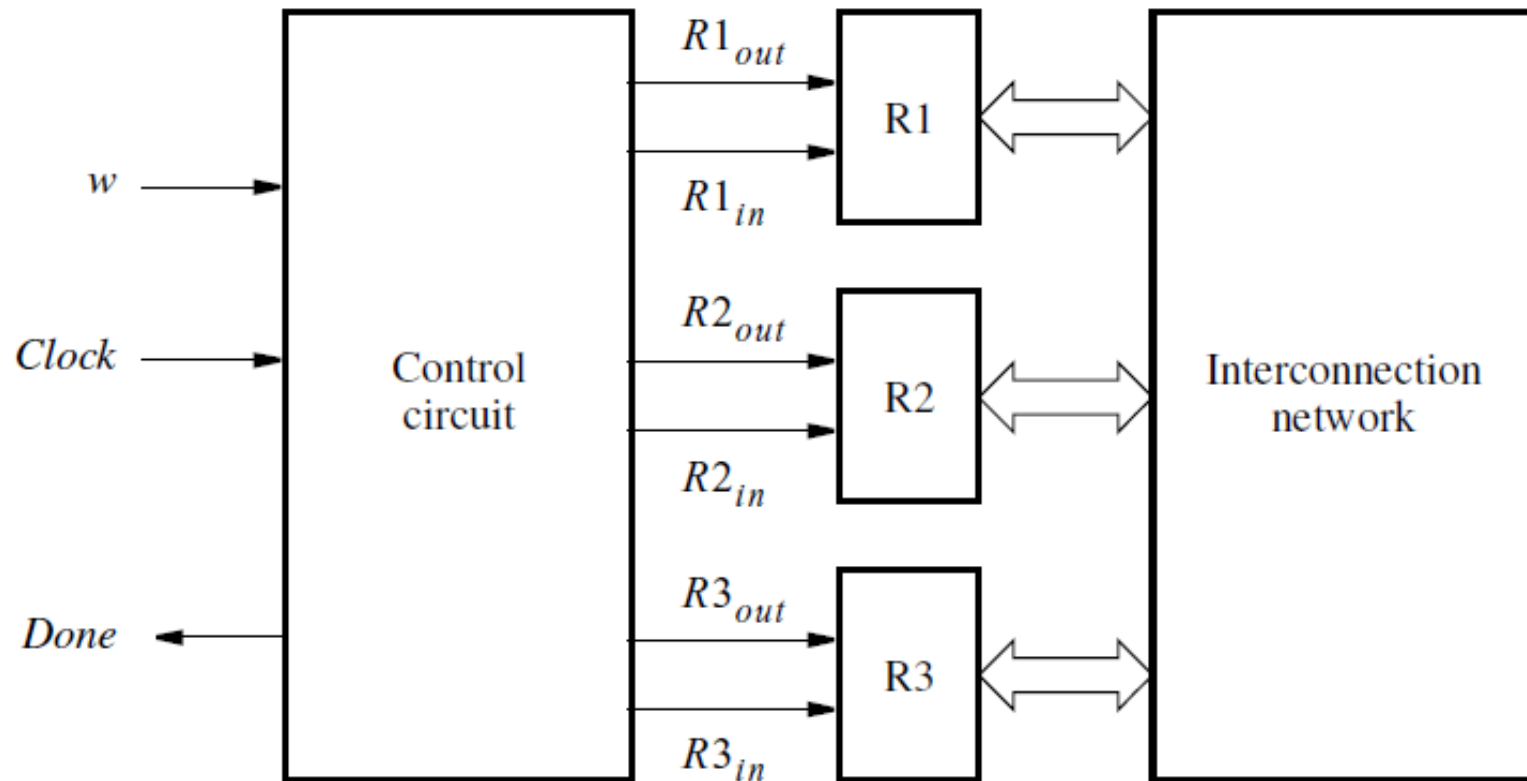
Different state assignments of the same Moore machine generally lead to different circuits.

Some may use fewer logic elements than others.

But they all do the same thing  
(i.e., implement the same Moore machine).

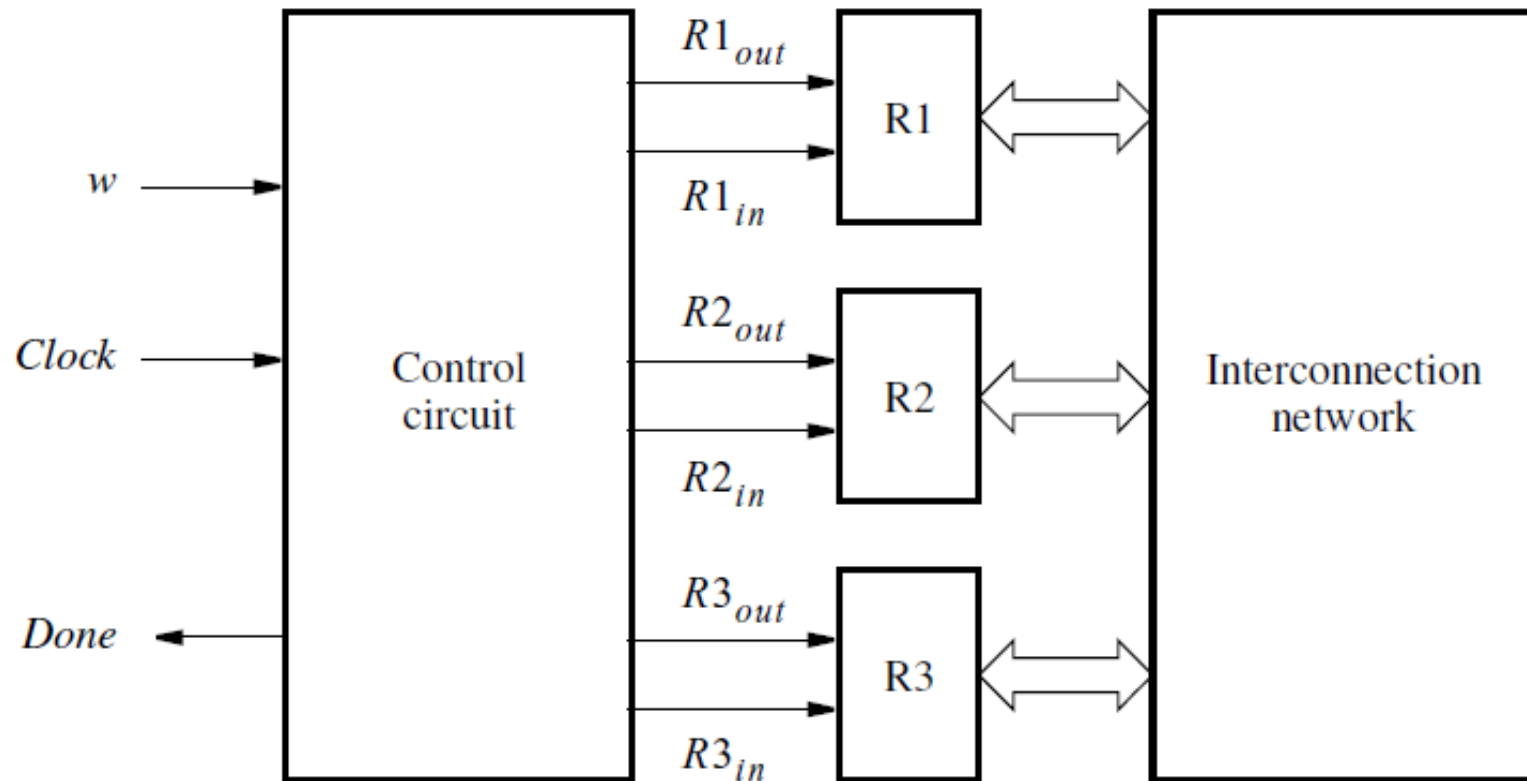
# **Example #2**

# Register Swap Controller



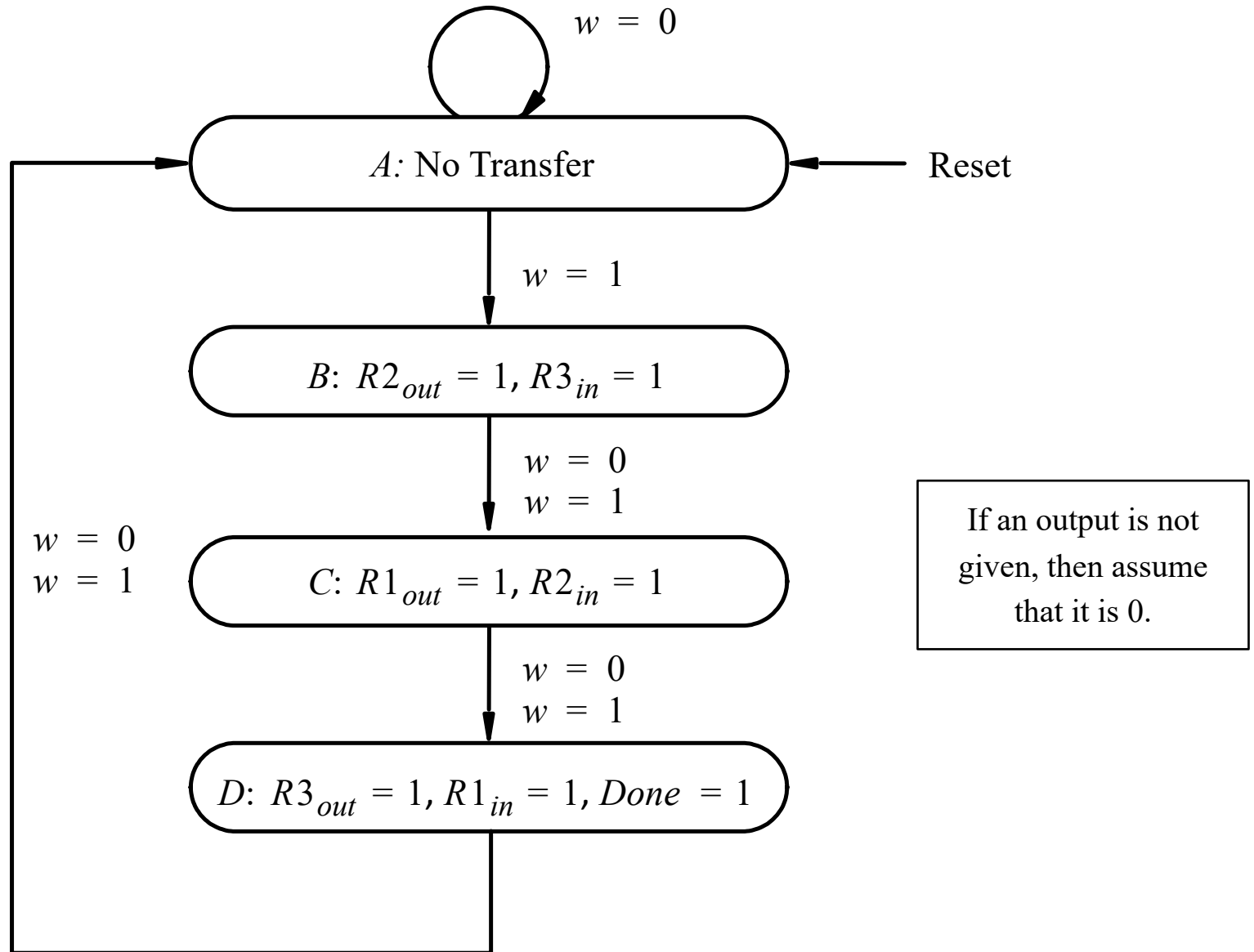


# Register Swap Controller



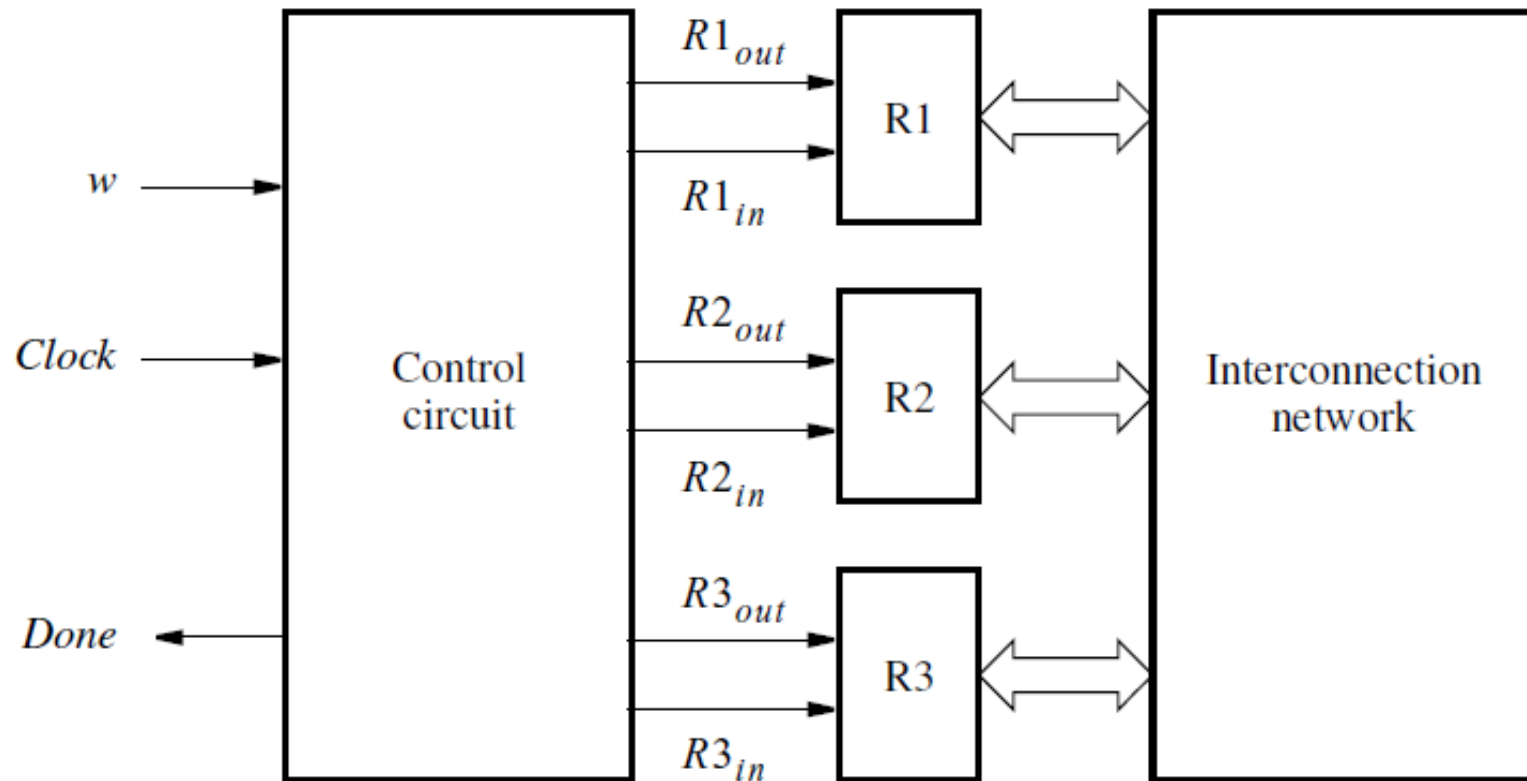
Design a Moore machine control circuit for swapping the contents of registers R1 and R2 by using R3 as a temporary.

# State Diagram

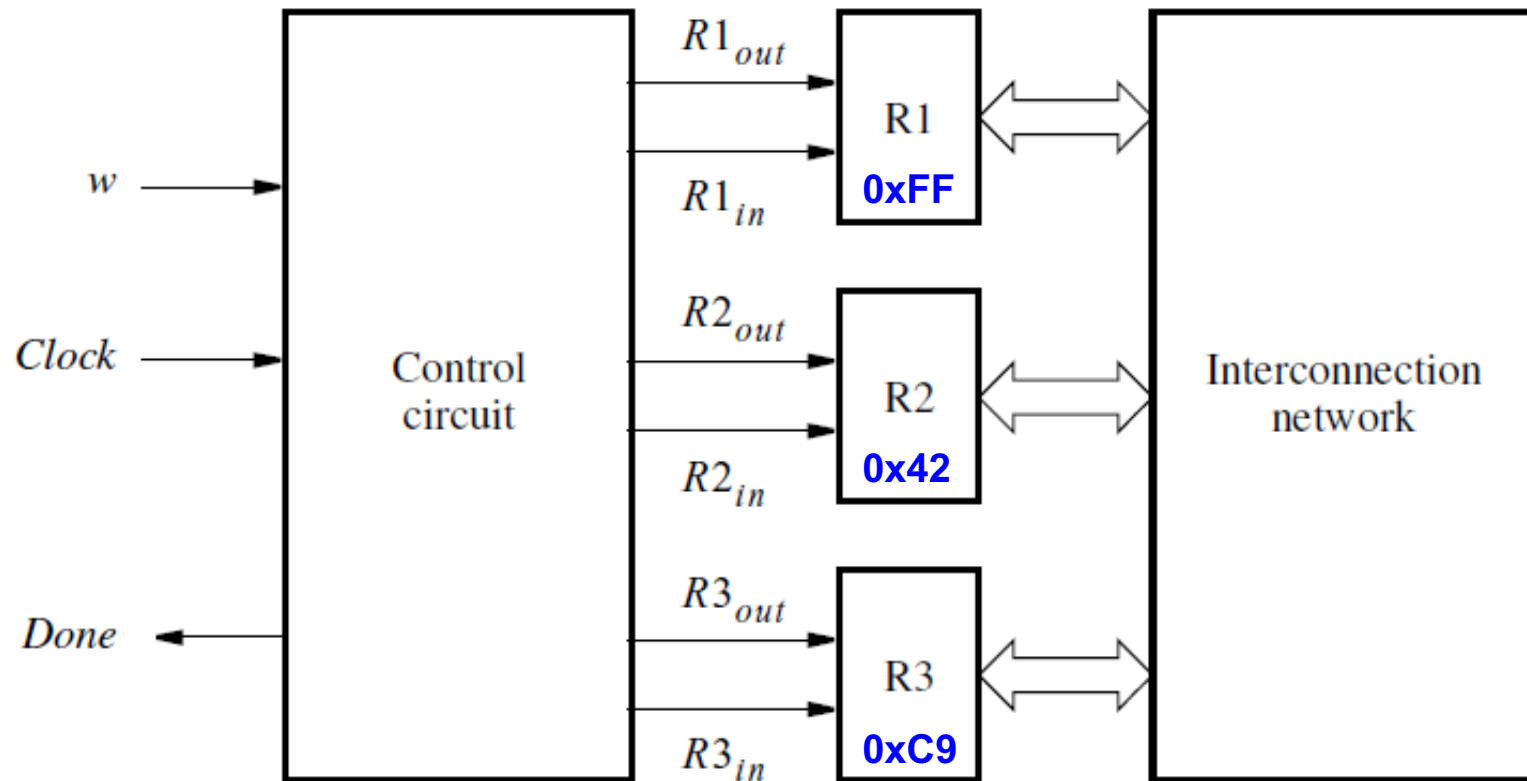


[ Figure 6.11 from the textbook ]

# Animated Register Swap

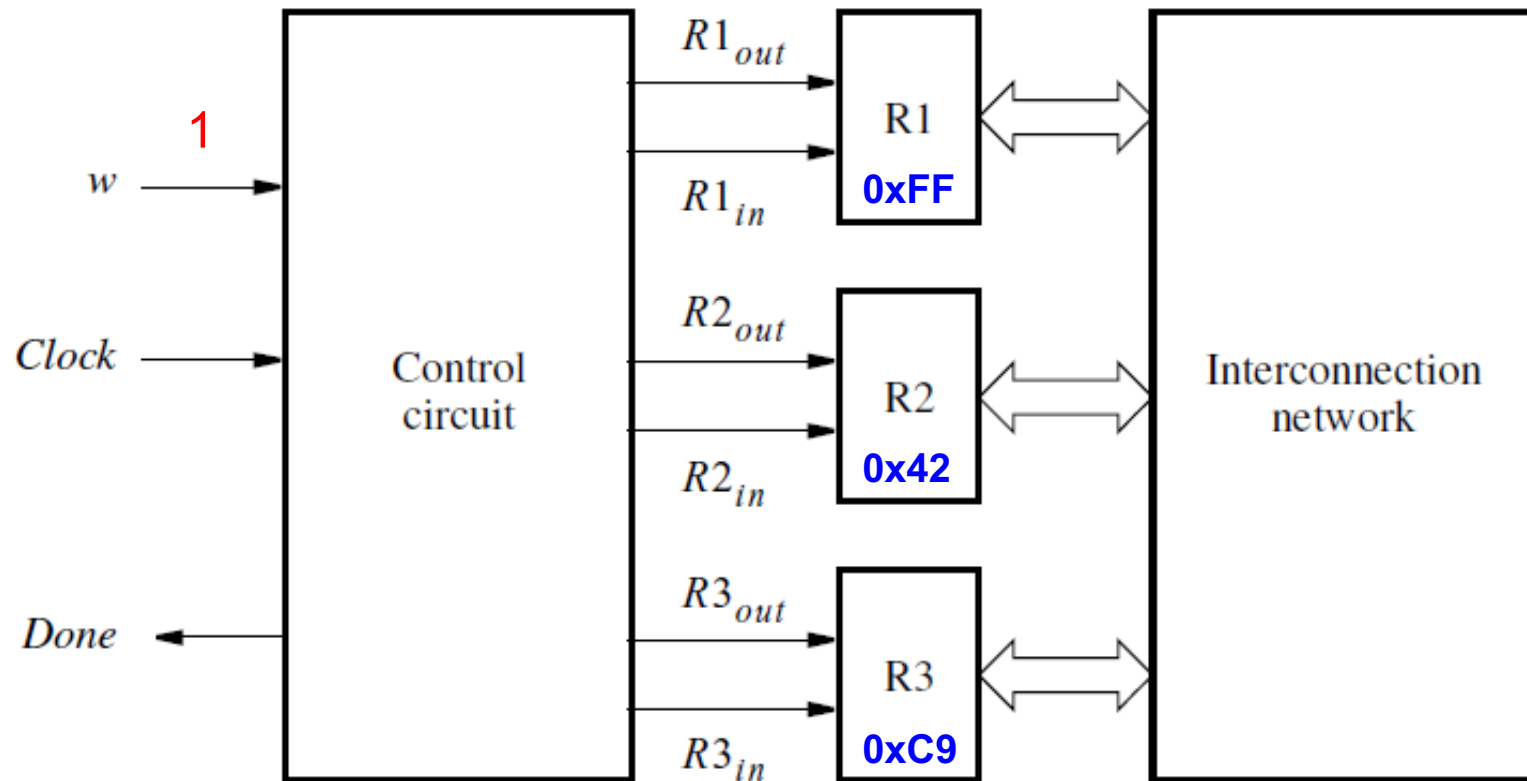


# Animated Register Swap



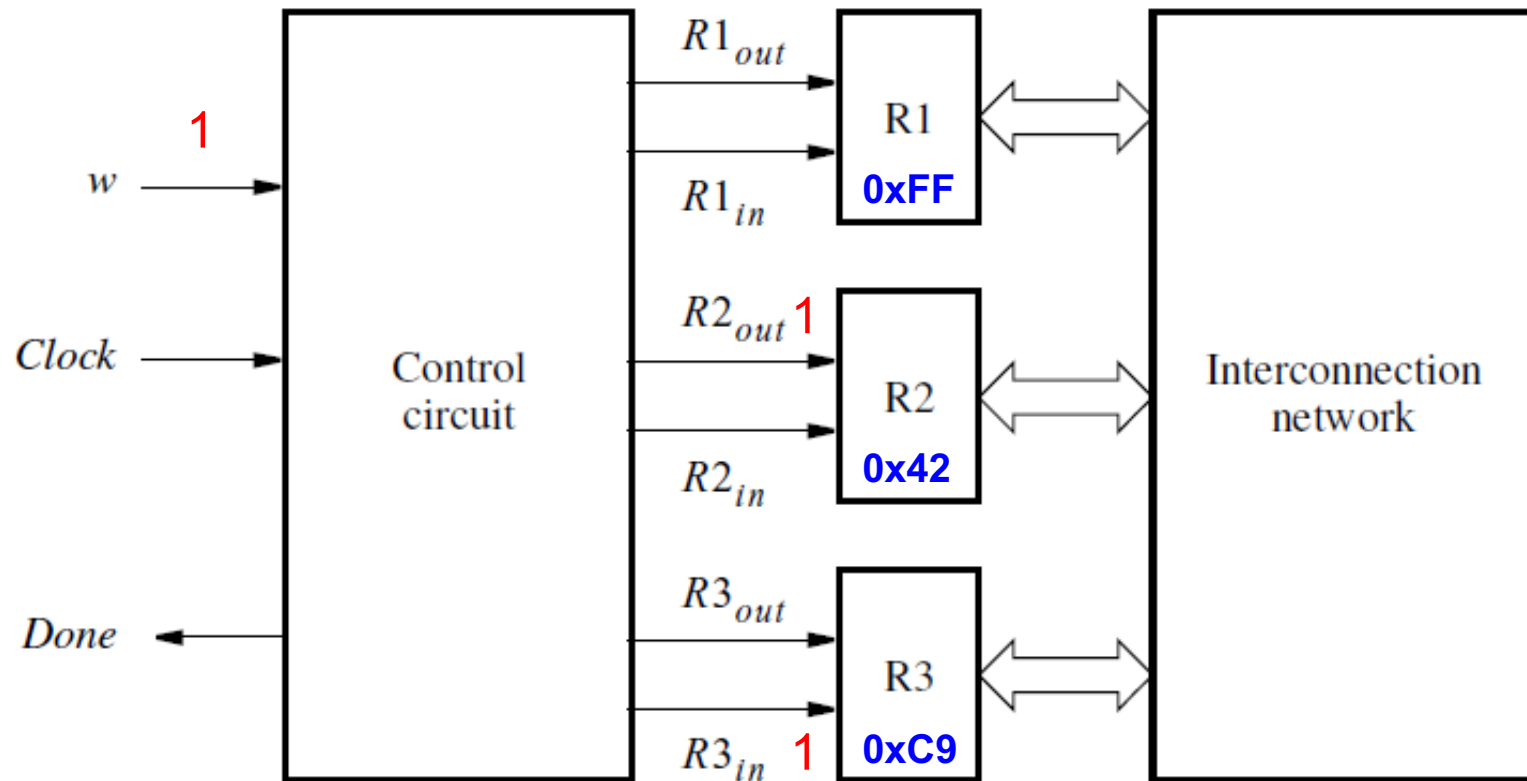
These are the original values of the 8-bit registers

# Animated Register Swap

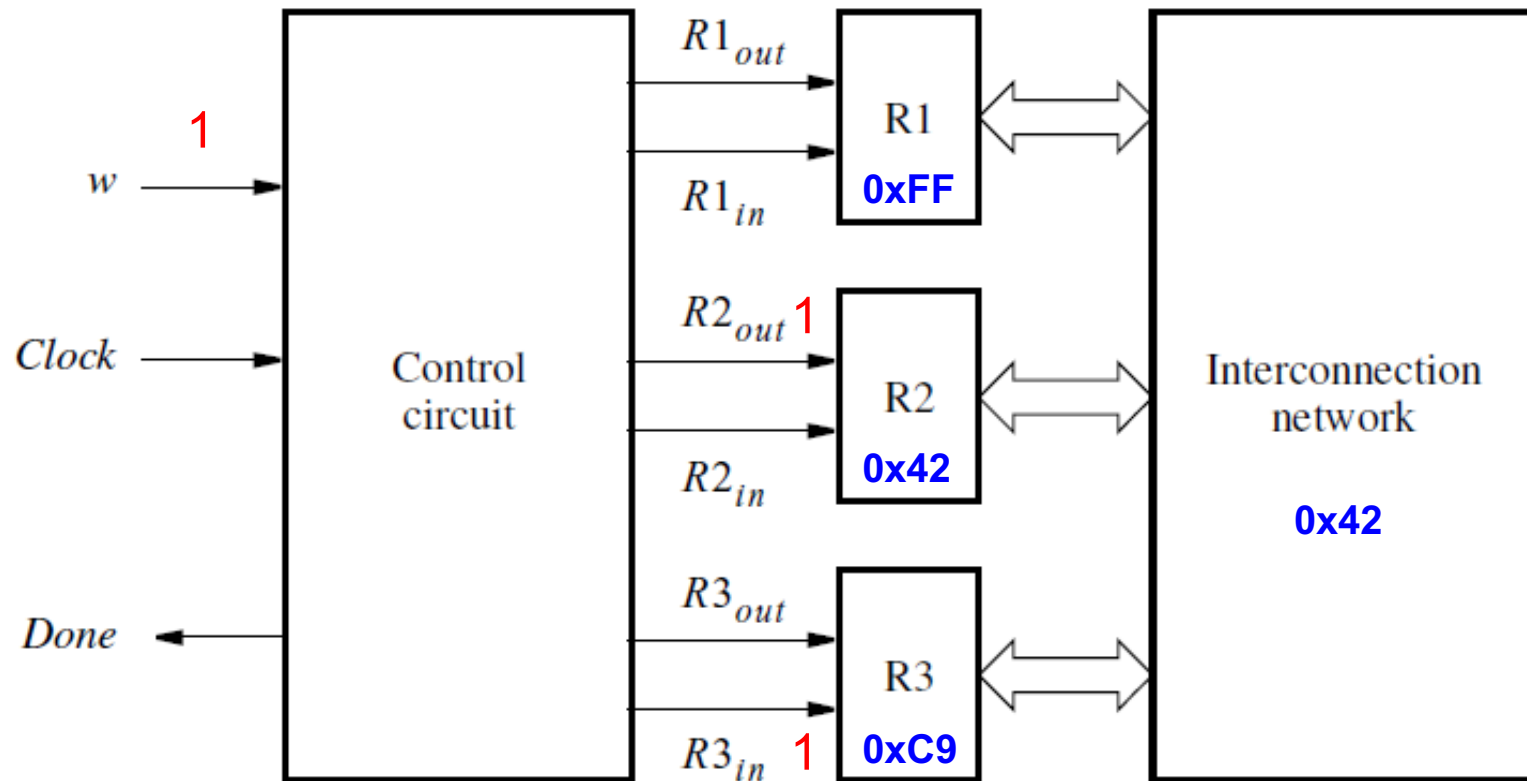


**For clarity, only inputs that are equal to 1 will be shown.**

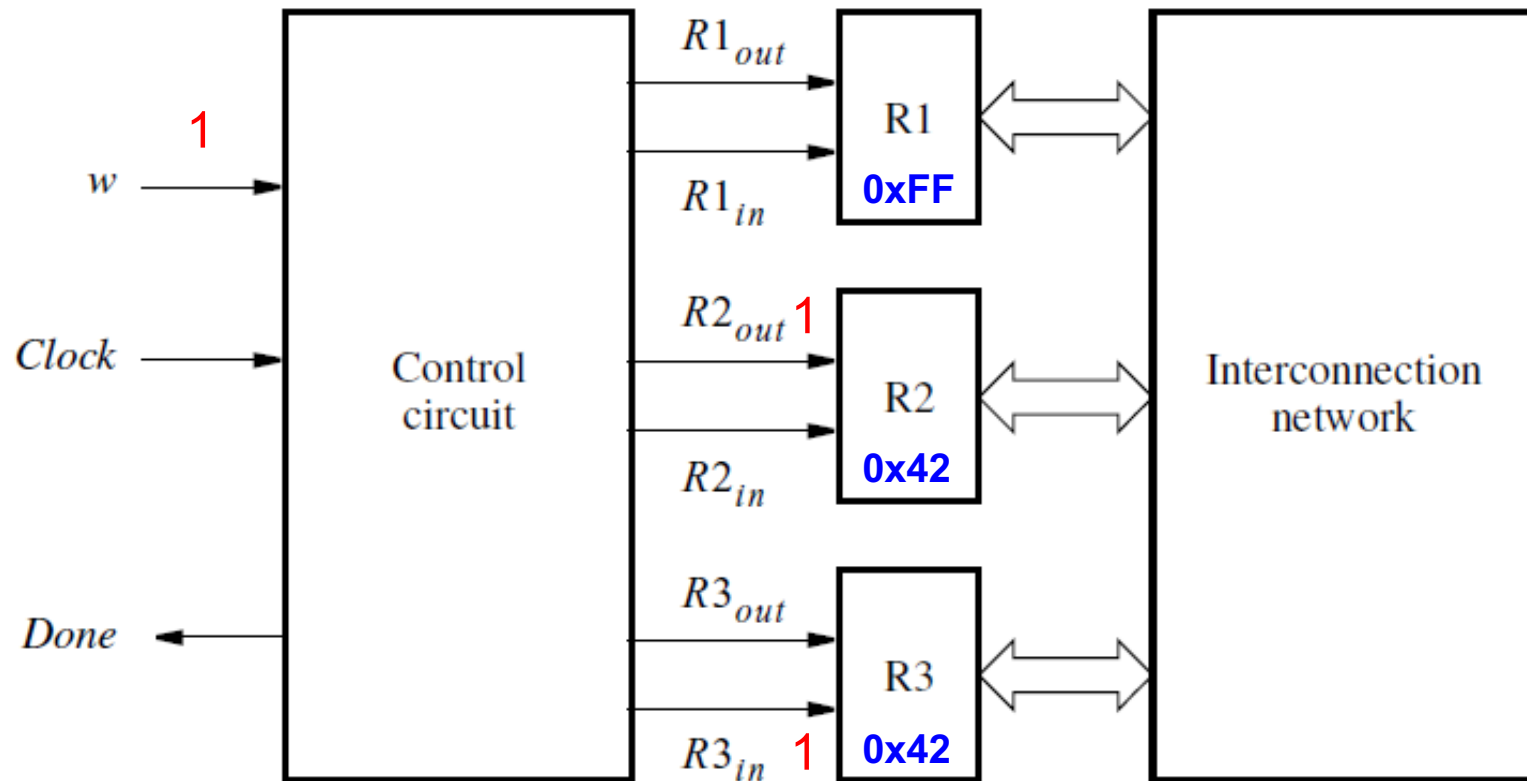
# Animated Register Swap



# Animated Register Swap

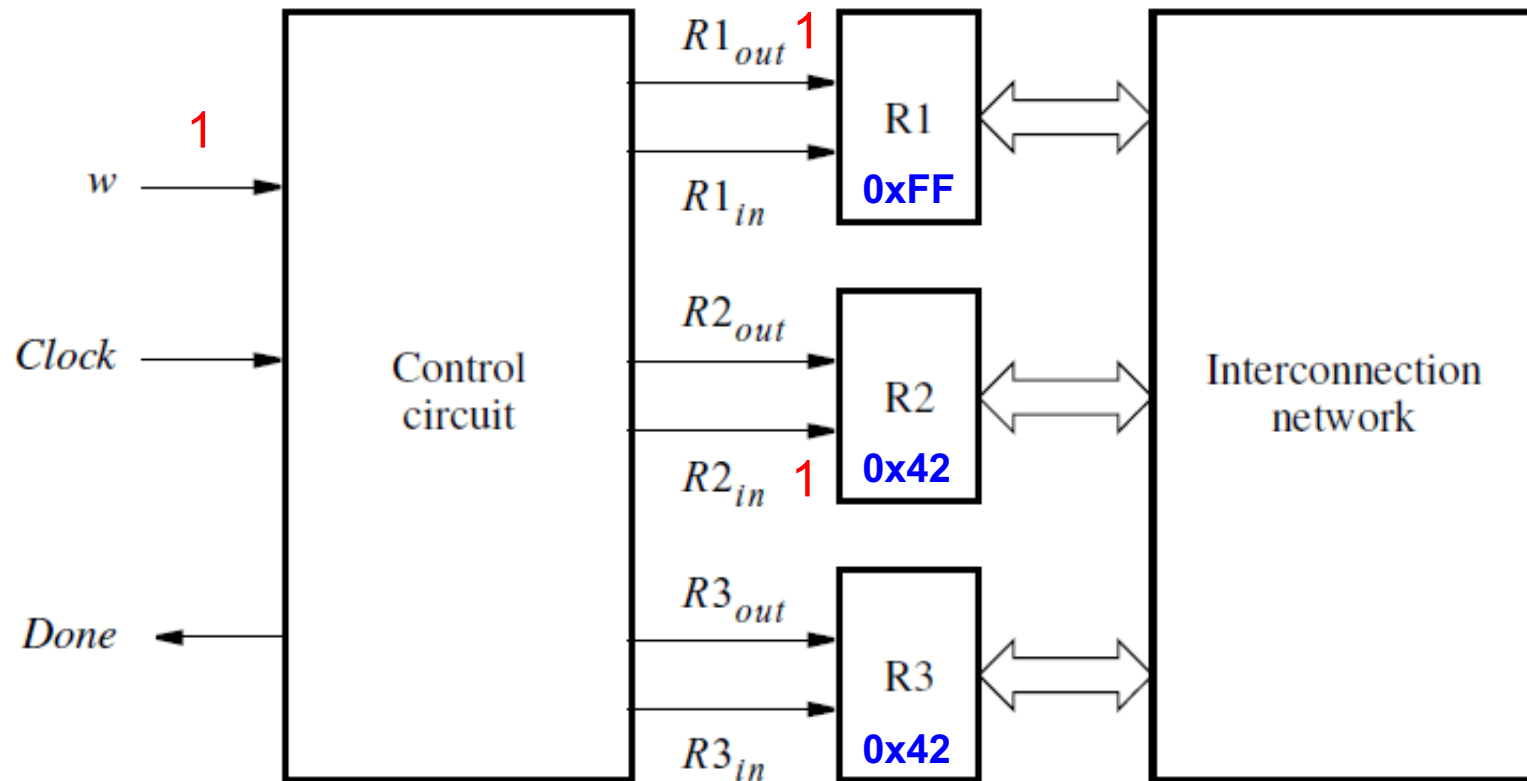


# Animated Register Swap

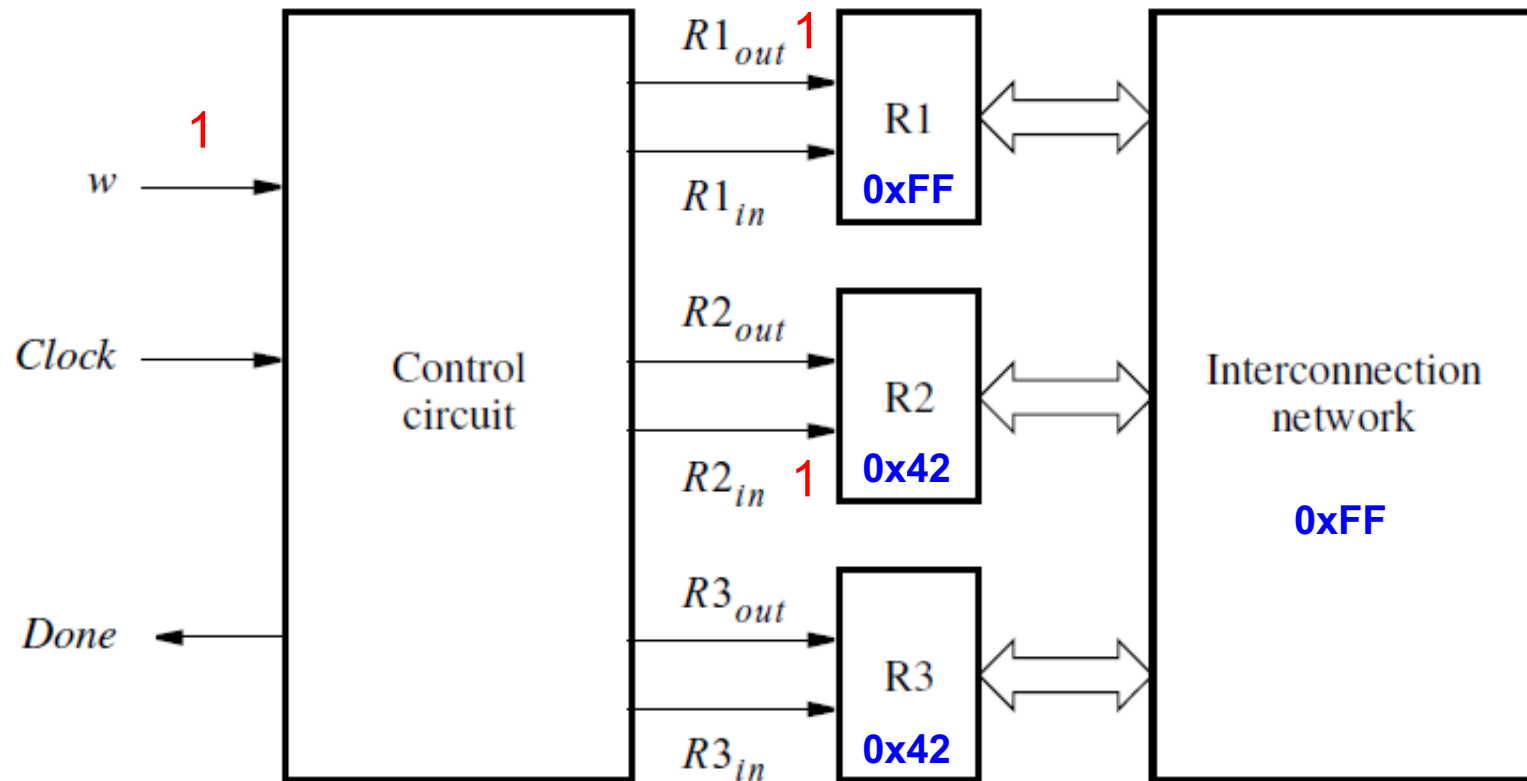




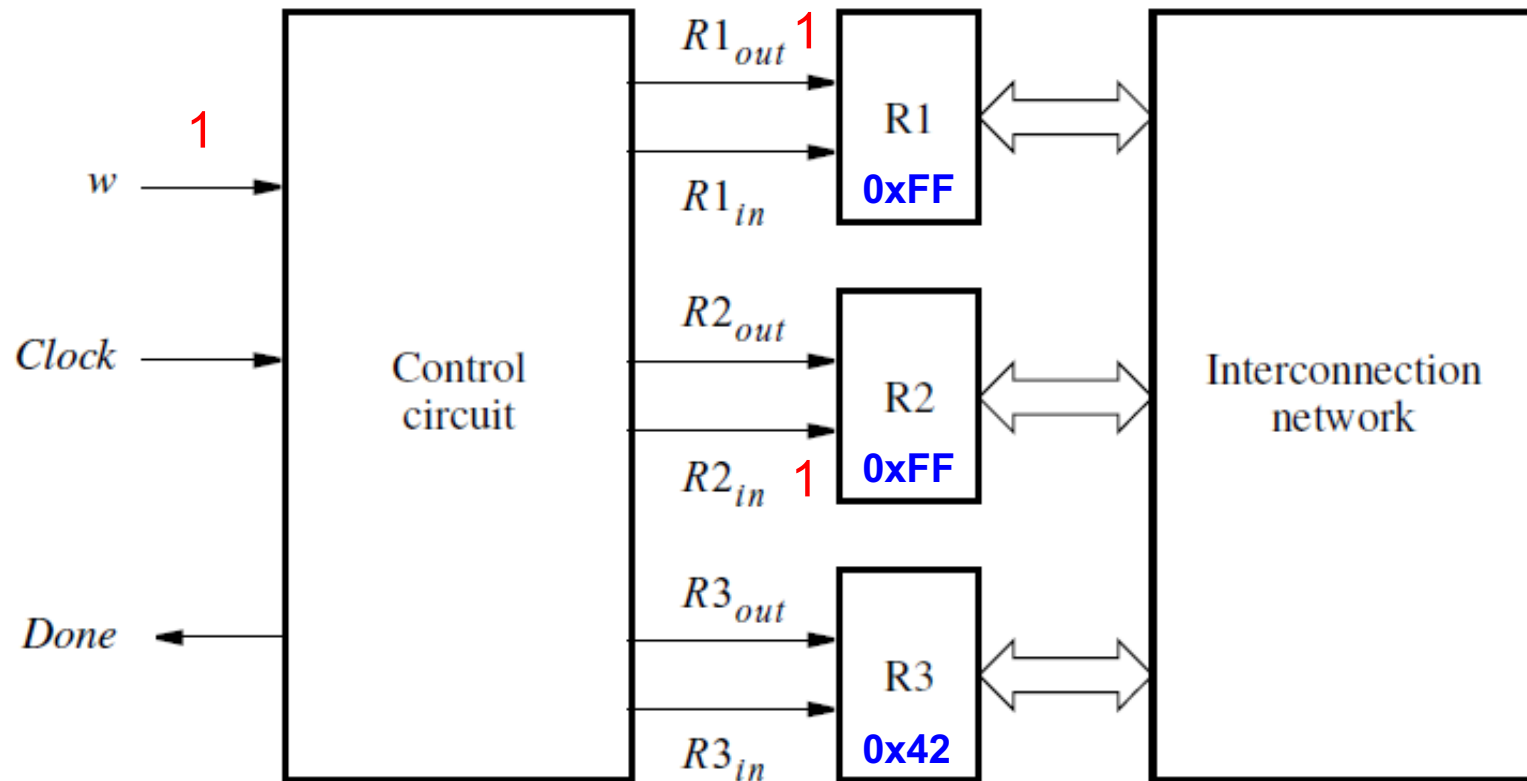
# Animated Register Swap



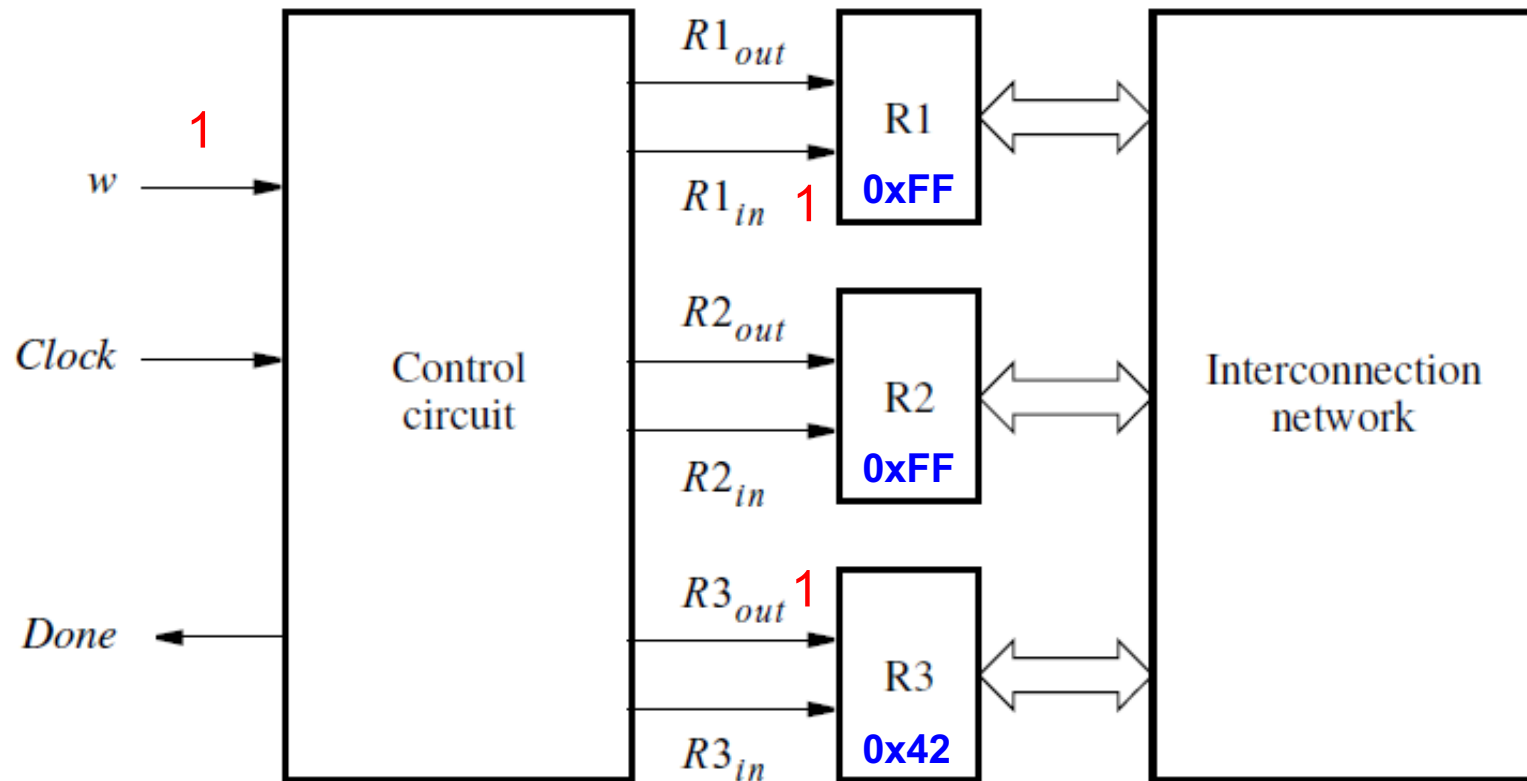
# Animated Register Swap



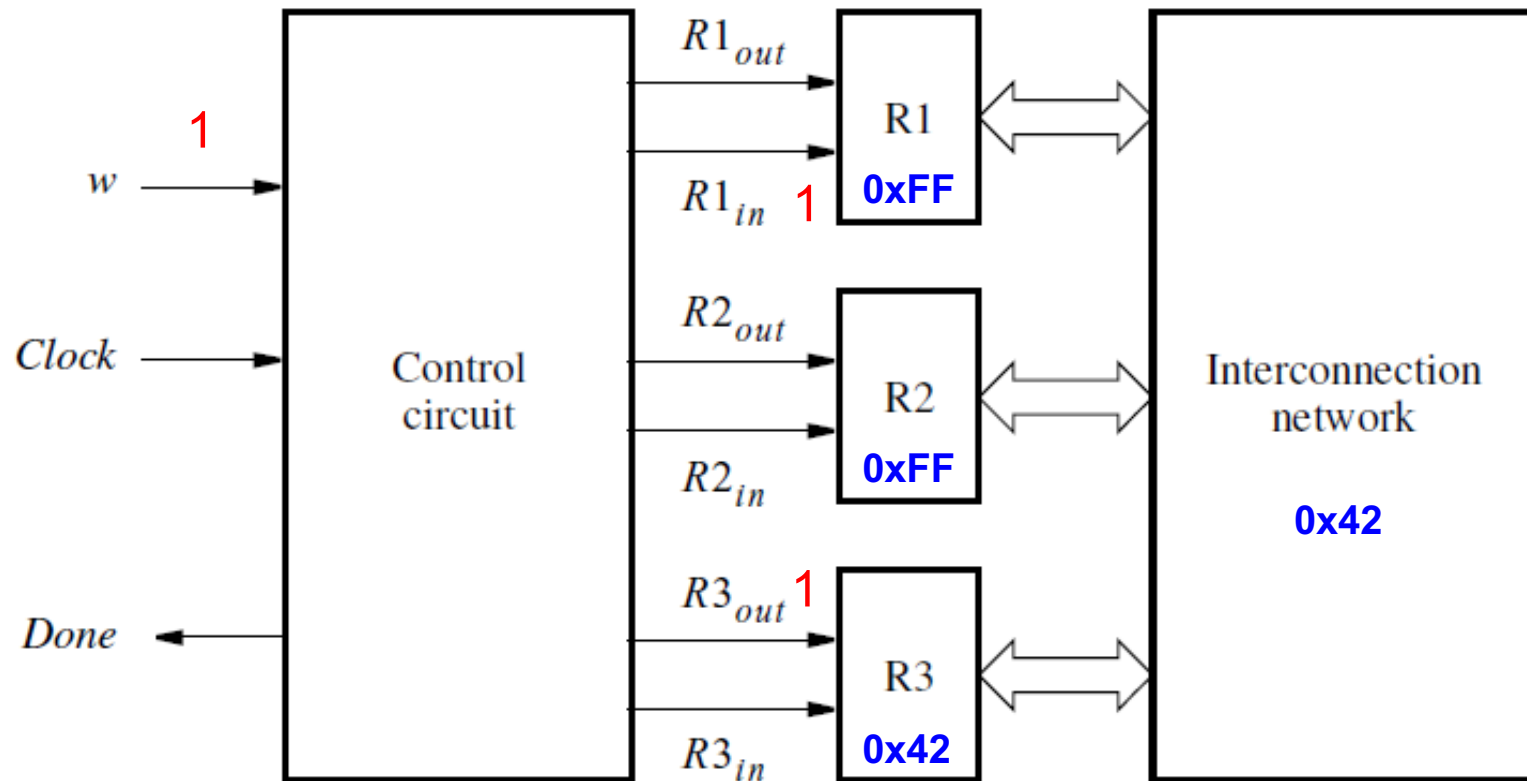
# Animated Register Swap



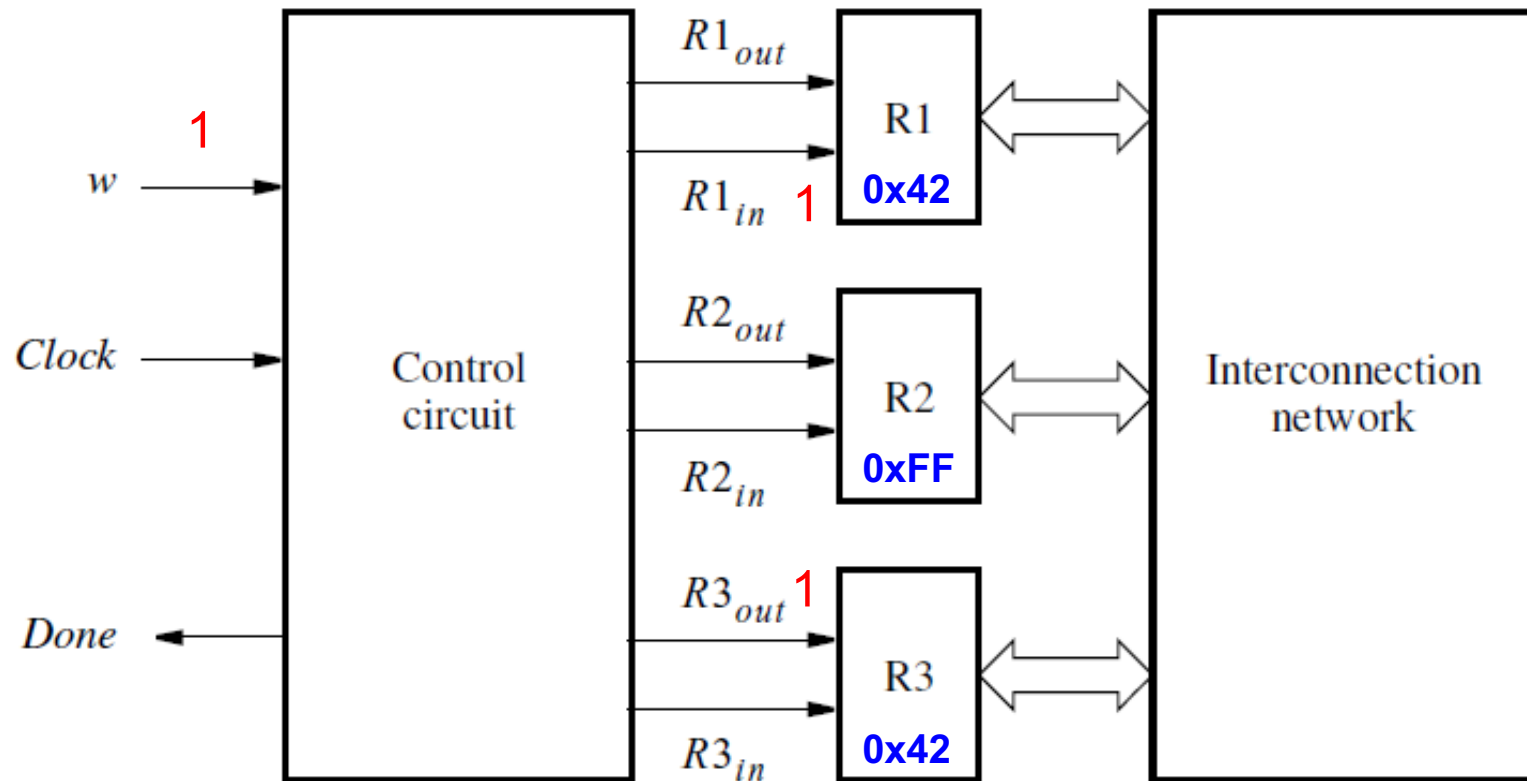
# Animated Register Swap



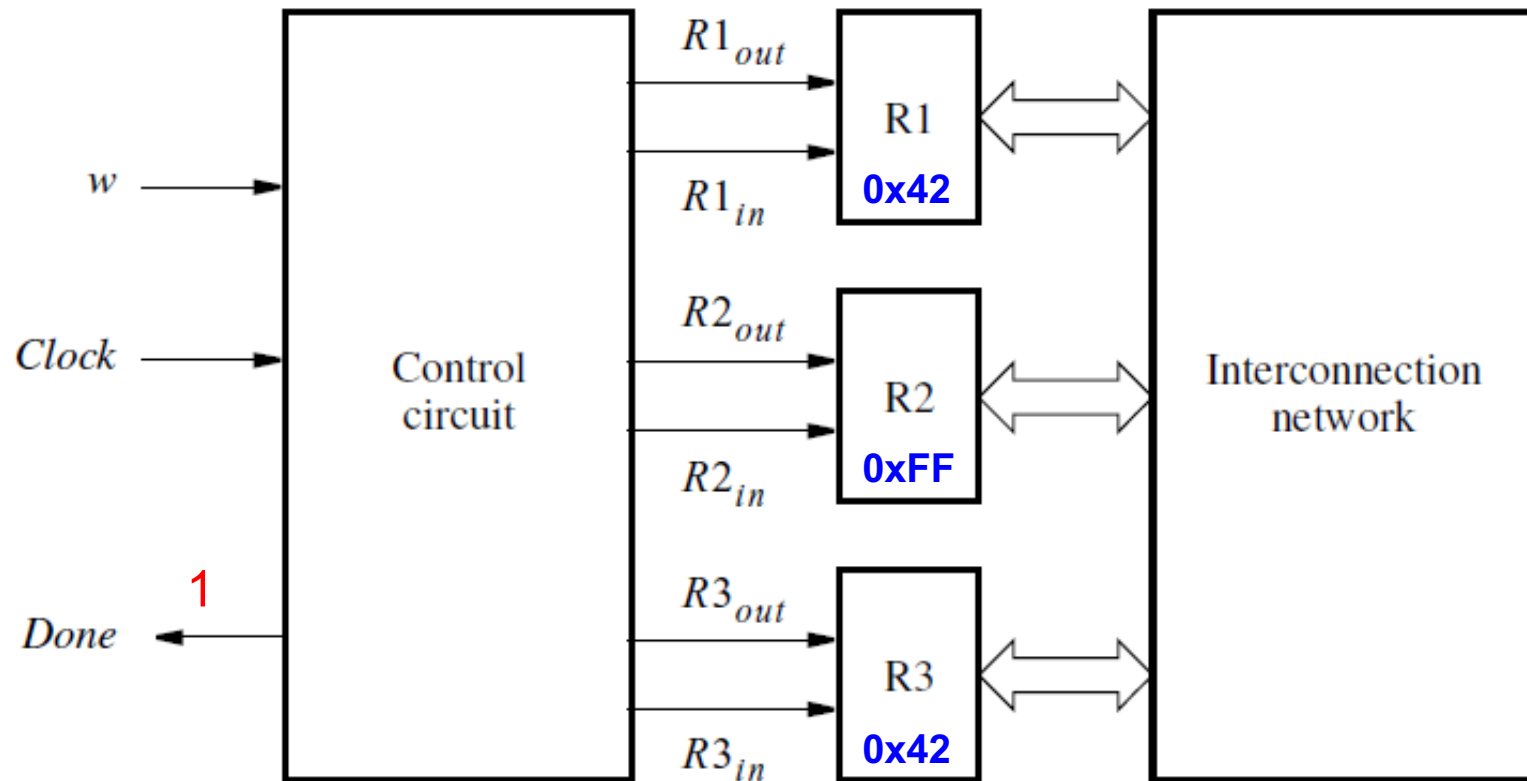
# Animated Register Swap



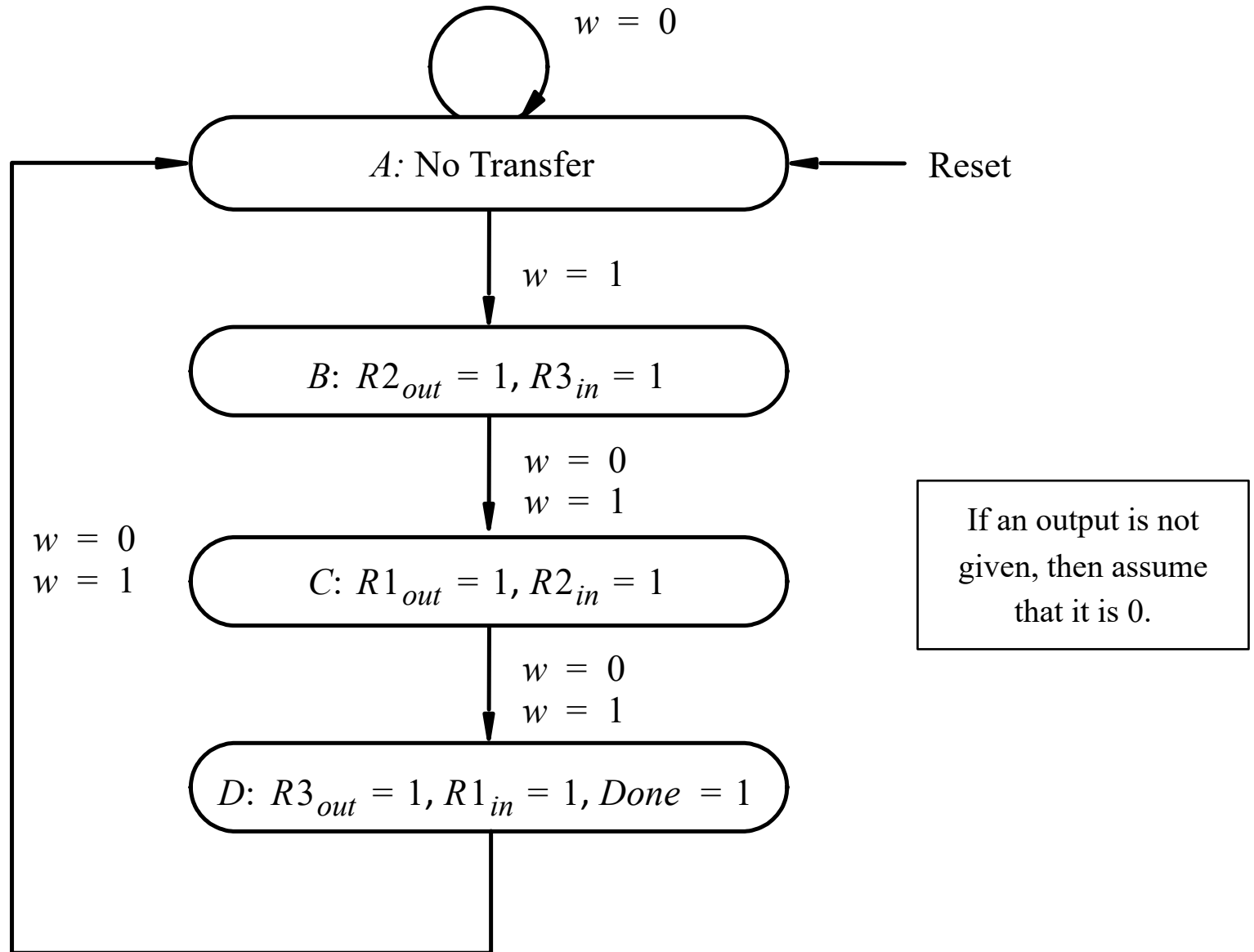
# Animated Register Swap



# Animated Register Swap



# State Diagram

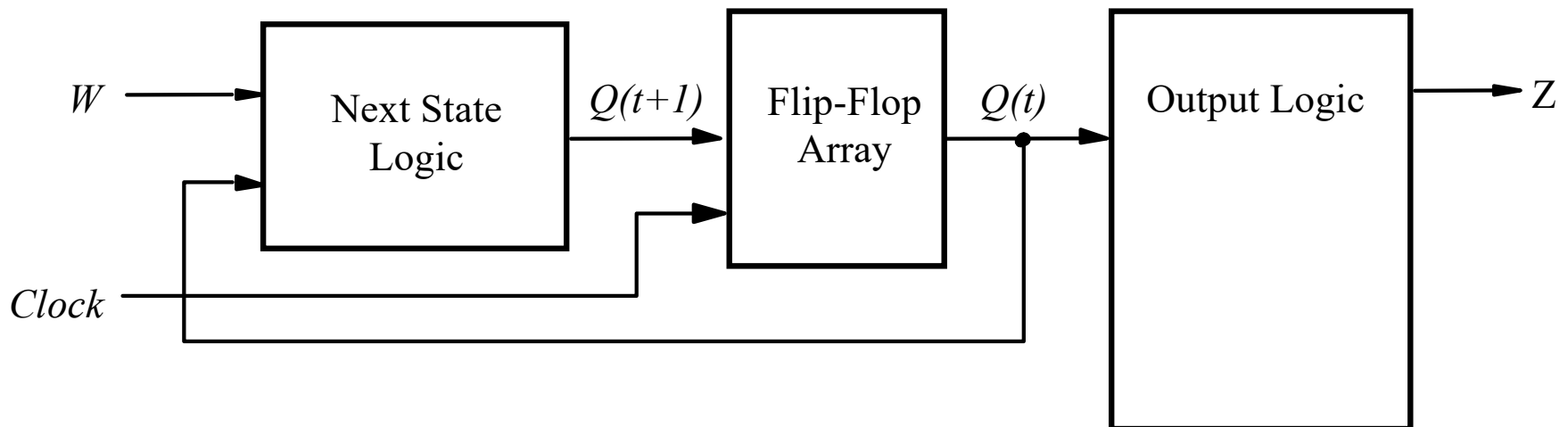
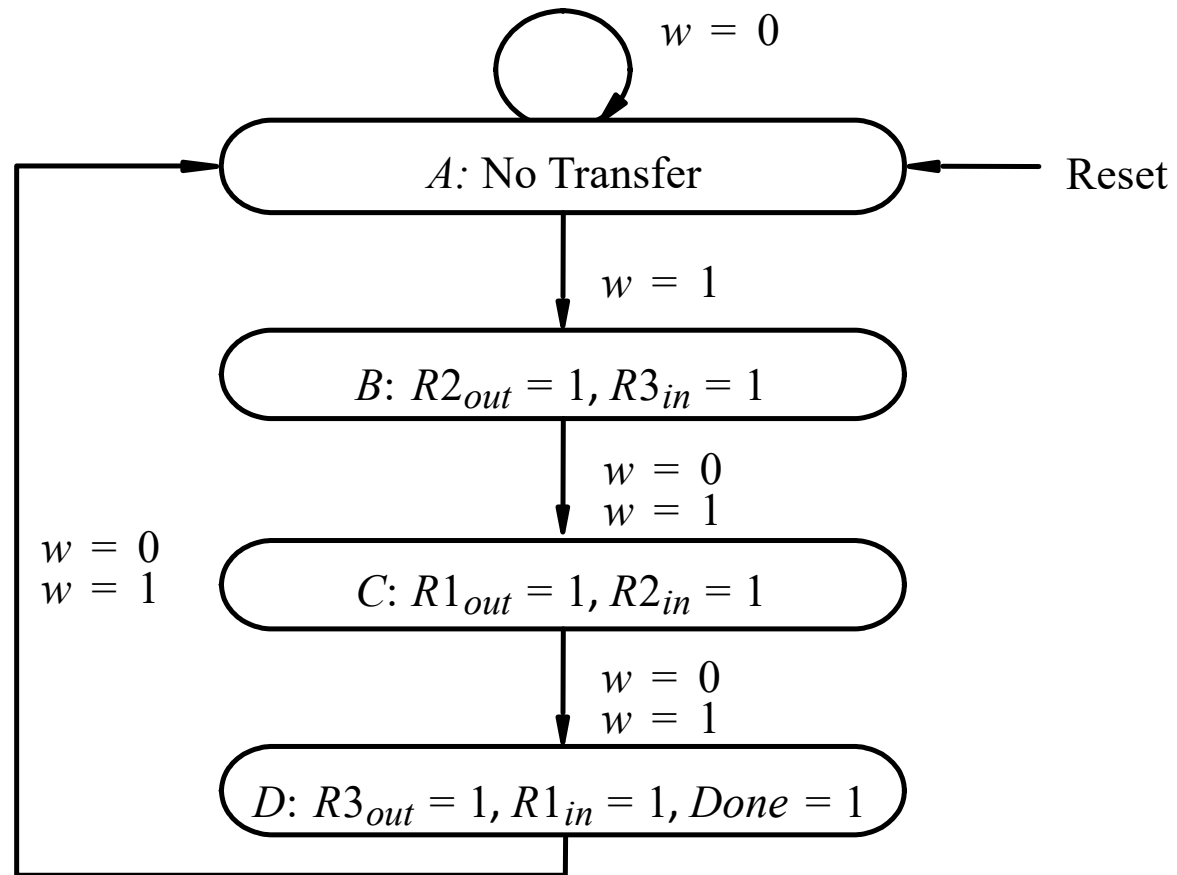


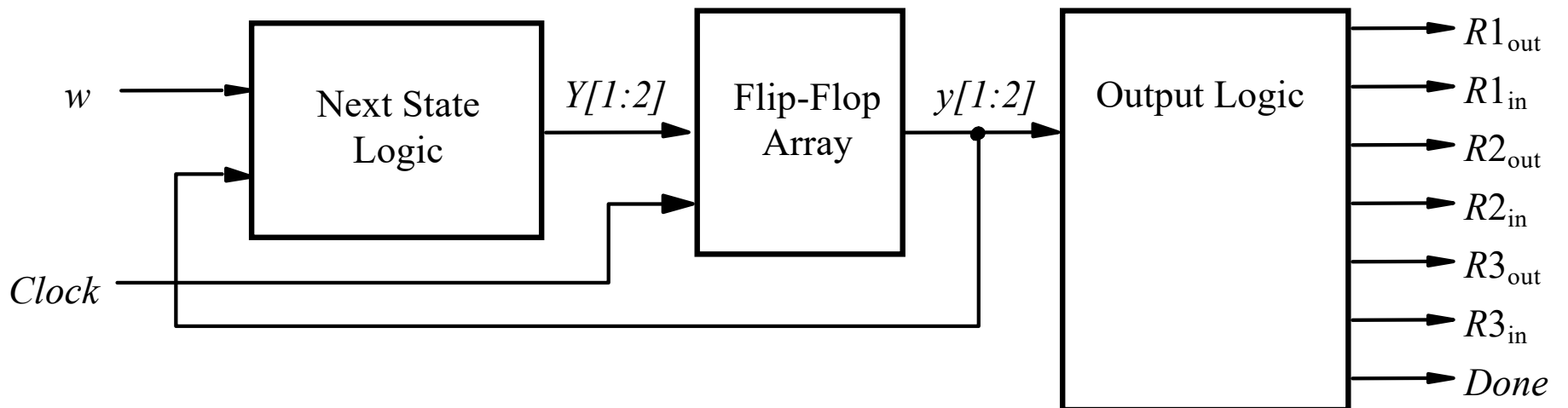
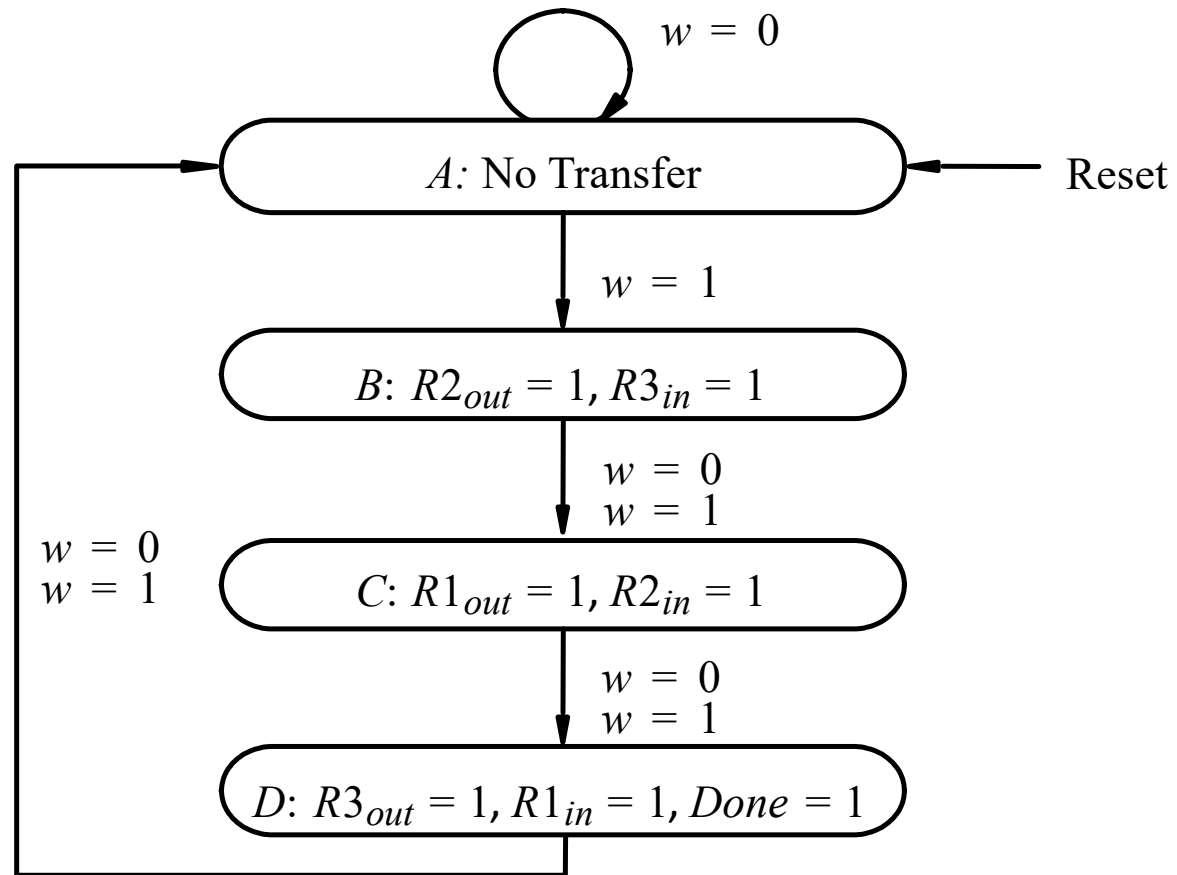
[ Figure 6.11 from the textbook ]



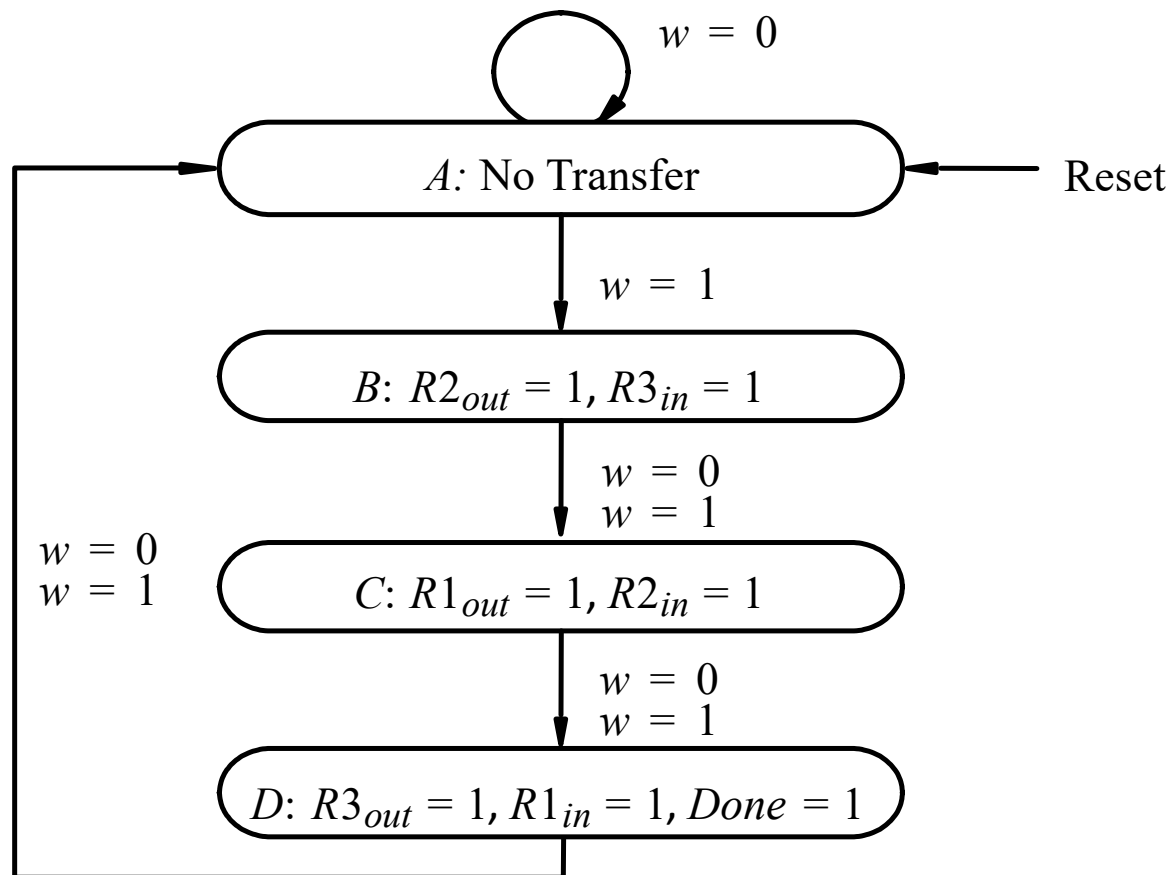
# Some Questions

- **How many flip-flops are we going to use?**
- **How many logic expressions do we need to find?**









Present state	Next state		Outputs						
	$w = 0$	$w = 1$	$R1_{out}$	$R1_{in}$	$R2_{out}$	$R2_{in}$	$R3_{out}$	$R3_{in}$	<i>Done</i>
A	A	B	0	0	0	0	0	0	0
B	C	C	0	0	1	0	0	1	0
C	D	D	1	0	0	1	0	0	0
D	A	A	0	1	0	0	1	0	1

**As we saw before, we can expect that some state encodings will be better than others.**

**We will consider three encoding schemes.**

**Encoding #1:**  
**A=00, B=01, C=10, D=11**

**(Uses Two Flip-Flops)**

## State Table

Present state	Next state		Outputs						
	$w = 0$	$w = 1$	R1 <sub>out</sub>	R1 <sub>in</sub>	R2 <sub>out</sub>	R2 <sub>in</sub>	R3 <sub>out</sub>	R3 <sub>in</sub>	<i>Done</i>
A	A	B	0	0	0	0	0	0	0
B	C	C	0	0	1	0	0	1	0
C	D	D	1	0	0	1	0	0	0
D	A	A	0	1	0	0	1	0	1

## State-Assigned Table

Present state	Next state		Outputs						
	$w = 0$	$w = 1$							
	$y_2y_1$	$Y_2Y_1$	$Y_2Y_1$	R1 <sub>out</sub>	R1 <sub>in</sub>	R2 <sub>out</sub>	R2 <sub>in</sub>	R3 <sub>out</sub>	R3 <sub>in</sub>
A									
B									
C									
D									



## State Table

Present state	Next state		Outputs						
	$w = 0$	$w = 1$	R1 <sub>out</sub>	R1 <sub>in</sub>	R2 <sub>out</sub>	R2 <sub>in</sub>	R3 <sub>out</sub>	R3 <sub>in</sub>	<i>Done</i>
A	A	B	0	0	0	0	0	0	0
B	C	C	0	0	1	0	0	1	0
C	D	D	1	0	0	1	0	0	0
D	A	A	0	1	0	0	1	0	1

## State Assigned Table

	Present state	Next state		Outputs						
		$w = 0$	$w = 1$							
	$y_2y_1$	$Y_2Y_1$	$Y_2Y_1$	R1 <sub>out</sub>	R1 <sub>in</sub>	R2 <sub>out</sub>	R2 <sub>in</sub>	R3 <sub>out</sub>	R3 <sub>in</sub>	<i>Done</i>
A	00									
B	01									
C	10									
D	11									

## State Table

Present state	Next state		Outputs						
	$w = 0$	$w = 1$	R1 <sub>out</sub>	R1 <sub>in</sub>	R2 <sub>out</sub>	R2 <sub>in</sub>	R3 <sub>out</sub>	R3 <sub>in</sub>	<i>Done</i>
A	A	B	0	0	0	0	0	0	0
B	C	C	0	0	1	0	0	1	0
C	D	D	1	0	0	1	0	0	0
D	A	A	0	1	0	0	1	0	1

## State Assigned Table

	Present state	Next state		Outputs						
		$w = 0$	$w = 1$							
	$y_2y_1$	$Y_2Y_1$	$Y_2Y_1$	R1 <sub>out</sub>	R1 <sub>in</sub>	R2 <sub>out</sub>	R2 <sub>in</sub>	R3 <sub>out</sub>	R3 <sub>in</sub>	<i>Done</i>
A	00	00	01							
B	01	10	10							
C	10	11	11							
D	11	00	00							

## State Table

Present state	Next state		Outputs						
	$w = 0$	$w = 1$	R1 <sub>out</sub>	R1 <sub>in</sub>	R2 <sub>out</sub>	R2 <sub>in</sub>	R3 <sub>out</sub>	R3 <sub>in</sub>	<i>Done</i>
A	A	B	0	0	0	0	0	0	0
B	C	C	0	0	1	0	0	1	0
C	D	D	1	0	0	1	0	0	0
D	A	A	0	1	0	0	1	0	1

## State Assigned Table

	Present state	Next state		Outputs						
		$w = 0$	$w = 1$	R1 <sub>out</sub>	R1 <sub>in</sub>	R2 <sub>out</sub>	R2 <sub>in</sub>	R3 <sub>out</sub>	R3 <sub>in</sub>	<i>Done</i>
	$Y_2Y_1$	$Y_2Y_1$								
A	00	00	0 1	0	0	0	0	0	0	0
B	01	10	1 0	0	0	1	0	0	1	0
C	10	11	1 1	1	0	0	1	0	0	0
D	11	00	0 0	0	1	0	0	1	0	1

	Present state	Next state		Outputs						
		$w = 0$	$w = 1$							
	$y_2y_1$	$Y_2Y_1$	$Y_2Y_1$	$R1_{out}$	$R1_{in}$	$R2_{out}$	$R2_{in}$	$R3_{out}$	$R3_{in}$	<i>Done</i>
A	00	00	0 1	0	0	0	0	0	0	0
B	01	10	1 0	0	0	1	0	0	1	0
C	10	11	1 1	1	0	0	1	0	0	0
D	11	00	0 0	0	1	0	0	1	0	1

$y_2$	$y_1$	$w$	$Y_2$	$Y_1$
0	0	0		
0	0	1		
0	1	0		
0	1	1		
1	0	0		
1	0	1		
1	1	0		
1	1	1		

Let's derive the next-state expressions.

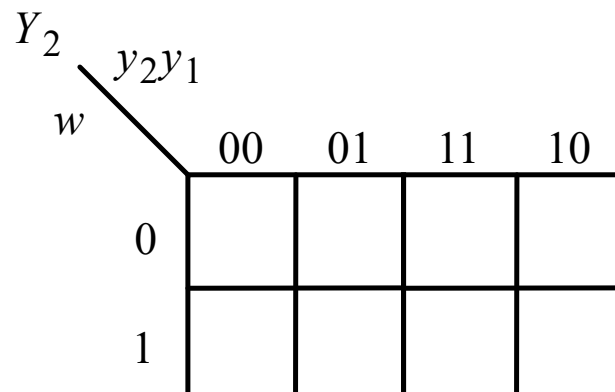
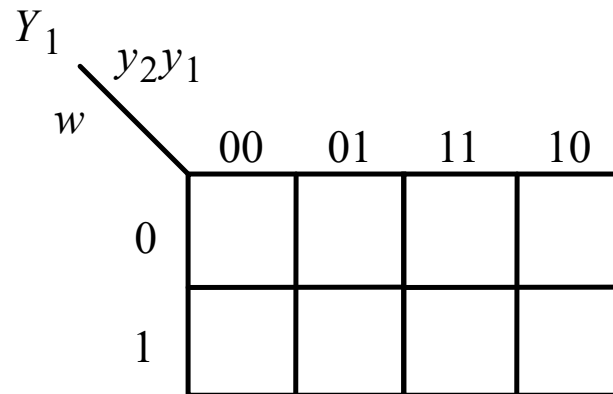
	Present state	Next state		Outputs						
		$w = 0$	$w = 1$							
	$y_2y_1$	$Y_2Y_1$	$Y_2Y_1$	$R1_{out}$	$R1_{in}$	$R2_{out}$	$R2_{in}$	$R3_{out}$	$R3_{in}$	<i>Done</i>
A	00	00	0 1	0	0	0	0	0	0	0
B	01	10	1 0	0	0	1	0	0	1	0
C	10	11	1 1	1	0	0	1	0	0	0
D	11	00	0 0	0	1	0	0	1	0	1

$y_2$	$y_1$	$w$	$Y_2$	$Y_1$
0	0	0	0	0
0	0	1	0	1
0	1	0	1	0
0	1	1	1	0
1	0	0	1	1
1	0	1	1	1
1	1	0	0	0
1	1	1	0	0

Pay attention to the way the columns of the truth table are labeled.

	Present state	Next state		Outputs						
		$w = 0$	$w = 1$							
	$y_2y_1$	$Y_2Y_1$	$Y_2Y_1$	$R1_{out}$	$R1_{in}$	$R2_{out}$	$R2_{in}$	$R3_{out}$	$R3_{in}$	<i>Done</i>
A	00	00	0 1	0	0	0	0	0	0	0
B	01	10	1 0	0	0	1	0	0	1	0
C	10	11	1 1	1	0	0	1	0	0	0
D	11	00	0 0	0	1	0	0	1	0	1

$y_2$	$y_1$	$w$	$Y_2$	$Y_1$
0	0	0	0	0
0	0	1	0	1
0	1	0	1	0
0	1	1	1	0
1	0	0	1	1
1	0	1	1	1
1	1	0	0	0
1	1	1	0	0



	Present state	Next state		Outputs						
		$w = 0$	$w = 1$							
	$y_2y_1$	$Y_2Y_1$	$Y_2Y_1$	$R1_{out}$	$R1_{in}$	$R2_{out}$	$R2_{in}$	$R3_{out}$	$R3_{in}$	<i>Done</i>
A	00	00	0 1	0	0	0	0	0	0	0
B	01	10	1 0	0	0	1	0	0	1	0
C	10	11	1 1	1	0	0	1	0	0	0
D	11	00	0 0	0	1	0	0	1	0	1

$y_2$	$y_1$	$w$	$Y_2$	$Y_1$
0	0	0	0	0
0	0	1	0	1
0	1	0	1	0
0	1	1	1	0
1	0	0	1	1
1	0	1	1	1
1	1	0	0	0
1	1	1	0	0

$Y_1$

$w$	$y_2y_1$	00	01	11	10
0		0	0	0	1
1		1	0	0	1

$Y_2$

$w$	$y_2y_1$	00	01	11	10
0		0	1	0	1
1		0	1	0	1

	Present state	Next state		Outputs						
		$w = 0$	$w = 1$							
	$y_2y_1$	$Y_2Y_1$	$Y_2Y_1$	$R1_{out}$	$R1_{in}$	$R2_{out}$	$R2_{in}$	$R3_{out}$	$R3_{in}$	<i>Done</i>
A	00	00	0 1	0	0	0	0	0	0	0
B	01	10	1 0	0	0	1	0	0	1	0
C	10	11	1 1	1	0	0	1	0	0	0
D	11	00	0 0	0	1	0	0	1	0	1

$y_2$	$y_1$	$w$	$Y_2$	$Y_1$
0	0	0	0	0
0	0	1	0	1
0	1	0	1	0
0	1	1	1	0
1	0	0	1	1
1	0	1	1	1
1	1	0	0	0
1	1	1	0	0

$Y_1$

$w$

$y_2y_1$	00	01	11	10
0	0	0	0	1
1	1	0	0	1

Detailed description: This is a Karnaugh map for the output Y1. The vertical axis is labeled 'w' with values 0 and 1. The horizontal axis is labeled 'y2y1' with values 00, 01, 11, and 10. The map contains 1s at (w=0, y2y1=10) and (w=1, y2y1=00), and 1s at (w=1, y2y1=10) and (w=1, y2y1=10). There are blue groupings: a horizontal group of two 1s at w=1, and a vertical group of two 1s at y2y1=10. There are red groupings: a vertical group of two 1s at y2y1=10, and a horizontal group of two 1s at w=1.

$Y_2$

$w$

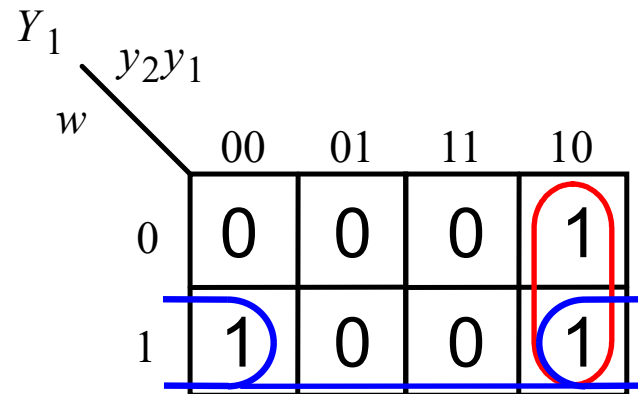
$y_2y_1$	00	01	11	10
0	0	1	0	1
1	0	1	0	1

Detailed description: This is a Karnaugh map for the output Y2. The vertical axis is labeled 'w' with values 0 and 1. The horizontal axis is labeled 'y2y1' with values 00, 01, 11, and 10. The map contains 1s at (w=0, y2y1=01), (w=0, y2y1=10), (w=1, y2y1=01), and (w=1, y2y1=10). There are red groupings: a vertical group of two 1s at y2y1=01, a vertical group of two 1s at y2y1=10, and a horizontal group of two 1s at w=1.

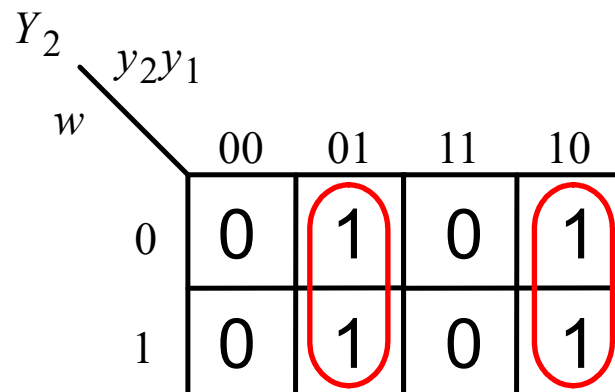


	Present state	Next state		Outputs						
		$w = 0$	$w = 1$							
	$y_2y_1$	$Y_2Y_1$	$Y_2Y_1$	$R1_{out}$	$R1_{in}$	$R2_{out}$	$R2_{in}$	$R3_{out}$	$R3_{in}$	<i>Done</i>
A	00	00	01	0	0	0	0	0	0	0
B	01	10	10	0	0	1	0	0	1	0
C	10	11	11	1	0	0	1	0	0	0
D	11	00	00	0	1	0	0	1	0	1

$y_2$	$y_1$	$w$	$Y_2$	$Y_1$
0	0	0	0	0
0	0	1	0	1
0	1	0	1	0
0	1	1	1	0
1	0	0	1	1
1	0	1	1	1
1	1	0	0	0
1	1	1	0	0



$$Y_1 = w \bar{y}_1 + \bar{y}_1 y_2$$



$$Y_2 = y_1 \bar{y}_2 + \bar{y}_1 y_2$$

	Present state	Next state		Outputs						
		$w = 0$	$w = 1$							
	$y_2y_1$	$Y_2Y_1$	$Y_2Y_1$	$R1_{out}$	$R1_{in}$	$R2_{out}$	$R2_{in}$	$R3_{out}$	$R3_{in}$	<i>Done</i>
A	00	00	0 1	0	0	0	0	0	0	0
B	01	10	1 0	0	0	1	0	0	1	0
C	10	11	1 1	1	0	0	1	0	0	0
D	11	00	0 0	0	1	0	0	1	0	1

$y_2$	$y_1$	$R1_{out}$	$R1_{in}$	$R2_{out}$
0	0			
0	1			
1	0			
1	1			

Let's derive the output expressions

	Present state	Next state		Outputs						
		$w = 0$	$w = 1$							
	$y_2y_1$	$Y_2Y_1$	$Y_2Y_1$	$R1_{out}$	$R1_{in}$	$R2_{out}$	$R2_{in}$	$R3_{out}$	$R3_{in}$	<i>Done</i>
A	00	00	0 1	0	0	0	0	0	0	0
B	01	10	1 0	0	0	1	0	0	1	0
C	10	11	1 1	1	0	0	1	0	0	0
D	11	00	0 0	0	1	0	0	1	0	1

$y_2$	$y_1$	$R1_{out}$	$R1_{in}$	$R2_{out}$
0	0			
0	1			
1	0			
1	1			

Let's derive the output expressions.

We need to derive only these 3 unique ones.

	Present state	Next state		Outputs						
		$w = 0$	$w = 1$							
	$y_2y_1$	$Y_2Y_1$	$Y_2Y_1$	$R1_{out}$	$R1_{in}$	$R2_{out}$	$R2_{in}$	$R3_{out}$	$R3_{in}$	<i>Done</i>
A	00	00	0 1	0	0	0	0	0	0	0
B	01	10	1 0	0	0	1	0	0	1	0
C	10	11	1 1	1	0	0	1	0	0	0
D	11	00	0 0	0	1	0	0	1	0	1

$y_2$	$y_1$	$R1_{out}$	$R1_{in}$	$R2_{out}$
0	0	0	0	0
0	1	0	0	1
1	0	1	0	0
1	1	0	1	0

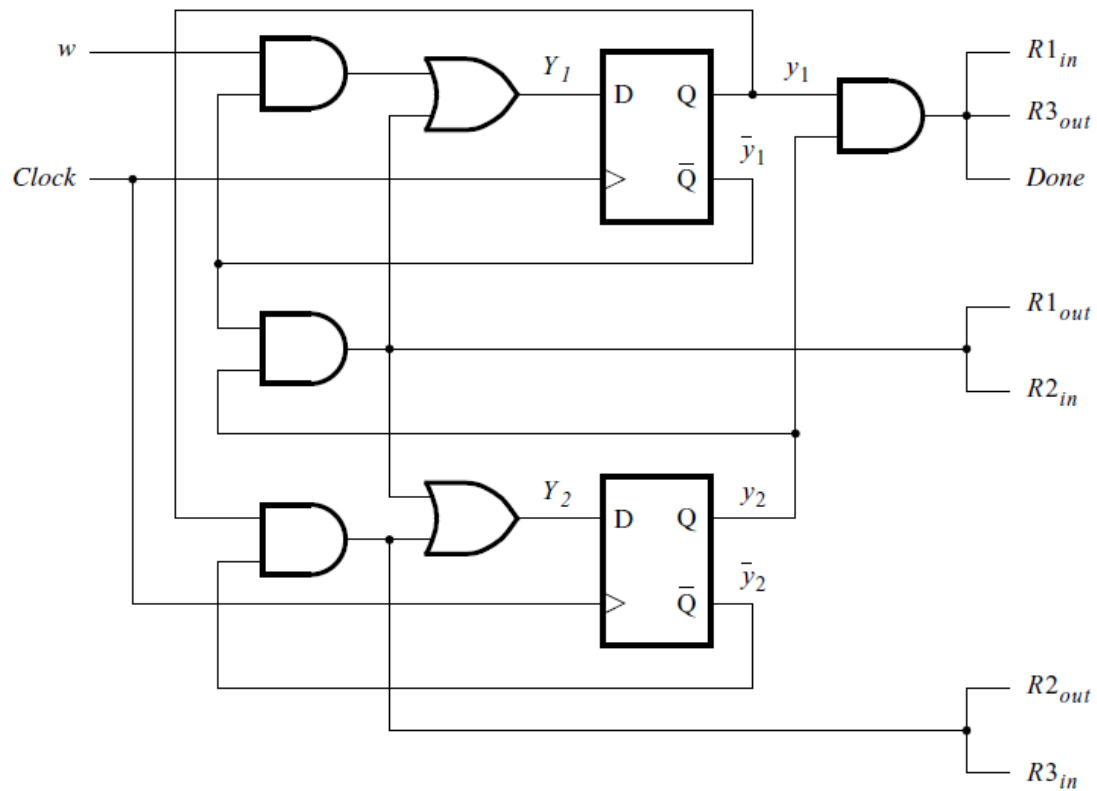
	Present state	Next state		Outputs						
		$w = 0$	$w = 1$							
	$y_2 y_1$	$Y_2 Y_1$	$Y_2 Y_1$	$R1_{out}$	$R1_{in}$	$R2_{out}$	$R2_{in}$	$R3_{out}$	$R3_{in}$	<i>Done</i>
A	00	00	0 1	0	0	0	0	0	0	0
B	01	10	1 0	0	0	1	0	0	1	0
C	10	11	1 1	1	0	0	1	0	0	0
D	11	00	0 0	0	1	0	0	1	0	1

$y_2$	$y_1$	$R1_{out}$	$R1_{in}$	$R2_{out}$
0	0	0	0	0
0	1	0	0	1
1	0	1	0	0
1	1	0	1	0

$$R1_{out} = R2_{in} = \overline{y_1} y_2$$

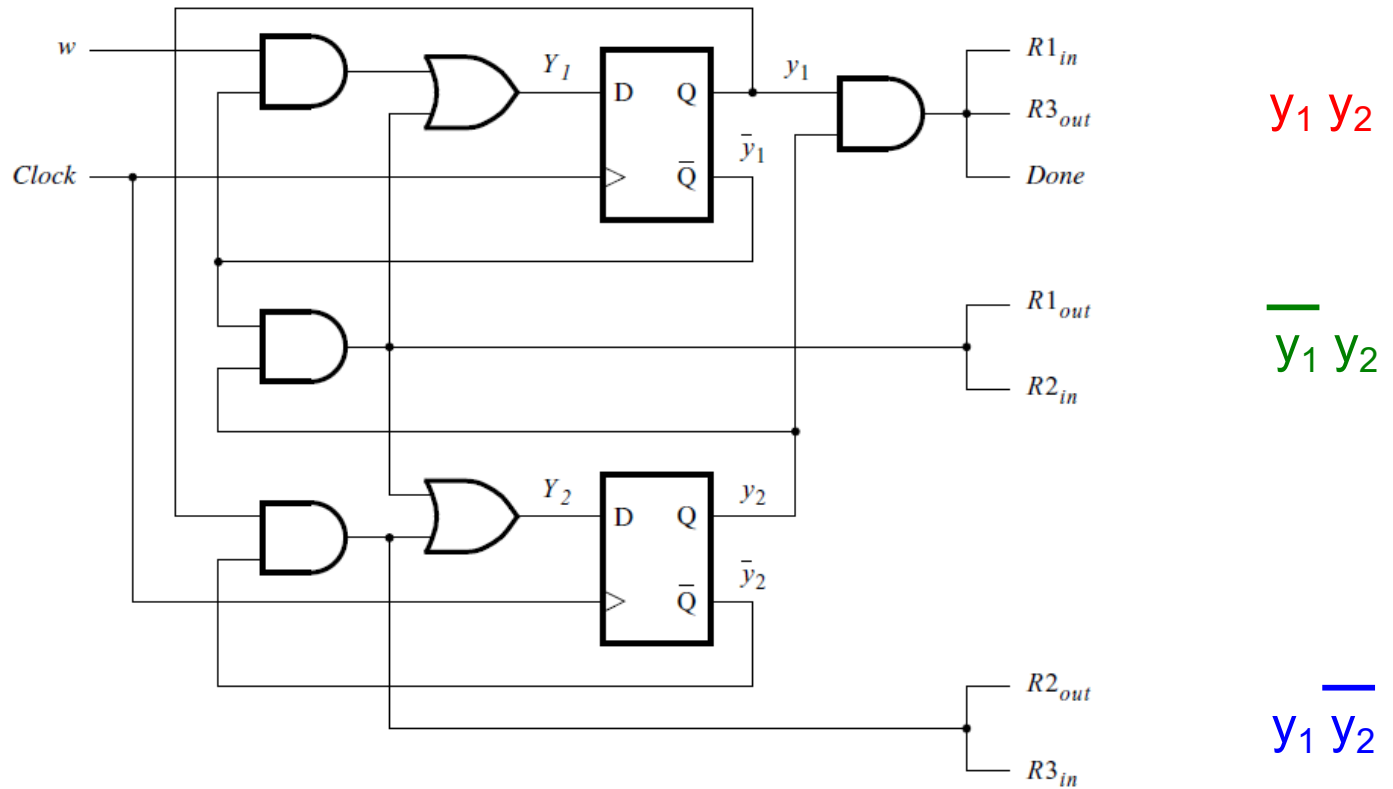
$$R1_{in} = R3_{out} = Done = y_1 y_2$$

$$R2_{out} = R3_{in} = y_1 \overline{y_2}$$



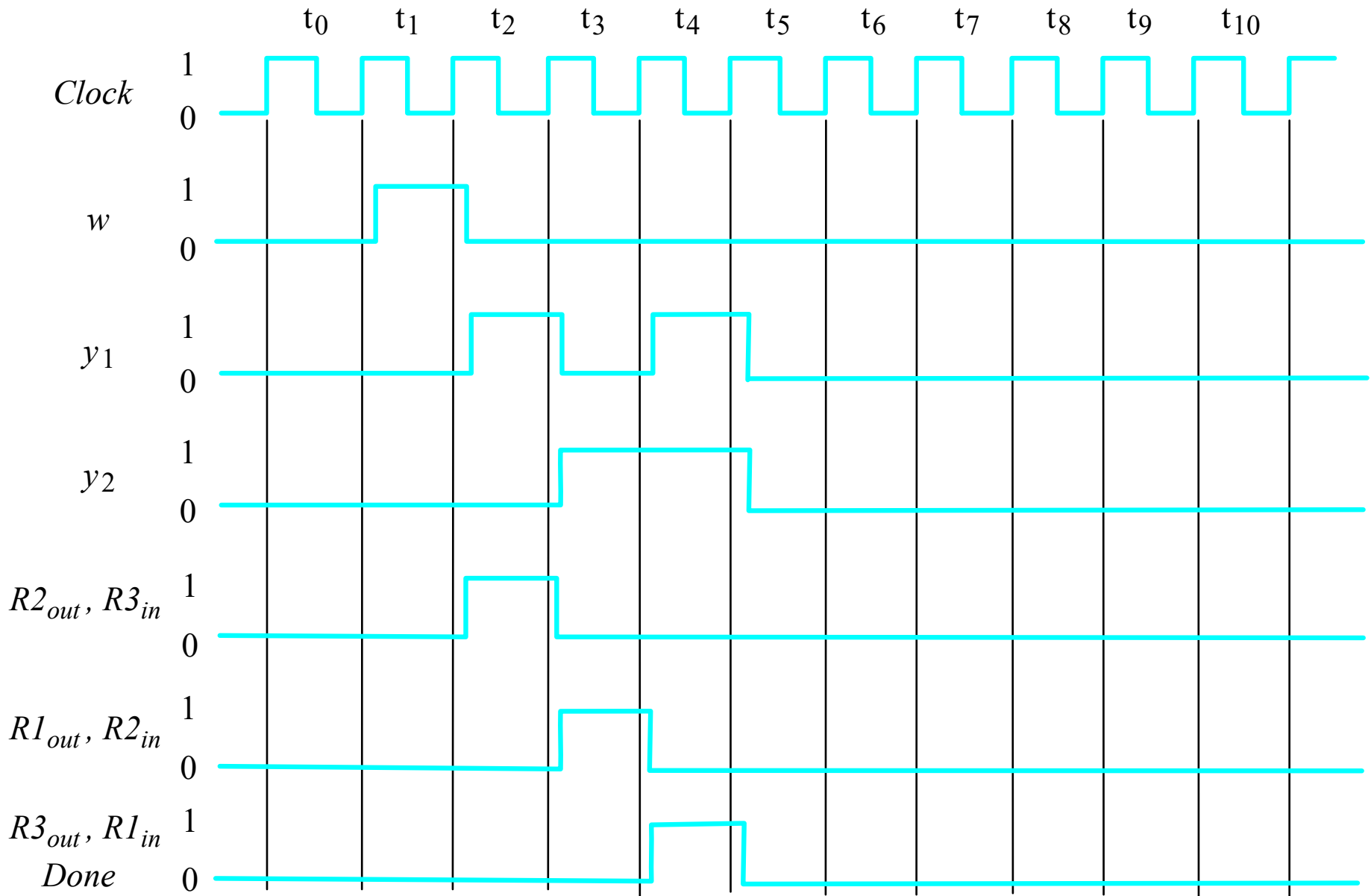
	Present state	Next state		Outputs						
		$w = 0$	$w = 1$							
	$y_2y_1$	$Y_2Y_1$	$Y_2Y_1$	$R1_{out}$	$R1_{in}$	$R2_{out}$	$R2_{in}$	$R3_{out}$	$R3_{in}$	$Done$
A	00	00	0 1	0	0	0	0	0	0	0
B	01	10	1 0	0	0	1	0	0	1	0
C	10	11	1 1	1	0	0	1	0	0	0
D	11	00	0 0	0	1	0	0	1	0	1

$$Y_1 = w\bar{y}_1 + \bar{y}_1y_2$$

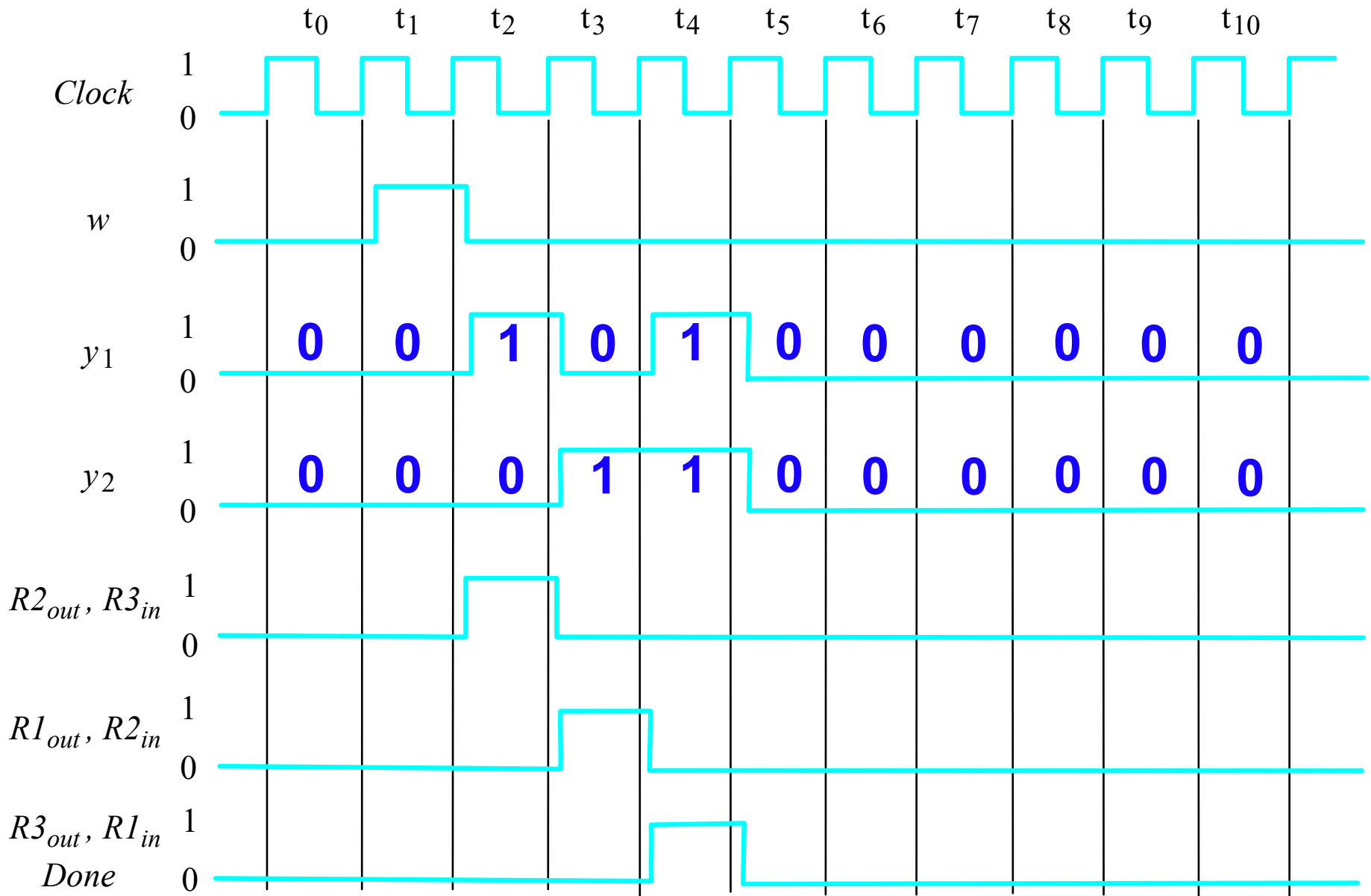


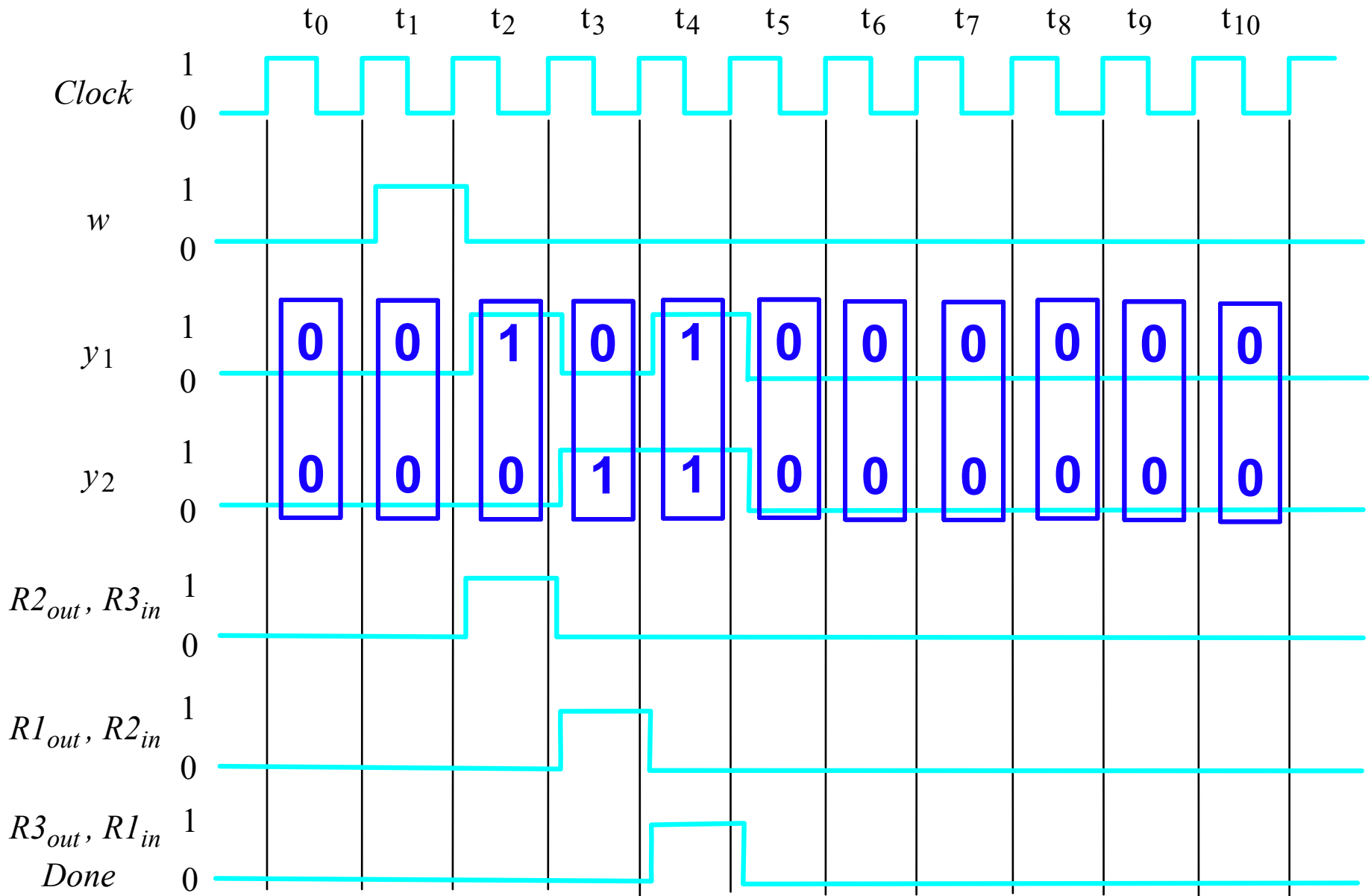
$$Y_2 = y_1\bar{y}_2 + \bar{y}_1y_2$$

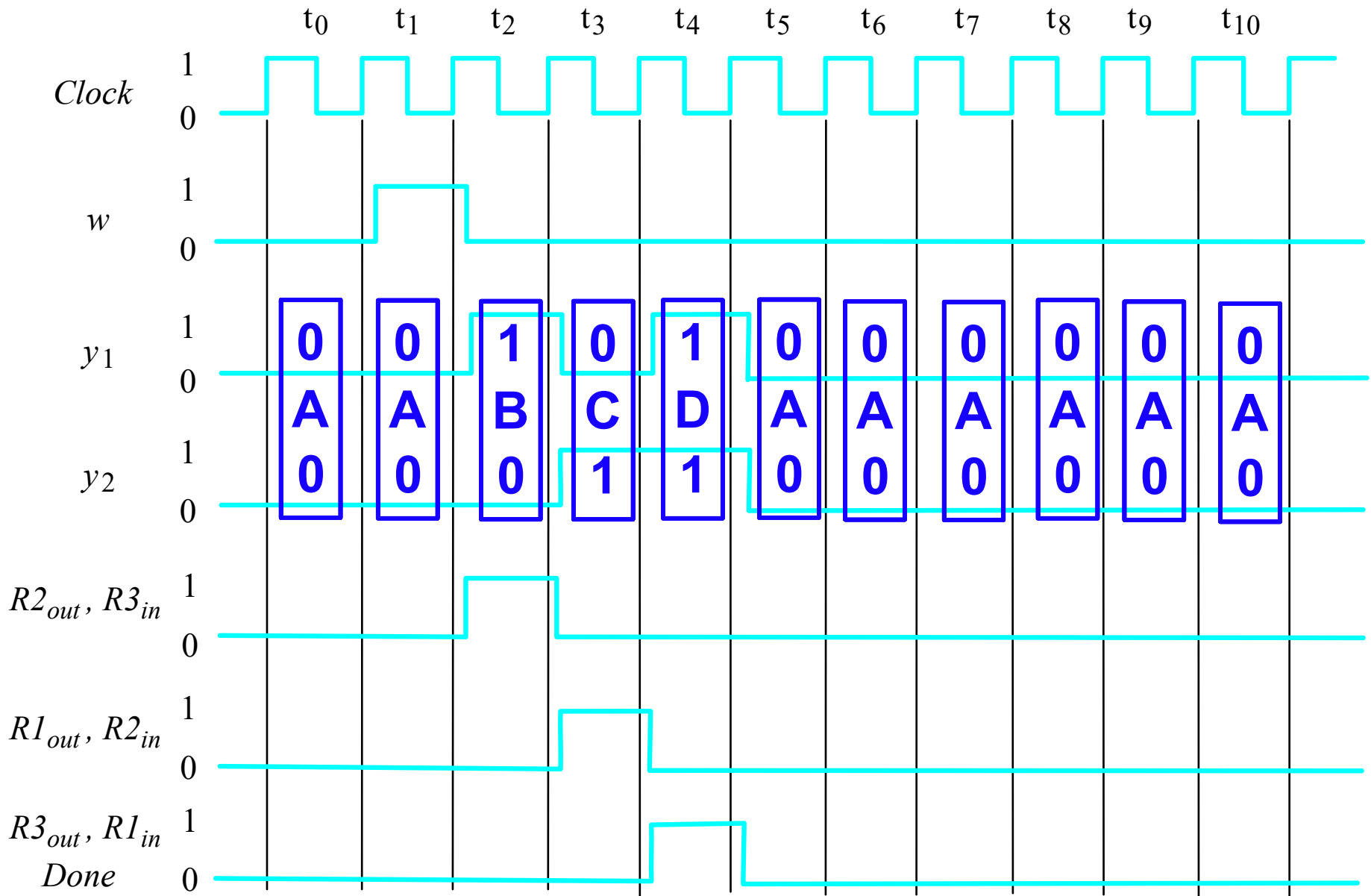
	Present state	Next state		Outputs						
		$w = 0$	$w = 1$							
	$y_2y_1$	$Y_2Y_1$	$Y_2Y_1$	$R1_{out}$	$R1_{in}$	$R2_{out}$	$R2_{in}$	$R3_{out}$	$R3_{in}$	<i>Done</i>
A	00	00	0 1	0	0	0	0	0	0	0
B	01	10	1 0	0	0	1	0	0	1	0
C	10	11	1 1	1	0	0	1	0	0	0
D	11	00	0 0	0	1	0	0	1	0	1

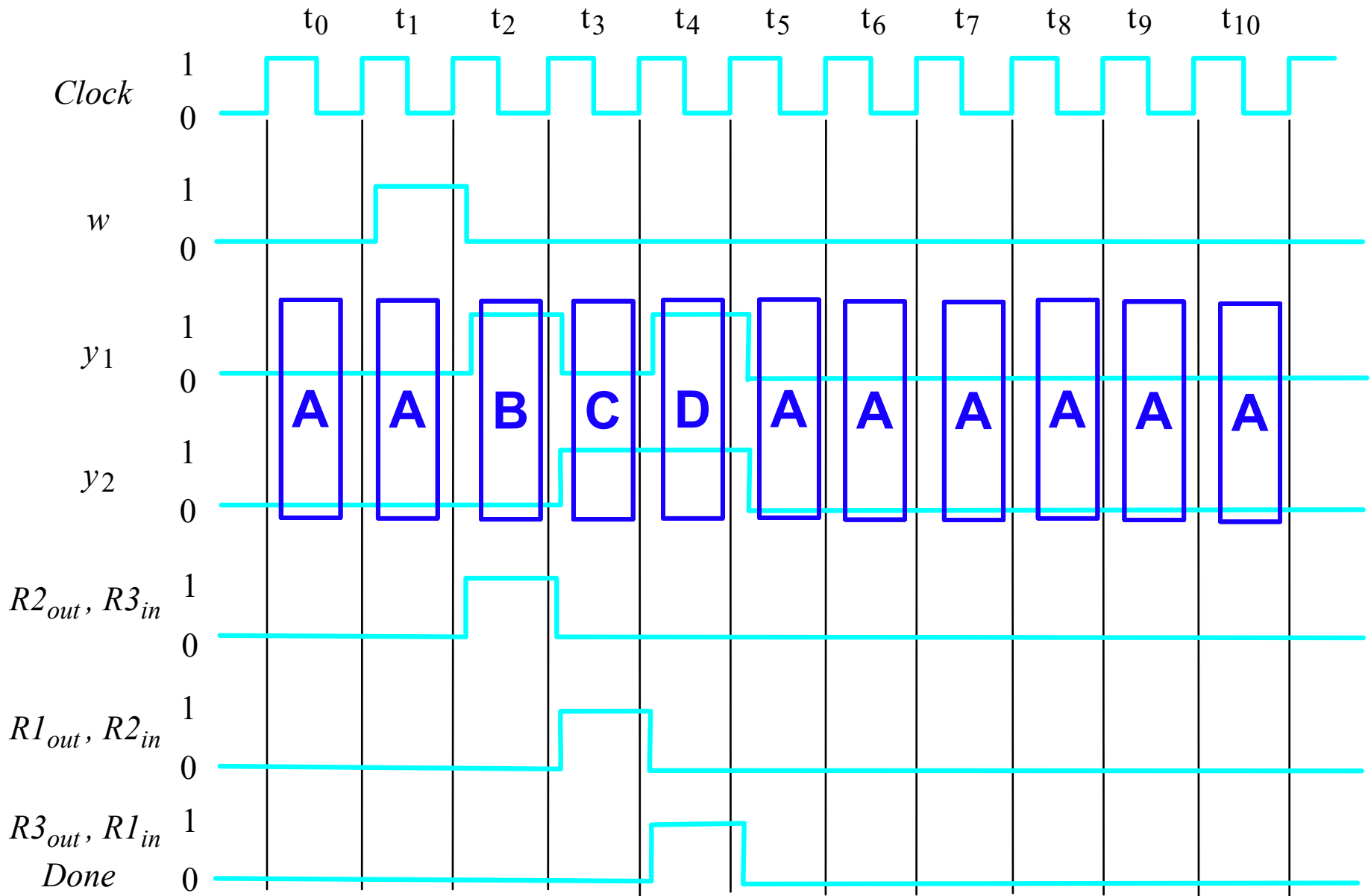


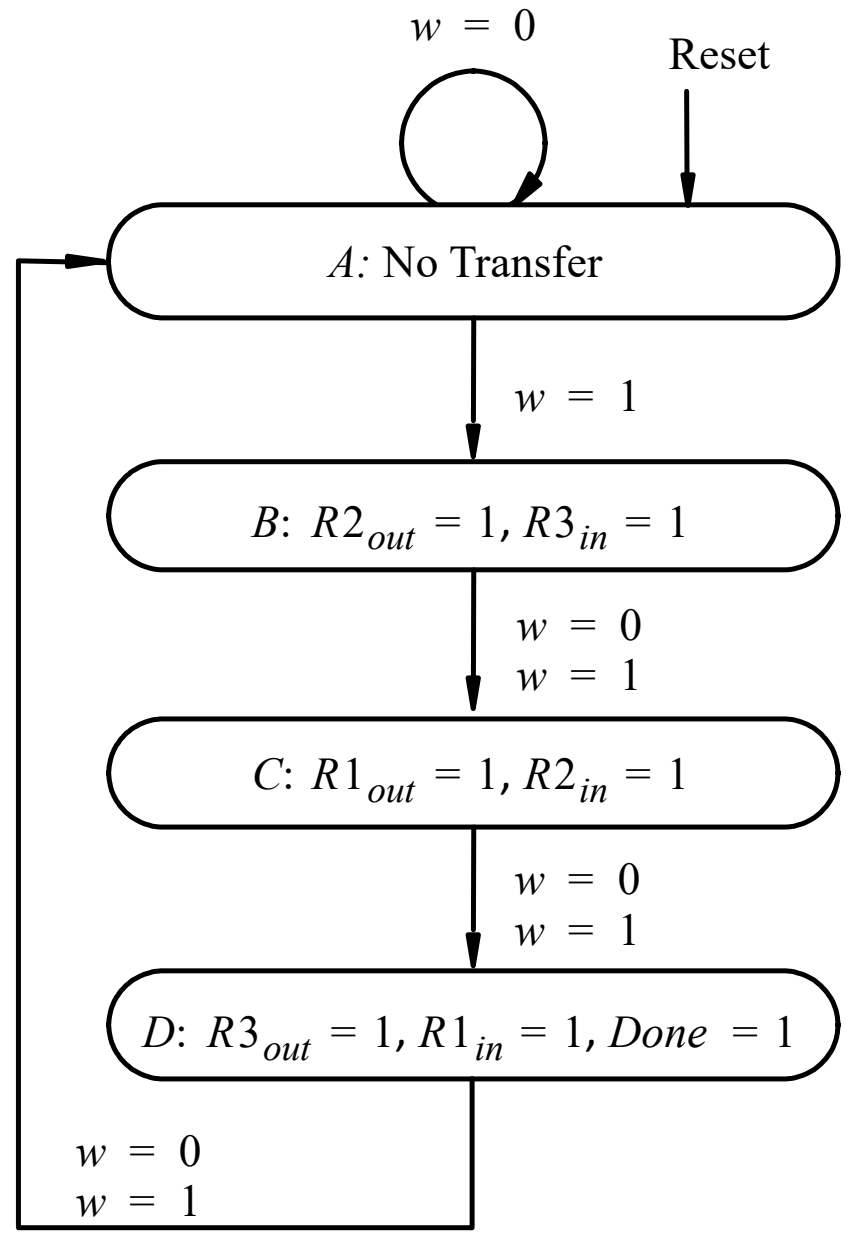
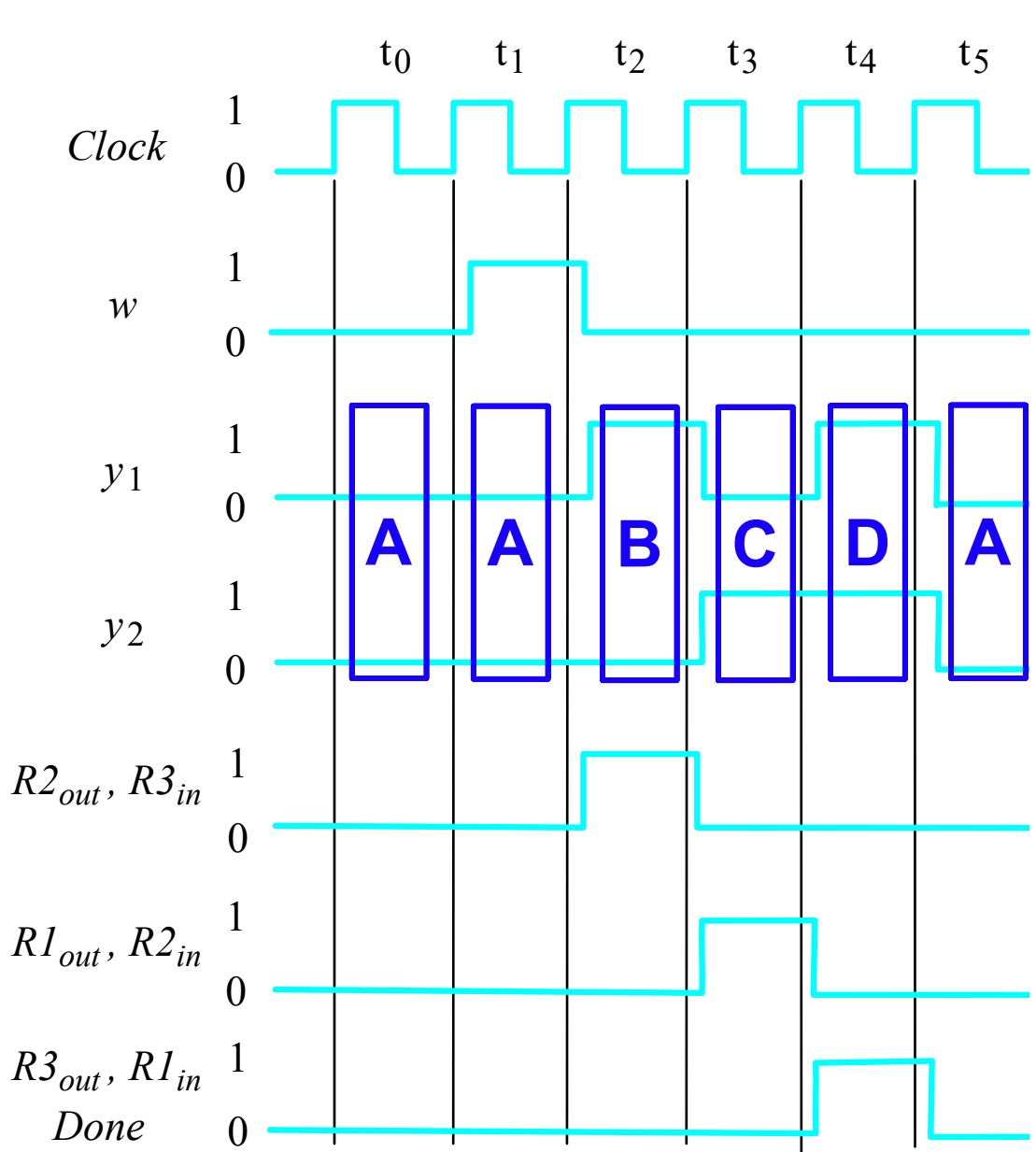


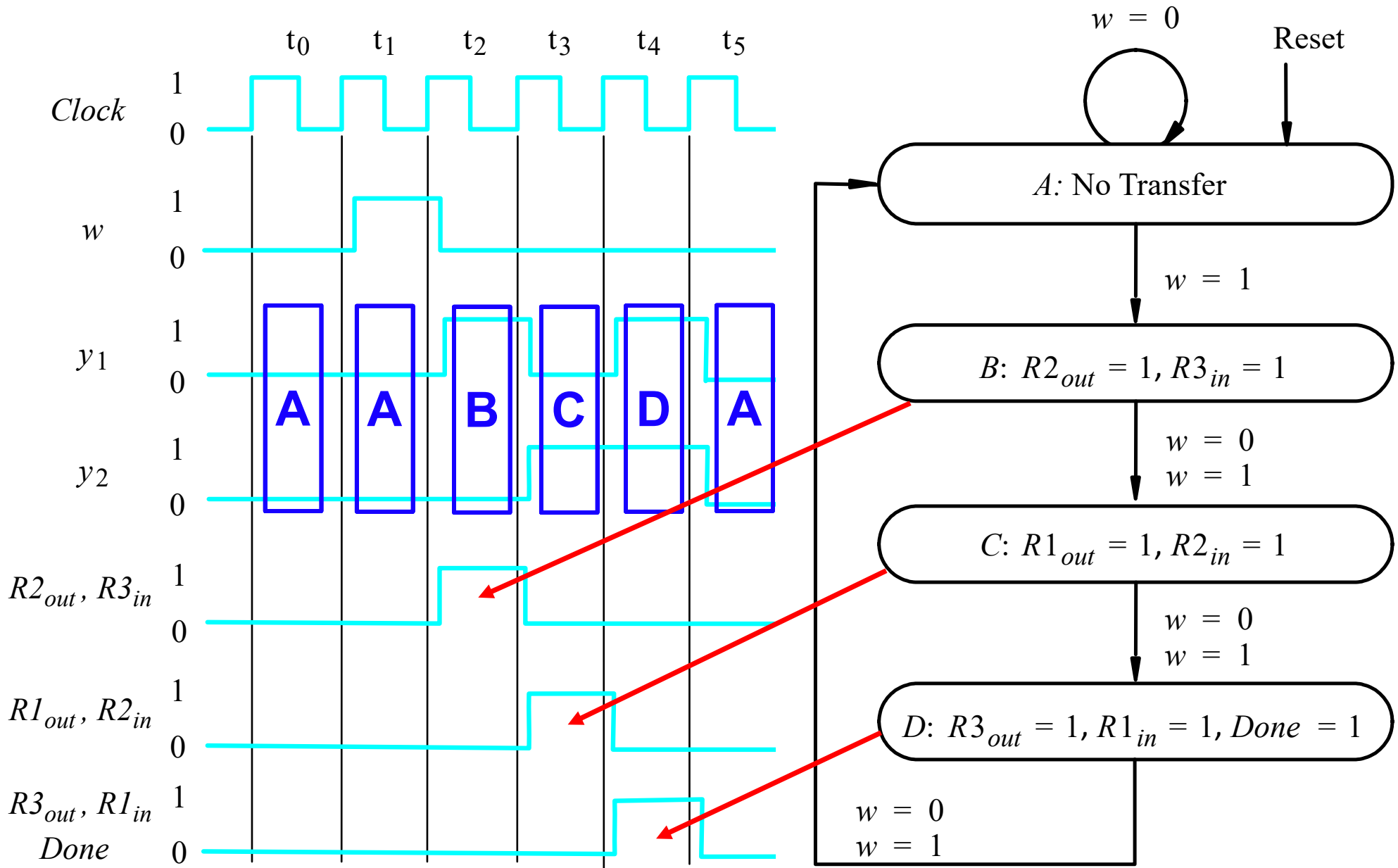












**Encoding #2:**  
**A=00, B=01, C=11, D=10**

**(Also Uses Two Flip-Flops)**

## State Table (same as before)

Present state	Next state		Outputs						
	$w = 0$	$w = 1$	R1 <sub>out</sub>	R1 <sub>in</sub>	R2 <sub>out</sub>	R2 <sub>in</sub>	R3 <sub>out</sub>	R3 <sub>in</sub>	<i>Done</i>
A	A	B	0	0	0	0	0	0	0
B	C	C	0	0	1	0	0	1	0
C	D	D	1	0	0	1	0	0	0
D	A	A	0	1	0	0	1	0	1

## State-Assigned Table

Present state $y_2y_1$	Next state		Outputs						
	$w = 0$	$w = 1$							
	$Y_2Y_1$	$Y_2Y_1$	R1 <sub>out</sub>	R1 <sub>in</sub>	R2 <sub>out</sub>	R2 <sub>in</sub>	R3 <sub>out</sub>	R3 <sub>in</sub>	<i>Done</i>
A									
B									
C									
D									



## State Table (same as before)

Present state	Next state		Outputs						
	$w = 0$	$w = 1$	R1 <sub>out</sub>	R1 <sub>in</sub>	R2 <sub>out</sub>	R2 <sub>in</sub>	R3 <sub>out</sub>	R3 <sub>in</sub>	<i>Done</i>
A	A	B	0	0	0	0	0	0	0
B	C	C	0	0	1	0	0	1	0
C	D	D	1	0	0	1	0	0	0
D	A	A	0	1	0	0	1	0	1

## State-Assigned Table

	Present state	Next state		Outputs						
		$w = 0$	$w = 1$							
	$y_2y_1$	$Y_2Y_1$	$Y_2Y_1$	R1 <sub>out</sub>	R1 <sub>in</sub>	R2 <sub>out</sub>	R2 <sub>in</sub>	R3 <sub>out</sub>	R3 <sub>in</sub>	<i>Done</i>
A	00									
B	01									
C	11									
D	10									

## State Table (same as before)

Present state	Next state		Outputs						
	$w = 0$	$w = 1$	R1 <sub>out</sub>	R1 <sub>in</sub>	R2 <sub>out</sub>	R2 <sub>in</sub>	R3 <sub>out</sub>	R3 <sub>in</sub>	<i>Done</i>
A	A	B	0	0	0	0	0	0	0
B	C	C	0	0	1	0	0	1	0
C	D	D	1	0	0	1	0	0	0
D	A	A	0	1	0	0	1	0	1

## State-Assigned Table

	Present state	Next state		Outputs						
		$w = 0$	$w = 1$							
	$y_2y_1$	$Y_2Y_1$	$Y_2Y_1$	R1 <sub>out</sub>	R1 <sub>in</sub>	R2 <sub>out</sub>	R2 <sub>in</sub>	R3 <sub>out</sub>	R3 <sub>in</sub>	<i>Done</i>
A	00	00	0 1							
B	01	11	1 1							
C	11	10	1 0							
D	10	00	0 0							

## State Table (same as before)

Present state	Next state		Outputs						
	$w = 0$	$w = 1$	R1 <sub>out</sub>	R1 <sub>in</sub>	R2 <sub>out</sub>	R2 <sub>in</sub>	R3 <sub>out</sub>	R3 <sub>in</sub>	<i>Done</i>
A	A	B	0	0	0	0	0	0	0
B	C	C	0	0	1	0	0	1	0
C	D	D	1	0	0	1	0	0	0
D	A	A	0	1	0	0	1	0	1

## State-Assigned Table

	Present state	Next state		Outputs						
		$w = 0$	$w = 1$							
	$y_2y_1$	$Y_2Y_1$	$Y_2Y_1$	R1 <sub>out</sub>	R1 <sub>in</sub>	R2 <sub>out</sub>	R2 <sub>in</sub>	R3 <sub>out</sub>	R3 <sub>in</sub>	<i>Done</i>
A	00	00	0 1	0	0	0	0	0	0	0
B	01	11	1 1	0	0	1	0	0	1	0
C	11	10	1 0	1	0	0	1	0	0	0
D	10	00	0 0	0	1	0	0	1	0	1

	Present state	Next state		Outputs						
		$w = 0$	$w = 1$							
	$y_2y_1$	$Y_2Y_1$	$Y_2Y_1$	$R1_{out}$	$R1_{in}$	$R2_{out}$	$R2_{in}$	$R3_{out}$	$R3_{in}$	<i>Done</i>
A	00	00	0 1	0	0	0	0	0	0	0
B	01	11	1 1	0	0	1	0	0	1	0
C	11	10	1 0	1	0	0	1	0	0	0
D	10	00	0 0	0	1	0	0	1	0	1

$y_2$	$y_1$	$w$	$Y_2$	$Y_1$
0	0	0		
0	0	1		
0	1	0		
0	1	1		
1	0	0		
1	0	1		
1	1	0		
1	1	1		

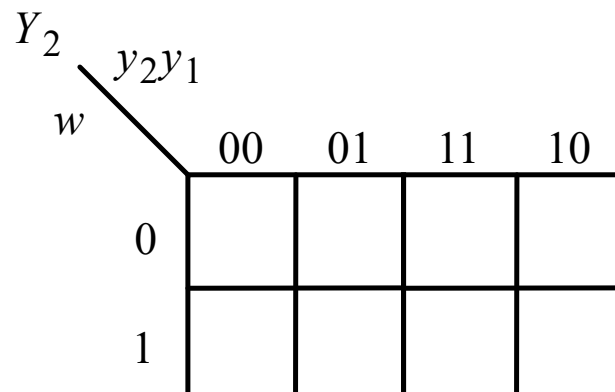
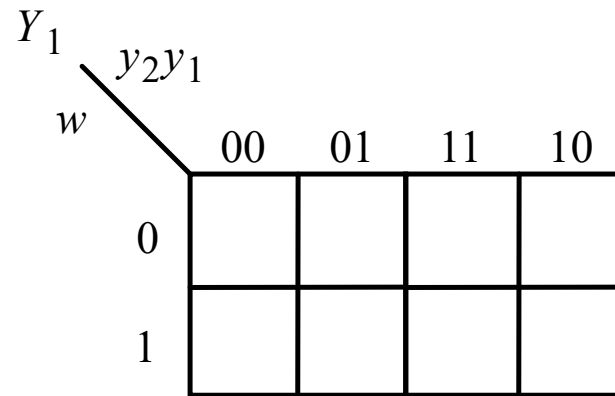
Let's derive the next-state expressions

	Present state	Next state		Outputs						
		$w = 0$	$w = 1$							
	$y_2y_1$	$Y_2Y_1$	$Y_2Y_1$	$R1_{out}$	$R1_{in}$	$R2_{out}$	$R2_{in}$	$R3_{out}$	$R3_{in}$	<i>Done</i>
A	00	00	0 1	0	0	0	0	0	0	0
B	01	11	1 1	0	0	1	0	0	1	0
C	11	10	1 0	1	0	0	1	0	0	0
D	10	00	0 0	0	1	0	0	1	0	1

$y_2$	$y_1$	$w$	$Y_2$	$Y_1$
0	0	0	0	0
0	0	1	0	1
0	1	0	1	1
0	1	1	1	1
1	0	0	0	0
1	0	1	0	0
1	1	0	1	0
1	1	1	1	0

	Present state	Next state		Outputs						
		$w = 0$	$w = 1$							
	$y_2y_1$	$Y_2Y_1$	$Y_2Y_1$	$R1_{out}$	$R1_{in}$	$R2_{out}$	$R2_{in}$	$R3_{out}$	$R3_{in}$	<i>Done</i>
A	00	00	0 1	0	0	0	0	0	0	0
B	01	11	1 1	0	0	1	0	0	1	0
C	11	10	1 0	1	0	0	1	0	0	0
D	10	00	0 0	0	1	0	0	1	0	1

$y_2$	$y_1$	$w$	$Y_2$	$Y_1$
0	0	0	0	0
0	0	1	0	1
0	1	0	1	1
0	1	1	1	1
1	0	0	0	0
1	0	1	0	0
1	1	0	1	0
1	1	1	1	0



	Present state	Next state		Outputs						
		$w = 0$	$w = 1$							
	$y_2y_1$	$Y_2Y_1$	$Y_2Y_1$	$R1_{out}$	$R1_{in}$	$R2_{out}$	$R2_{in}$	$R3_{out}$	$R3_{in}$	<i>Done</i>
A	00	00	0 1	0	0	0	0	0	0	0
B	01	11	1 1	0	0	1	0	0	1	0
C	11	10	1 0	1	0	0	1	0	0	0
D	10	00	0 0	0	1	0	0	1	0	1

$y_2$	$y_1$	$w$	$Y_2$	$Y_1$
0	0	0	0	0
0	0	1	0	1
0	1	0	1	1
0	1	1	1	1
1	0	0	0	0
1	0	1	0	0
1	1	0	1	0
1	1	1	1	0

$Y_1$

$w$

$y_2y_1$	00	01	11	10
0	0	1	0	0
1	1	1	0	0

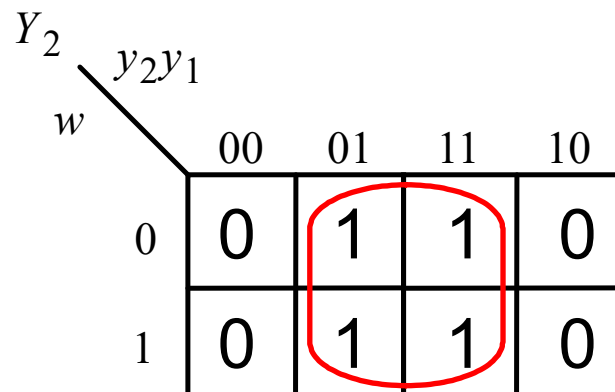
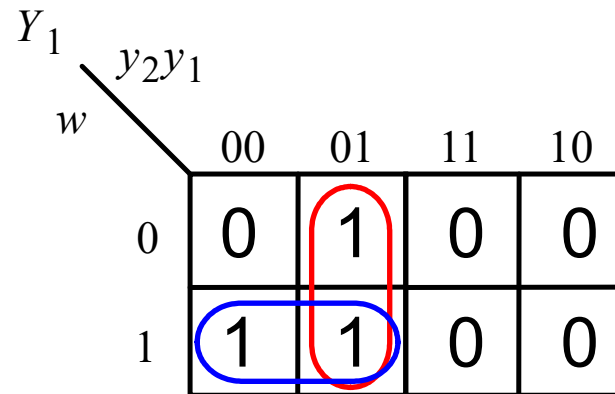
$Y_2$

$w$

$y_2y_1$	00	01	11	10
0	0	1	1	0
1	0	1	1	0

	Present state	Next state		Outputs						
		$w = 0$	$w = 1$							
	$y_2y_1$	$Y_2Y_1$	$Y_2Y_1$	$R1_{out}$	$R1_{in}$	$R2_{out}$	$R2_{in}$	$R3_{out}$	$R3_{in}$	<i>Done</i>
A	00	00	0 1	0	0	0	0	0	0	0
B	01	11	1 1	0	0	1	0	0	1	0
C	11	10	1 0	1	0	0	1	0	0	0
D	10	00	0 0	0	1	0	0	1	0	1

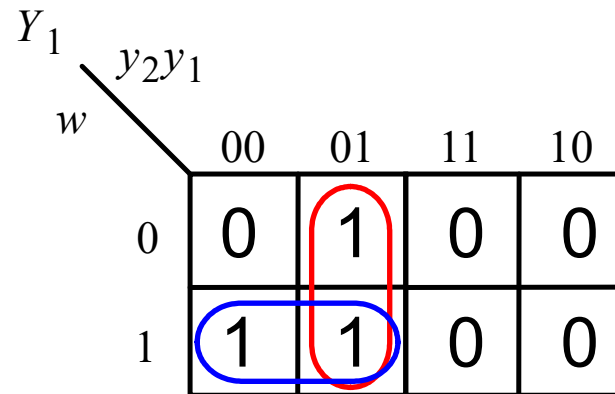
$y_2$	$y_1$	$w$	$Y_2$	$Y_1$
0	0	0	0	0
0	0	1	0	1
0	1	0	1	1
0	1	1	1	1
1	0	0	0	0
1	0	1	0	0
1	1	0	1	0
1	1	1	1	0



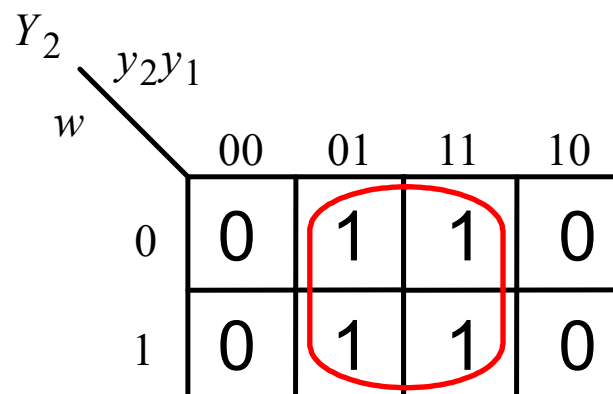


	Present state	Next state		Outputs						
		$w = 0$	$w = 1$							
	$y_2y_1$	$Y_2Y_1$	$Y_2Y_1$	$R1_{out}$	$R1_{in}$	$R2_{out}$	$R2_{in}$	$R3_{out}$	$R3_{in}$	<i>Done</i>
A	00	00	0 1	0	0	0	0	0	0	0
B	01	11	1 1	0	0	1	0	0	1	0
C	11	10	1 0	1	0	0	1	0	0	0
D	10	00	0 0	0	1	0	0	1	0	1

$y_2$	$y_1$	$w$	$Y_2$	$Y_1$
0	0	0	0	0
0	0	1	0	1
0	1	0	1	1
0	1	1	1	1
1	0	0	0	0
1	0	1	0	0
1	1	0	1	0
1	1	1	1	0



$$Y_1 = w\bar{y}_2 + y_1\bar{y}_2$$



$$Y_2 = y_1$$

	Present state	Next state		Outputs						
		$w = 0$	$w = 1$							
	$y_2y_1$	$Y_2Y_1$	$Y_2Y_1$	$R1_{out}$	$R1_{in}$	$R2_{out}$	$R2_{in}$	$R3_{out}$	$R3_{in}$	<i>Done</i>
A	00	00	0 1	0	0	0	0	0	0	0
B	01	11	1 1	0	0	1	0	0	1	0
C	11	10	1 0	1	0	0	1	0	0	0
D	10	00	0 0	0	1	0	0	1	0	1

$y_2$	$y_1$	$R1_{out}$	$R1_{in}$	$R2_{out}$
0	0			
0	1			
1	0			
1	1			

Let's derive the output expressions

	Present state	Next state		Outputs						
		$w = 0$	$w = 1$	$R1_{out}$	$R1_{in}$	$R2_{out}$	$R2_{in}$	$R3_{out}$	$R3_{in}$	<i>Done</i>
	$y_2y_1$	$Y_2Y_1$	$Y_2Y_1$							
A	00	00	0 1	0	0	0	0	0	0	0
B	01	11	1 1	0	0	1	0	0	1	0
C	11	10	1 0	1	0	0	1	0	0	0
D	10	00	0 0	0	1	0	0	1	0	1

$y_2$	$y_1$	$R1_{out}$	$R1_{in}$	$R2_{out}$
0	0			
0	1			
1	0			
1	1			

Let's derive the output expressions

Once again, we only need to derive these three unique ones.

	Present state	Next state		Outputs						
		$w = 0$	$w = 1$	$R1_{out}$	$R1_{in}$	$R2_{out}$	$R2_{in}$	$R3_{out}$	$R3_{in}$	<i>Done</i>
	$y_2y_1$	$Y_2Y_1$	$Y_2Y_1$							
A	00	00	0 1	0	0	0	0	0	0	0
B	01	11	1 1	0	0	1	0	0	1	0
C	11	10	1 0	1	0	0	1	0	0	0
D	10	00	0 0	0	1	0	0	1	0	1

	$y_2$	$y_1$	$R1_{out}$	$R1_{in}$	$R2_{out}$
A	0	0	0		
B	0	1	0		
D	1	0	0		
C	1	1	<b>1</b>		

**Note that C and D are swapped in the truth table due to the new state encoding that was chosen.**

	Present state	Next state		Outputs						
		$w = 0$	$w = 1$	$R1_{out}$	$R1_{in}$	$R2_{out}$	$R2_{in}$	$R3_{out}$	$R3_{in}$	<i>Done</i>
	$y_2y_1$	$Y_2Y_1$	$Y_2Y_1$							
A	00	00	0 1	0	0	0	0	0	0	0
B	01	11	1 1	0	0	1	0	0	1	0
C	11	10	1 0	1	0	0	1	0	0	0
D	10	00	0 0	0	1	0	0	1	0	1

	$y_2$	$y_1$	$R1_{out}$	$R1_{in}$	$R2_{out}$
A	0	0	0	0	0
B	0	1	0	0	1
D	1	0	0	1	0
C	1	1	1	0	0

	Present state	Next state		Outputs						
		$w = 0$	$w = 1$	$R1_{out}$	$R1_{in}$	$R2_{out}$	$R2_{in}$	$R3_{out}$	$R3_{in}$	<i>Done</i>
	$y_2 y_1$	$Y_2 Y_1$	$Y_2 Y_1$							
A	00	00	0 1	0	0	0	0	0	0	0
B	01	11	1 1	0	0	1	0	0	1	0
C	11	10	1 0	1	0	0	1	0	0	0
D	10	00	0 0	0	1	0	0	1	0	1

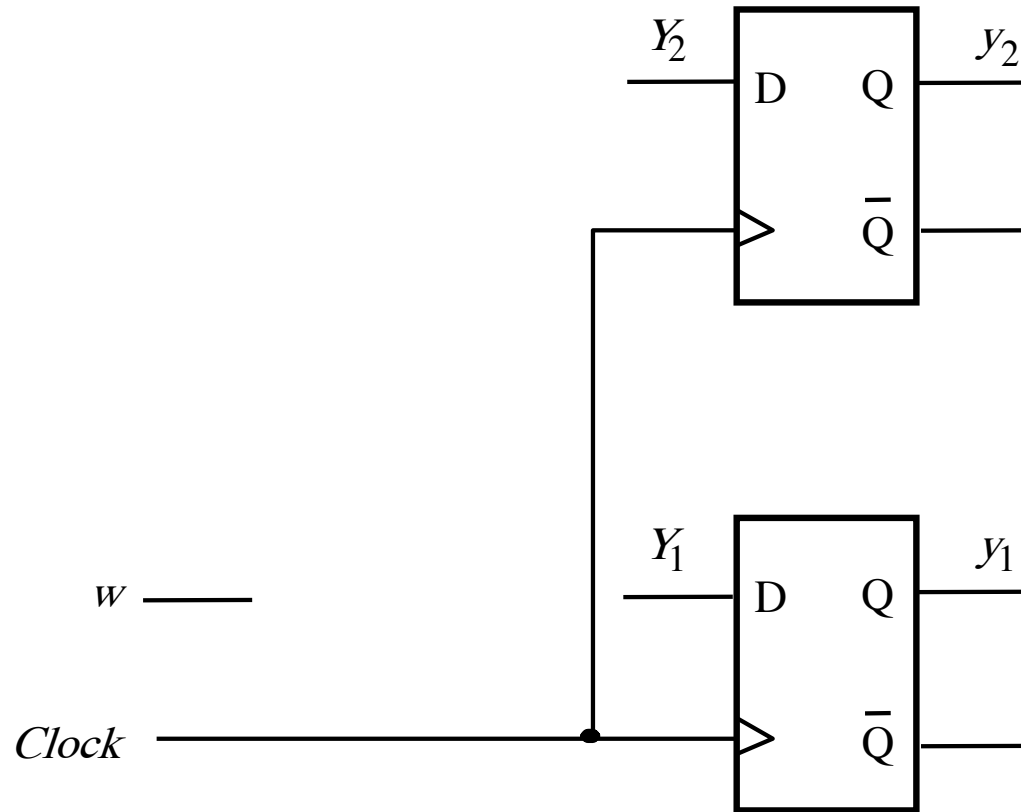
	$y_2$	$y_1$	$R1_{out}$	$R1_{in}$	$R2_{out}$
A	0	0	0	0	0
B	0	1	0	0	1
D	1	0	0	1	0
C	1	1	1	0	0

$$R1_{out} = R2_{in} = y_1 y_2$$

$$R1_{in} = R3_{out} = Done = \overline{y_1} y_2$$

$$R2_{out} = R3_{in} = y_1 \overline{y_2}$$

# Let's Complete the Circuit Diagram



$$Y_1 = w \overline{y_2} + y_1 \overline{y_2}$$

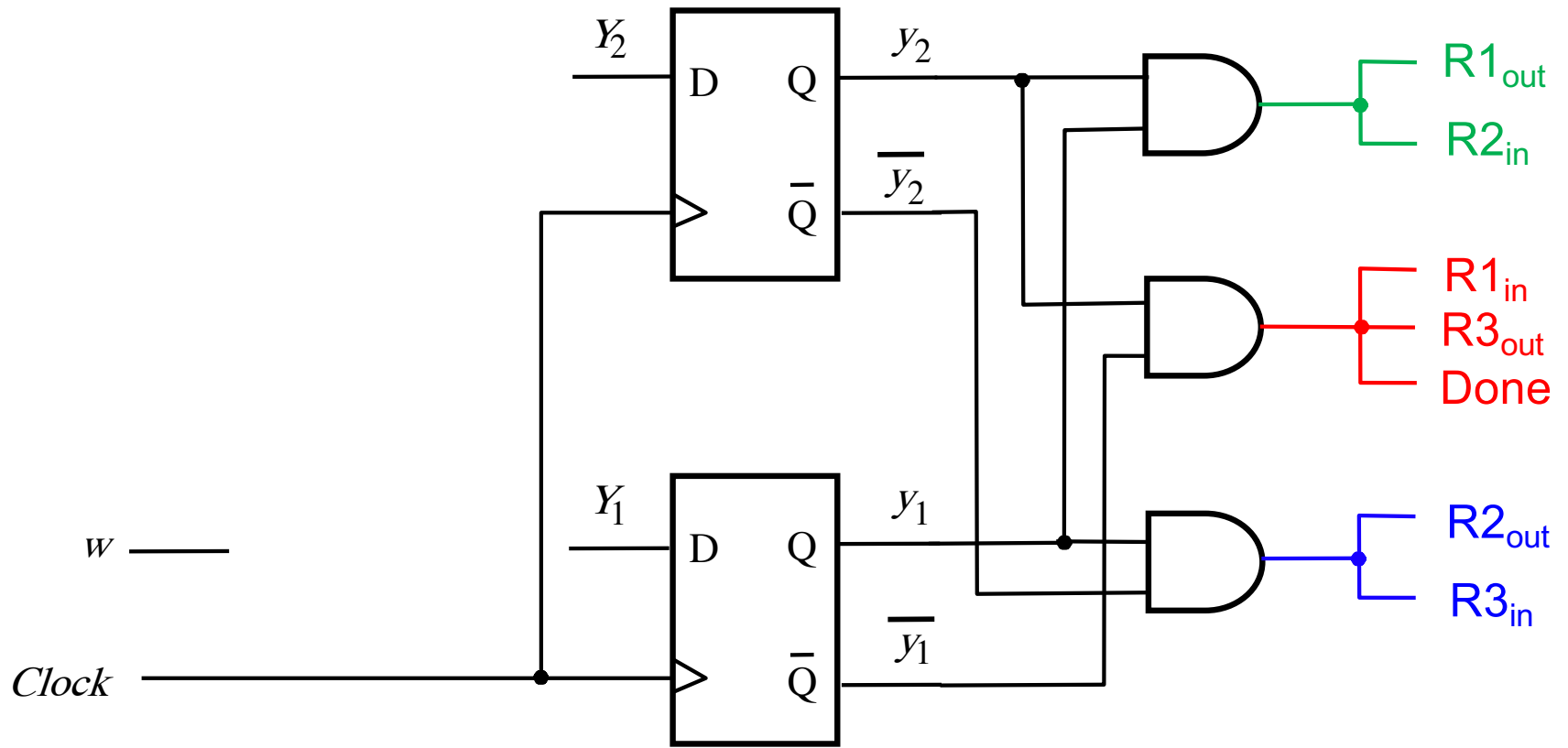
$$Y_2 = y_1$$

$$R1_{out} = R2_{in} = y_1 y_2$$

$$R1_{in} = R3_{out} = Done = \overline{y_1} y_2$$

$$R2_{out} = R3_{in} = y_1 \overline{y_2}$$

# Let's Complete the Circuit Diagram



$$Y_1 = w \overline{y_2} + y_1 \overline{y_2}$$

$$Y_2 = y_1$$

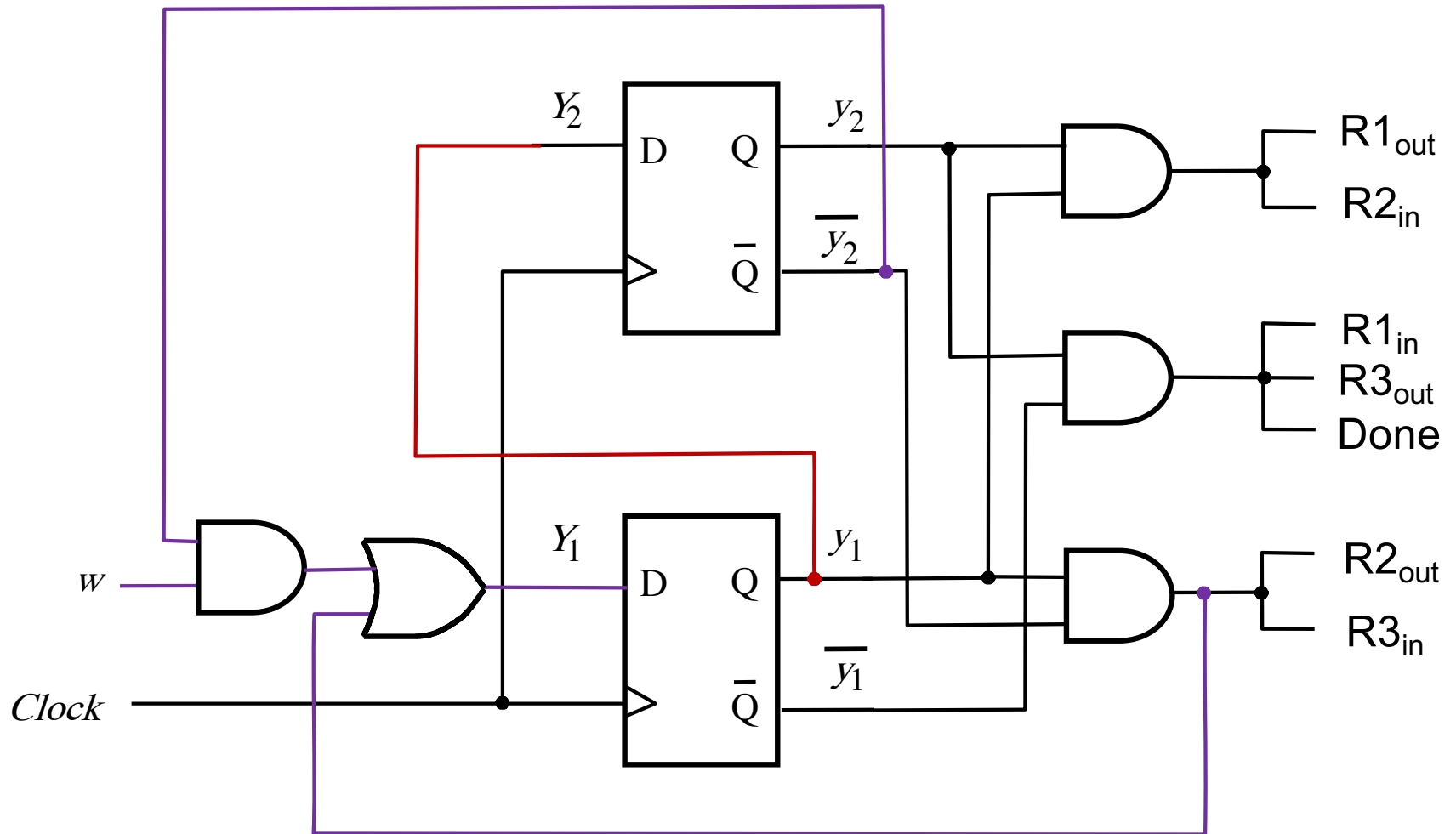
$$R1_{out} = R2_{in} = y_1 y_2$$

$$R1_{in} = R3_{out} = \text{Done} = \overline{y_1} y_2$$

$$R2_{out} = R3_{in} = y_1 \overline{y_2}$$



# Let's Complete the Circuit Diagram



$$Y_1 = w \overline{y_2} + y_1 \overline{y_2}$$

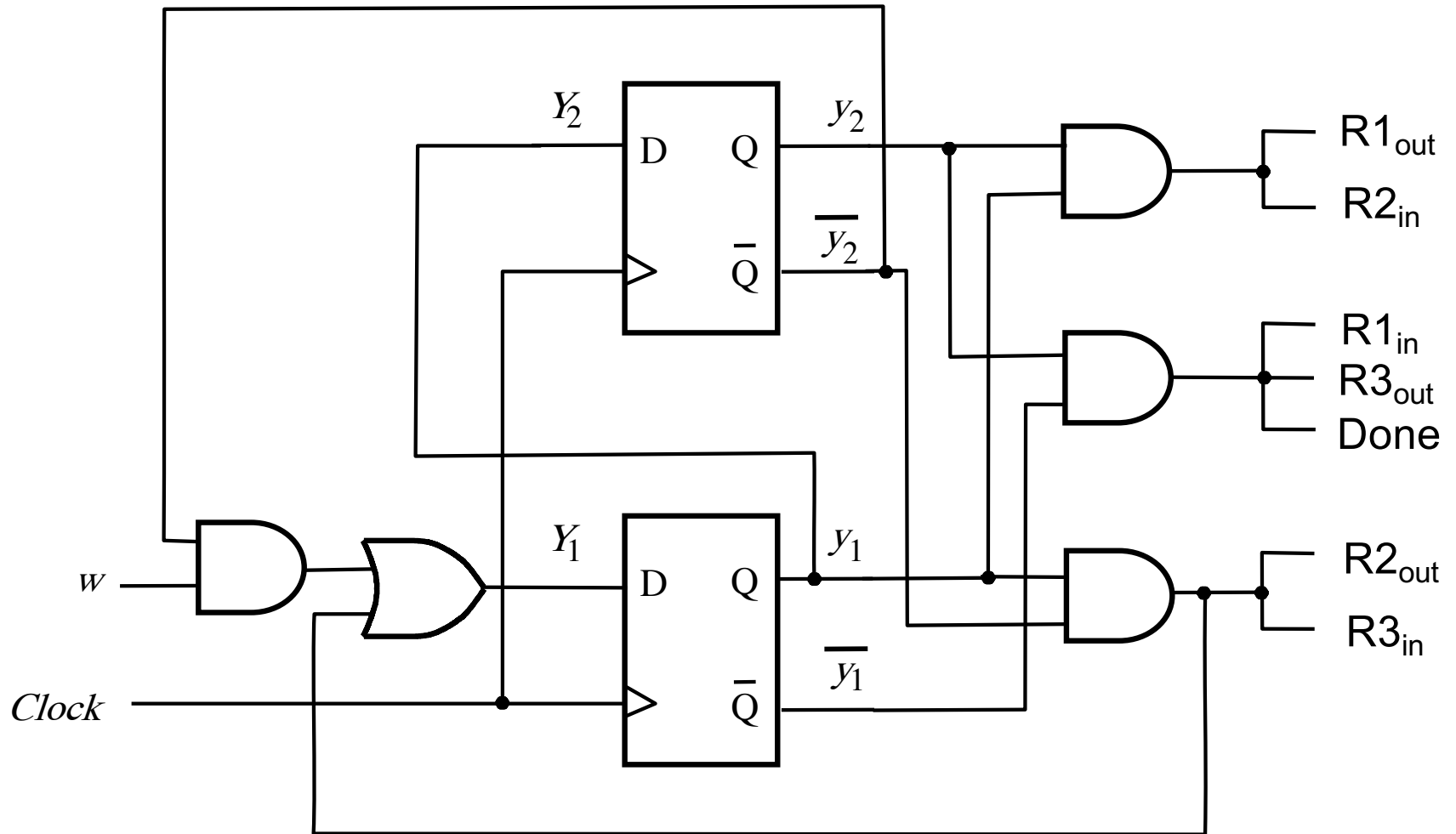
$$Y_2 = y_1$$

$$R1_{out} = R2_{in} = y_1 y_2$$

$$R1_{in} = R3_{out} = \text{Done} = \overline{y_1} y_2$$

$$R2_{out} = R3_{in} = y_1 \overline{y_2}$$

# Let's Complete the Circuit Diagram



$$Y_1 = w \overline{y_2} + y_1 \overline{y_2}$$

$$Y_2 = y_1$$

$$R1_{out} = R2_{in} = y_1 y_2$$

$$R1_{in} = R3_{out} = \text{Done} = \overline{y_1} y_2$$

$$R2_{out} = R3_{in} = y_1 \overline{y_2}$$

## **Encoding #3:**

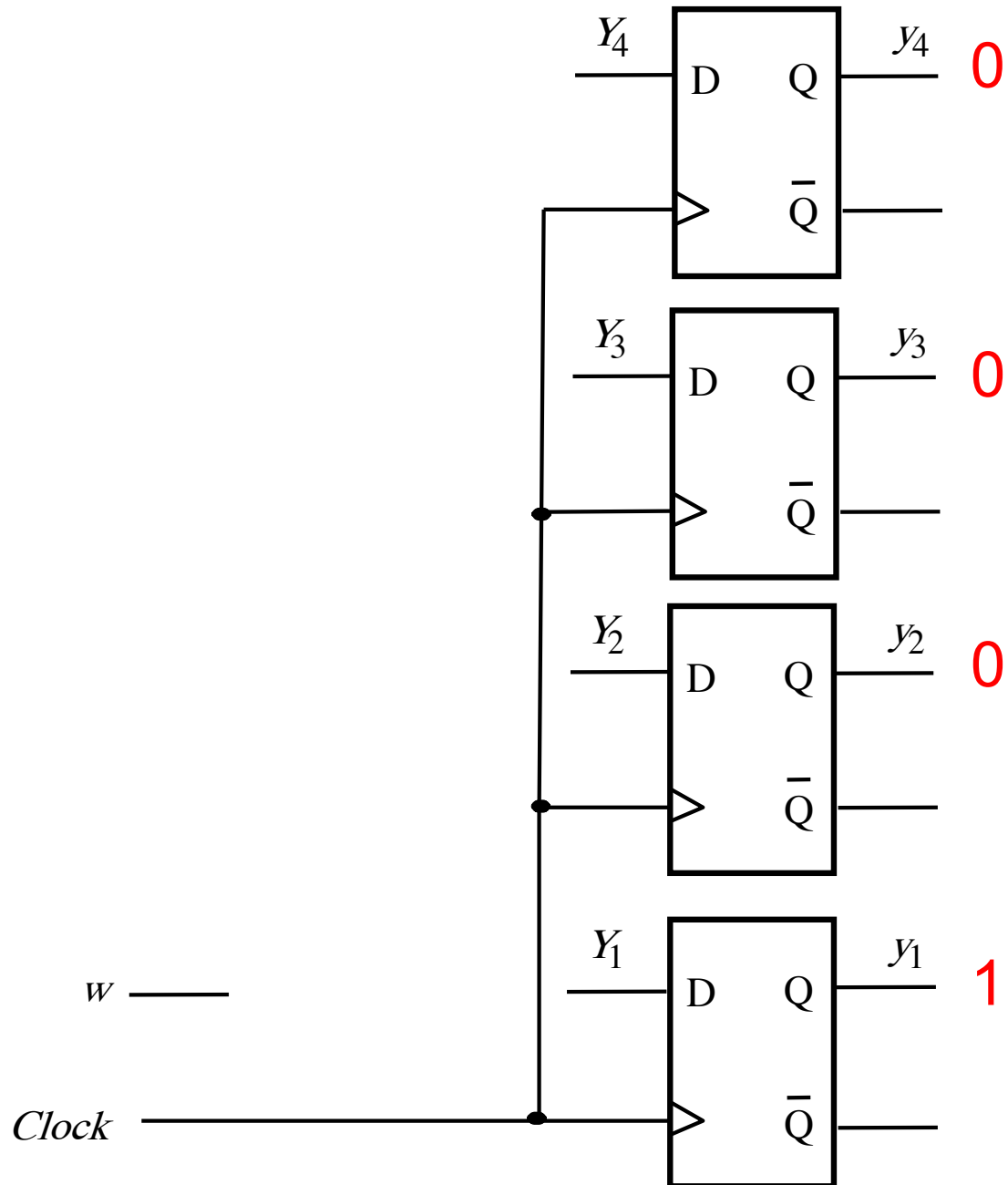
**A=0001, B=0010, C=0100, D=1000**

**(One-Hot Encoding – Uses Four Flip-Flops)**

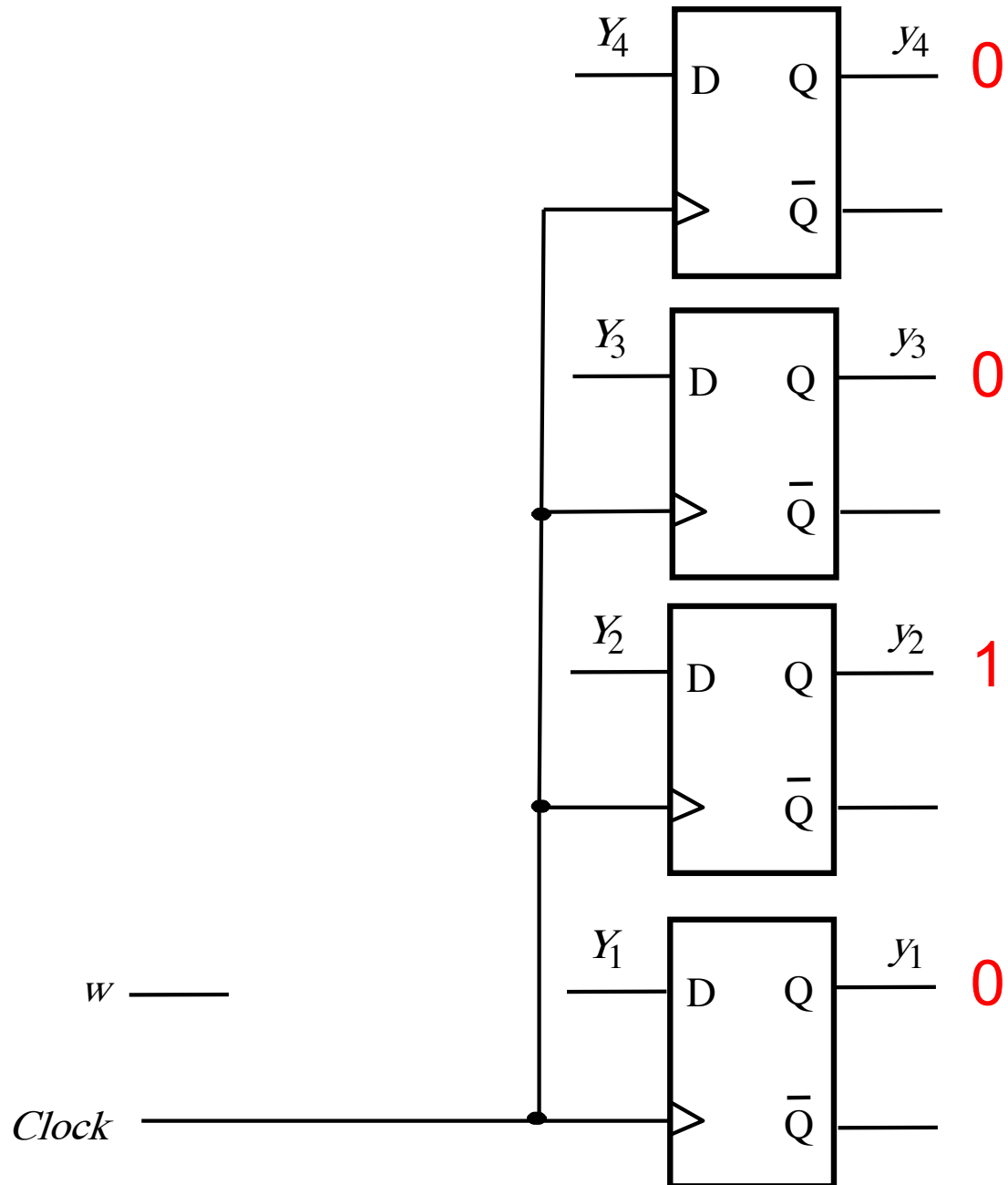
# One-Hot State Encoding

- **So far, we have been encoding states in a way that minimizes the number of flip-flops.**
- **But sometimes we can decrease the complexity of our logic if we encode states more sparsely.**

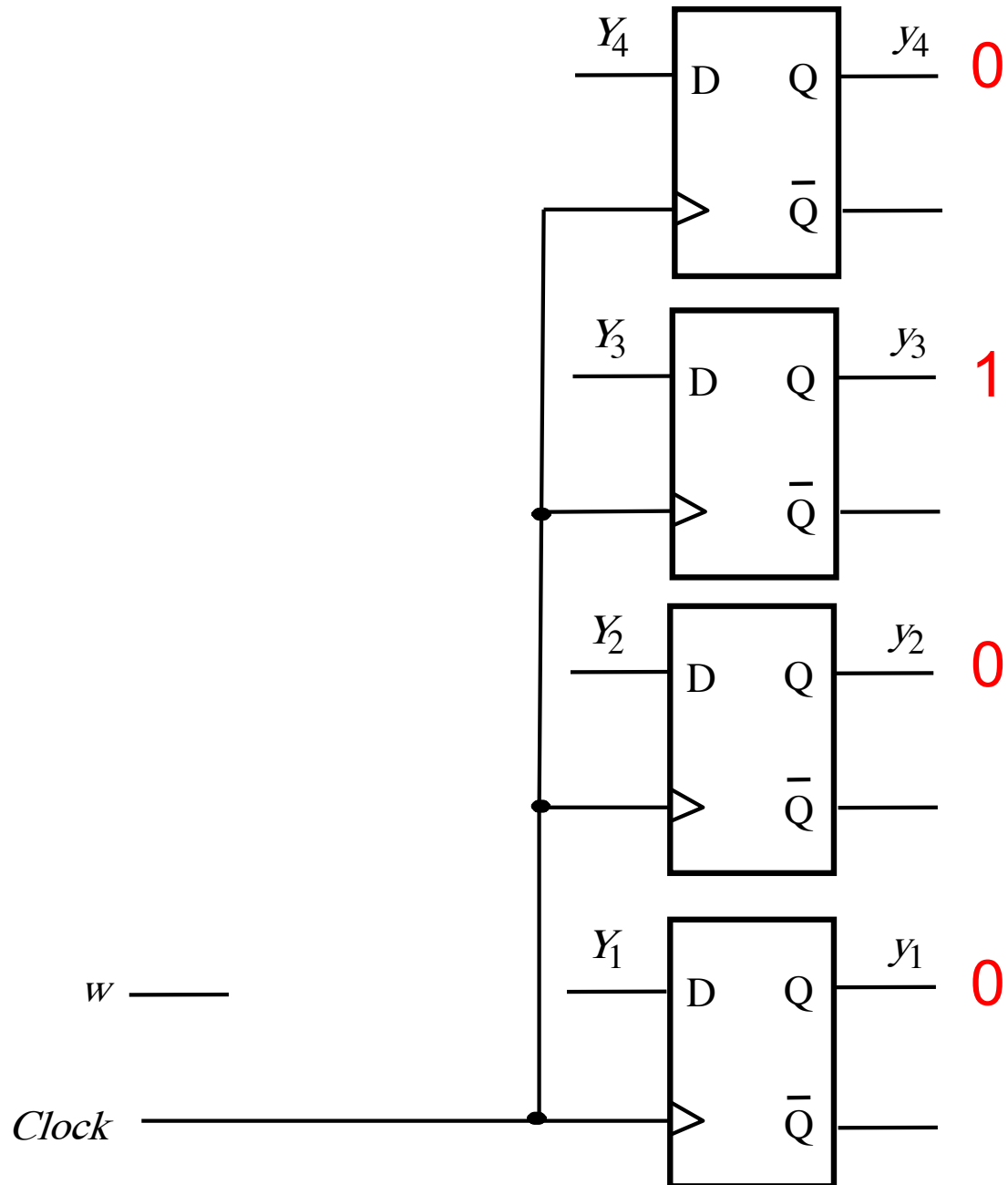
# Encoding for State A



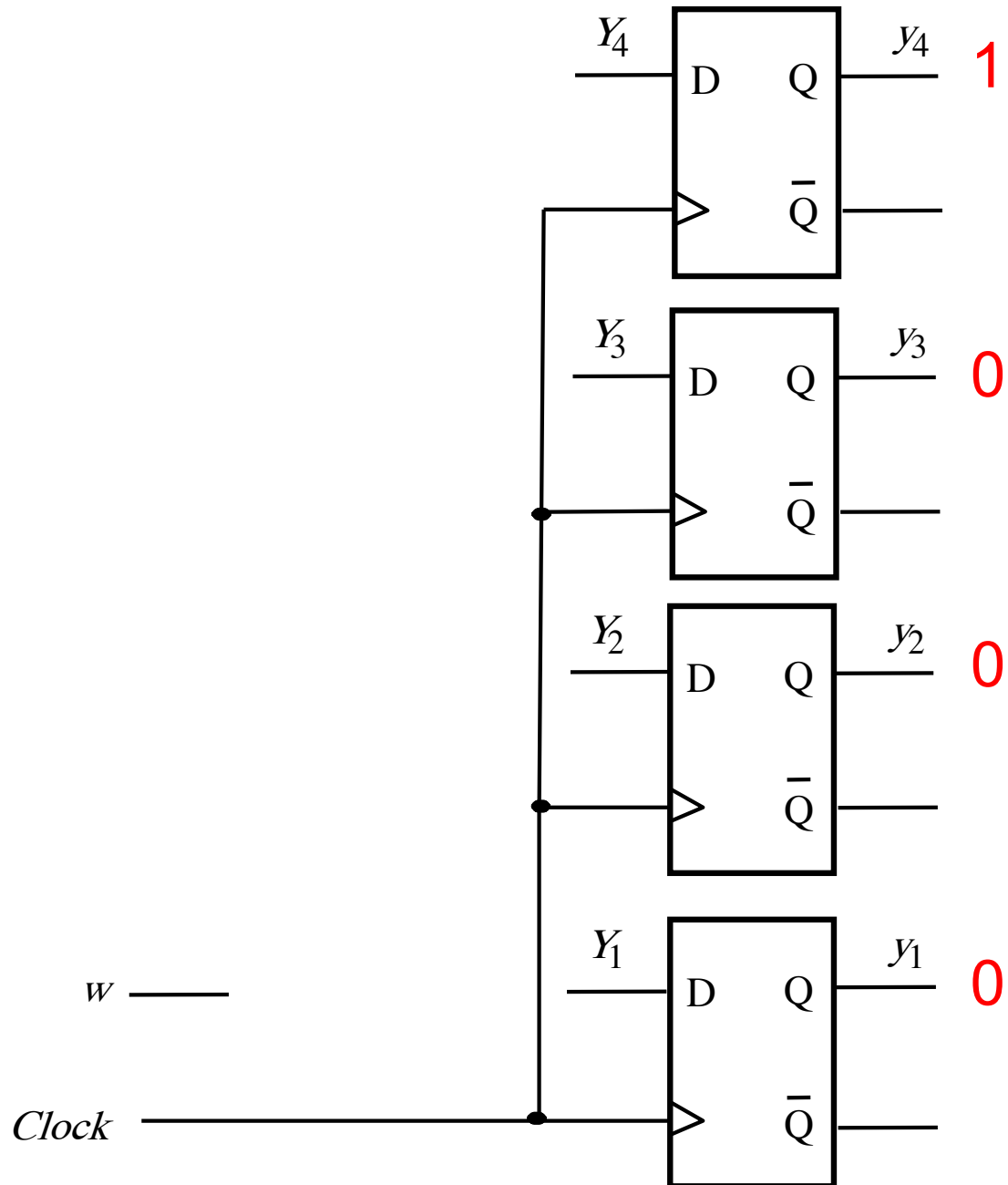
# Encoding for State B



# Encoding for State C



# Encoding for State D





# Register Swap Controller

Present state	Next state		Outputs						
	$w = 0$	$w = 1$	R1 <sub>out</sub>	R1 <sub>in</sub>	R2 <sub>out</sub>	R2 <sub>in</sub>	R3 <sub>out</sub>	R3 <sub>in</sub>	<i>Done</i>
A	A	B	0	0	0	0	0	0	0
B	C	C	0	0	1	0	0	1	0
C	D	D	1	0	0	1	0	0	0
D	A	A	0	1	0	0	1	0	1

# Register Swap Controller

Present state	Next state		Outputs						
	$w = 0$	$w = 1$	R1 <sub>out</sub>	R1 <sub>in</sub>	R2 <sub>out</sub>	R2 <sub>in</sub>	R3 <sub>out</sub>	R3 <sub>in</sub>	<i>Done</i>
A	A	B	0	0	0	0	0	0	0
B	C	C	0	0	1	0	0	1	0
C	D	D	1	0	0	1	0	0	0
D	A	A	0	1	0	0	1	0	1

Let's use four flip-flops and the following one-hot state encoding scheme:

$$A = 0001$$

$$B = 0010$$

$$C = 0100$$

$$D = 1000$$

## State Table (same as before)

Present state	Next state		Outputs						
	$w = 0$	$w = 1$	R1 <sub>out</sub>	R1 <sub>in</sub>	R2 <sub>out</sub>	R2 <sub>in</sub>	R3 <sub>out</sub>	R3 <sub>in</sub>	<i>Done</i>
A	A	B	0	0	0	0	0	0	0
B	C	C	0	0	1	0	0	1	0
C	D	D	1	0	0	1	0	0	0
D	A	A	0	1	0	0	1	0	1

## State-Assigned Table

Present State $y_4y_3y_2y_1$	Next State		Outputs						
	$w = 0$	$w = 1$							
	$Y_4Y_3Y_2Y_1$	$Y_4Y_3Y_2Y_1$	R1 <sub>out</sub>	R1 <sub>in</sub>	R2 <sub>out</sub>	R2 <sub>in</sub>	R3 <sub>out</sub>	R3 <sub>in</sub>	<i>Done</i>
A									
B									
C									
D									

## State Table (same as before)

Present state	Next state		Outputs						
	$w = 0$	$w = 1$	R1 <sub>out</sub>	R1 <sub>in</sub>	R2 <sub>out</sub>	R2 <sub>in</sub>	R3 <sub>out</sub>	R3 <sub>in</sub>	<i>Done</i>
A	A	B	0	0	0	0	0	0	0
B	C	C	0	0	1	0	0	1	0
C	D	D	1	0	0	1	0	0	0
D	A	A	0	1	0	0	1	0	1

## State-Assigned Table

	Present State	Next State		Outputs						
		$w = 0$	$w = 1$							
	$y_4y_3y_2y_1$	$Y_4Y_3Y_2Y_1$	$Y_4Y_3Y_2Y_1$	R1 <sub>out</sub>	R1 <sub>in</sub>	R2 <sub>out</sub>	R2 <sub>in</sub>	R3 <sub>out</sub>	R3 <sub>in</sub>	<i>Done</i>
A	0 001									
B	0 010									
C	0 100									
D	1 000									

## State Table (same as before)

Present state	Next state		Outputs						
	$w = 0$	$w = 1$	R1 <sub>out</sub>	R1 <sub>in</sub>	R2 <sub>out</sub>	R2 <sub>in</sub>	R3 <sub>out</sub>	R3 <sub>in</sub>	<i>Done</i>
A	A	B	0	0	0	0	0	0	0
B	C	C	0	0	1	0	0	1	0
C	D	D	1	0	0	1	0	0	0
D	A	A	0	1	0	0	1	0	1

## State-Assigned Table

	Present State	Next State		Outputs						
		$w = 0$	$w = 1$							
	$y_4y_3y_2y_1$	$Y_4Y_3Y_2Y_1$	$Y_4Y_3Y_2Y_1$	R1 <sub>out</sub>	R1 <sub>in</sub>	R2 <sub>out</sub>	R2 <sub>in</sub>	R3 <sub>out</sub>	R3 <sub>in</sub>	<i>Done</i>
A	0 001	0001	0010							
B	0 010	0100	0100							
C	0 100	1000	1000							
D	1 000	0001	0001							

## State Table (same as before)

Present state	Next state		Outputs						
	$w = 0$	$w = 1$	R1 <sub>out</sub>	R1 <sub>in</sub>	R2 <sub>out</sub>	R2 <sub>in</sub>	R3 <sub>out</sub>	R3 <sub>in</sub>	<i>Done</i>
A	A	B	0	0	0	0	0	0	0
B	C	C	0	0	1	0	0	1	0
C	D	D	1	0	0	1	0	0	0
D	A	A	0	1	0	0	1	0	1

## State-Assigned Table

	Present State	Next State		Outputs						
		$w = 0$	$w = 1$							
	$y_4y_3y_2y_1$	$Y_4Y_3Y_2Y_1$	$Y_4Y_3Y_2Y_1$	R1 <sub>out</sub>	R1 <sub>in</sub>	R2 <sub>out</sub>	R2 <sub>in</sub>	R3 <sub>out</sub>	R3 <sub>in</sub>	<i>Done</i>
A	0 001	0001	0010	0	0	0	0	0	0	0
B	0 010	0100	0100	0	0	1	0	0	1	0
C	0 100	1000	1000	1	0	0	1	0	0	0
D	1 000	0001	0001	0	1	0	0	1	0	1

# Let's Derive the Next-State Expressions

	Present State	Next State		Outputs						
		$w = 0$	$w = 1$							
	$y_4y_3y_2y_1$	$Y_4Y_3Y_2Y_1$	$Y_4Y_3Y_2Y_1$	R1 <sub>out</sub>	R1 <sub>in</sub>	R2 <sub>out</sub>	R2 <sub>in</sub>	R3 <sub>out</sub>	R3 <sub>in</sub>	<i>Done</i>
A	0 001	0001	0010	0	0	0	0	0	0	0
B	0 010	0100	0100	0	0	1	0	0	1	0
C	0 100	1000	1000	1	0	0	1	0	0	0
D	1 000	0001	0001	0	1	0	0	1	0	1

# Let's Derive the Next-State Expressions

$$Y_1(w, y_4, y_3, y_2, y_1)$$

$$Y_2(w, y_4, y_3, y_2, y_1)$$

$$Y_3(w, y_4, y_3, y_2, y_1)$$

$$Y_4(w, y_4, y_3, y_2, y_1)$$

We need to do four 5-variable K-maps!

	Present State	Next State		Outputs						
		$w = 0$	$w = 1$							
	$y_4y_3y_2y_1$	$Y_4Y_3Y_2Y_1$	$Y_4Y_3Y_2Y_1$	R1 <sub>out</sub>	R1 <sub>in</sub>	R2 <sub>out</sub>	R2 <sub>in</sub>	R3 <sub>out</sub>	R3 <sub>in</sub>	<i>Done</i>
A	0 001	0001	0010	0	0	0	0	0	0	0
B	0 010	0100	0100	0	0	1	0	0	1	0
C	0 100	1000	1000	1	0	0	1	0	0	0
D	1 000	0001	0001	0	1	0	0	1	0	1



# Let's Derive the Next-State Expressions

$$Y_1(w, y_4, y_3, y_2, y_1) = \bar{w}y_1 + y_4$$

$$Y_2(w, y_4, y_3, y_2, y_1) = wy_1$$

$$Y_3(w, y_4, y_3, y_2, y_1) = y_2$$

$$Y_4(w, y_4, y_3, y_2, y_1) = y_3$$

Or we can be smarter than that 😊

	Present State	Next State		Outputs						
		$w = 0$	$w = 1$							
	$y_4y_3y_2y_1$	$Y_4Y_3Y_2Y_1$	$Y_4Y_3Y_2Y_1$	R1 <sub>out</sub>	R1 <sub>in</sub>	R2 <sub>out</sub>	R2 <sub>in</sub>	R3 <sub>out</sub>	R3 <sub>in</sub>	Done
A	0 001	0001	0010	0	0	0	0	0	0	0
B	0 010	0100	0100	0	0	1	0	0	1	0
C	0 100	1000	1000	1	0	0	1	0	0	0
D	1 000	0001	0001	0	1	0	0	1	0	1

# Let's Derive the Next-State Expressions

$$Y_1(w, y_4, y_3, y_2, y_1) = \bar{w}y_1 + y_4 \quad (\text{why?})$$

$$Y_2(w, y_4, y_3, y_2, y_1) = wy_1 \quad (\text{why?})$$

$$Y_3(w, y_4, y_3, y_2, y_1) = y_2 \quad =1 \text{ only in B}$$

$$Y_4(w, y_4, y_3, y_2, y_1) = y_3 \quad =1 \text{ only in C}$$

Or we can be smarter than that 😊

	Present State	Next State		Outputs						
		$w = 0$	$w = 1$							
	$y_4y_3y_2y_1$	$Y_4Y_3Y_2Y_1$	$Y_4Y_3Y_2Y_1$	R1 <sub>out</sub>	R1 <sub>in</sub>	R2 <sub>out</sub>	R2 <sub>in</sub>	R3 <sub>out</sub>	R3 <sub>in</sub>	Done
A	0 001	0001	0010	0	0	0	0	0	0	0
B	0 010	0100	0100	0	0	1	0	0	1	0
C	0 100	1000	1000	1	0	0	1	0	0	0
D	1 000	0001	0001	0	1	0	0	1	0	1

# Let's Derive the Output Expressions

	Present State	Next State		Outputs						
		$w = 0$	$w = 1$							
	$y_4y_3y_2y_1$	$Y_4Y_3Y_2Y_1$	$Y_4Y_3Y_2Y_1$	R1 <sub>out</sub>	R1 <sub>in</sub>	R2 <sub>out</sub>	R2 <sub>in</sub>	R3 <sub>out</sub>	R3 <sub>in</sub>	<i>Done</i>
A	0 001	0001	0010	0	0	0	0	0	0	0
B	0 010	0100	0100	0	0	1	0	0	1	0
C	0 100	1000	1000	1	0	0	1	0	0	0
D	1 000	0001	0001	0	1	0	0	1	0	1

# Let's Derive the Output Expressions

$R1_{out}(y_4, y_3, y_2, y_1)$   
 $R1_{in}(y_4, y_3, y_2, y_1)$   
 $R2_{out}(y_4, y_3, y_2, y_1)$   
 $R2_{in}(y_4, y_3, y_2, y_1)$   
 $R3_{out}(y_4, y_3, y_2, y_1)$   
 $R3_{in}(y_4, y_3, y_2, y_1)$   
 $Done(y_4, y_3, y_2, y_1)$

We need to do seven 4-variable K-maps!

	Present State	Next State		Outputs						
		$w = 0$	$w = 1$							
	$y_4 y_3 y_2 y_1$	$Y_4 Y_3 Y_2 Y_1$	$Y_4 Y_3 Y_2 Y_1$	$R1_{out}$	$R1_{in}$	$R2_{out}$	$R2_{in}$	$R3_{out}$	$R3_{in}$	<i>Done</i>
A	0 001	0001	0010	0	0	0	0	0	0	0
B	0 010	0100	0100	0	0	1	0	0	1	0
C	0 100	1000	1000	1	0	0	1	0	0	0
D	1 000	0001	0001	0	1	0	0	1	0	1

# Let's Derive the Output Expressions

$$\begin{aligned}
 R1_{\text{out}}(y_4, y_3, y_2, y_1) &= y_3 && \text{equal to 1 only in State C} \\
 R1_{\text{in}}(y_4, y_3, y_2, y_1) &= y_4 && \text{equal to 1 only in State D} \\
 R2_{\text{out}}(y_4, y_3, y_2, y_1) &= y_2 && \text{equal to 1 only in State B} \\
 R2_{\text{in}}(y_4, y_3, y_2, y_1) &= y_3 && \text{equal to 1 only in State C} \\
 R3_{\text{out}}(y_4, y_3, y_2, y_1) &= y_4 && \text{equal to 1 only in State D} \\
 R3_{\text{in}}(y_4, y_3, y_2, y_1) &= y_2 && \text{equal to 1 only in State B} \\
 Done(y_4, y_3, y_2, y_1) &= y_4 && \text{equal to 1 only in State D}
 \end{aligned}$$

Or we can be smarter than that by exploiting the one-hot encoded property

	Present State	Next State		Outputs						
		$w = 0$	$w = 1$							
	$y_4 y_3 y_2 y_1$	$Y_4 Y_3 Y_2 Y_1$	$Y_4 Y_3 Y_2 Y_1$	$R1_{\text{out}}$	$R1_{\text{in}}$	$R2_{\text{out}}$	$R2_{\text{in}}$	$R3_{\text{out}}$	$R3_{\text{in}}$	<i>Done</i>
A	0 001	0001	0010	0	0	0	0	0	0	0
B	0 010	0100	0100	0	0	<b>1</b>	0	0	<b>1</b>	0
C	0 100	1000	1000	<b>1</b>	0	0	<b>1</b>	0	0	0
D	1 000	0001	0001	0	<b>1</b>	0	0	<b>1</b>	0	<b>1</b>

# Let's Complete the Circuit Diagram

$$R1_{out} = R2_{in} = y_3$$

$$R1_{in} = R3_{out} = Done = y_4$$

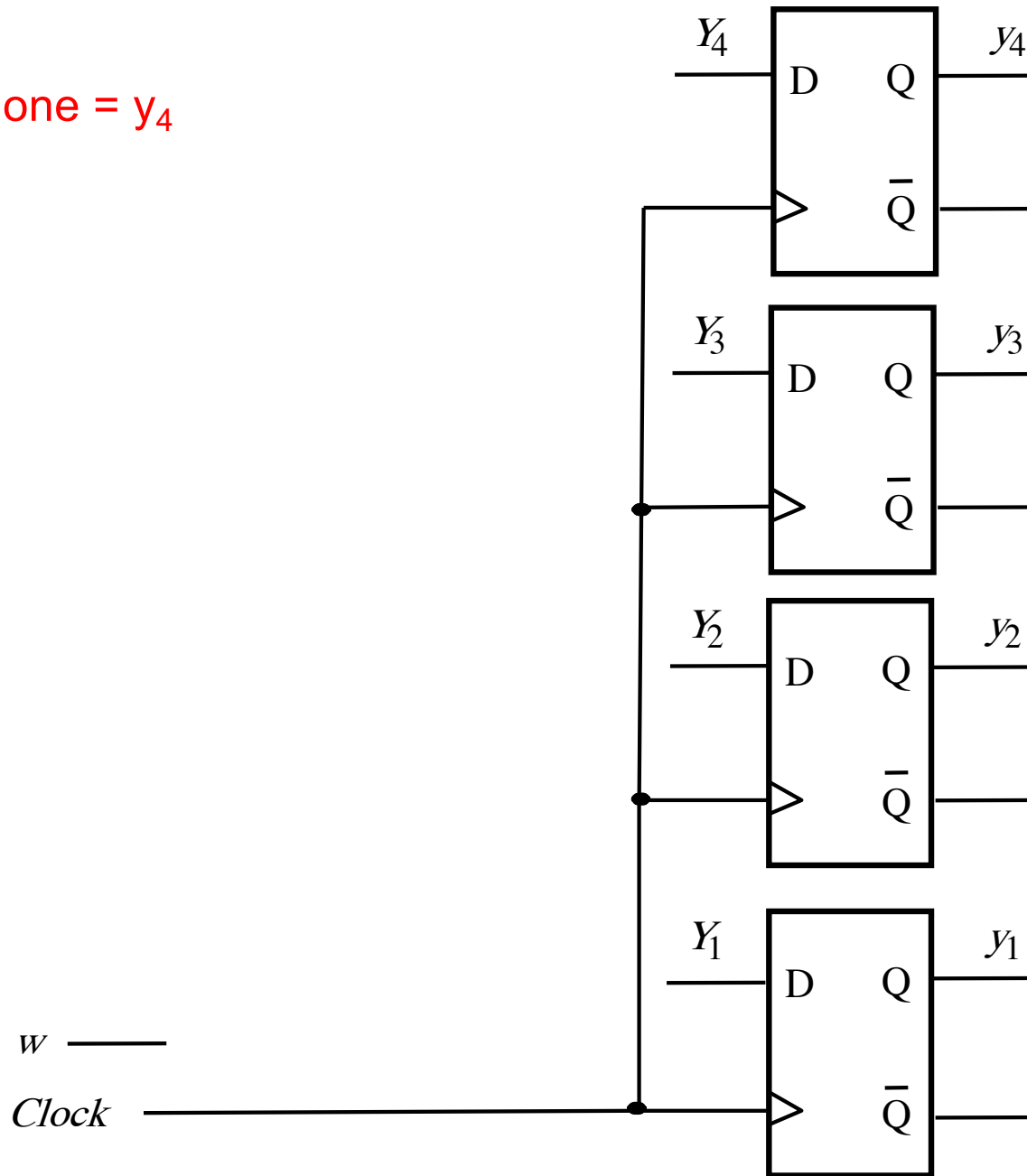
$$R2_{out} = R3_{in} = y_2$$

$$Y_1 = \bar{w} y_1 + y_4$$

$$Y_2 = w y_1$$

$$Y_3 = y_2$$

$$Y_4 = y_3$$

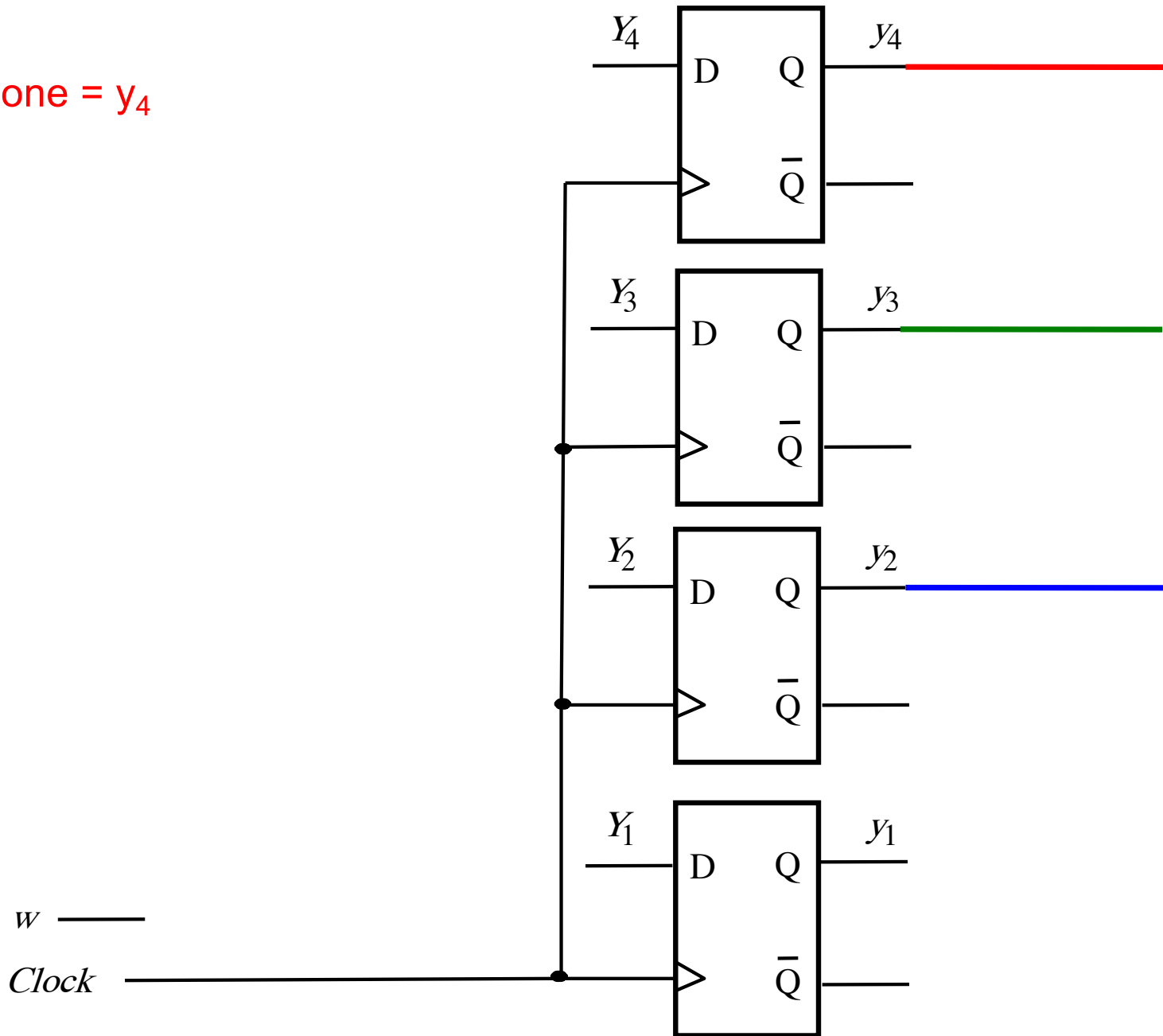


# Let's Complete the Circuit Diagram

$$R1_{out} = R2_{in} = y_3$$

$$R1_{in} = R3_{out} = Done = y_4$$

$$R2_{out} = R3_{in} = y_2$$



$$Y_1 = \bar{w} y_1 + y_4$$

$$Y_2 = w y_1$$

$$Y_3 = y_2$$

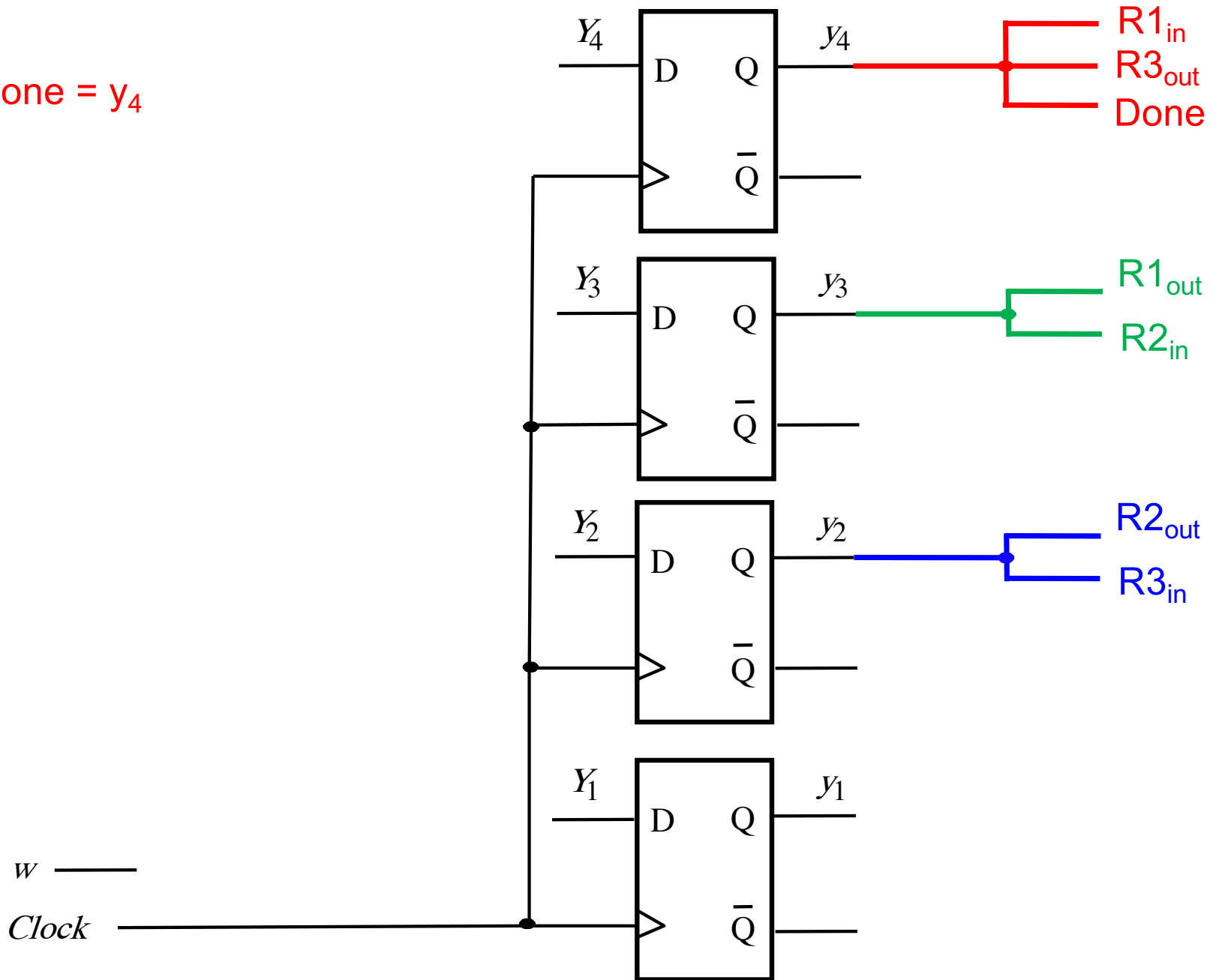
$$Y_4 = y_3$$

# Let's Complete the Circuit Diagram

$$R1_{out} = R2_{in} = y_3$$

$$R1_{in} = R3_{out} = Done = y_4$$

$$R2_{out} = R3_{in} = y_2$$



$$Y_1 = \bar{w} y_1 + y_4$$

$$Y_2 = w y_1$$

$$Y_3 = y_2$$

$$Y_4 = y_3$$

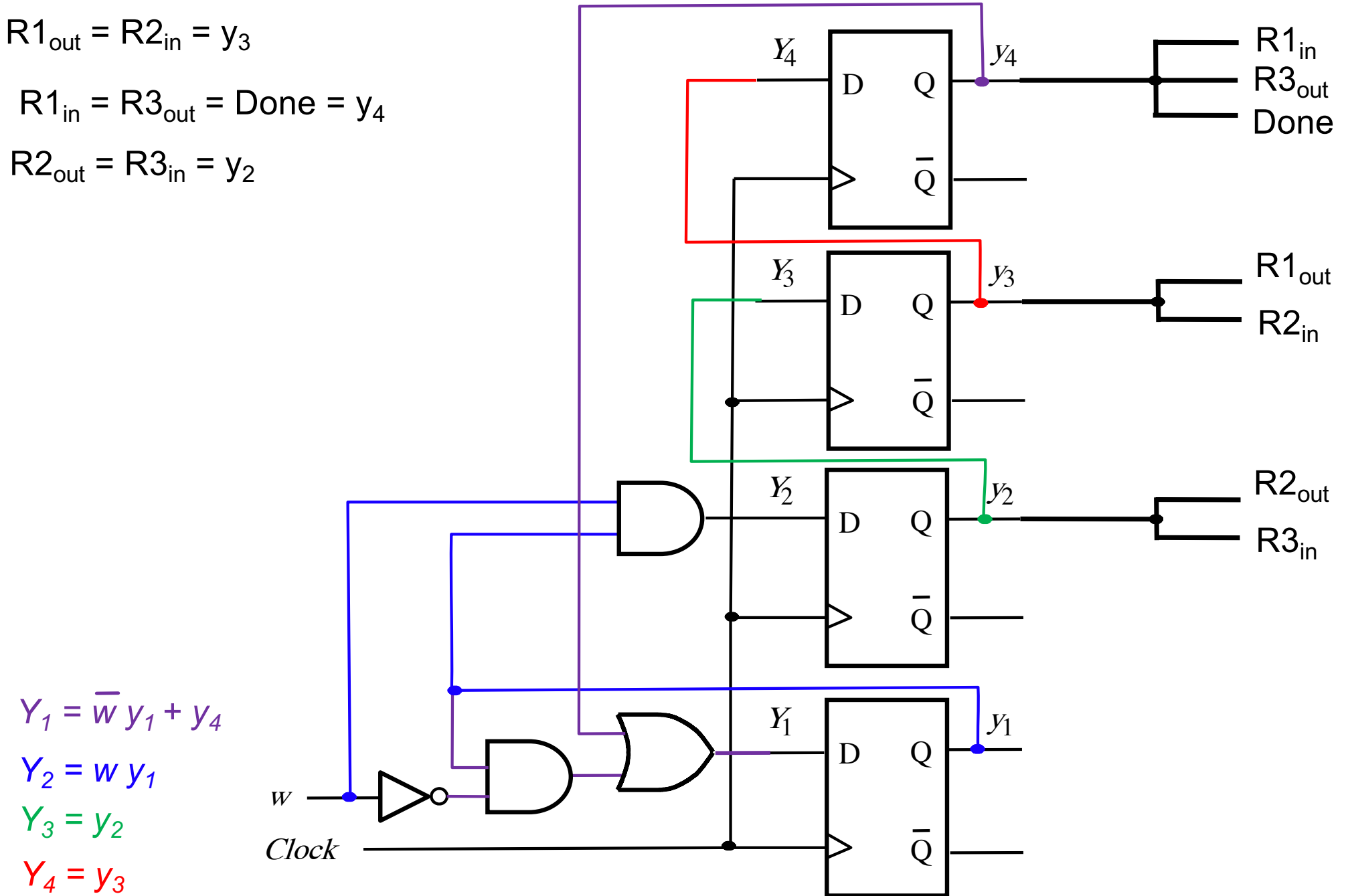


# Let's Complete the Circuit Diagram

$$R1_{out} = R2_{in} = y_3$$

$$R1_{in} = R3_{out} = Done = y_4$$

$$R2_{out} = R3_{in} = y_2$$



$$Y_1 = \bar{w} y_1 + y_4$$

$$Y_2 = w y_1$$

$$Y_3 = y_2$$

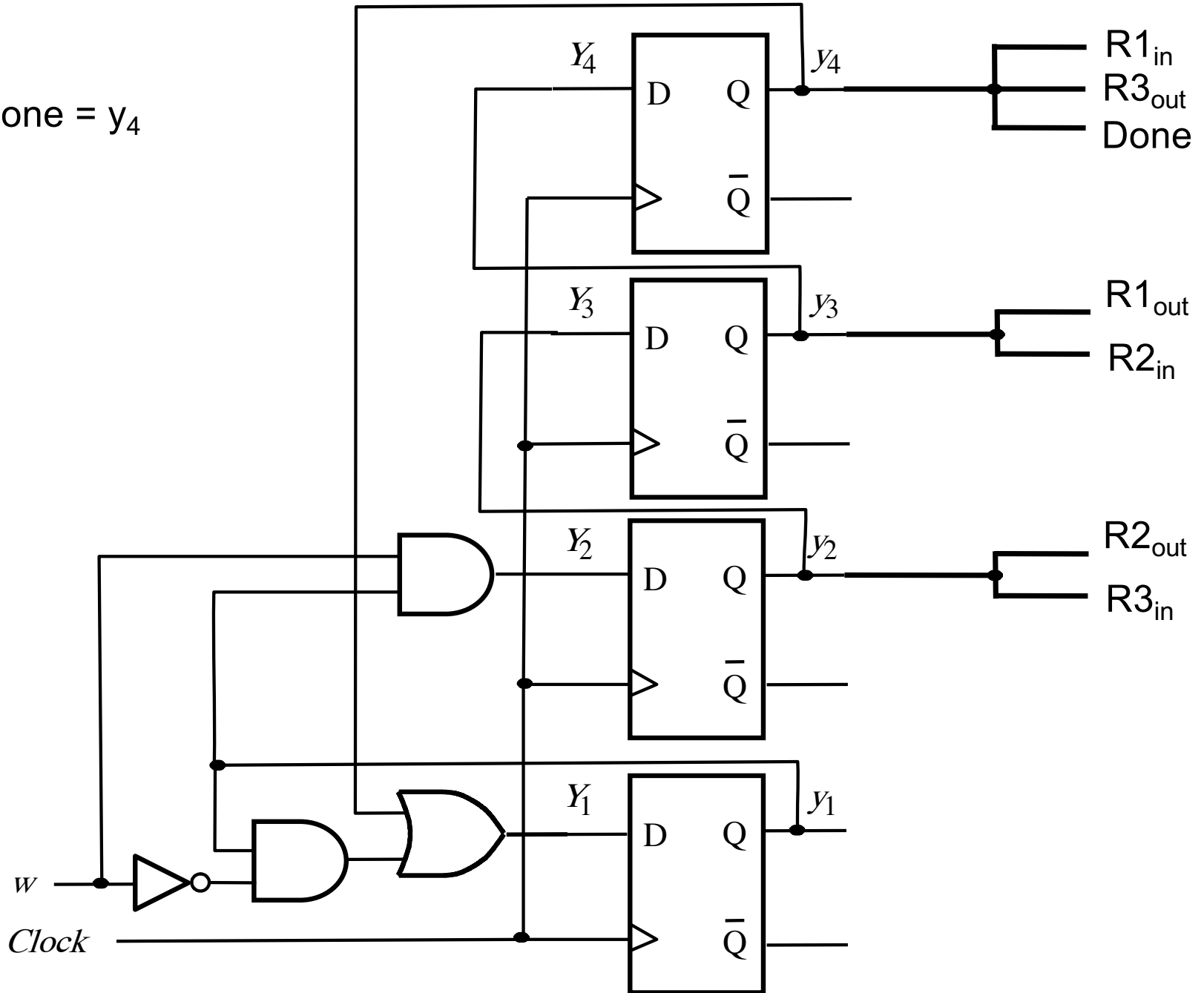
$$Y_4 = y_3$$

# Let's Complete the Circuit Diagram

$$R1_{out} = R2_{in} = y_3$$

$$R1_{in} = R3_{out} = Done = y_4$$

$$R2_{out} = R3_{in} = y_2$$



$$Y_1 = \bar{w} y_1 + y_4$$

$$Y_2 = w y_1$$

$$Y_3 = y_2$$

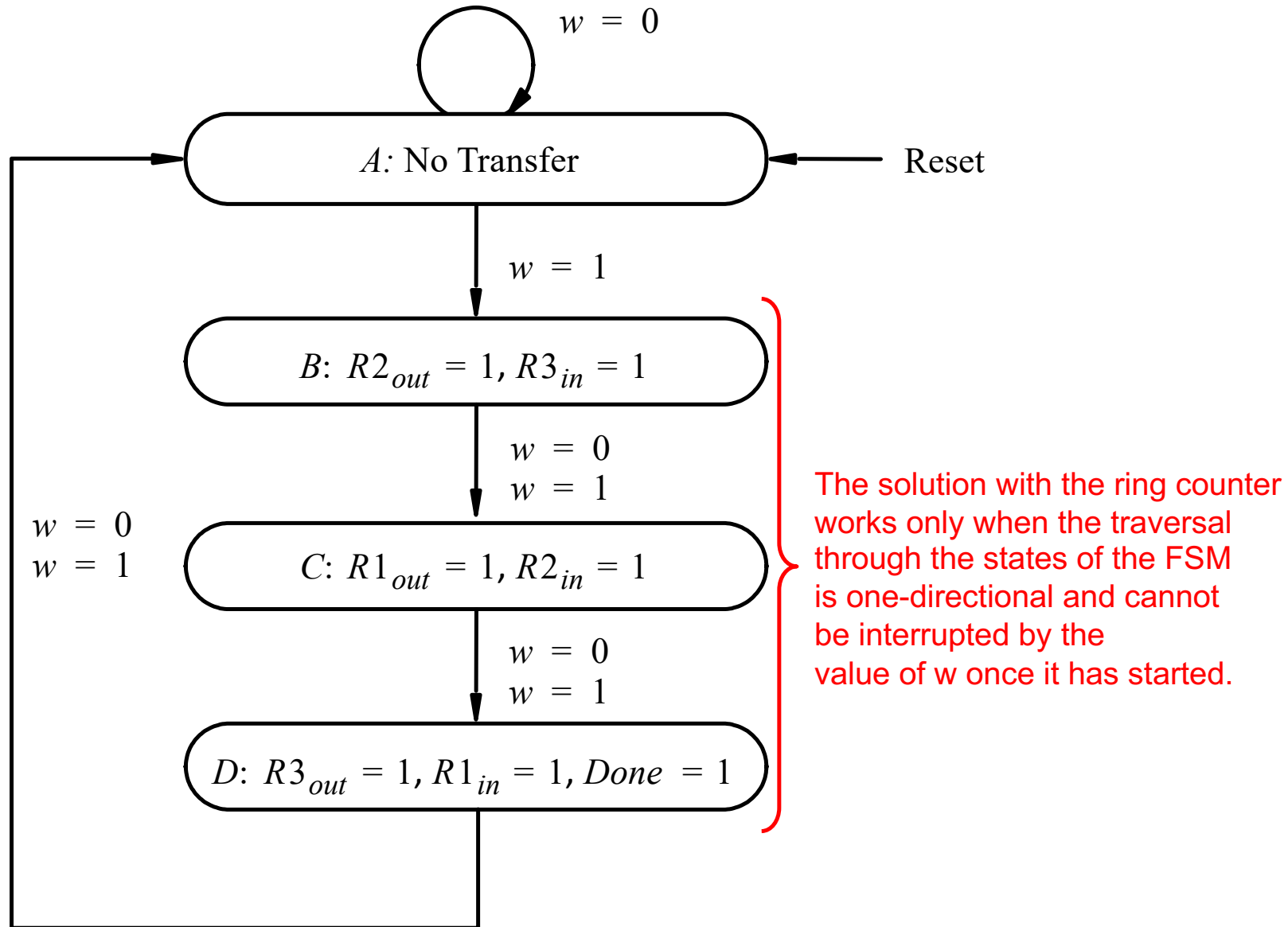
$$Y_4 = y_3$$

## **Encoding #4:**

**A=0001, B=0010, C=0100, D=1000**

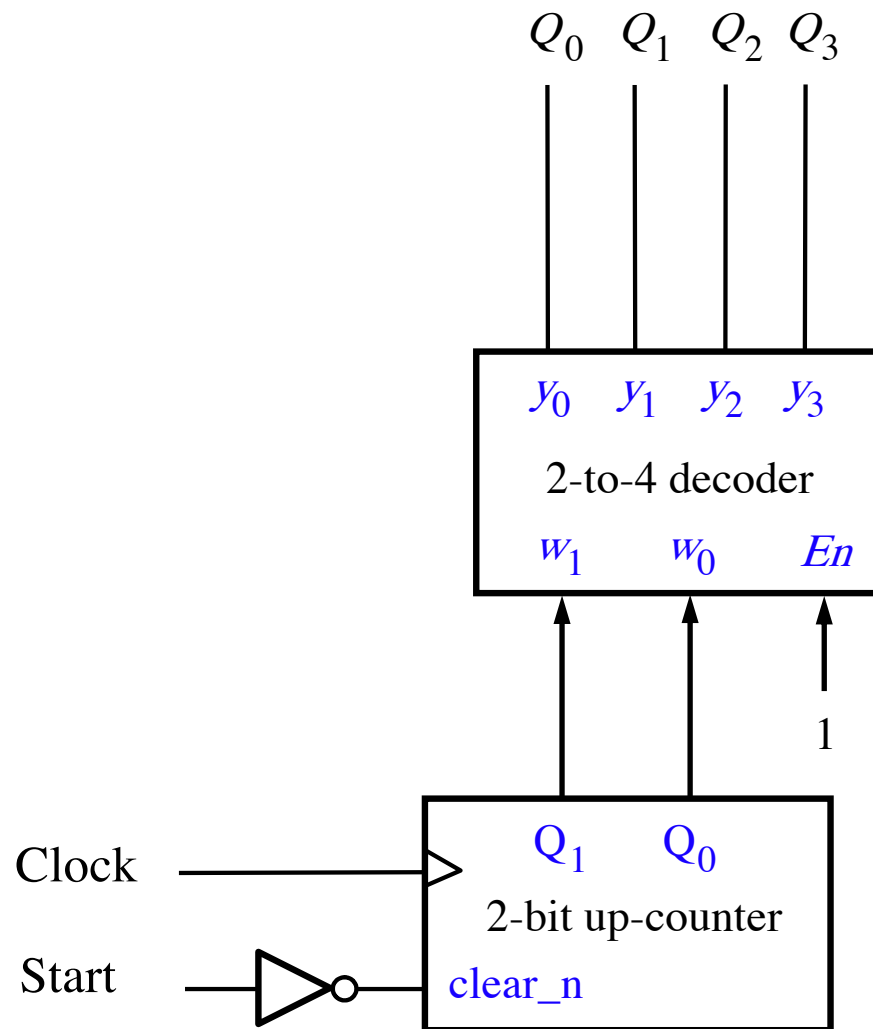
**(same as before, but shows an alternative implementation with a 4-bit ring counter)**

# Exploit the Structure of the FSM

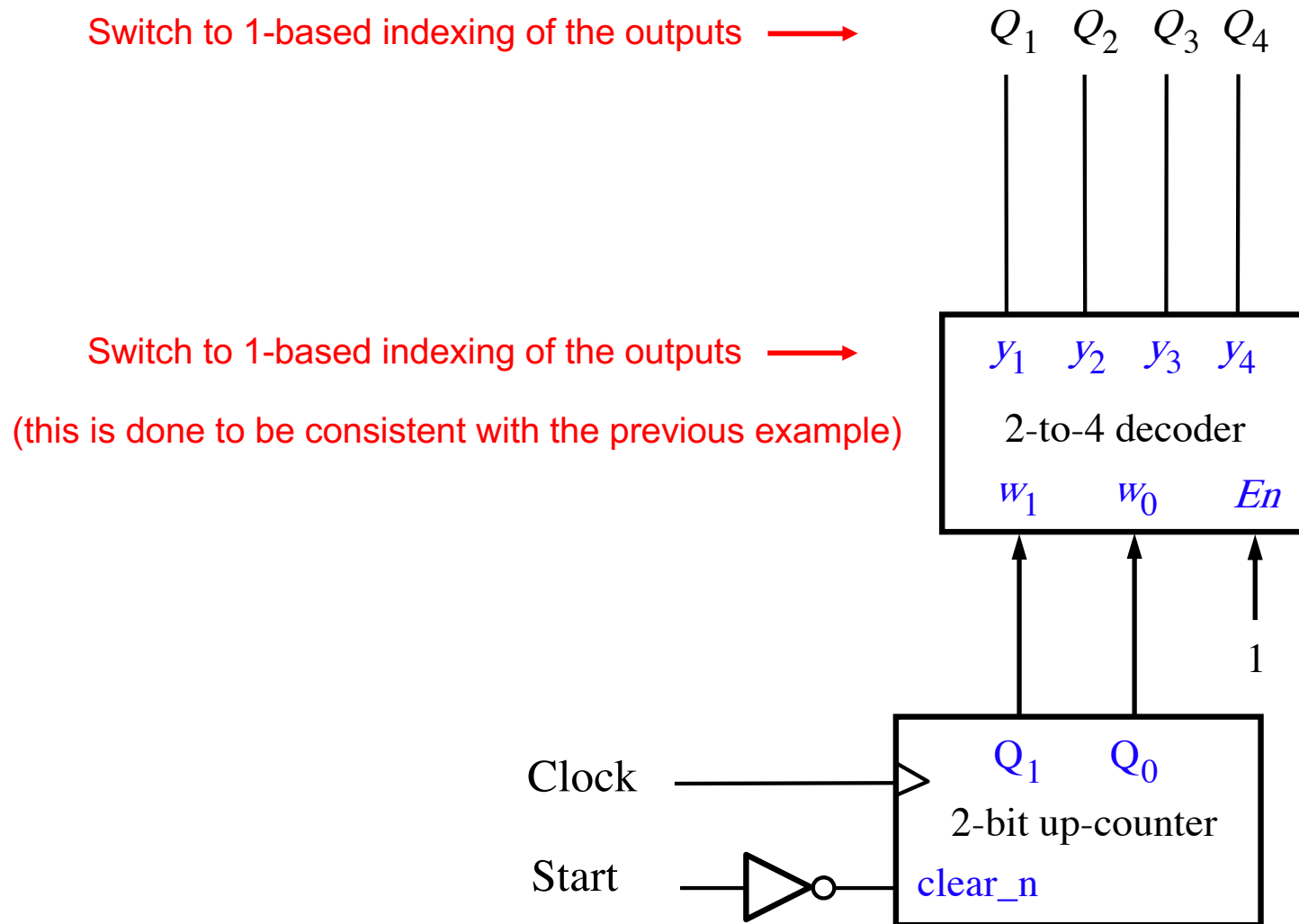


[ Figure 6.11 from the textbook ]

# Alternative version of a 4-bit ring counter

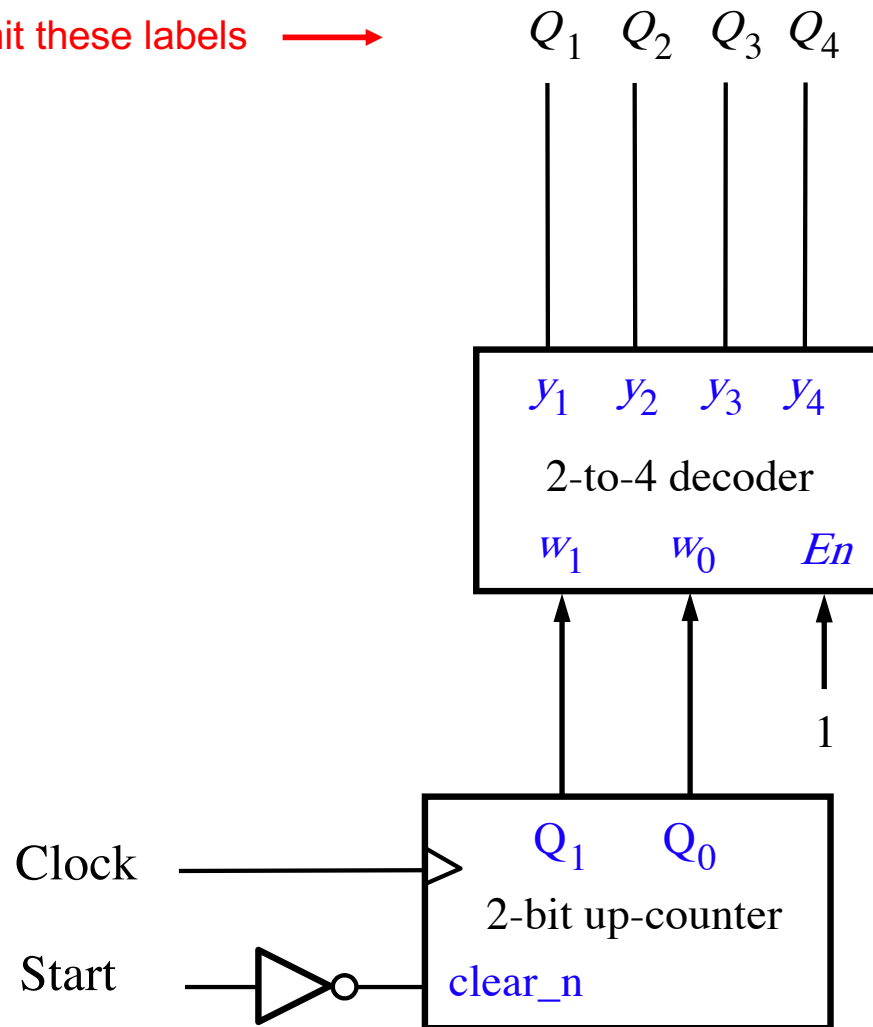


# Alternative version of a 4-bit ring counter

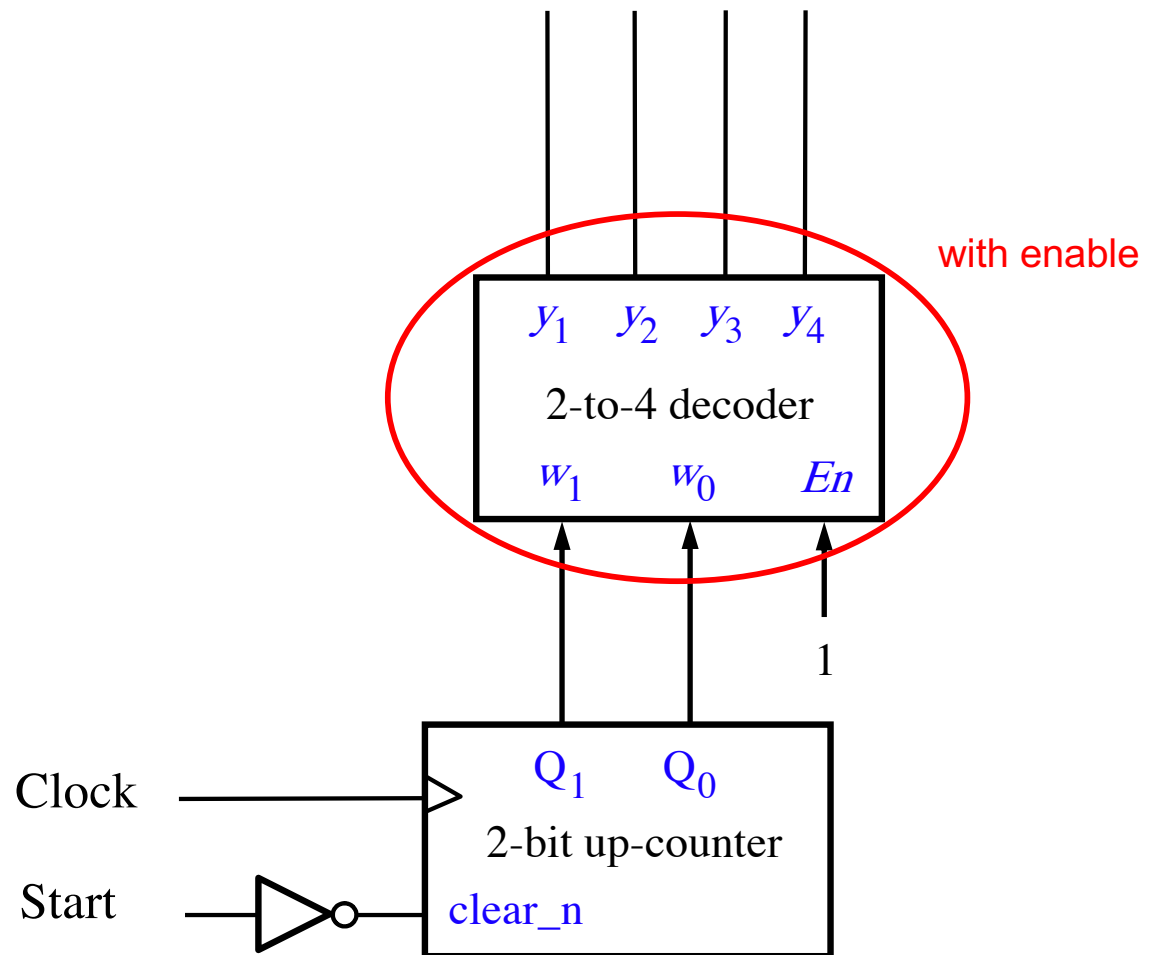


# Alternative version of a 4-bit ring counter

Also, omit these labels  $\rightarrow$

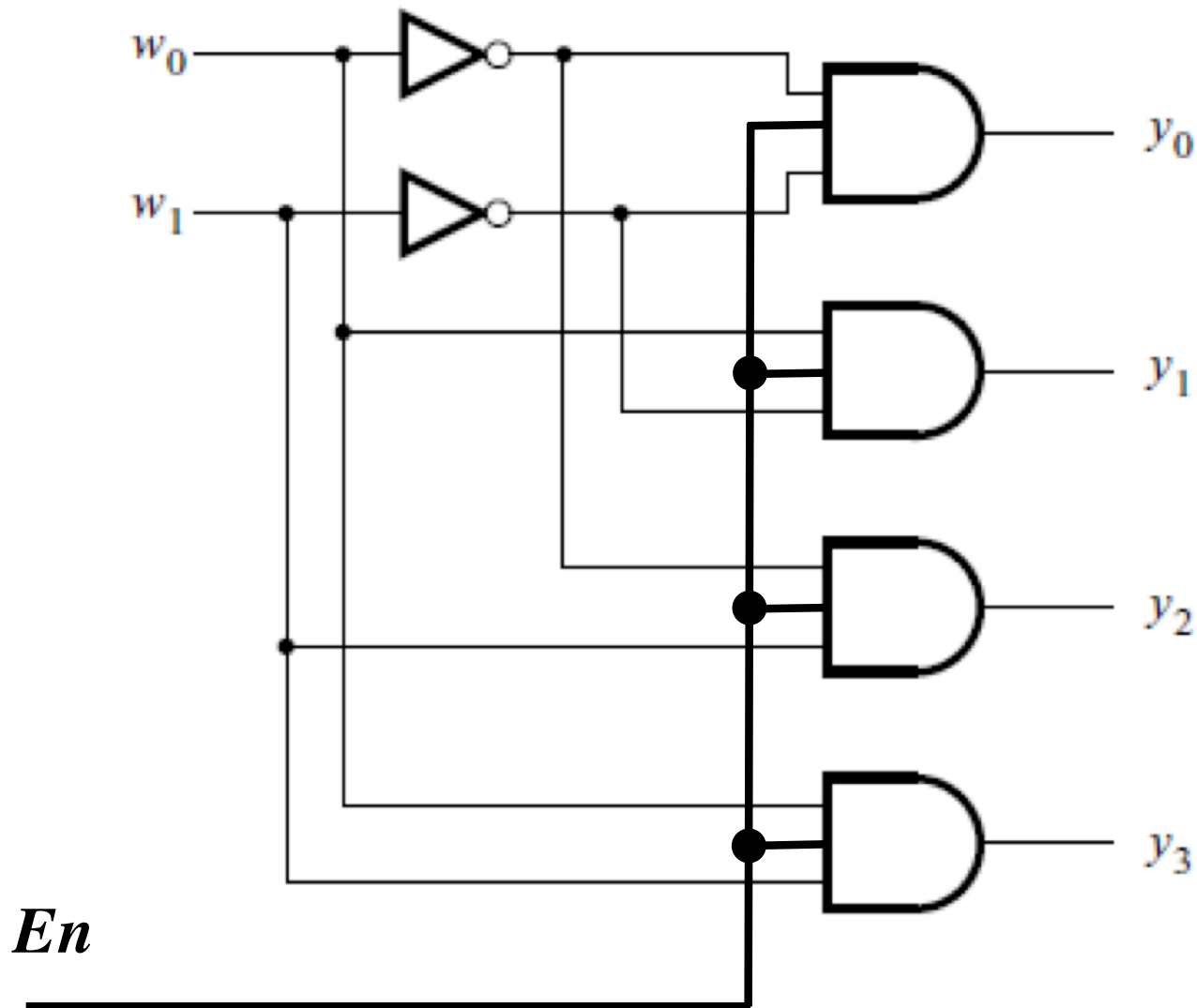


# Alternative version of a 4-bit ring counter



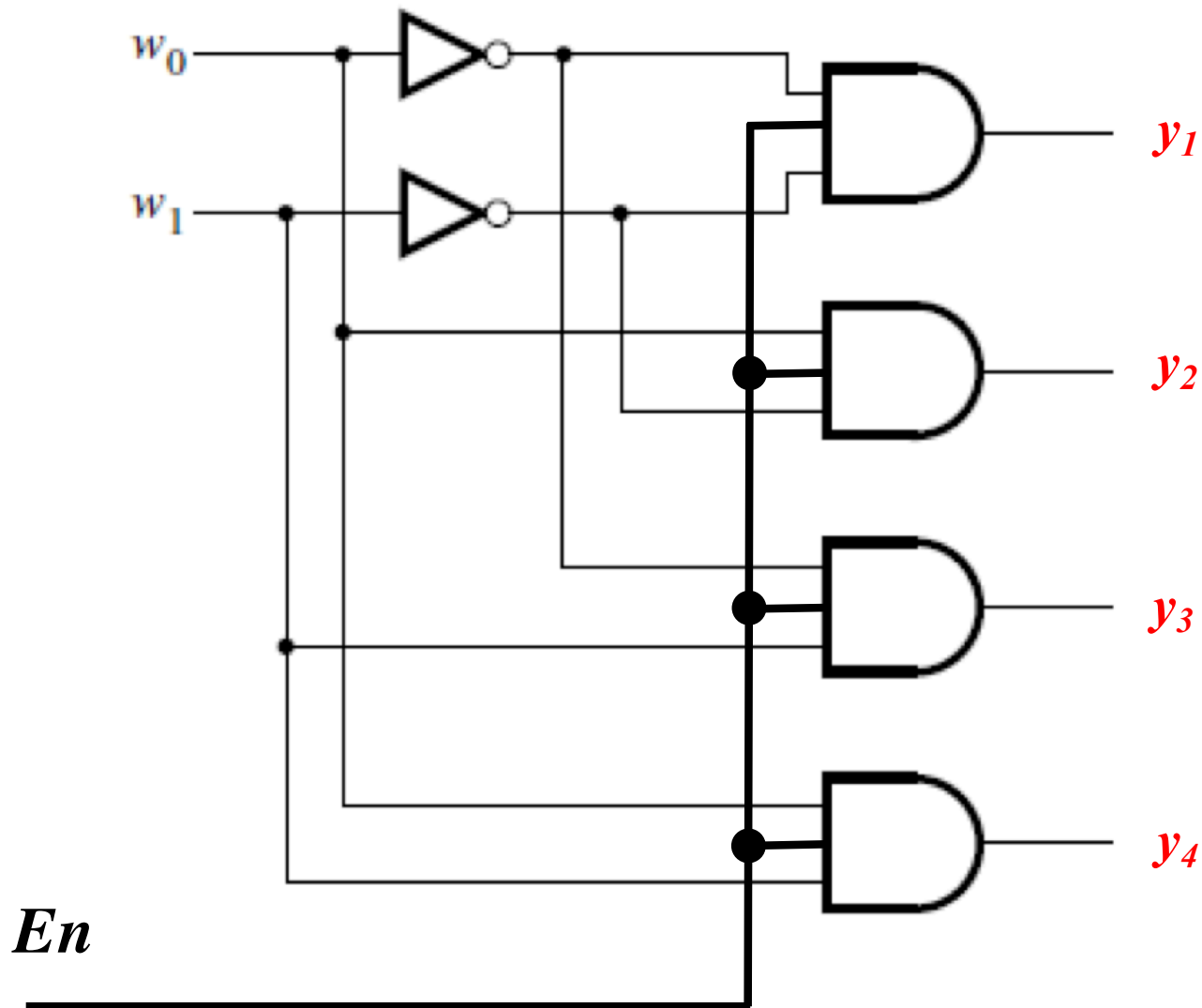


# 2-to-4 Decoder with Enable Input



[ Figure 4.14c from the textbook ]

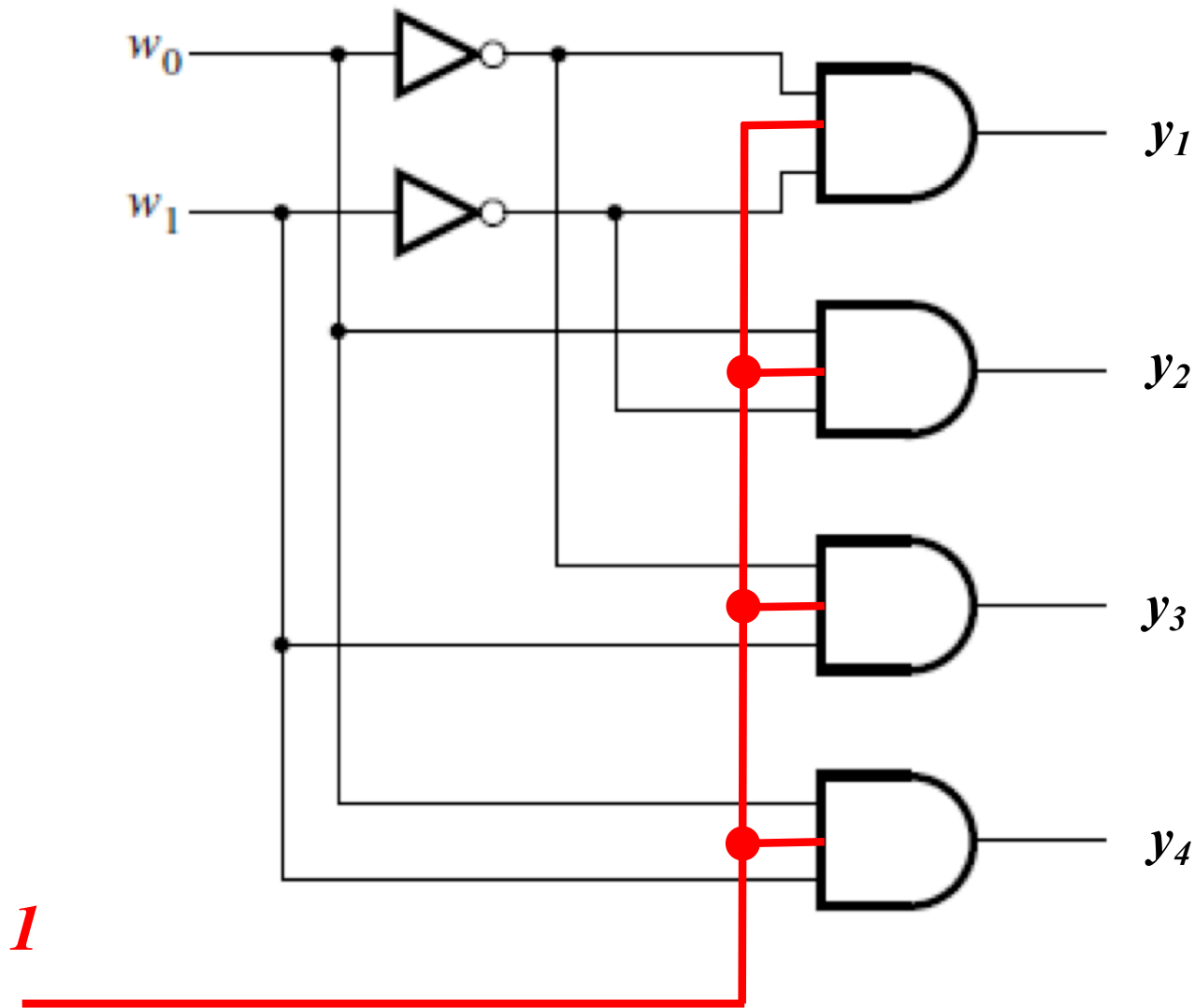
# 2-to-4 Decoder with Enable Input



Switch to 1-based indexing of the outputs

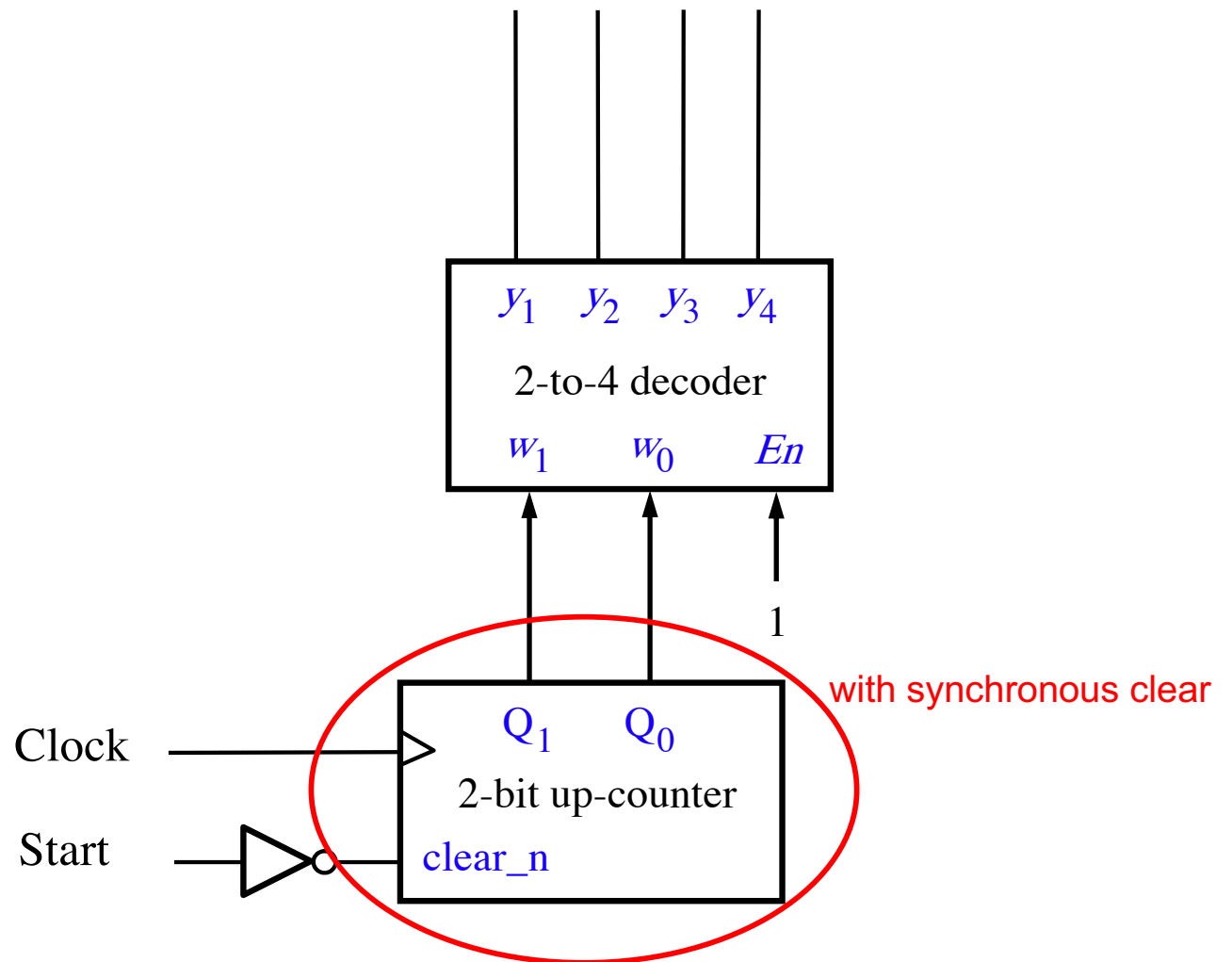
(this is done to be consistent with the previous example)

# 2-to-4 Decoder with Enable Input

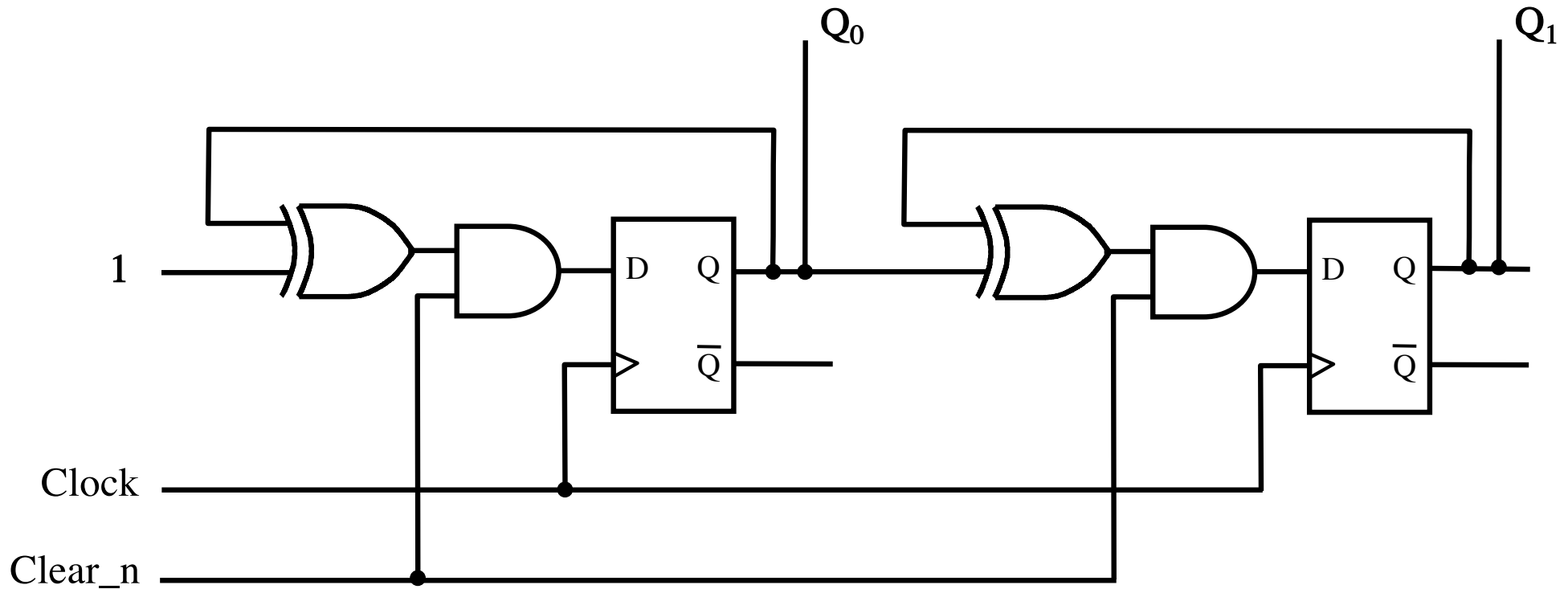


(always enabled in this example)

# Alternative version of a 4-bit ring counter

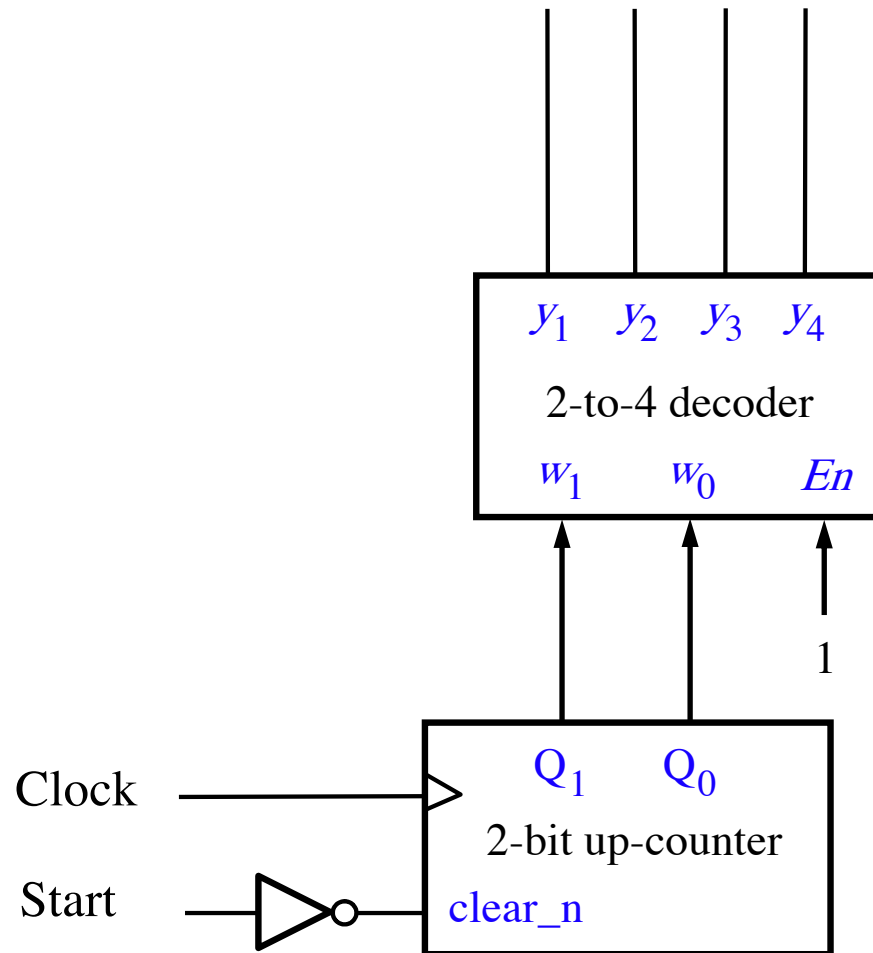


# 2-Bit Synchronous Up-Counter (with synchronous clear)

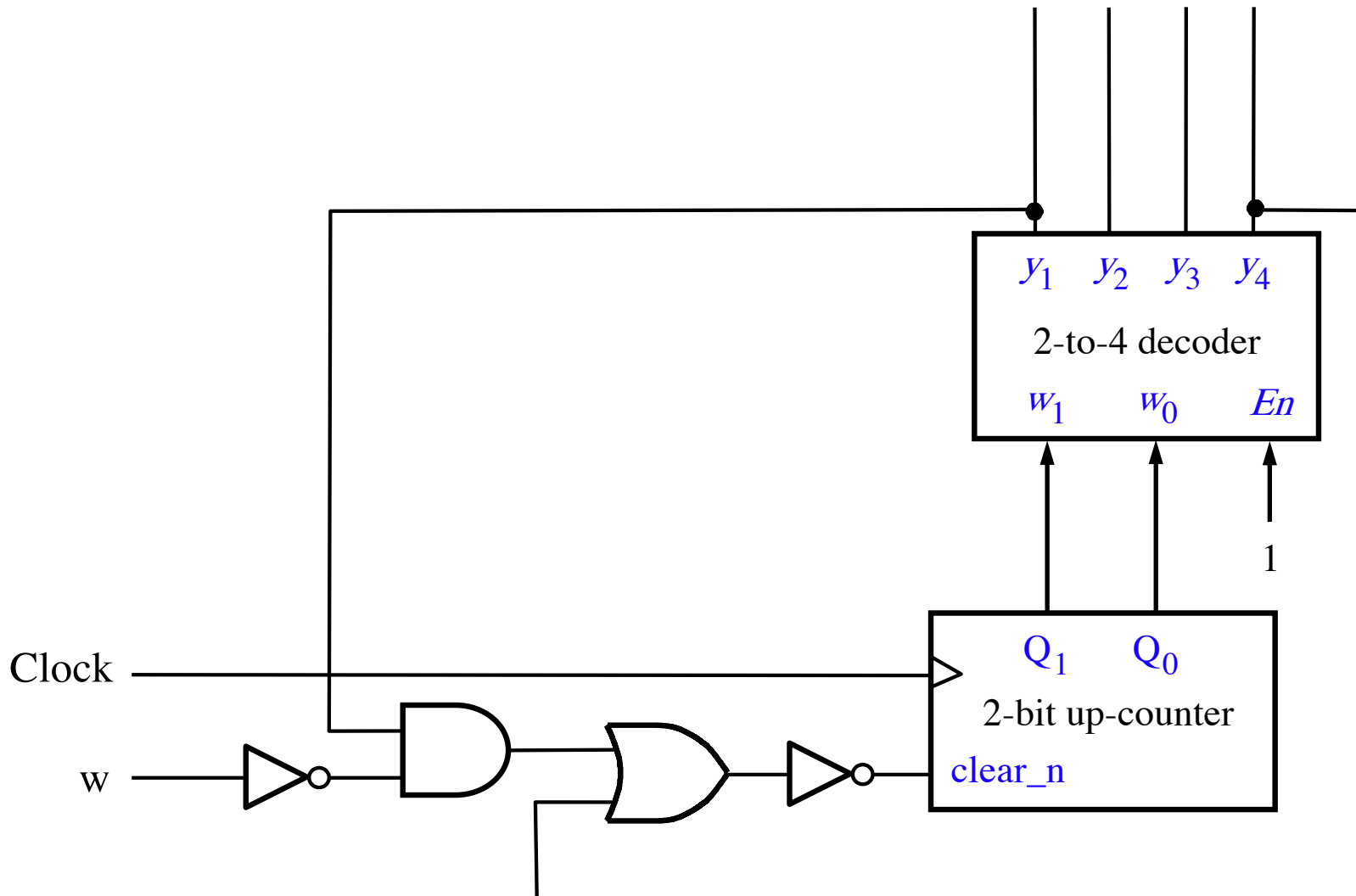


This counter can be cleared only on the positive clock edge.

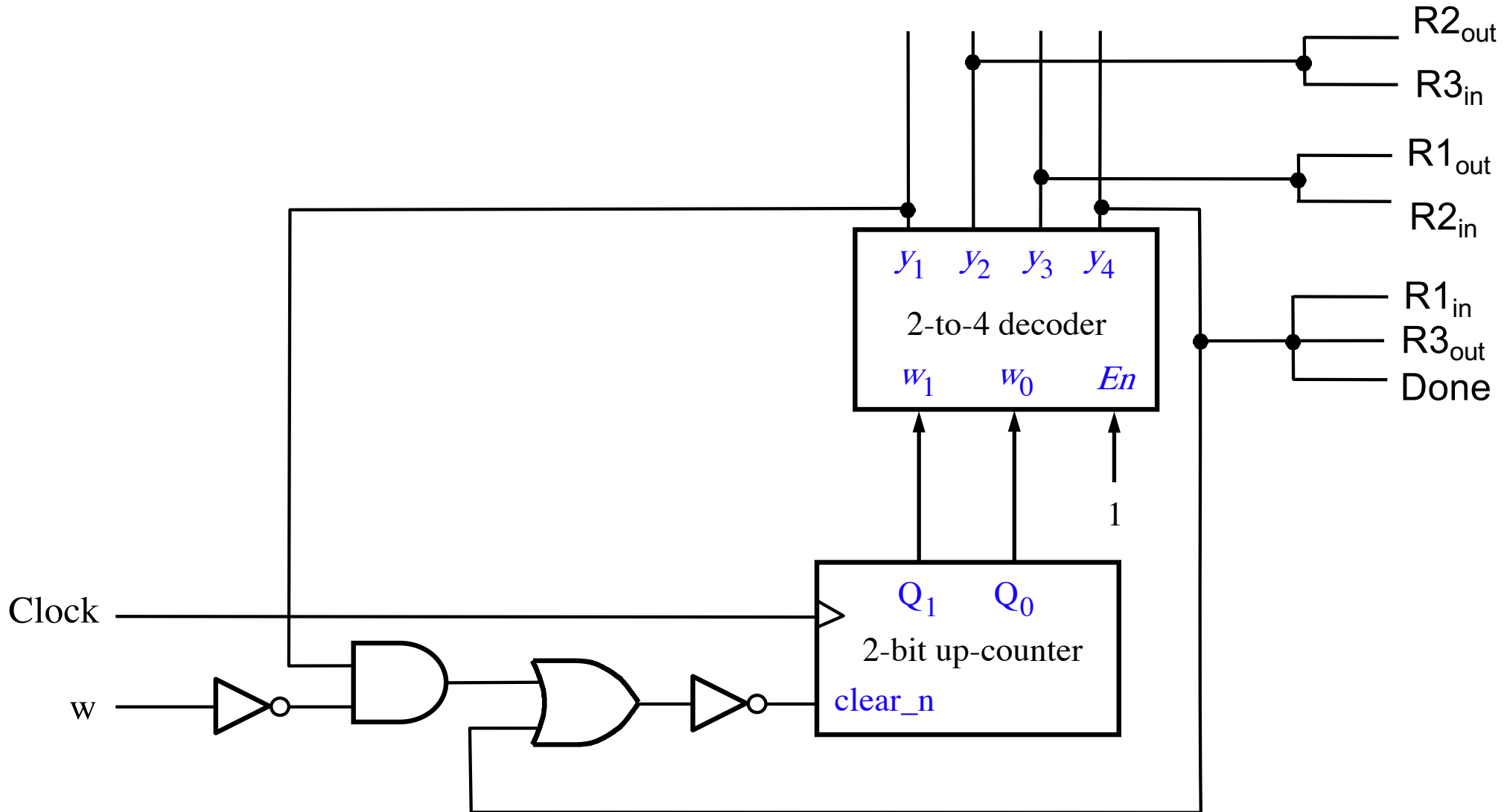
# Let's Complete the Circuit Diagram



# Let's Complete the Circuit Diagram

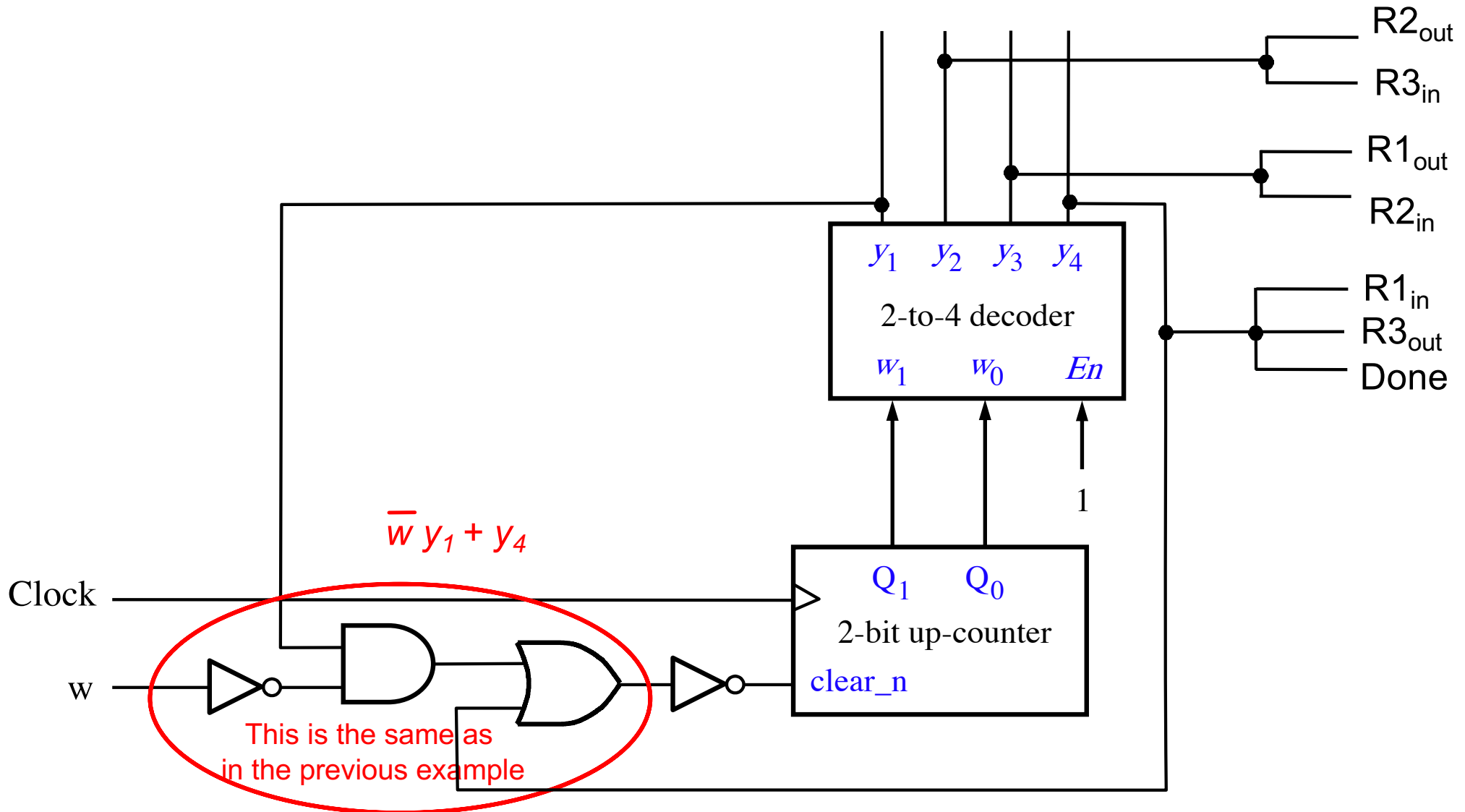


# Let's Complete the Circuit Diagram





# Let's Complete the Circuit Diagram

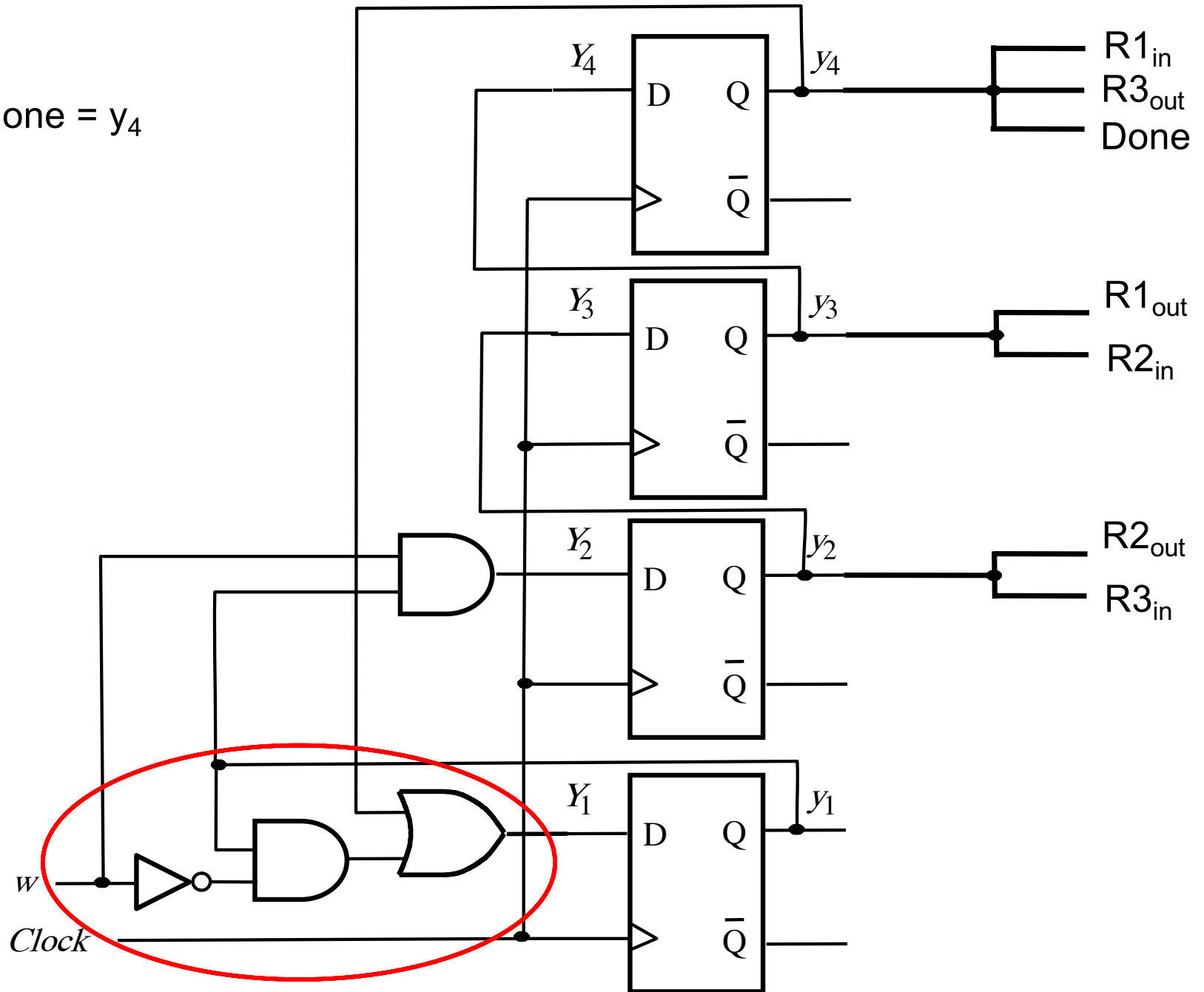


# The Solution for Encoding #3

$$R1_{out} = R2_{in} = y_3$$

$$R1_{in} = R3_{out} = Done = y_4$$

$$R2_{out} = R3_{in} = y_2$$



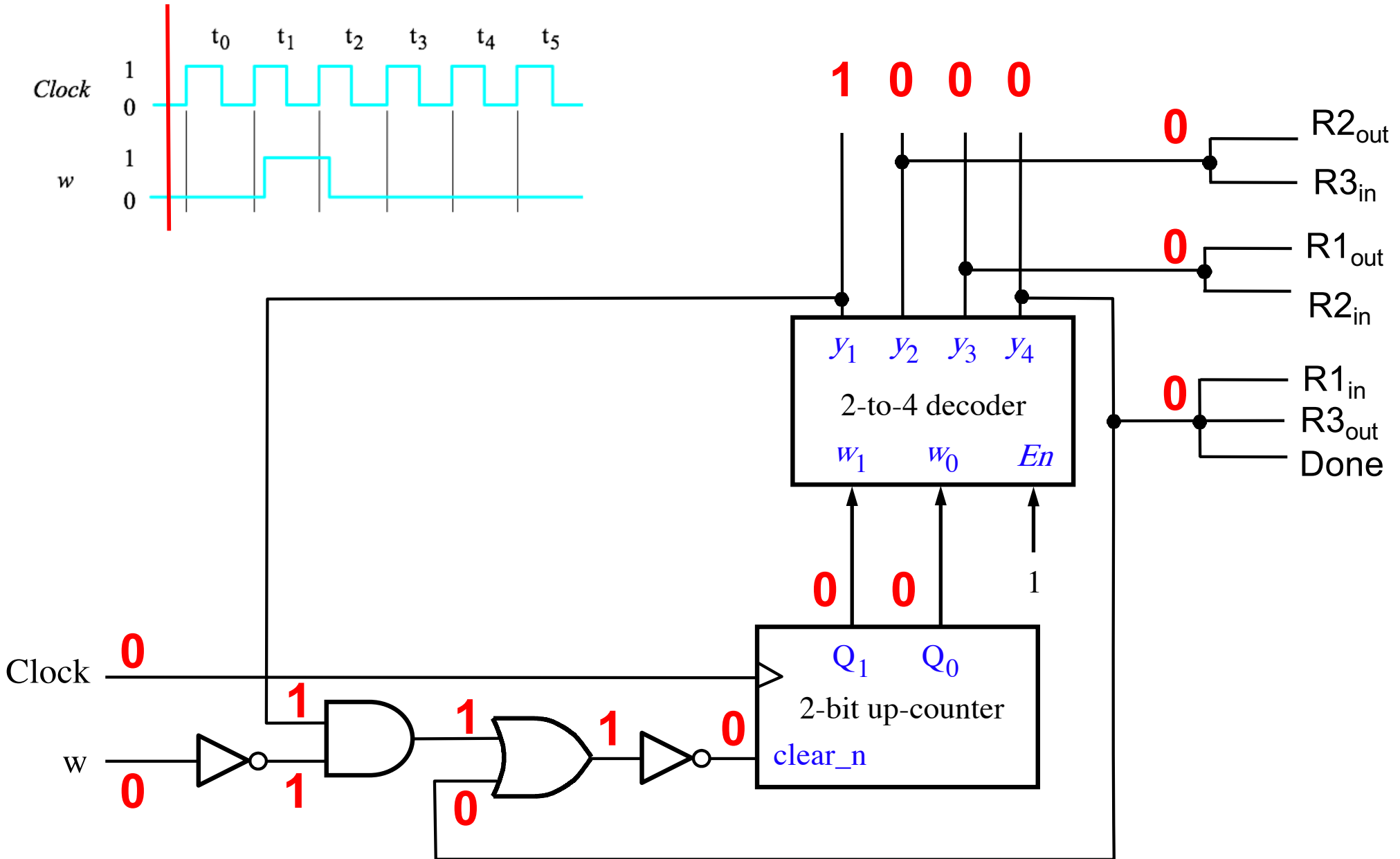
$$Y_1 = \bar{w} y_1 + y_4$$

$$Y_2 = w y_1$$

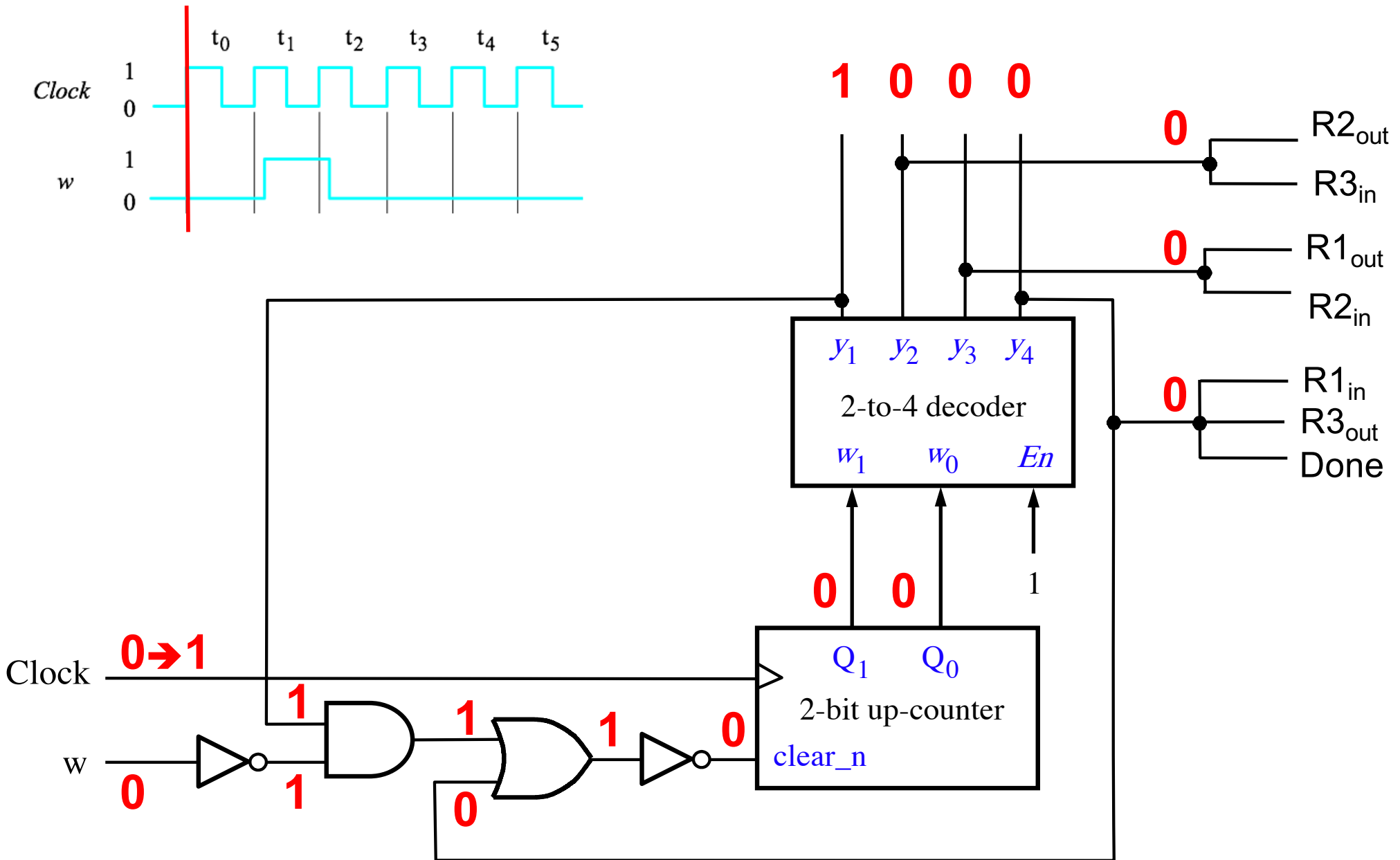
$$Y_3 = y_2$$

$$Y_4 = y_3$$

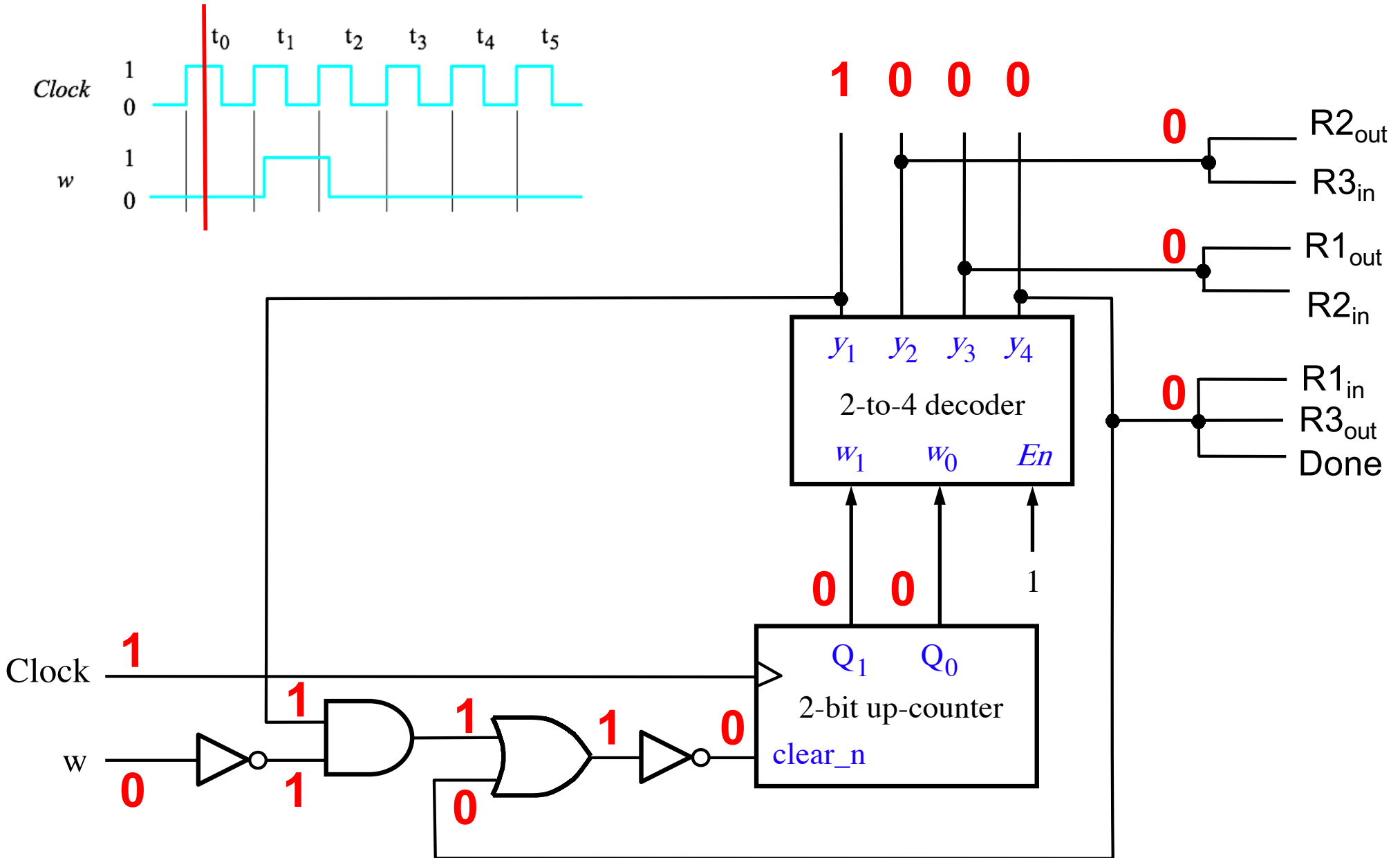
# How Does It Work?



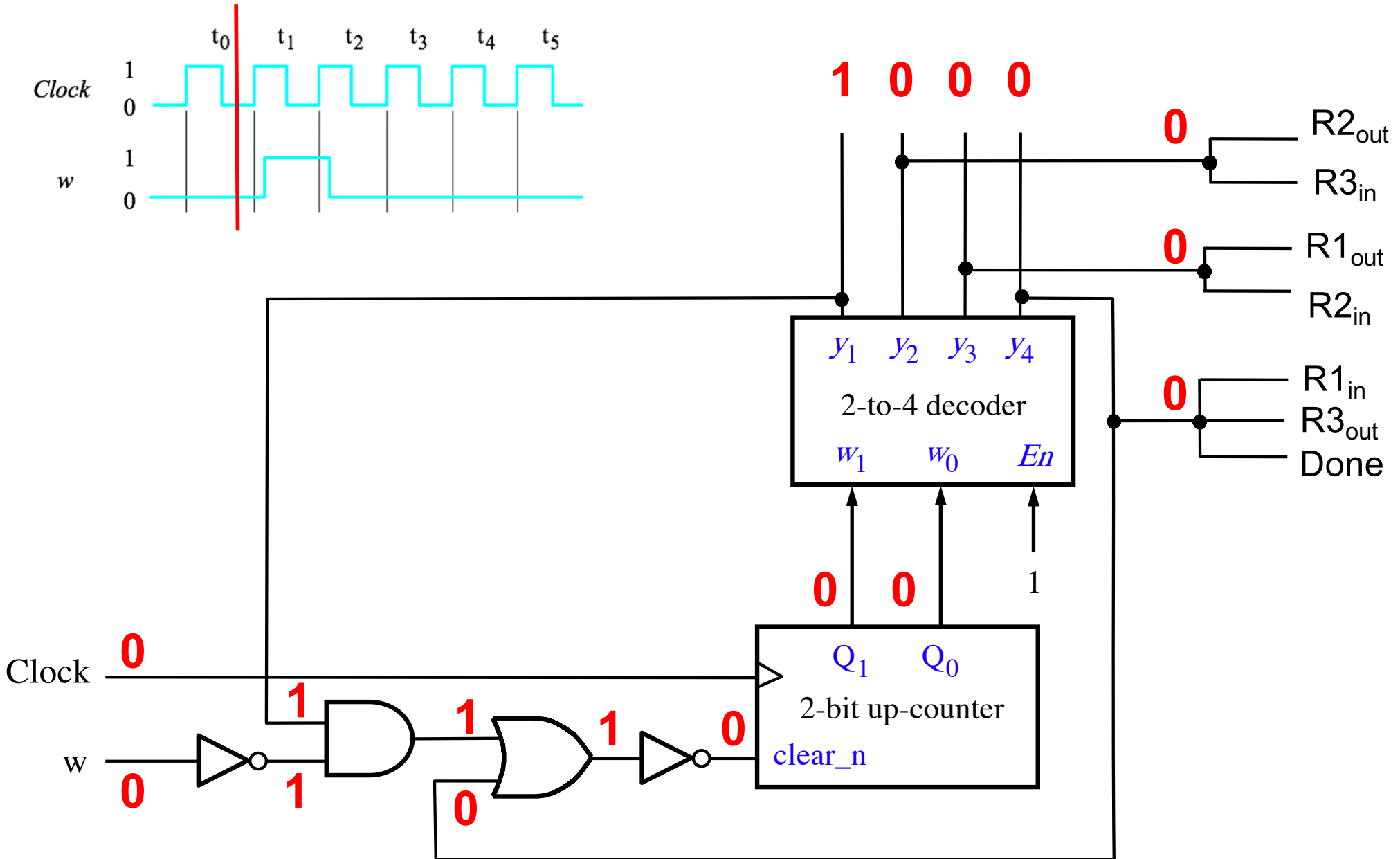
# How Does It Work?



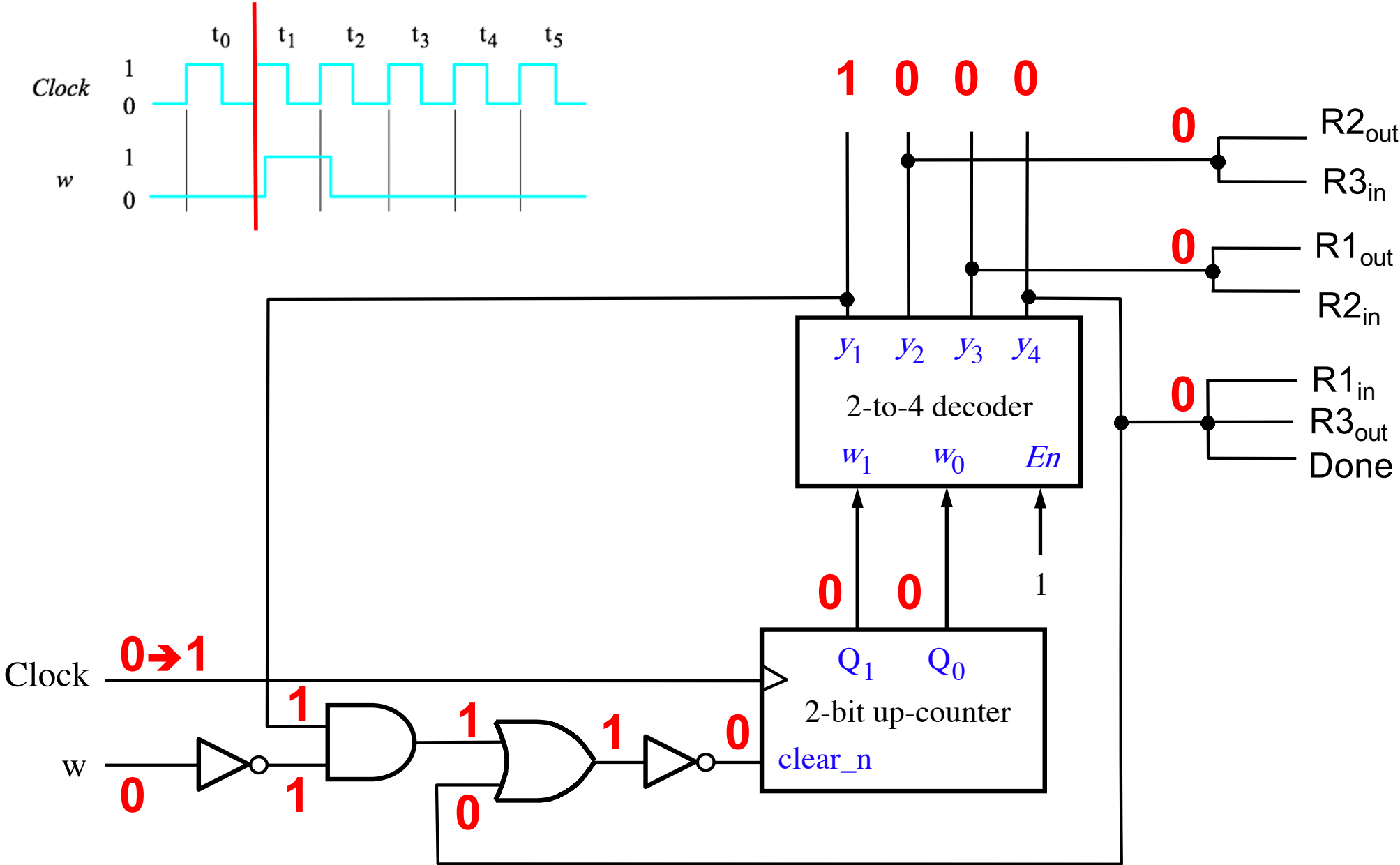
# How Does It Work?



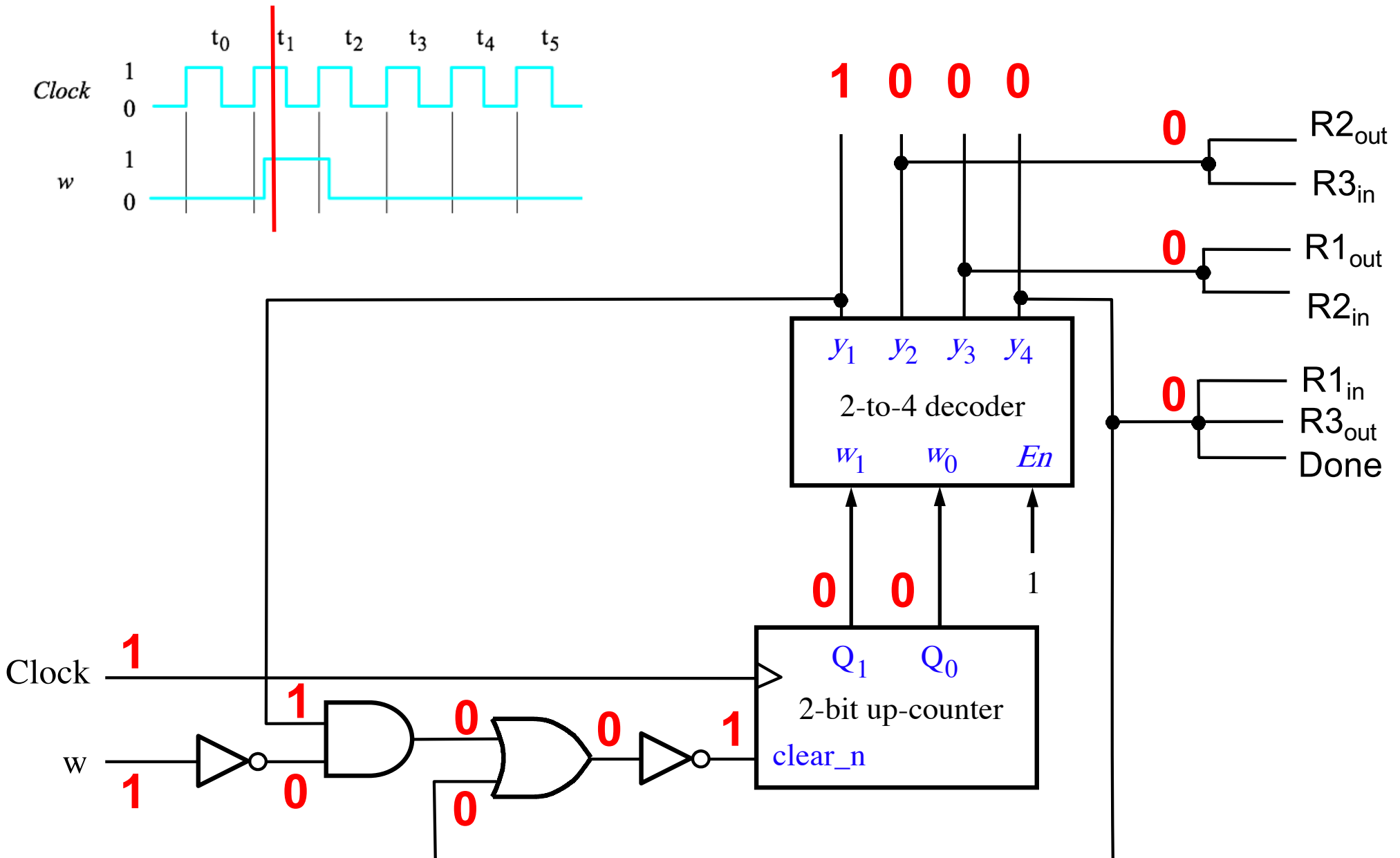
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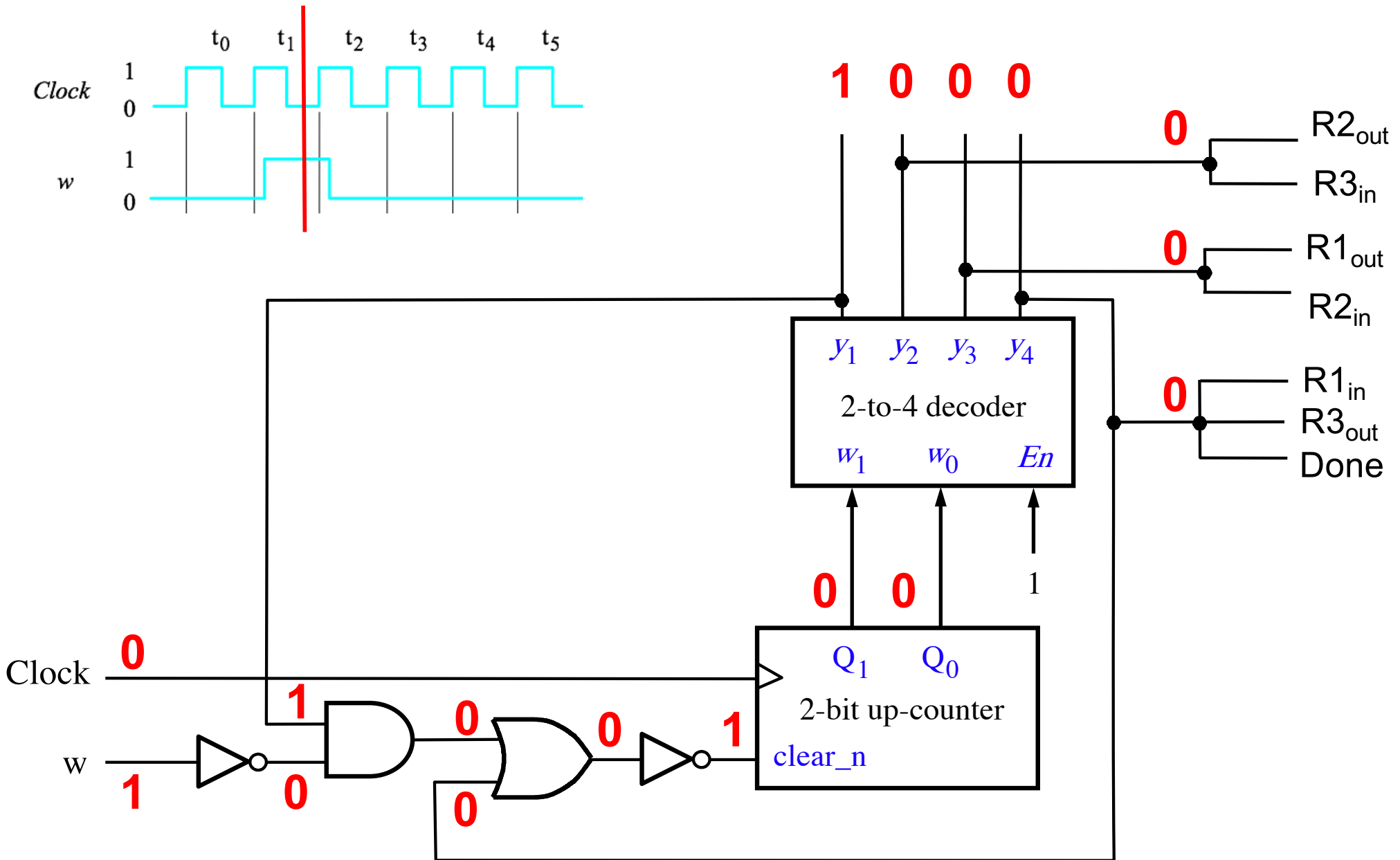


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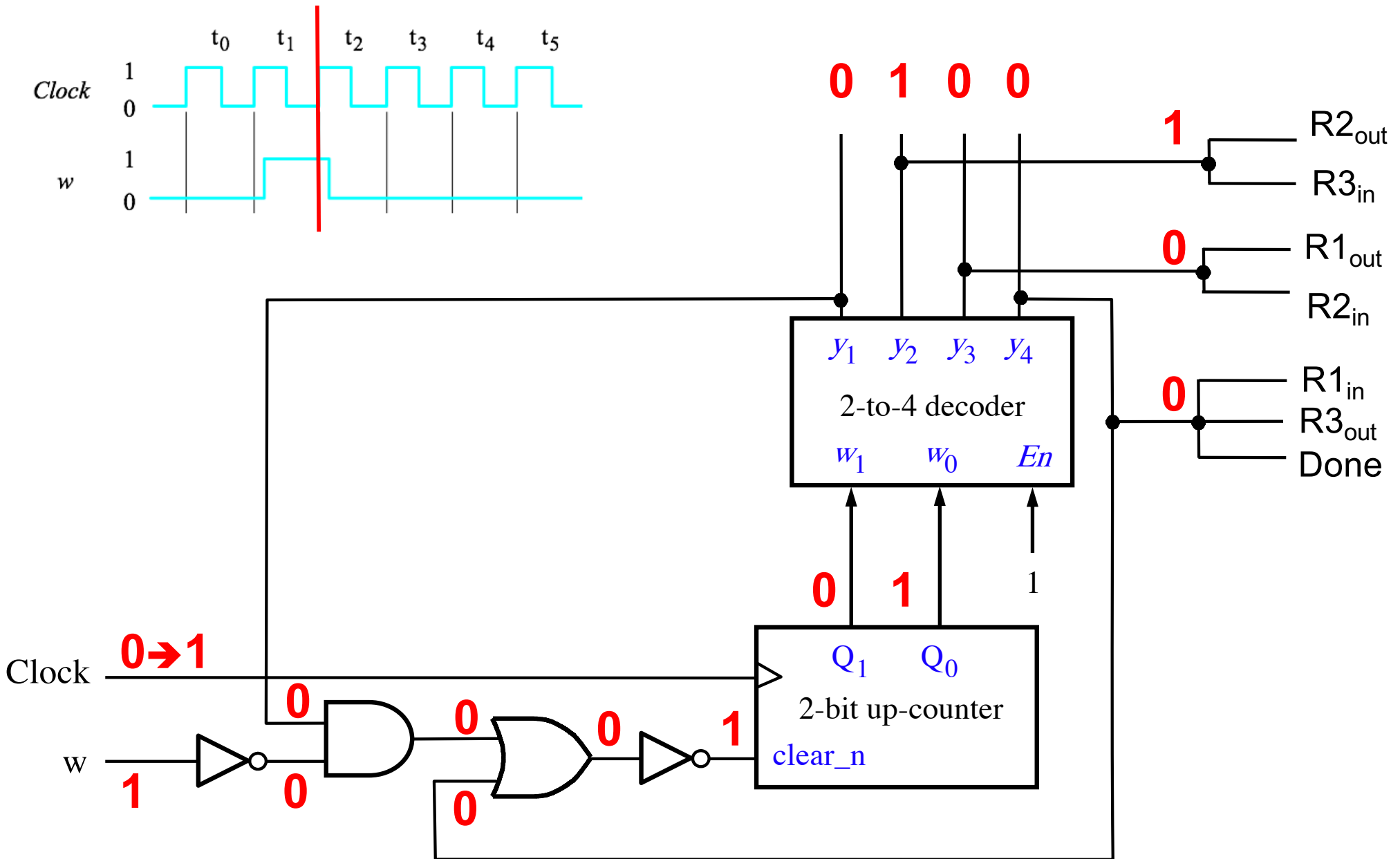




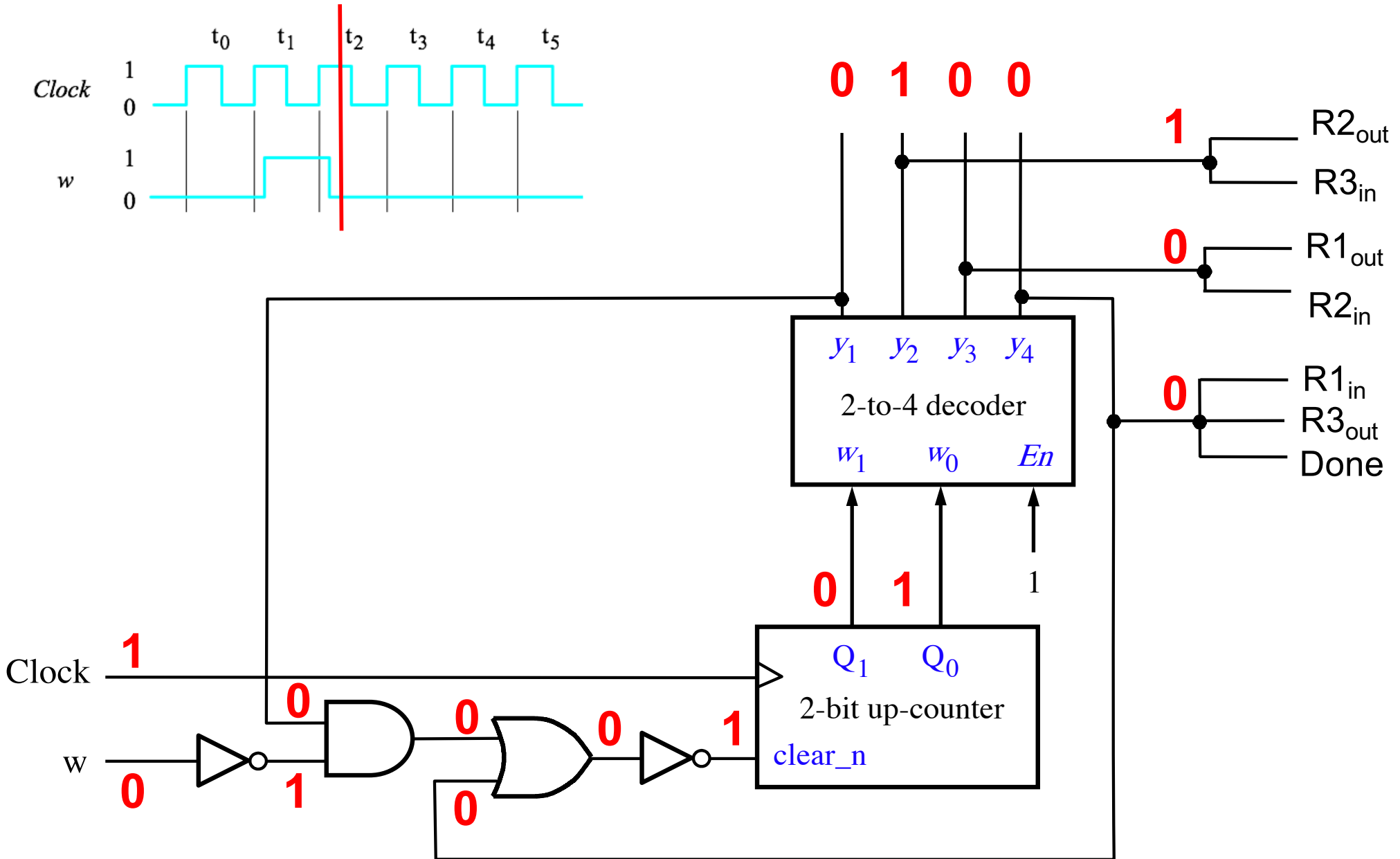
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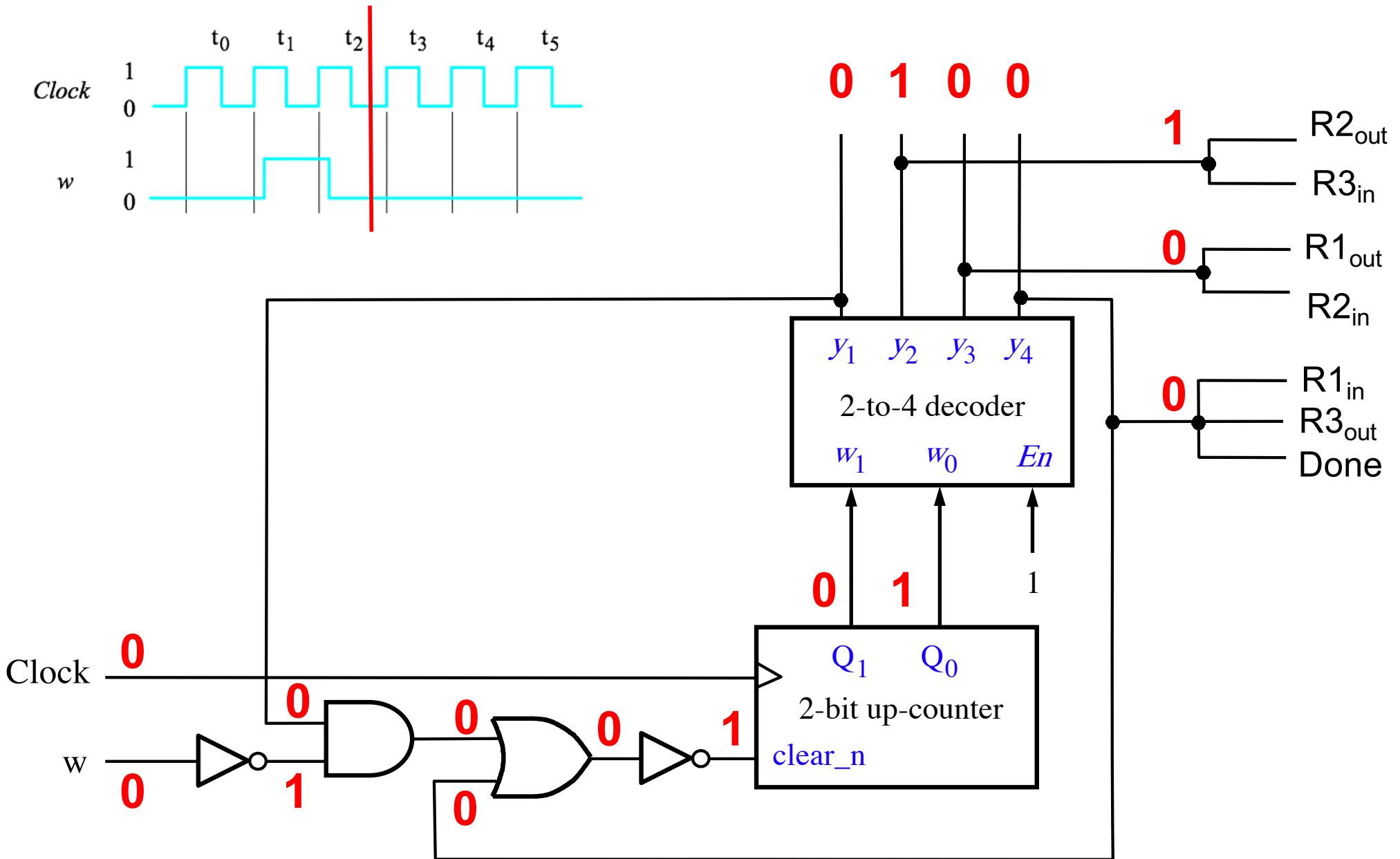
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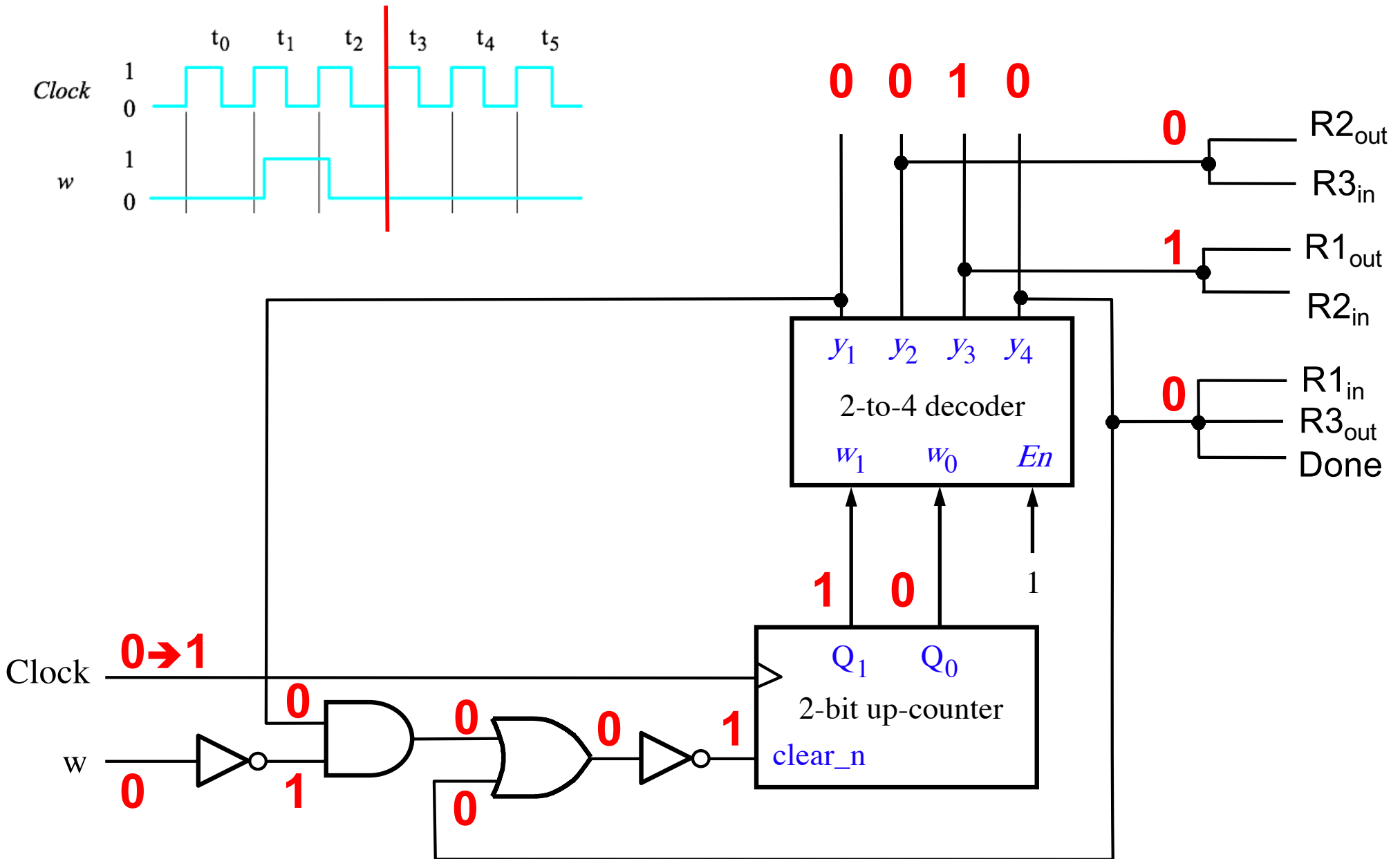
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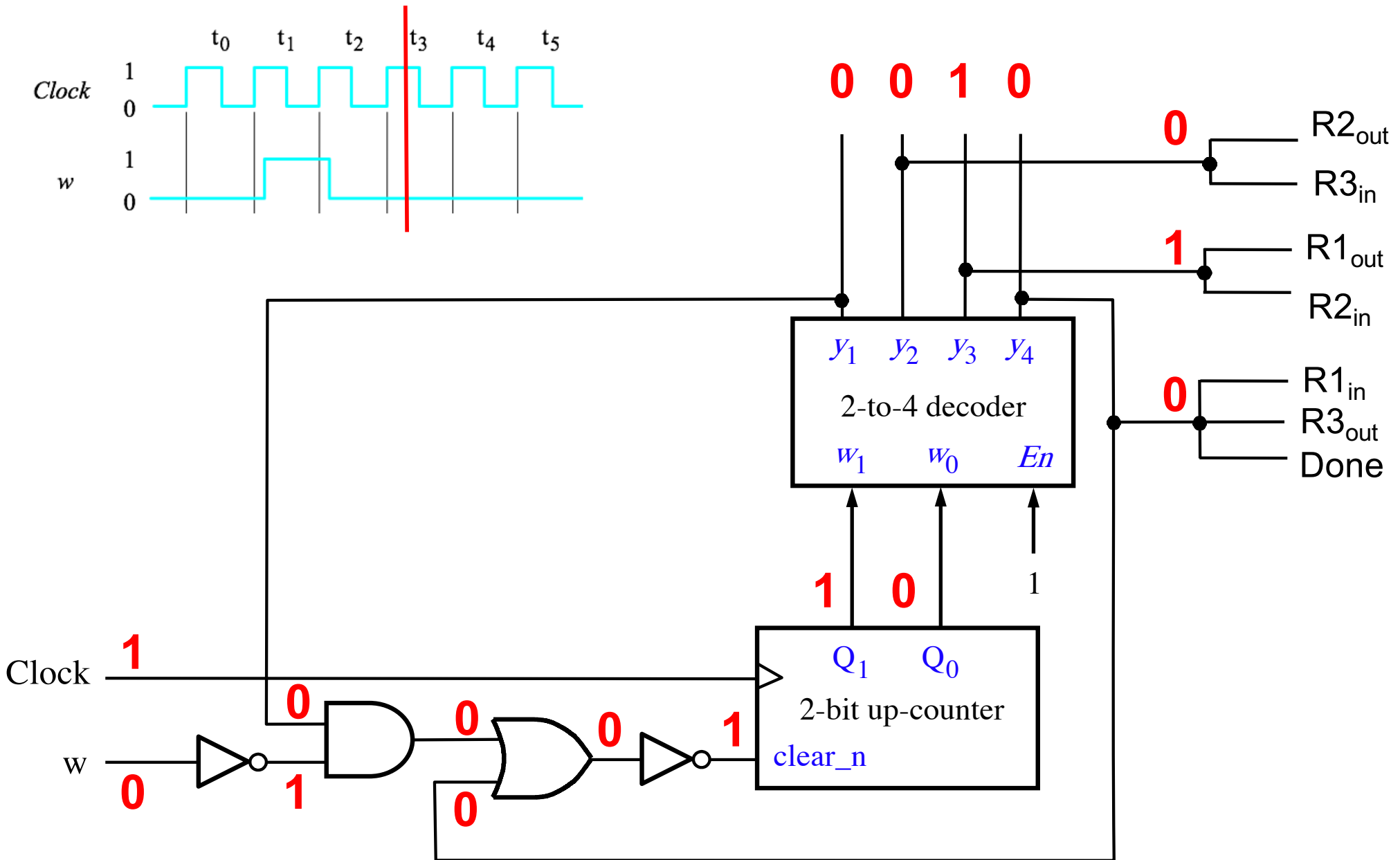
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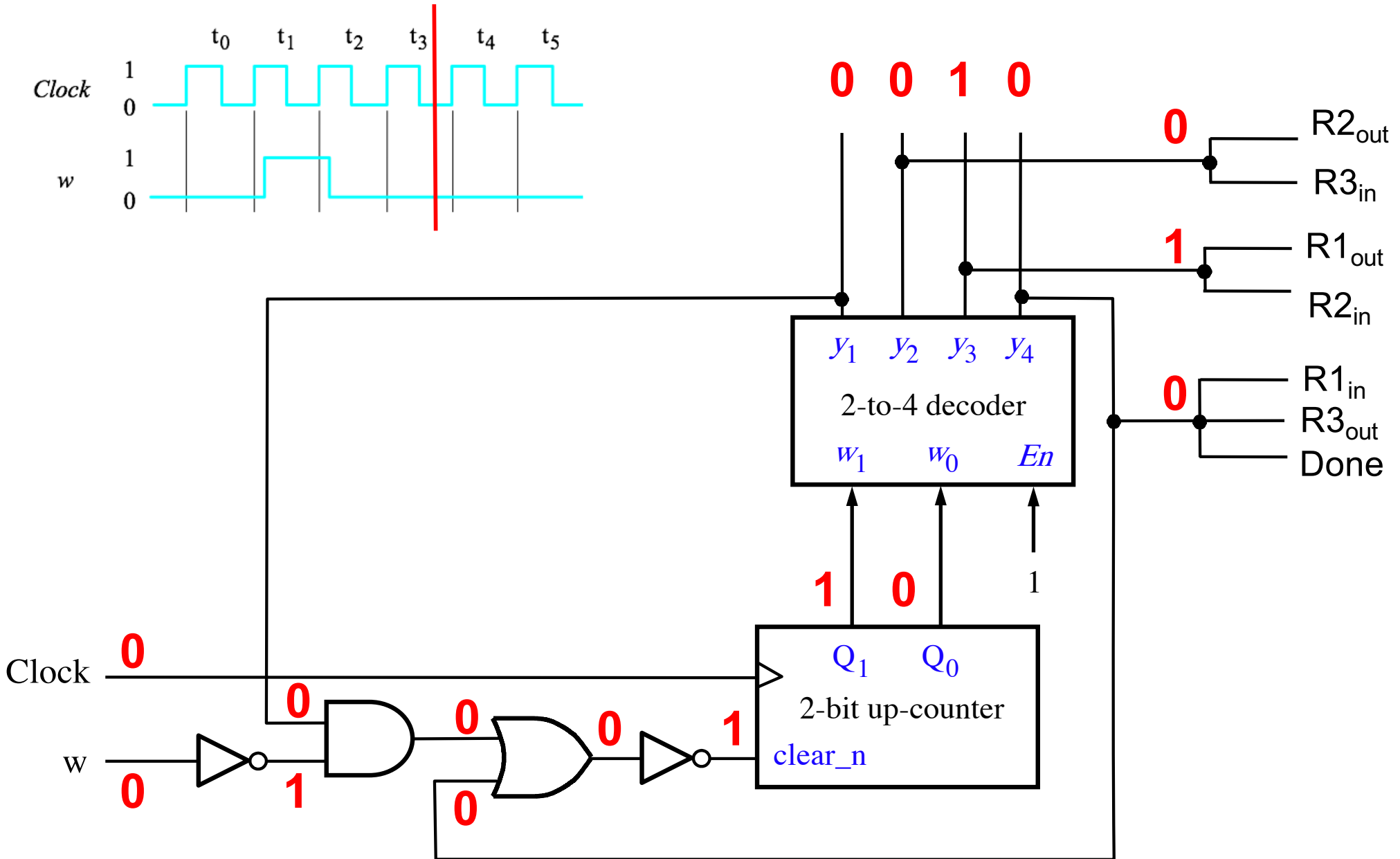
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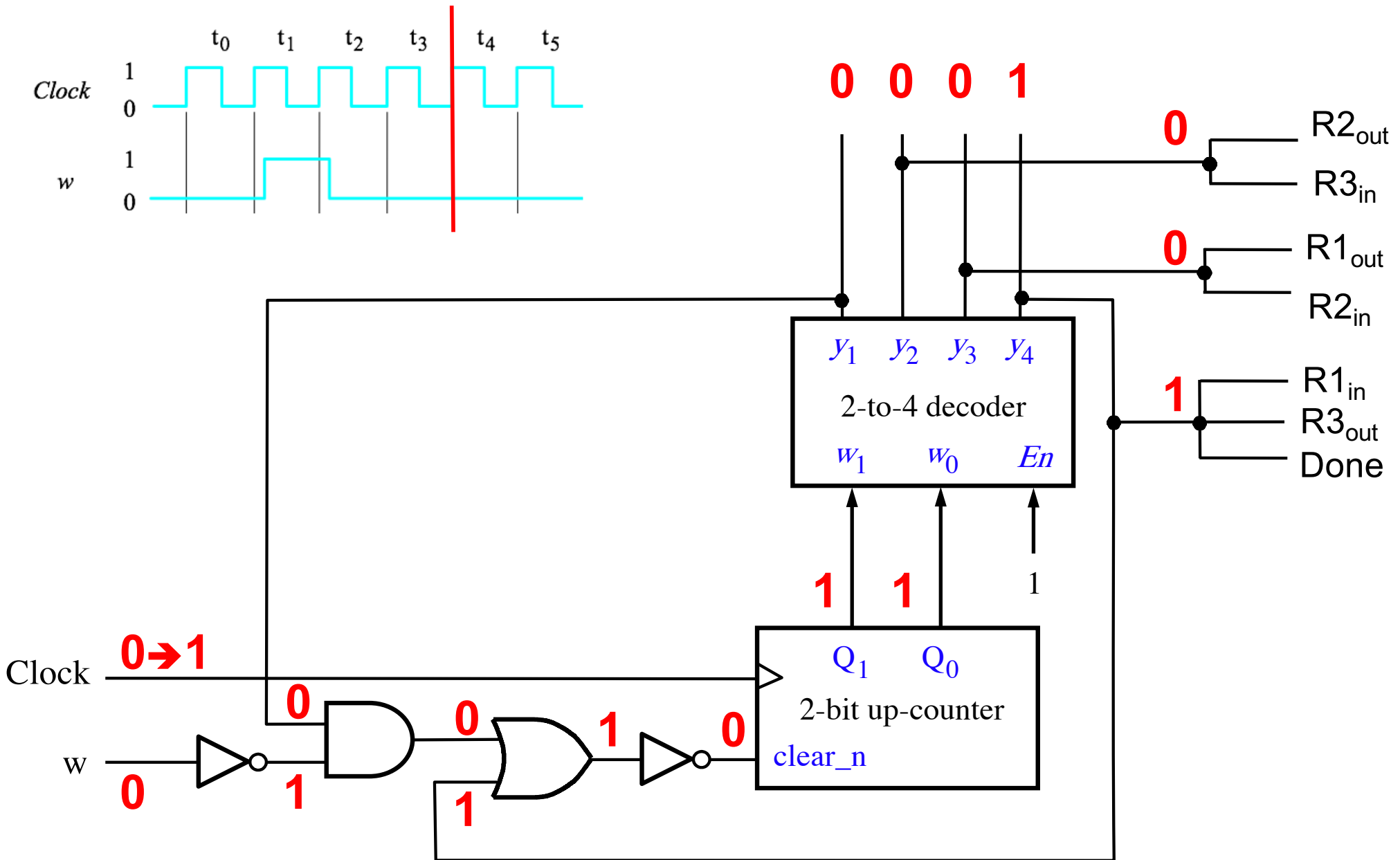
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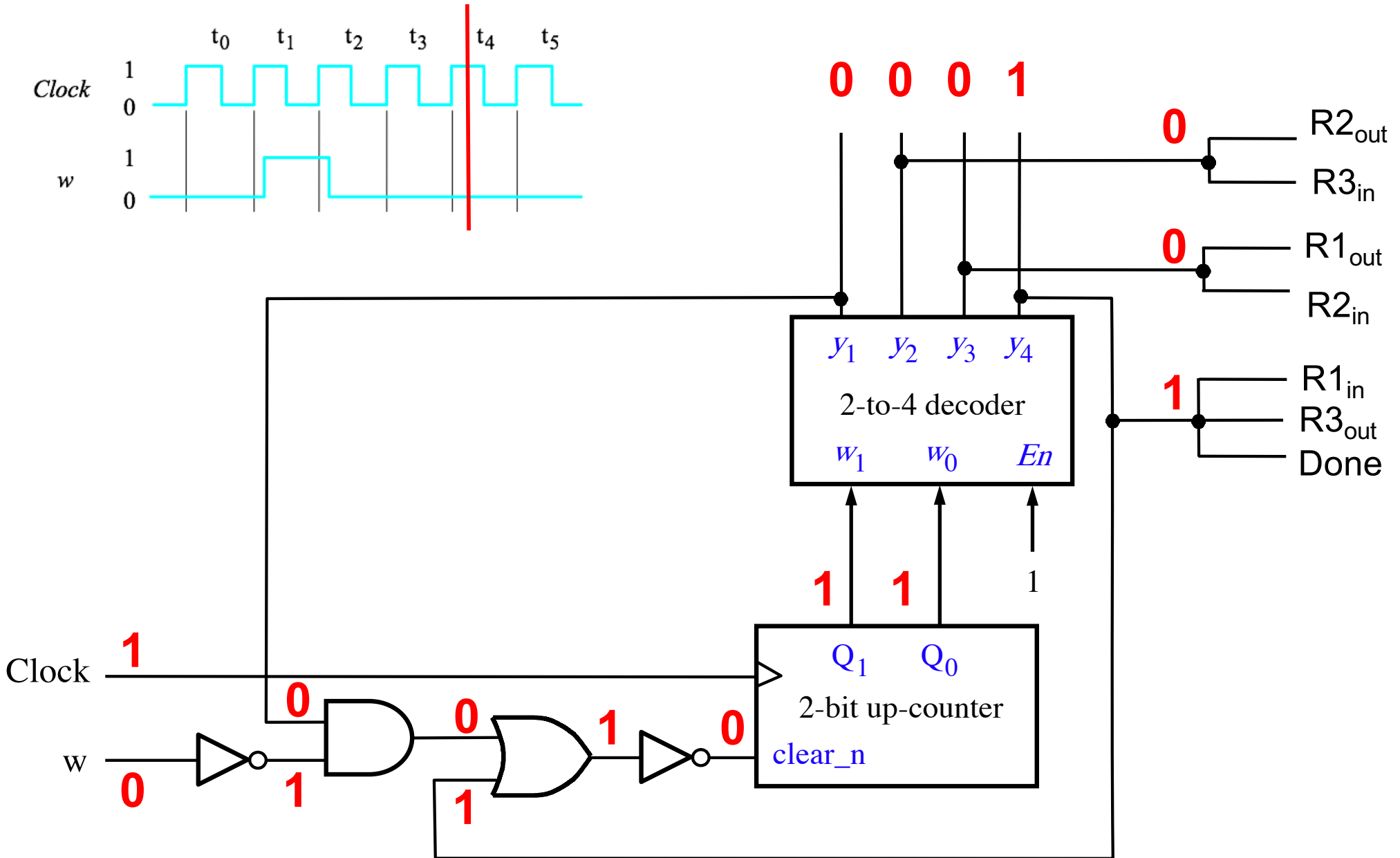


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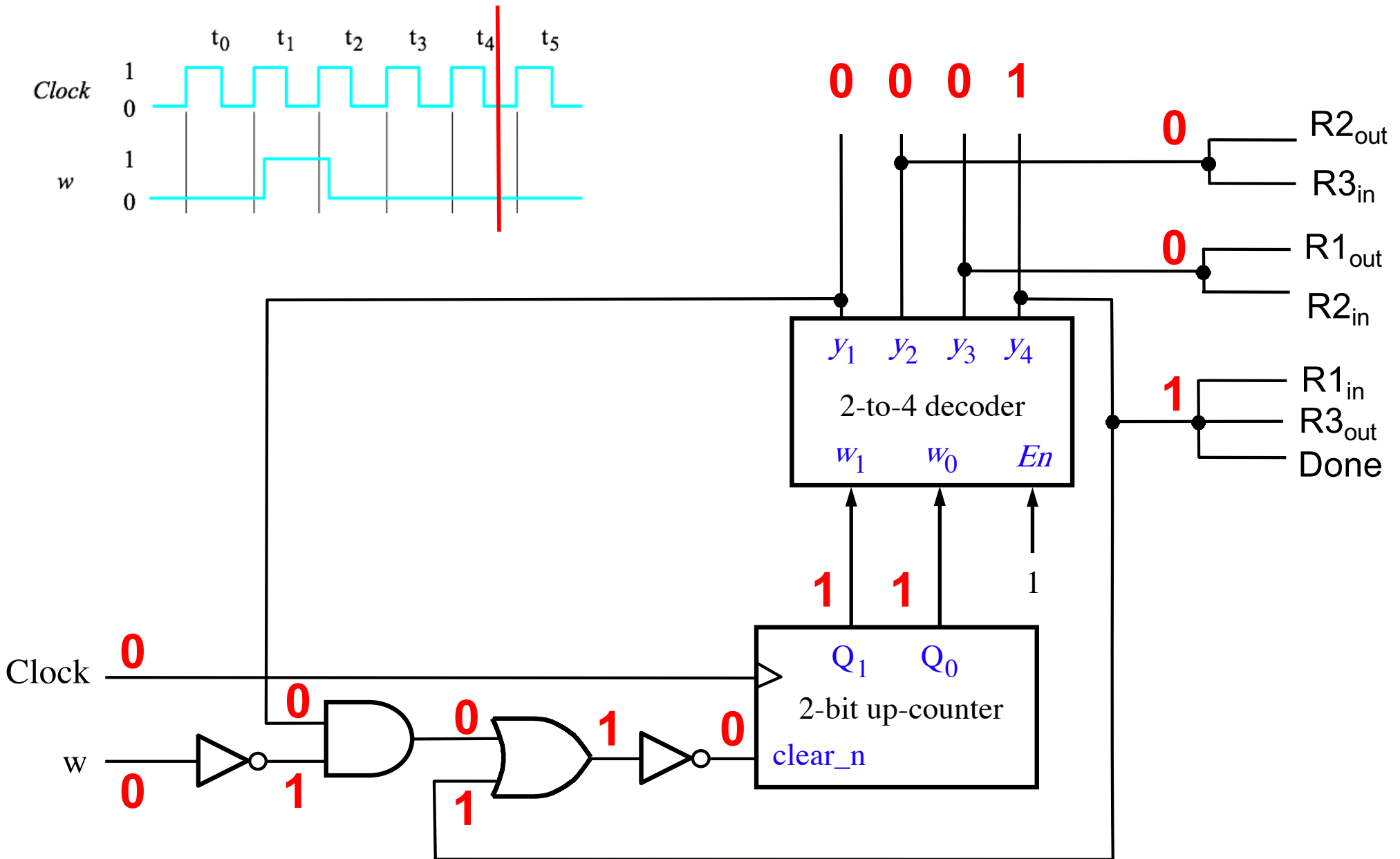




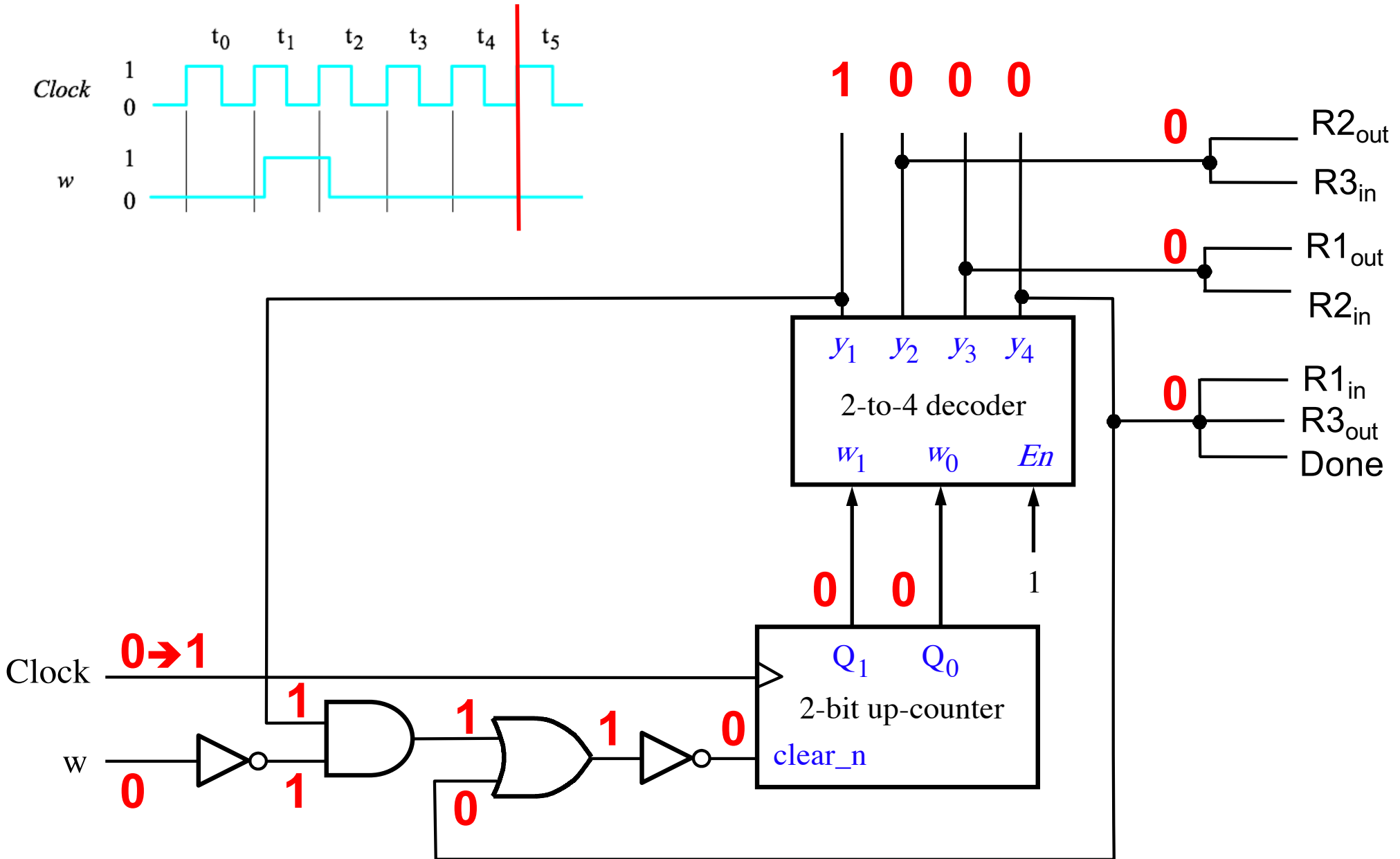
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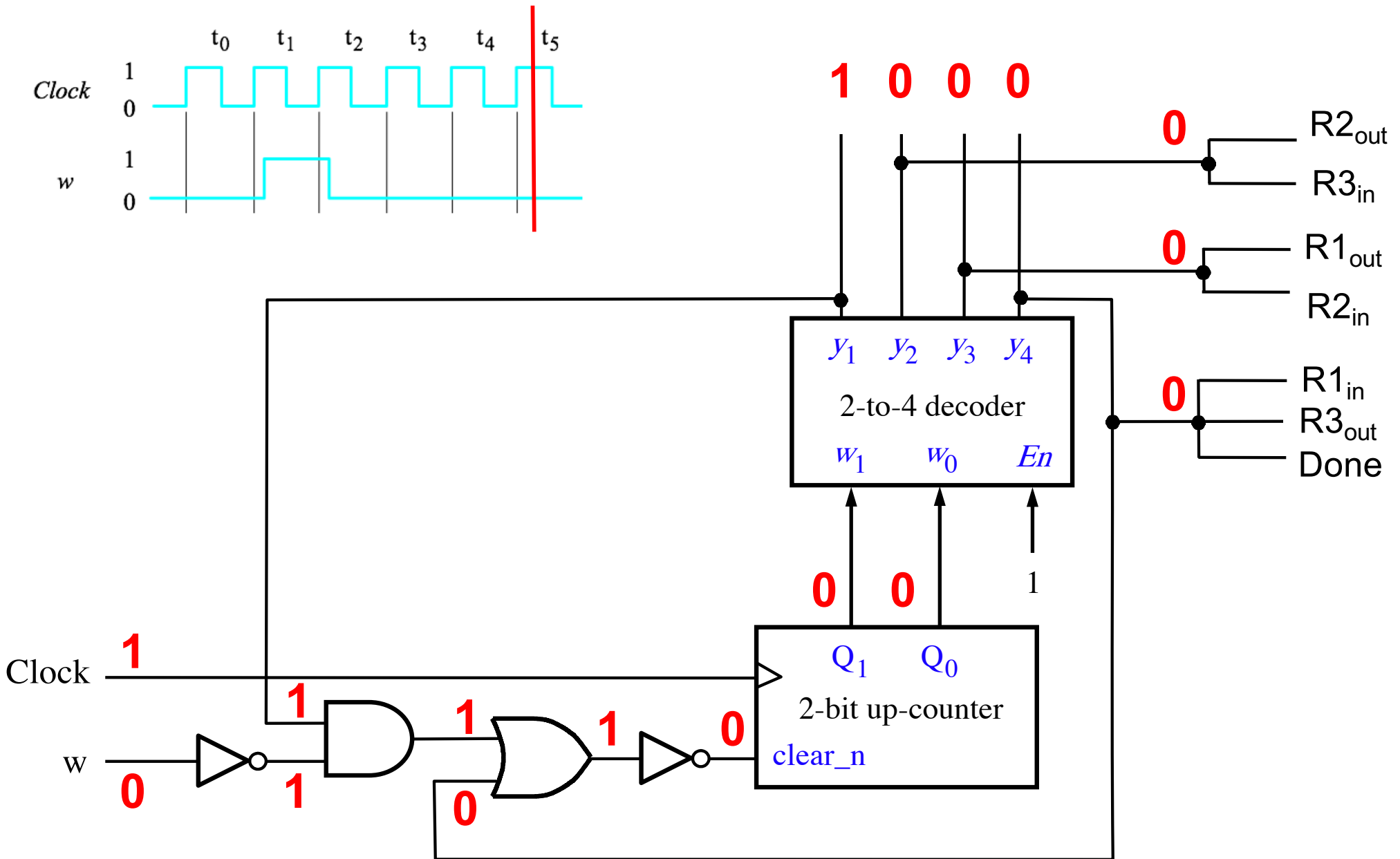
# How Does It Work?



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**Questions?**

**THE END**