

Introduction to Digital Systems

Part III (Sequential Components)

2024/2025

Sequential Synchronous
Modules/Blocks

Multibit registers, Counters and
Shift-registers

Arnaldo Oliveira, Augusto Silva, Ioulia Skliarova

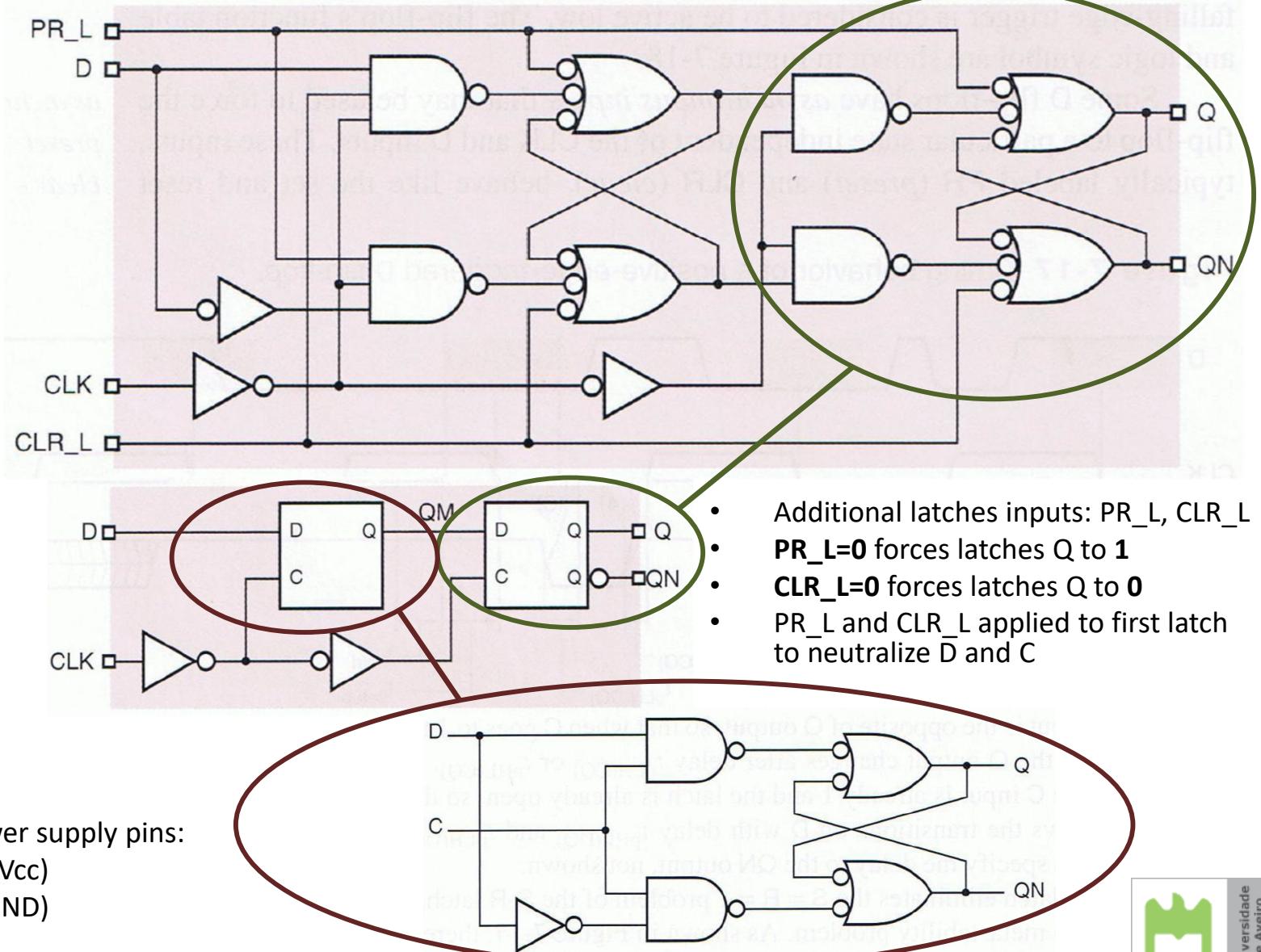
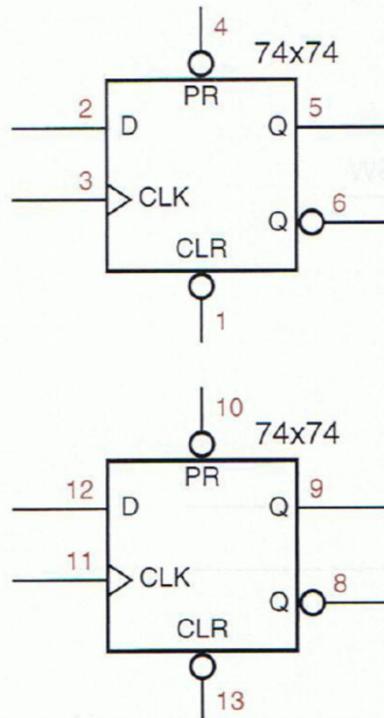
Lecture Contents

- Single and multibit registers
 - Flip-flop based
 - Latch based
- Binary counter design
 - Up counter synthesis
 - Up/down counter synthesis
- Standard counters
 - Free running
 - Constrained counting
 - Cascading counters
- Shift-registers
 - Applications
 - Serial-in, serial-out
 - Serial-in, parallel-out
 - Parallel-in, serial-out
 - Parallel-in , parallel-out
 - Universal (load, shift, hold)

Some figures and content extracted from: John F. Wakerly, “Digital Design – Principles and Practices”, 4 ed., Pearson – Prentice Hall, 2006 (chapter 7). Reading chapter 7 (4th ed.) or chapter 11 (5th ed.) is highly recommended.

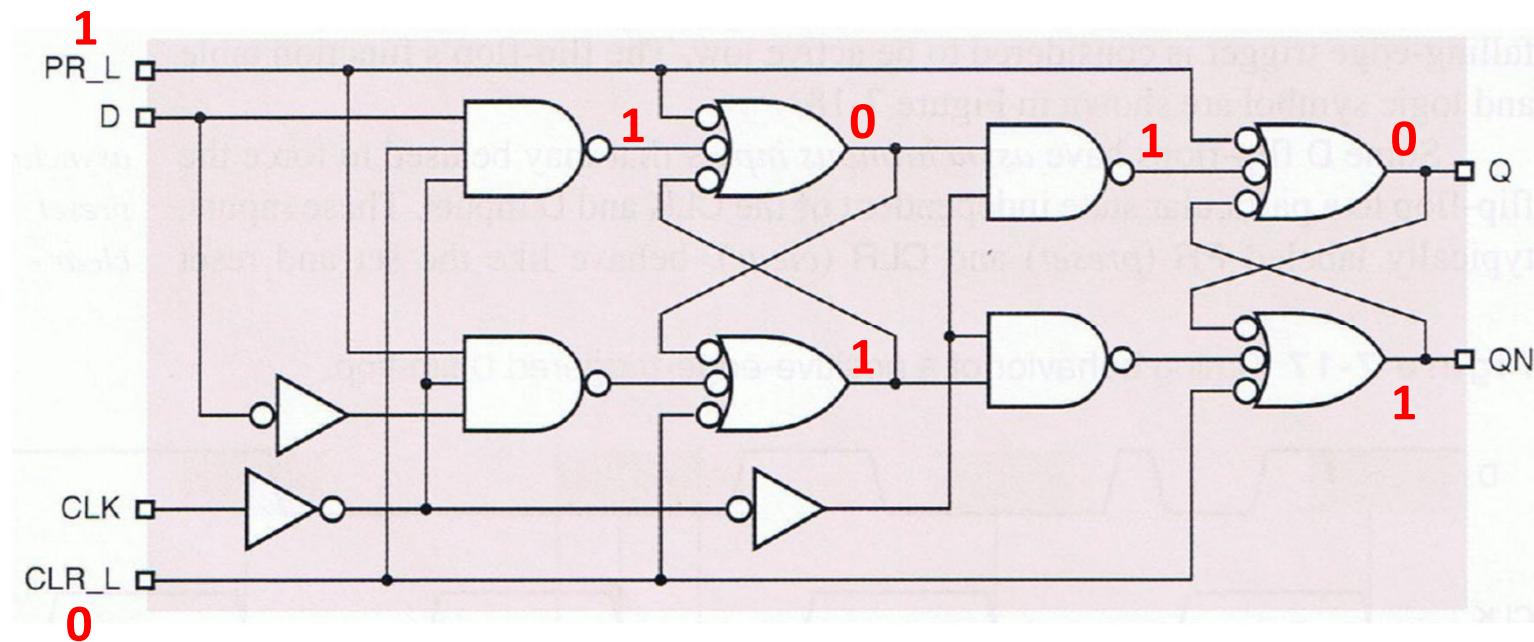


74x74 – Dual Positive-edge-triggered D Flip-flop w/ Asynchronous Preset (Set) and Clear (Reset)



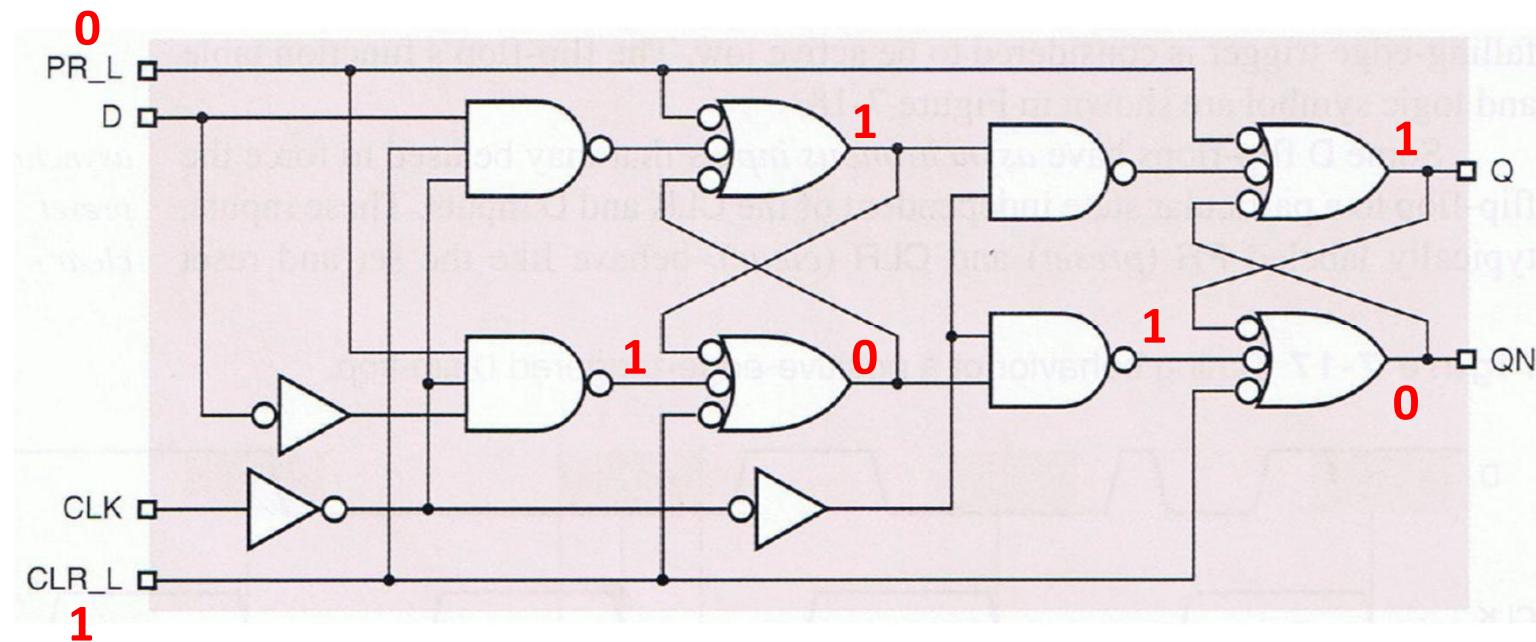
74x74 – Dual Positive-edge-triggered D Flip-flop w/ Asynchronous Preset (Set) and Clear (Reset)

Forcing>Loading 0 (Clear / Reset) at Q output

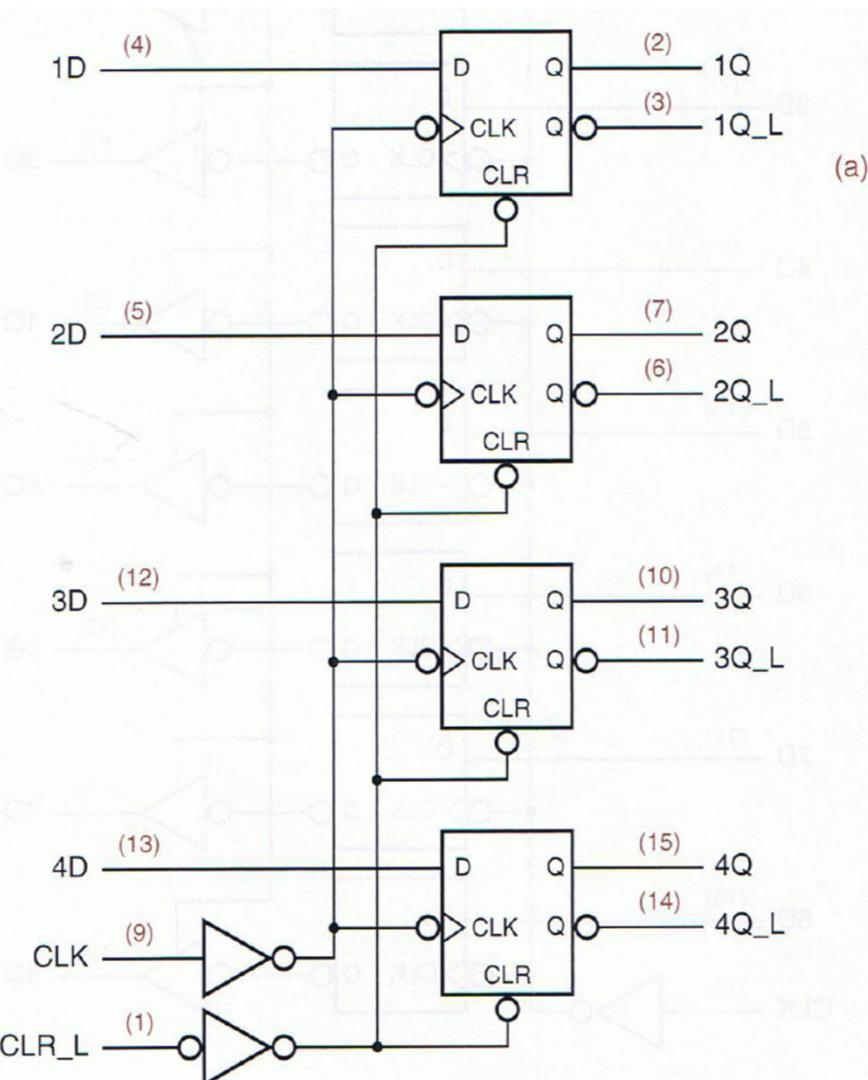


74x74 – Dual Positive-edge-triggered D Flip-flop w/ Asynchronous Preset (Set) and Clear (Reset)

Forcing>Loading 1 (Preset / Set) at Q output



74x175/174 4-bit Flip-flop Based Register



(a)

(b)

Figure 8-8

The 74x175 4-bit register:
(a) logic diagram, including
pin numbers for a standard
16-pin dual in-line package;
(b) traditional logic symbol.

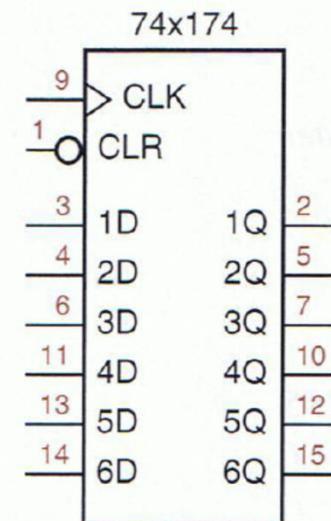
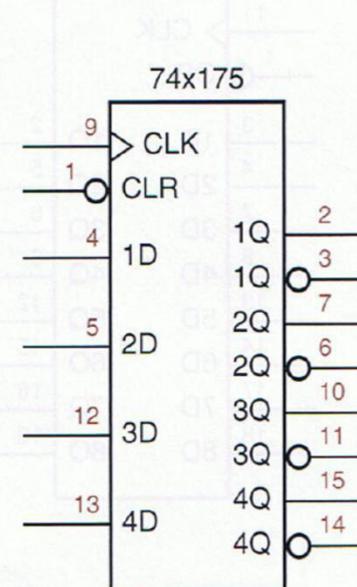


Figure 8-9
Logic symbol for the
74x174 6-bit register.



74x373/74x374 8-bit Latch/Register with 3-State Outputs

Figure 8-10
The 74x374 8-bit register:
(a) logic diagram, including pin numbers for a standard 20-pin dual in-line package;
(b) traditional logic symbol.

Latch – level triggered

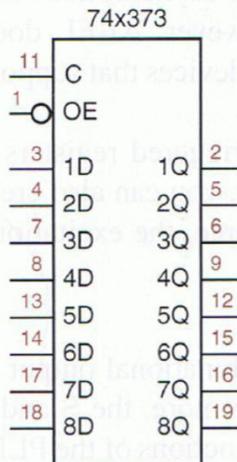
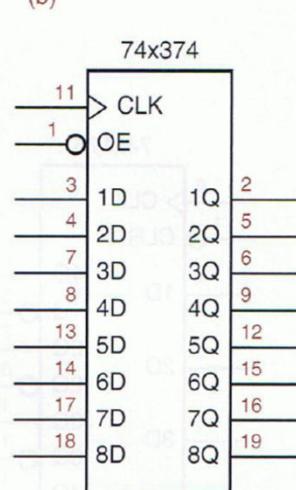
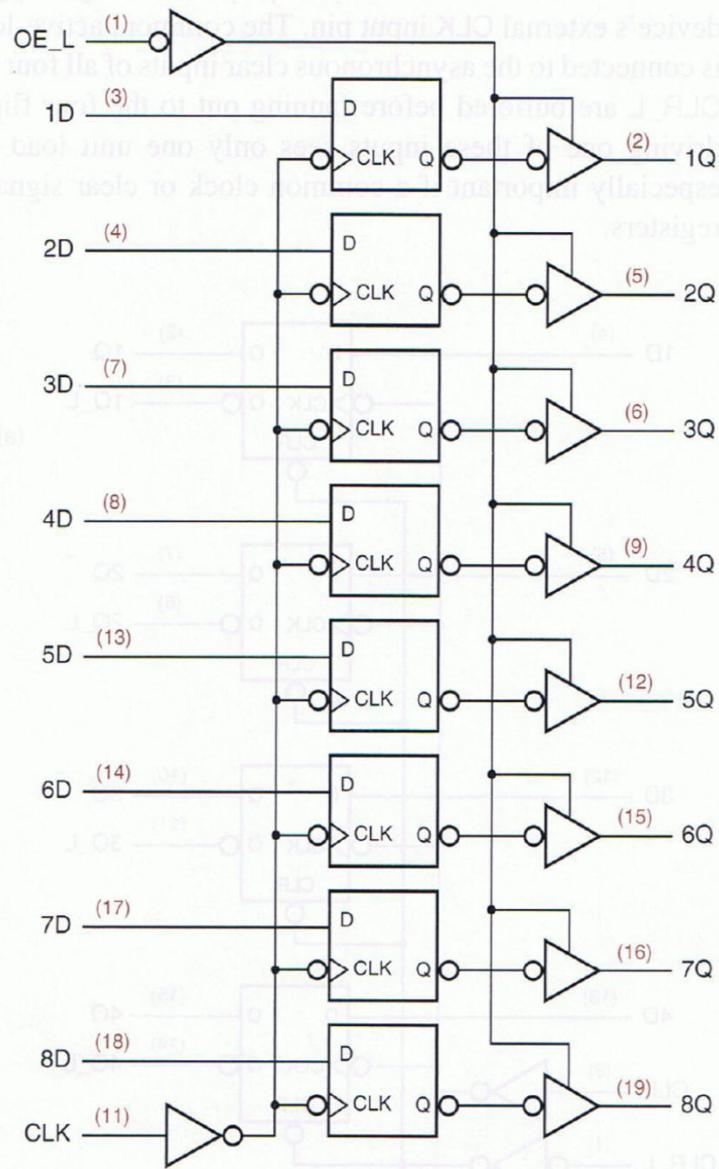


Figure 8-11
Logic symbol for the 74x373 8-bit latch.



Flip-flop – edge triggered



74x273/74x377 8-bit Flip-flop Based Register with Clear/Enable Input

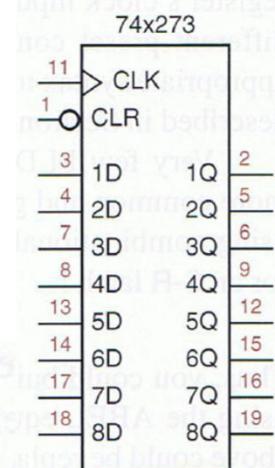
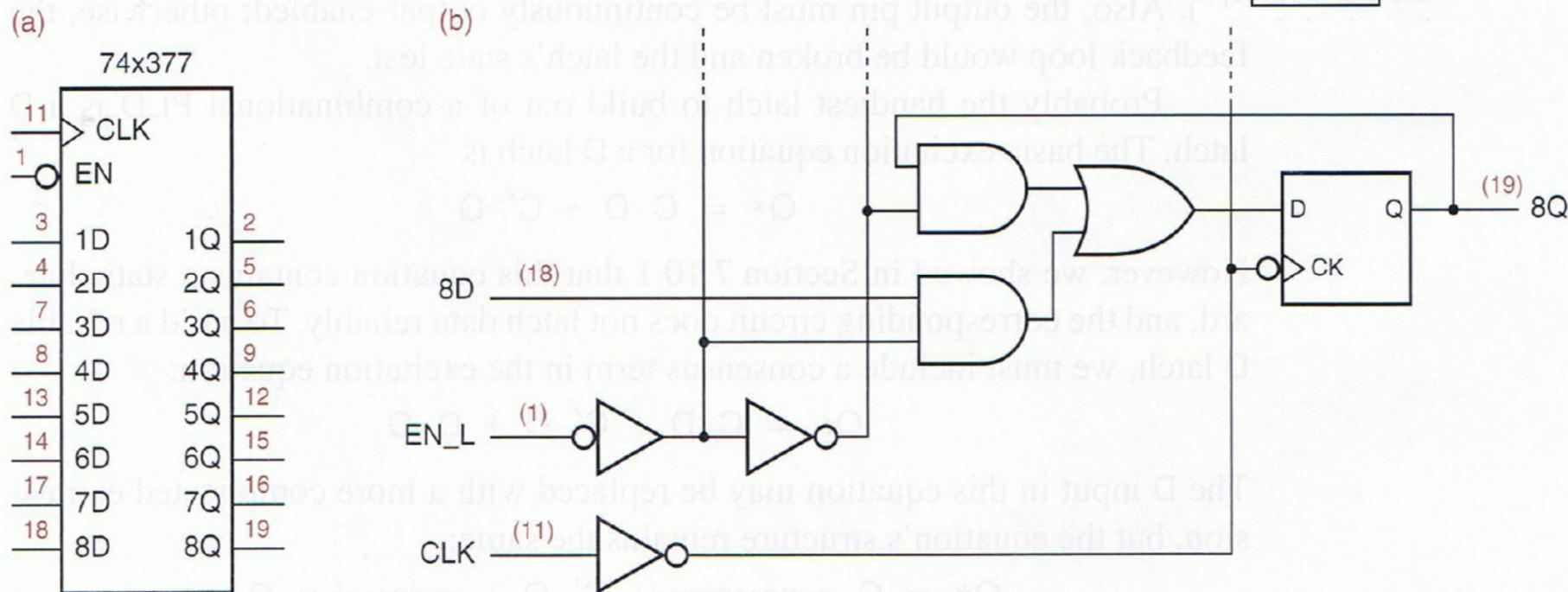


Figure 8-12
Logic symbol for the
74x273 8-bit register.

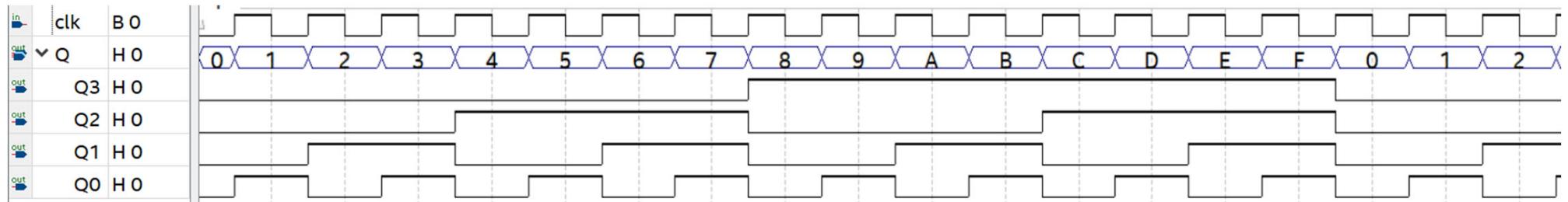
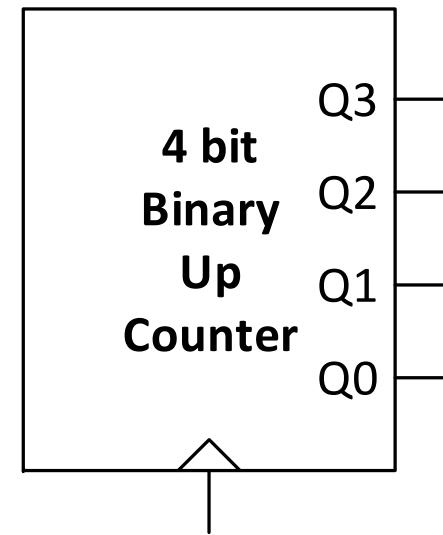
Figure 8-13 The 74x377 8-bit register with gated clock:

(a) logic symbol; (b) logical behavior of one bit.



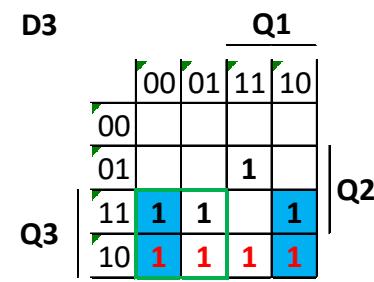
4 bit Binary Up Counter Operation

Decimal	Q3 Q2 Q1 Q0	Q3* Q2* Q1* Q0*	Decimal
		D3 D2 D1 D0	
0	0000	0001	1
1	0001	0010	2
2	0010	0011	3
3	0011	0100	4
4	0100	0101	5
5	0101	0110	6
6	0110	0111	7
7	0111	1000	8
8	1000	1001	9
9	1001	1010	10
10	1010	1011	11
11	1011	1100	12
12	1100	1101	13
13	1101	1110	14
14	1110	1111	15
15	1111	0000	0

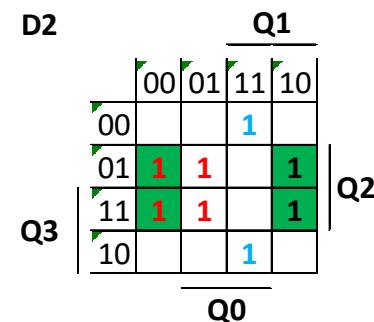


4 bit Binary Up Counter Synthesis

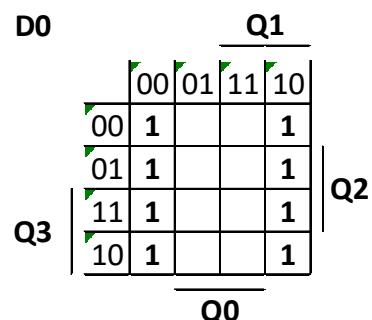
Decimal	Q3 Q2 Q1 Q0				Q3* Q2* Q1* Q0*				Decimal
	D3	D2	D1	D0	Q3	Q2	Q1	Q0	
0	0000		0001		1				
1	0001		0010		2				
2	0010		0011		3				
3	0011		0100		4				
4	0100		0101		5				
5	0101		0110		6				
6	0110		0111		7				
7	0111		1000		8				
8	1000		1001		9				
9	1001		1010		10				
10	1010		1011		11				
11	1011		1100		12				
12	1100		1101		13				
13	1101		1110		14				
14	1110		1111		15				
15	1111		0000		0				



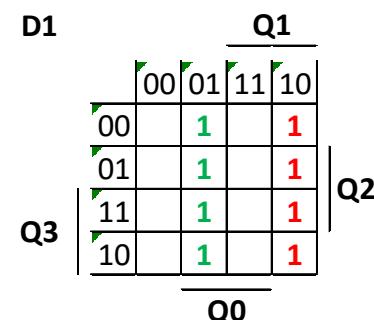
$$D_3 = Q_3 \cdot \overline{Q_2} + Q_3 \cdot \overline{Q_1} + Q_3 \cdot \overline{Q_0} + \overline{Q_3} \cdot Q_2 \cdot Q_1 \cdot Q_0$$



$$D_2 = Q_2 \cdot \overline{Q_1} + Q_2 \cdot \overline{Q_0} + \overline{Q_2} \cdot Q_1 \cdot Q_0$$



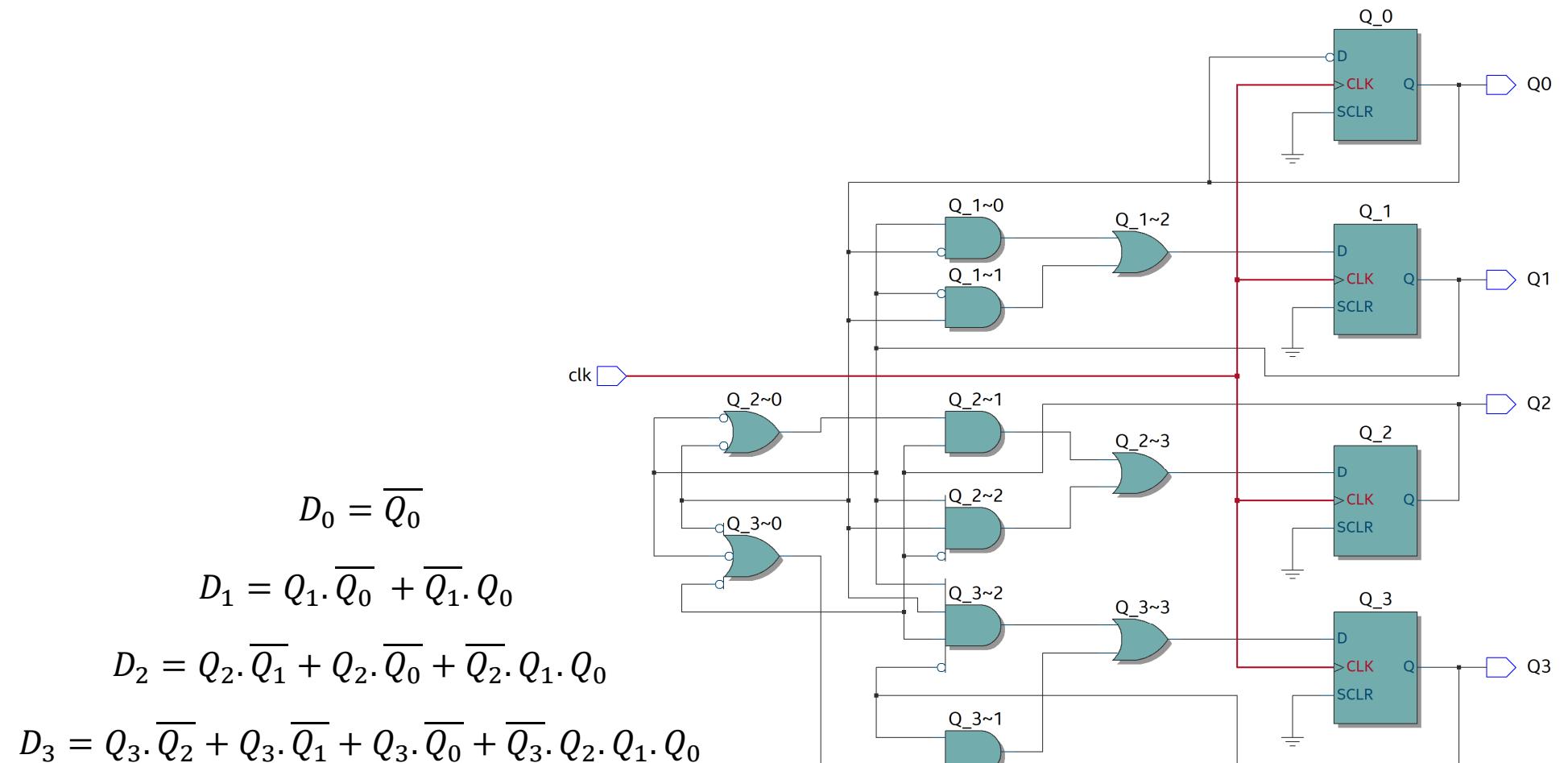
$$D_0 = \overline{Q_0}$$



$$D_1 = Q_1 \cdot \overline{Q_0} + \overline{Q_1} \cdot Q_0$$

Minimized
Excitation
equations

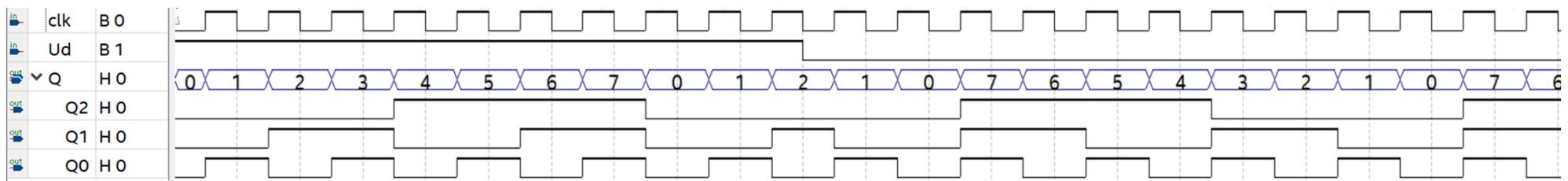
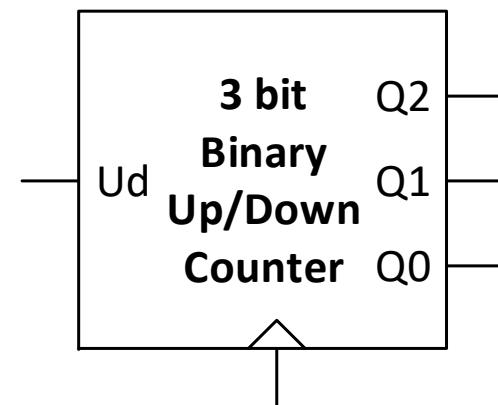
4 bit Binary Up Counter Logic Diagram



In a real circuit, flip-flops reset/clear must be connected to a reset input!

3 bit Binary Up/Down Counter Operation

Decimal	Ud	Q2 Q1 Q0	Q2*	Q1*	Q0*	Decimal
			D2	D1	D0	
0	0	000	1	1	1	7
1	0	001	0	0	0	0
2	0	010	0	0	1	1
3	0	011	0	1	0	2
4	0	100	0	1	1	3
5	0	101	1	0	0	4
6	0	110	1	0	1	5
7	0	111	1	1	0	6
0	1	000	0	0	1	1
1	1	001	0	1	0	2
2	1	010	0	1	1	3
3	1	011	1	0	0	4
4	1	100	1	0	1	5
5	1	101	1	1	0	6
6	1	110	1	1	1	7
7	1	111	0	0	0	0



3 bit Binary Up/Down Counter Synthesis

D2	Q1			
	00	01	11	10
Ud	00	1		
01	1	1	1	1
11	1	1		1
10			1	

Q0

$$D_2 = \overline{Ud} \cdot \overline{Q}_2 \cdot \overline{Q}_1 \cdot \overline{Q}_0 + \overline{Ud} \cdot Q_2 \cdot Q_0 + Ud \cdot Q_2 \cdot \overline{Q}_1 + Q_2 \cdot Q_1 \cdot \overline{Q}_0 + Ud \cdot \overline{Q}_2 \cdot Q_1 \cdot Q_0$$

Minimized
Excitation
equations

Decimal	Ud	Q2 Q1 Q0	Q2* Q1* Q0*	Decimal
			D2 D1 D0	
0	0	000	111	7
1	0	001	000	0
2	0	010	001	1
3	0	011	010	2
4	0	100	011	3
5	0	101	100	4
6	0	110	101	5
7	0	111	110	6
0	1	000	001	1
1	1	001	010	2
2	1	010	011	3
3	1	011	100	4
4	1	100	101	5
5	1	101	110	6
6	1	110	111	7
7	1	111	000	0

D1	Q1			
	00	01	11	10
Ud	00	1		
01	1		1	
11		1		1
10		1		1

Q0

$$D_1 = \overline{Ud} \cdot \overline{Q}_1 \cdot \overline{Q}_0 + \overline{Ud} \cdot Q_1 \cdot Q_0 + Ud \cdot \overline{Q}_1 \cdot Q_0 + Ud \cdot Q_1 \cdot \overline{Q}_0$$

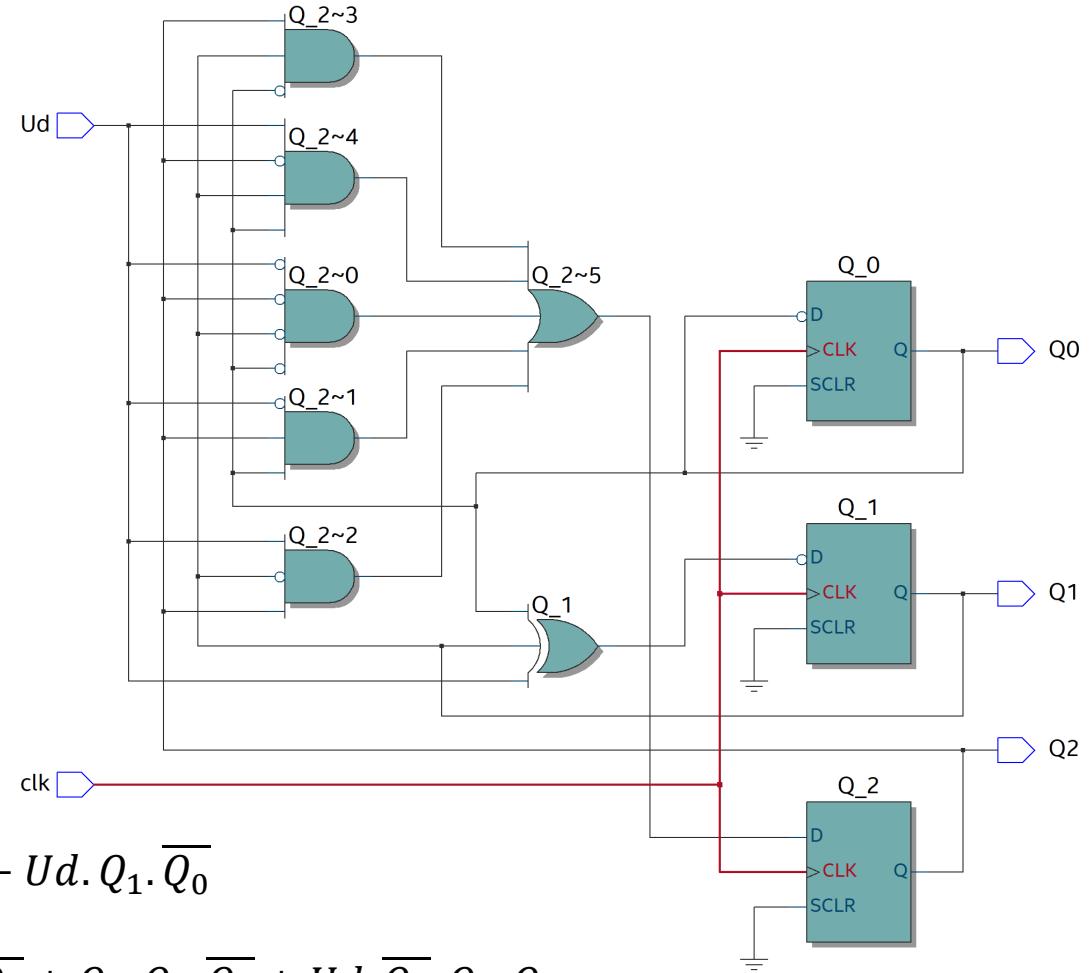
D0	Q1			
	00	01	11	10
Ud	00	1		1
01	1			1
11	1			1
10	1			1

Q0

$$D_0 = \overline{Q}_0$$

3 bit Binary Up/Down Counter

Logic Diagram



$$D_0 = \overline{Q}_0$$

$$D_1 = \overline{Ud} \cdot \overline{Q}_1 \cdot \overline{Q}_0 + \overline{Ud} \cdot Q_1 \cdot Q_0 + Ud \cdot \overline{Q}_1 \cdot Q_0 + Ud \cdot Q_1 \cdot \overline{Q}_0$$

$$D_2 = \overline{Ud} \cdot \overline{Q}_2 \cdot \overline{Q}_1 \cdot \overline{Q}_0 + \overline{Ud} \cdot Q_2 \cdot Q_0 + Ud \cdot Q_2 \cdot \overline{Q}_1 + Q_2 \cdot Q_1 \cdot \overline{Q}_0 + Ud \cdot \overline{Q}_2 \cdot Q_1 \cdot Q_0$$

In a real circuit, flip-flops reset/clear must be connected to a reset input!

74x163 Standard 4-bit Binary Up Counter

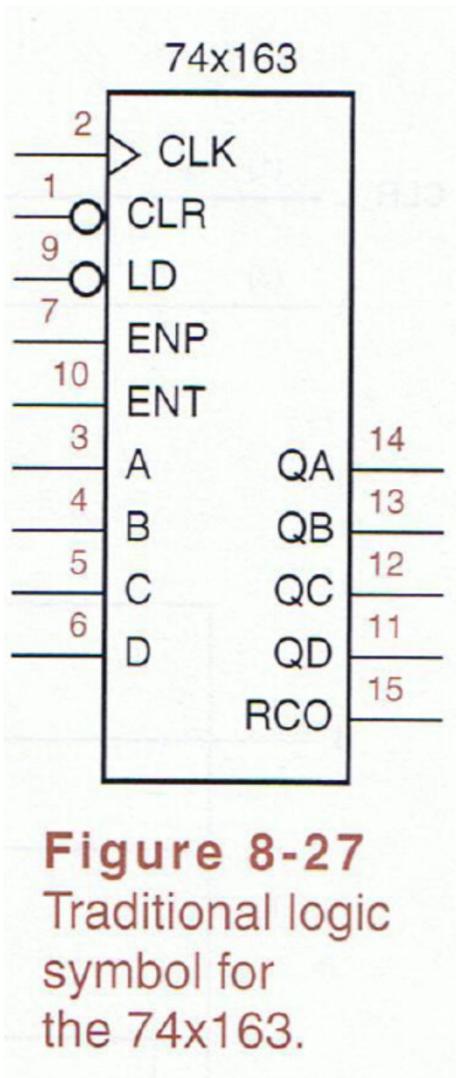


Figure 8-27
Traditional logic
symbol for
the 74x163.

Port	Meaning
CLK	Clock input
CLR	Synchronous clear, active low
LD	Synchronous parallel load enable, active low
ENP, ENT	Enable input
A – D	Parallel load data value
QA – QD	Counter output value
RCO	Ripple counter output (for cascading)

Table 8-13 State table for a 74x163 4-bit binary counter.

Inputs				Current State				Next State			
CLR_L	LD_L	ENT	ENP	QD	QC	QB	QA	QD*	QC*	QB*	QA*
0	x	x	x	x	x	x	x	0	0	0	0
1	0	x	x	x	x	x	x	D	C	B	A
1	1	0	x	x	x	x	x	QD	QC	QB	QA
1	1	x	0	x	x	x	x	QD	QC	QB	QA
1	1	1	1	0	0	0	0	0	0	0	1
1	1	1	1	0	0	0	1	0	0	1	0
1	1	1	1	0	0	1	0	0	0	1	1
1	1	1	1	0	0	1	1	0	1	0	0
1	1	1	1	0	1	0	0	0	1	0	1
1	1	1	1	0	1	0	1	0	1	1	0
1	1	1	1	0	1	0	1	0	1	1	1
1	1	1	1	0	1	1	1	1	0	0	0
1	1	1	1	1	0	0	0	1	0	0	1
1	1	1	1	1	0	0	1	1	0	0	1
1	1	1	1	1	0	1	0	1	0	1	0
1	1	1	1	1	0	1	1	1	0	1	1
1	1	1	1	1	1	0	0	1	1	1	1
1	1	1	1	1	1	1	1	0	0	0	0

Clear

Load

Freeze

Count

74x163 Counter Operation

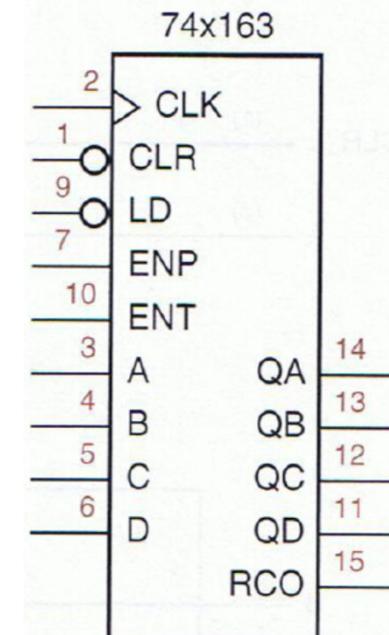


Figure 8-27
Traditional logic
symbol for
the 74x163.



74x163

Counter Internal Structure

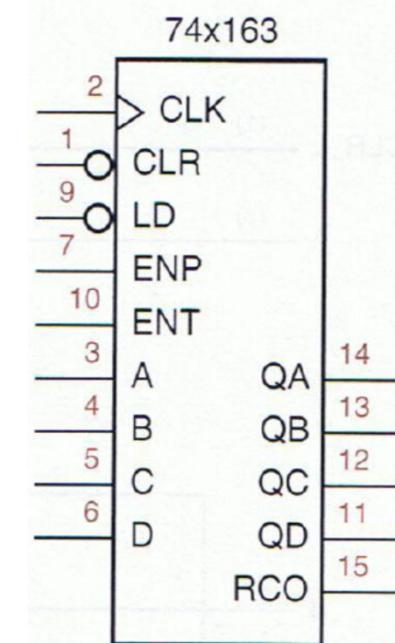
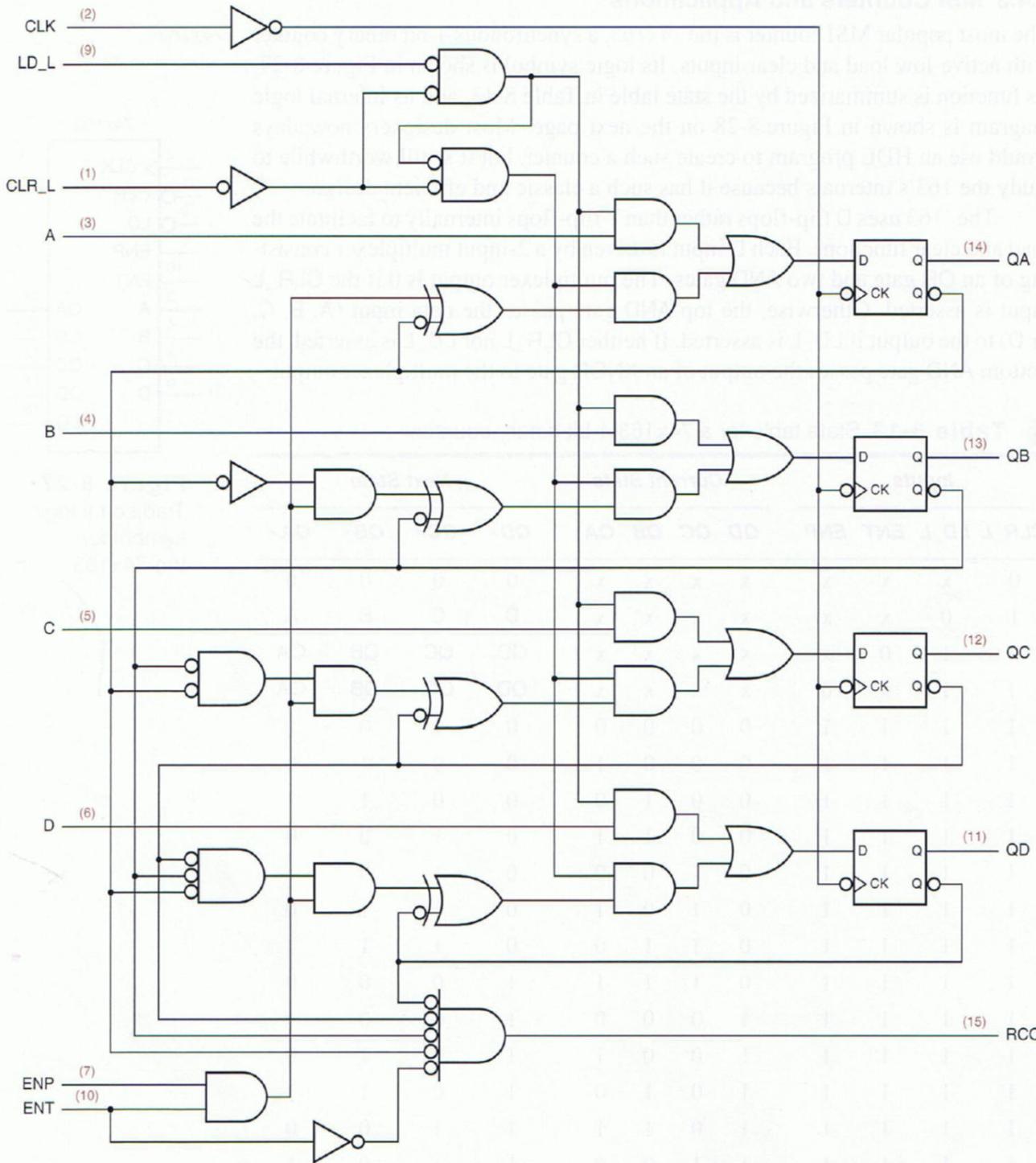


Figure 8-27
Traditional logic
symbol for
the 74x163.



74x163

Clearing Count Value

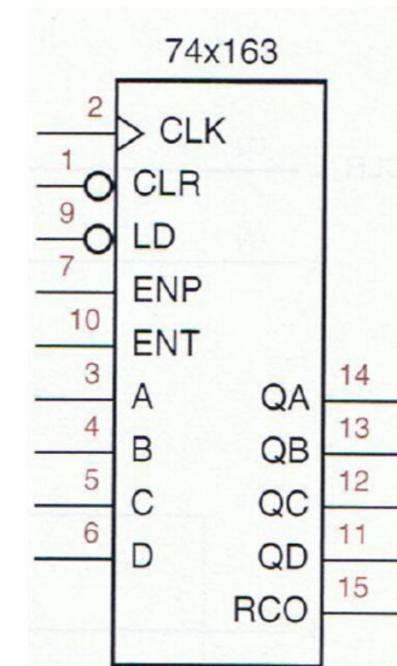
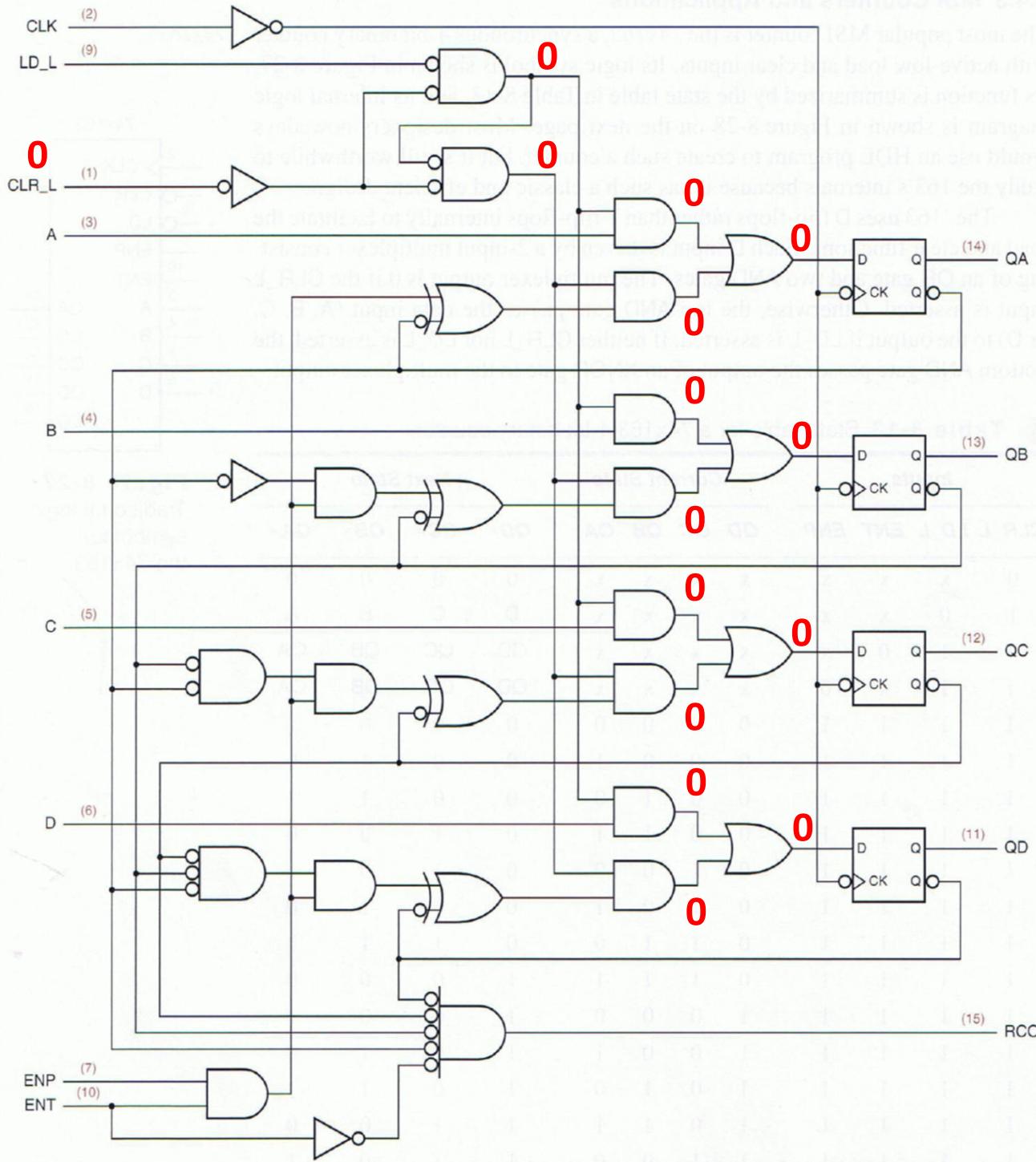


Figure 8-27
Traditional logic symbol for the 74x163.



74x163

Loading Parallel Data

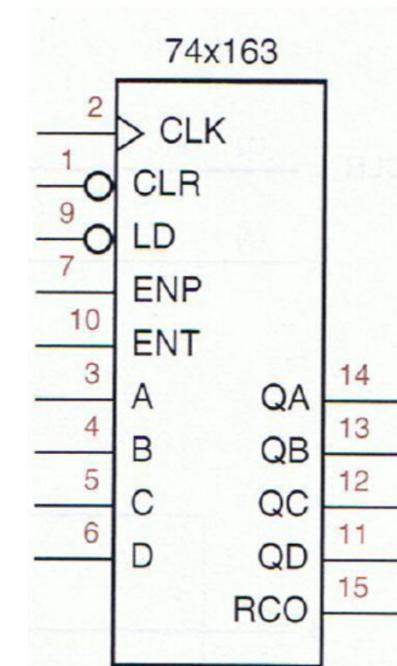
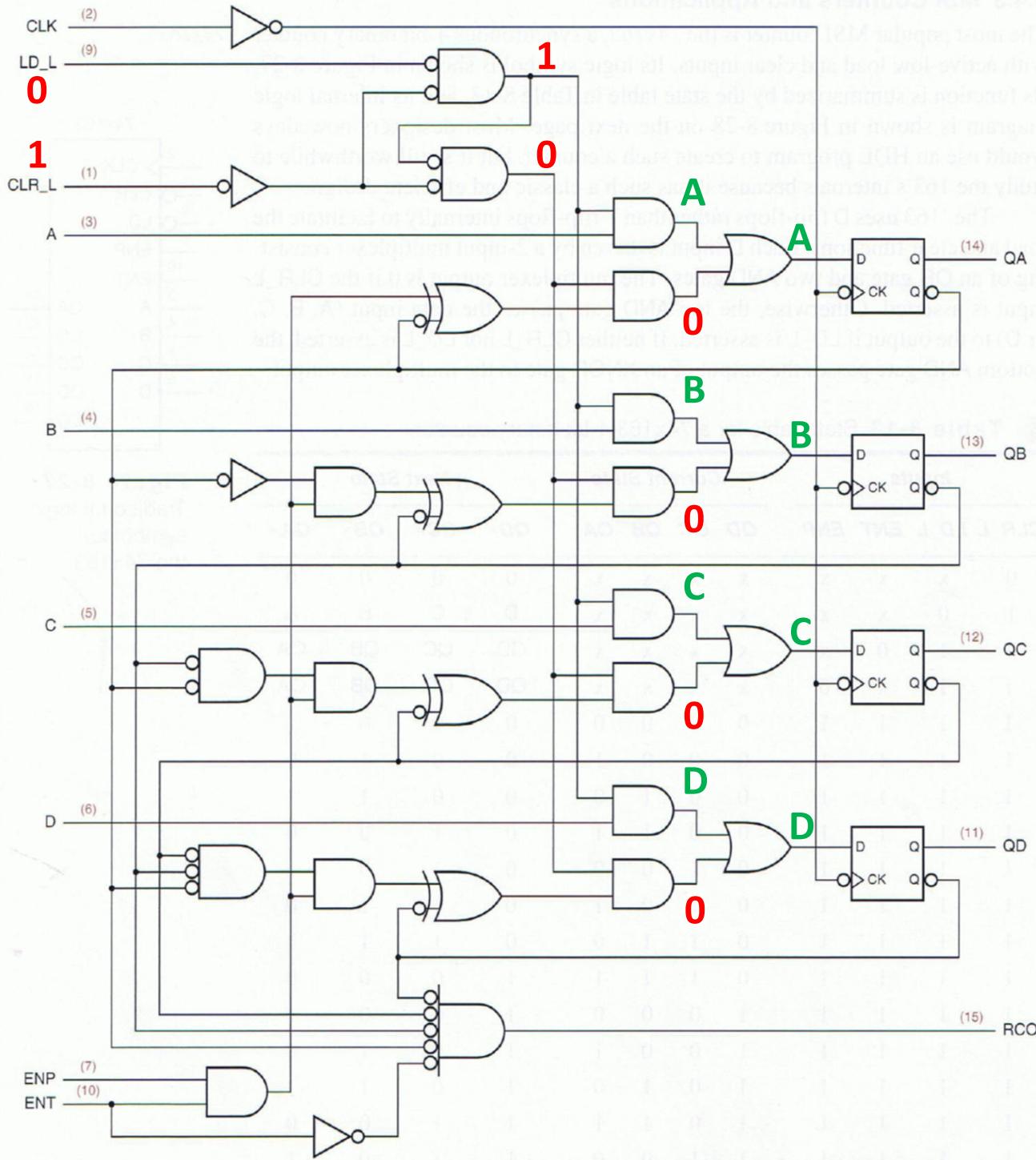


Figure 8-27
Traditional logic
symbol for
the 74x163.



74x163 Freeze Counter Value

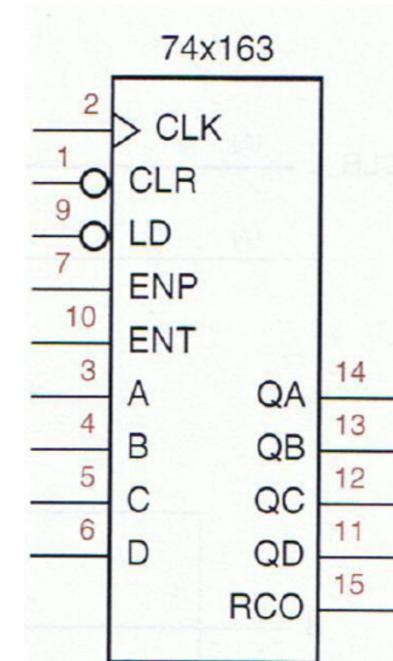
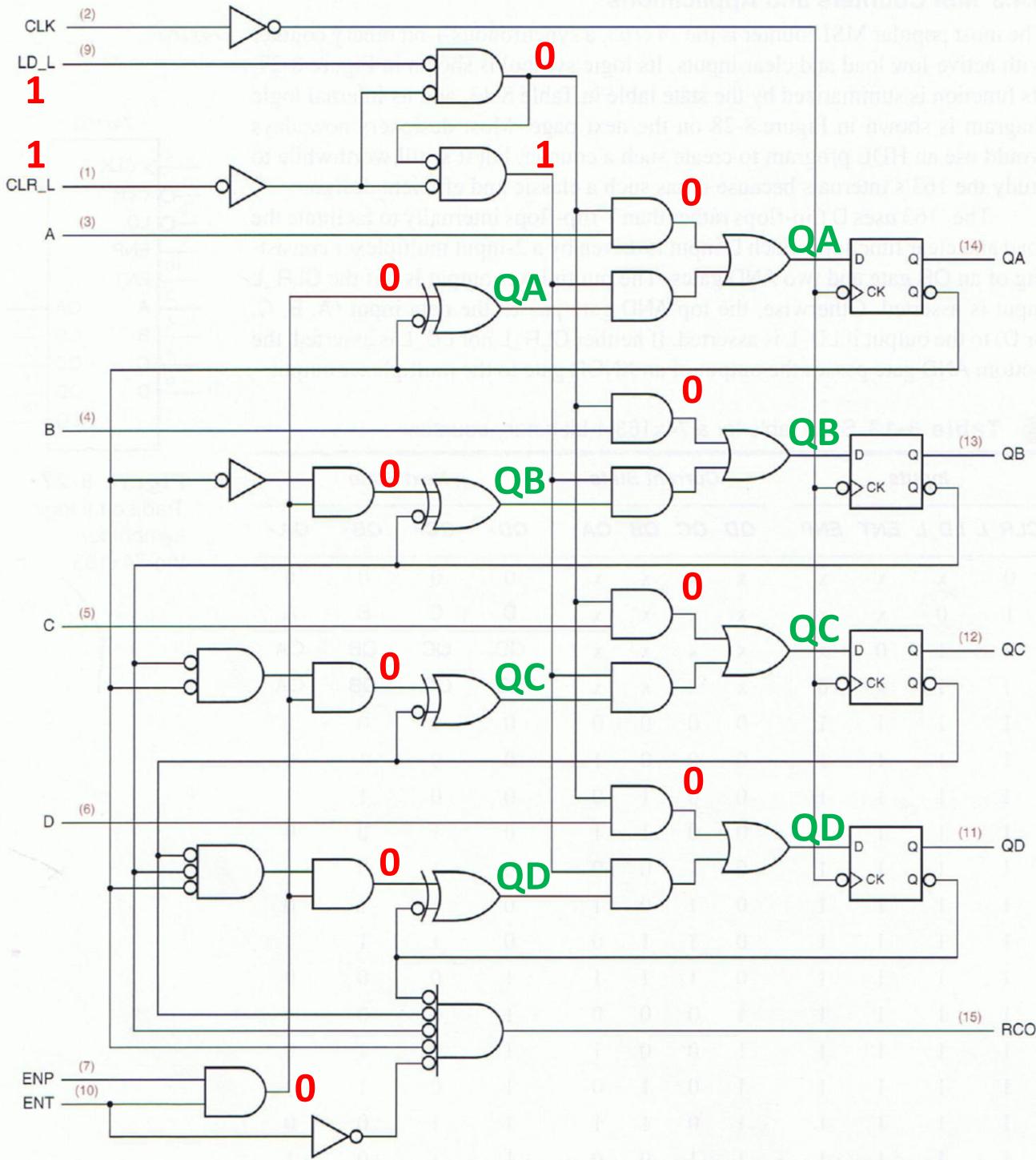


Figure 8-27
Traditional logic
symbol for
the 74x163.



74x163 Counting Up

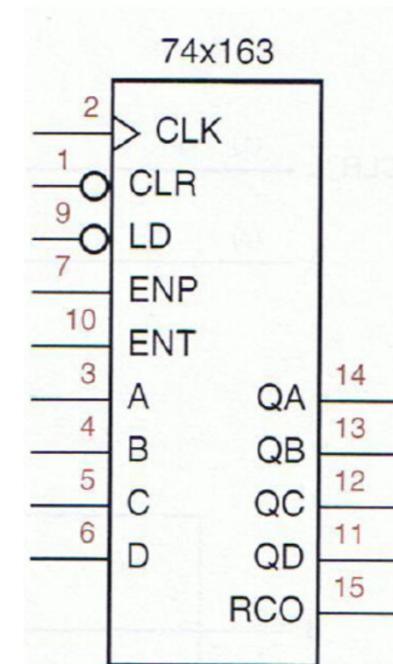
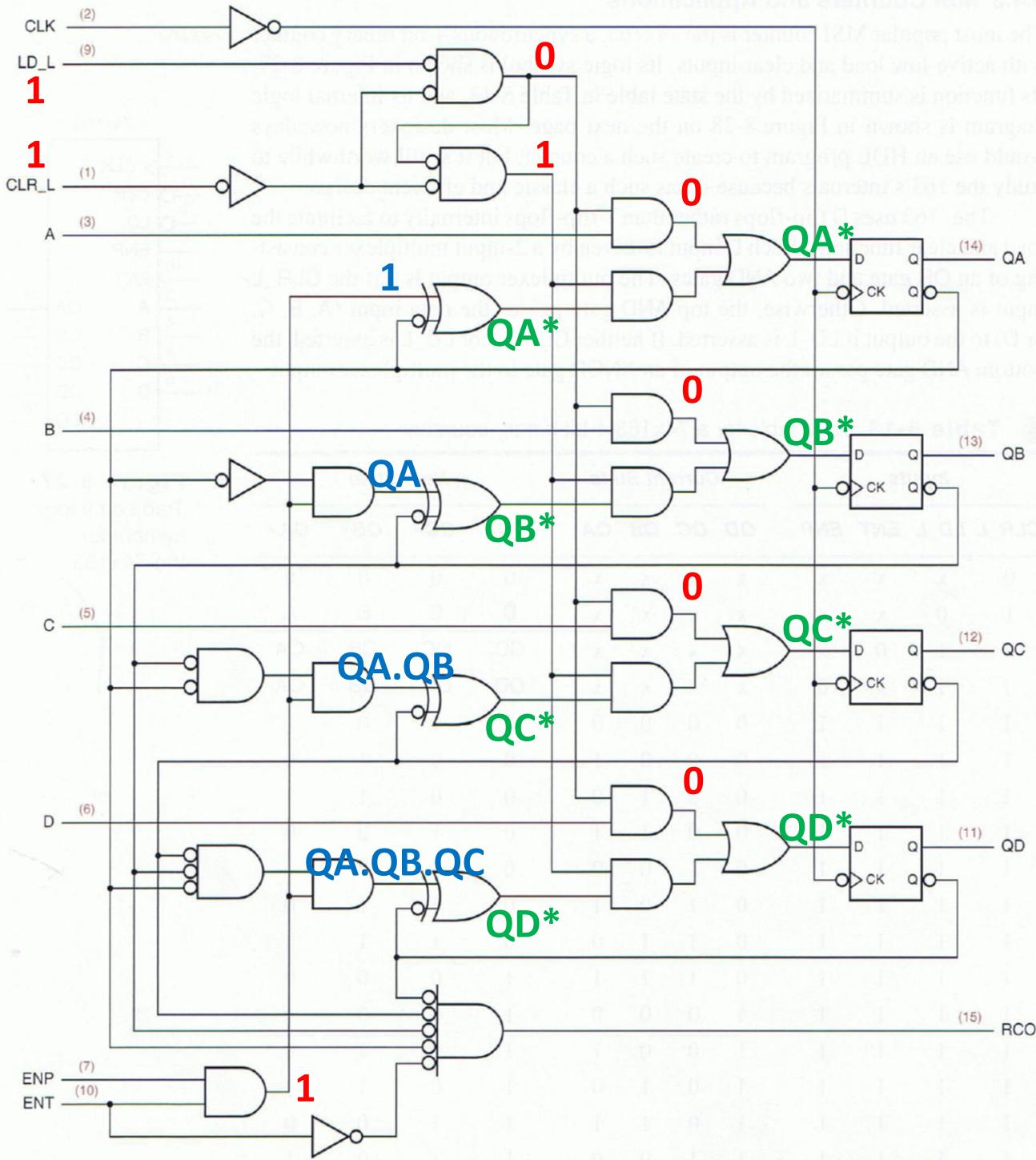


Figure 8-27
Traditional logic
symbol for
the 74x163.



Free Running Counter

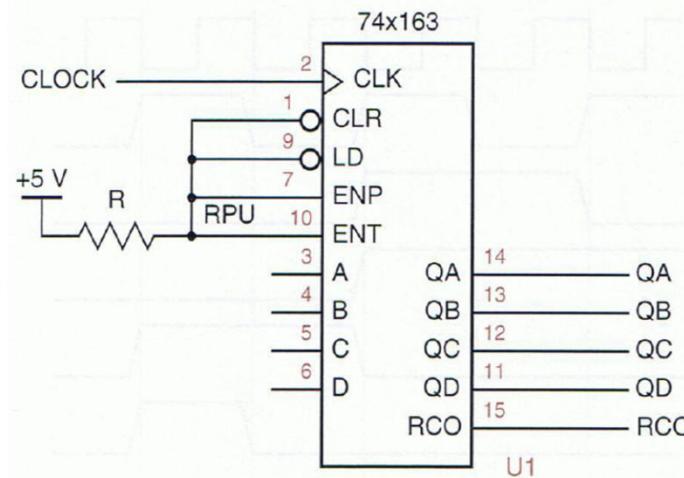
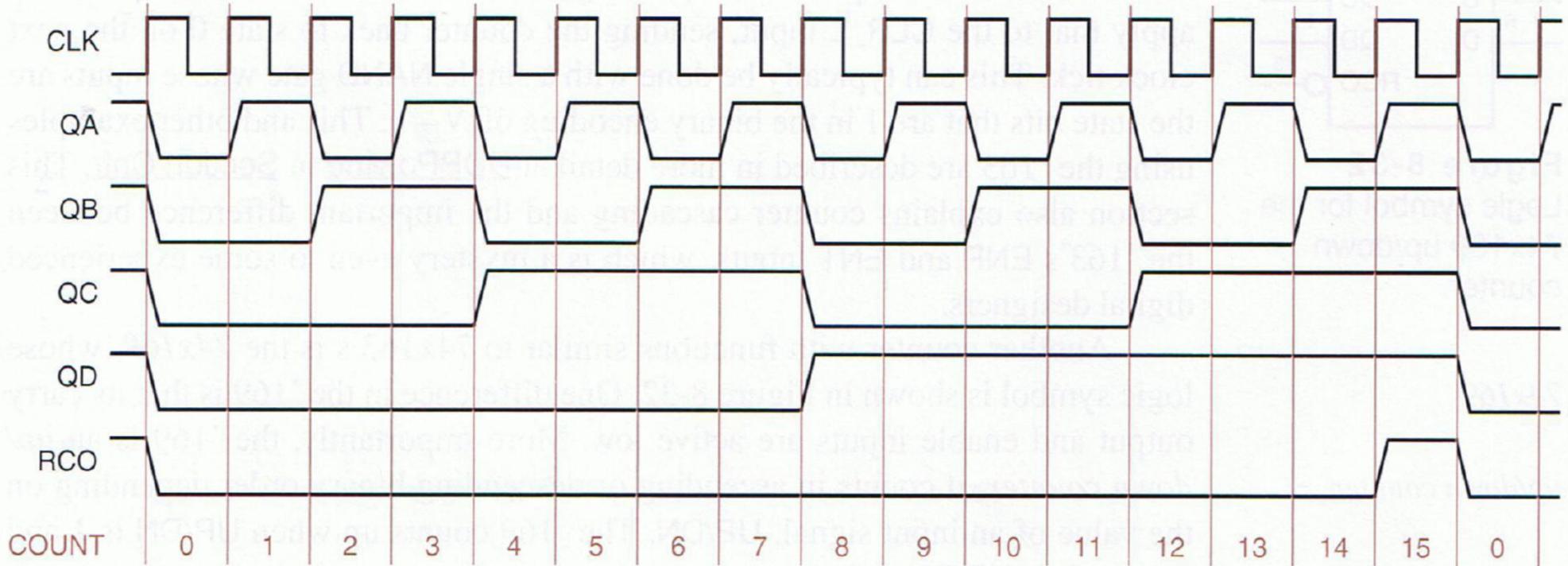


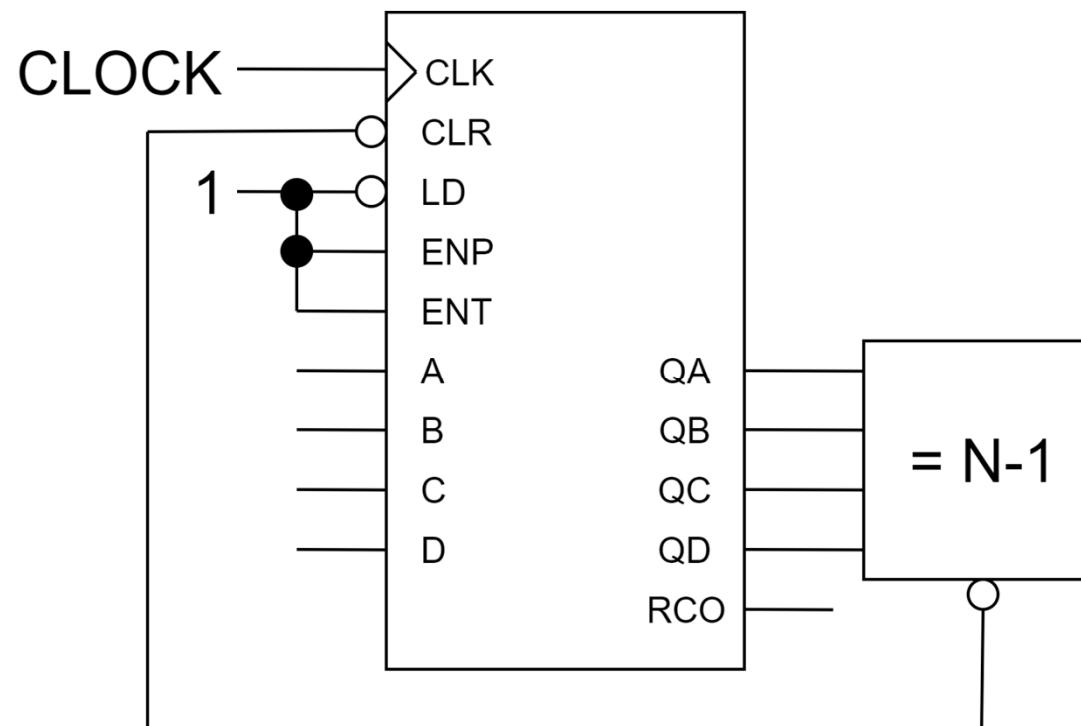
Figure 8-29
Connections for the
74x163 to operate in
a free-running mode.

Figure 8-30 Clock and output waveforms for a free-running divide-by-16 counter.



Modulo “N” Counter Based on 74x163 (with $1 \leq "N" \leq 16$)

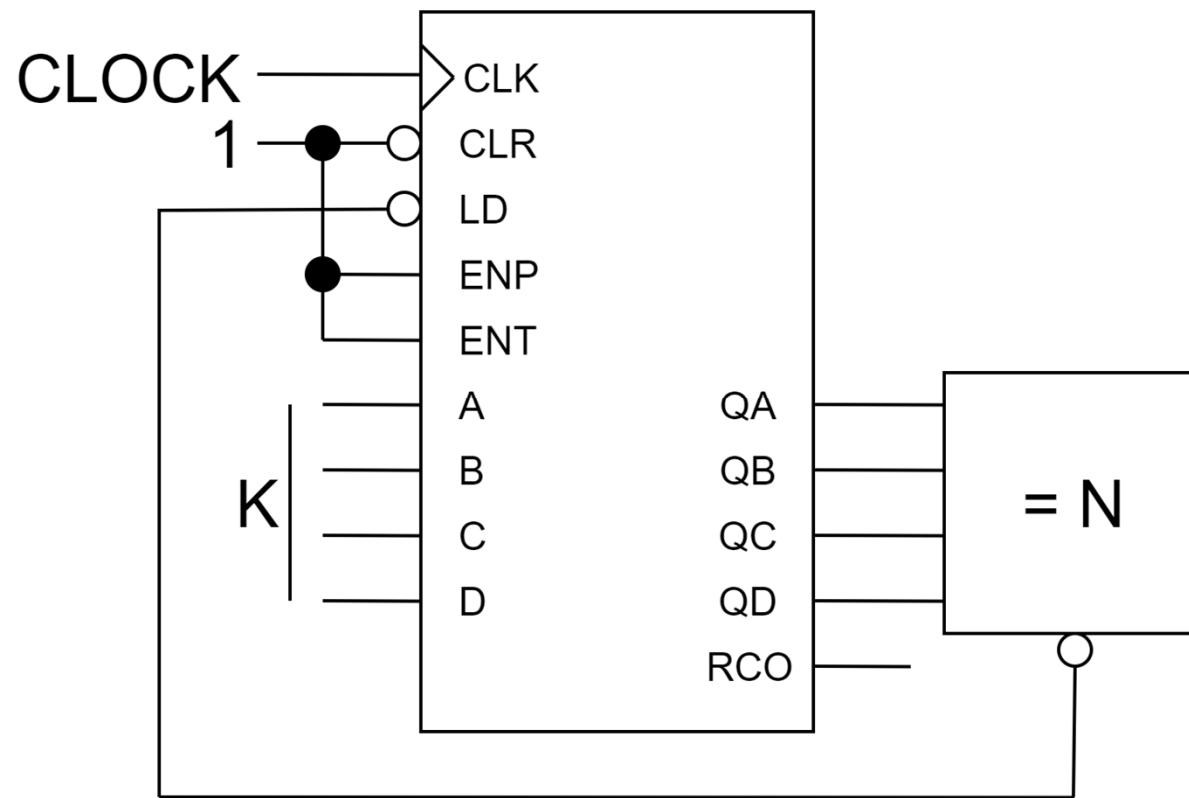
Counts from 0 up to “N-1” and wrap around



How to implement efficiently the comparator with the constant N-1?

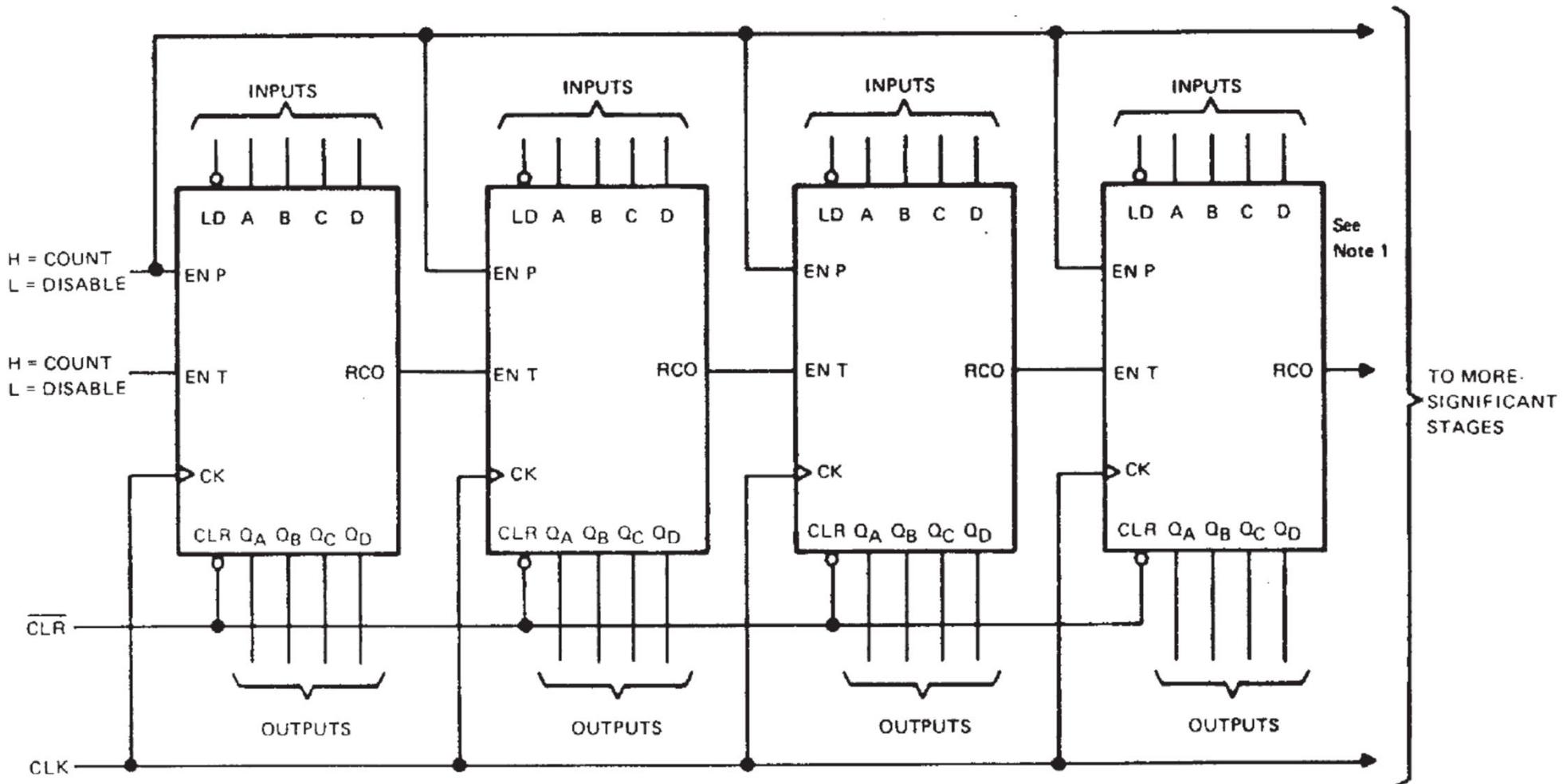
Constrained “K” to “N” Counter Based on 74x163 (with “N”>“K”)

Counts from “K” up to “N” and wrap around to
“K”

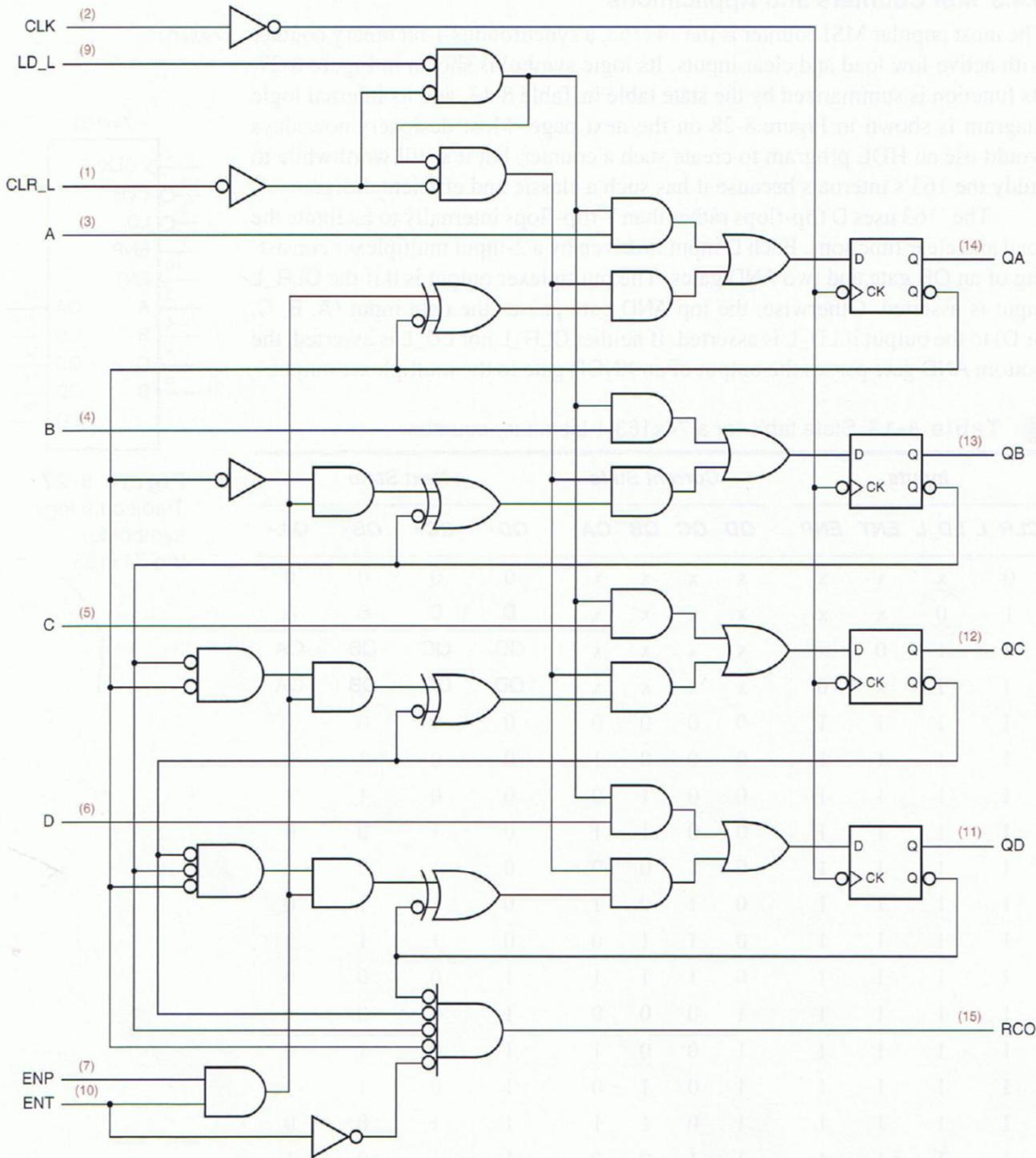


How to implement efficiently the comparator with the constant N?

Cascading 74x163 Counters



Maximum Operating Frequency



$$T_{\min} = ?$$

$$f_{\max} = ?$$

Consider:

$$T_{pHL} = 6 \text{ ns}$$

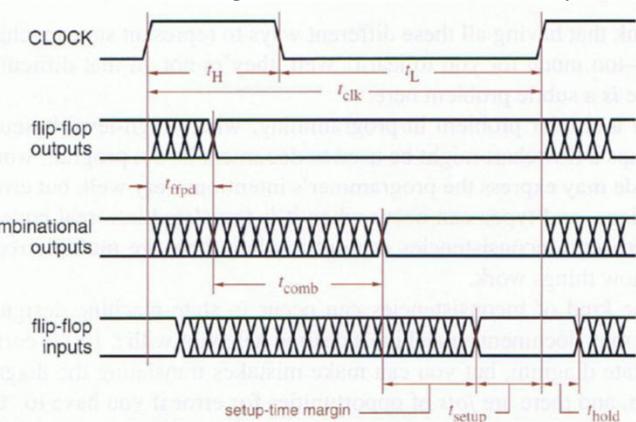
$$T_{plH} = 5 \text{ ns}$$

$$T_{\text{setup}} = 4 \text{ ns}$$

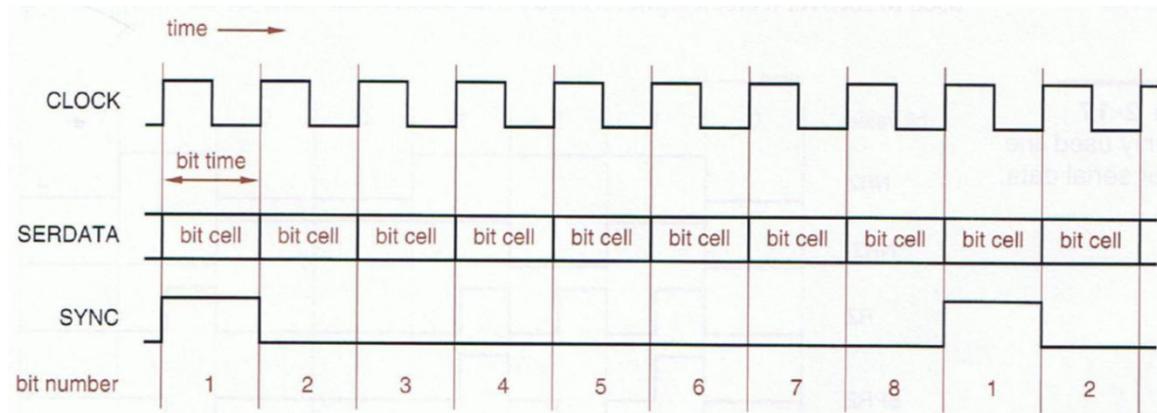
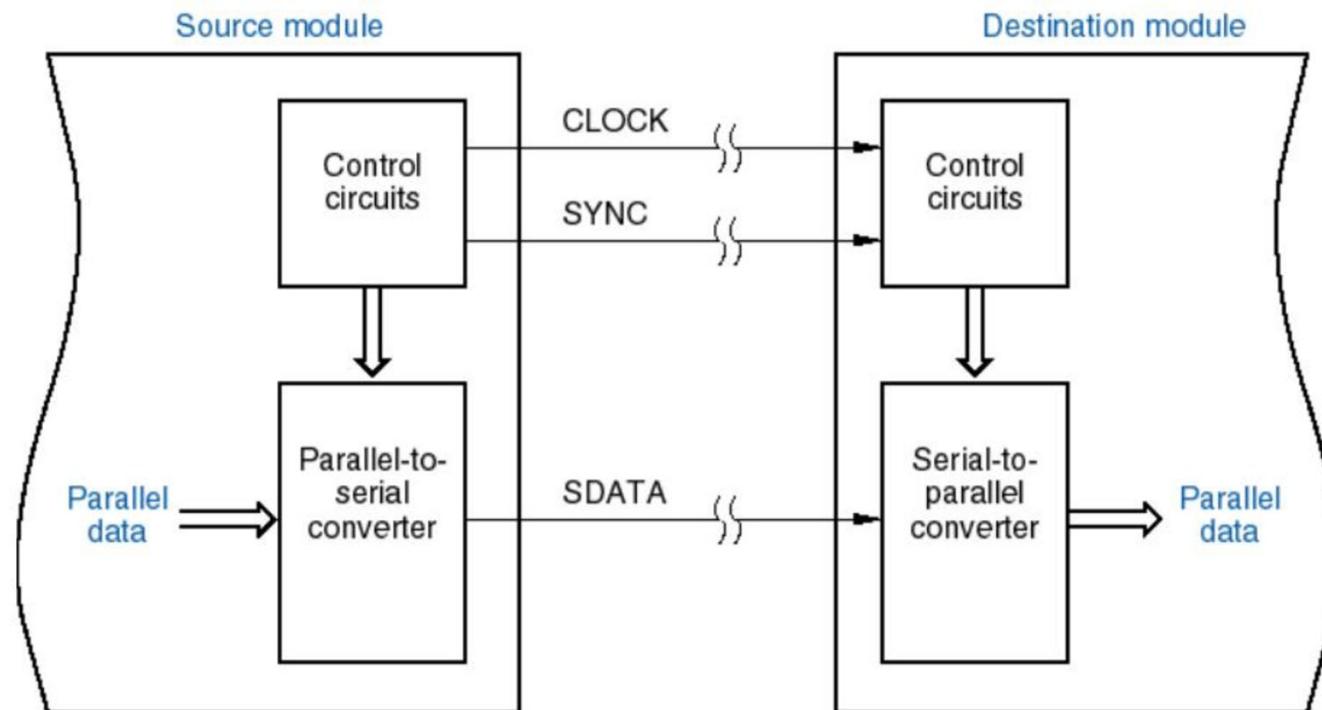
$$T_{\text{hold}} = 1 \text{ ns}$$

$$T_{\text{gate}} = 6 \text{ ns}$$

(assume that all gates exhibit the same delay)



Serial Communication Among Different Devices



Shift Registers (Serial-in, Serial-out)

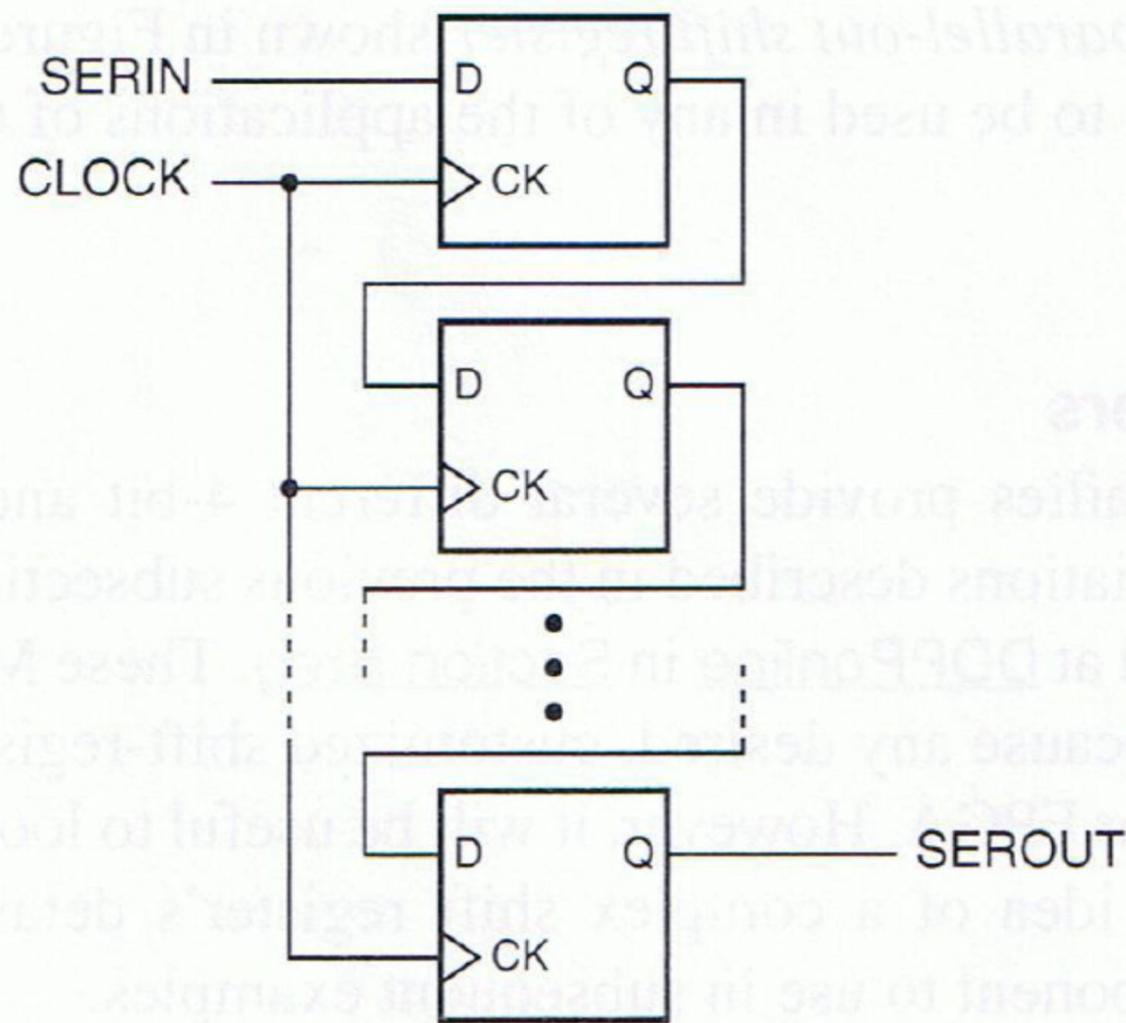


Figure 8-37
Structure of a
serial-in, serial-out
shift register.

Why flip-flop
hold times are
not violated?



Shift Registers (Serial-in, Parallel-out)

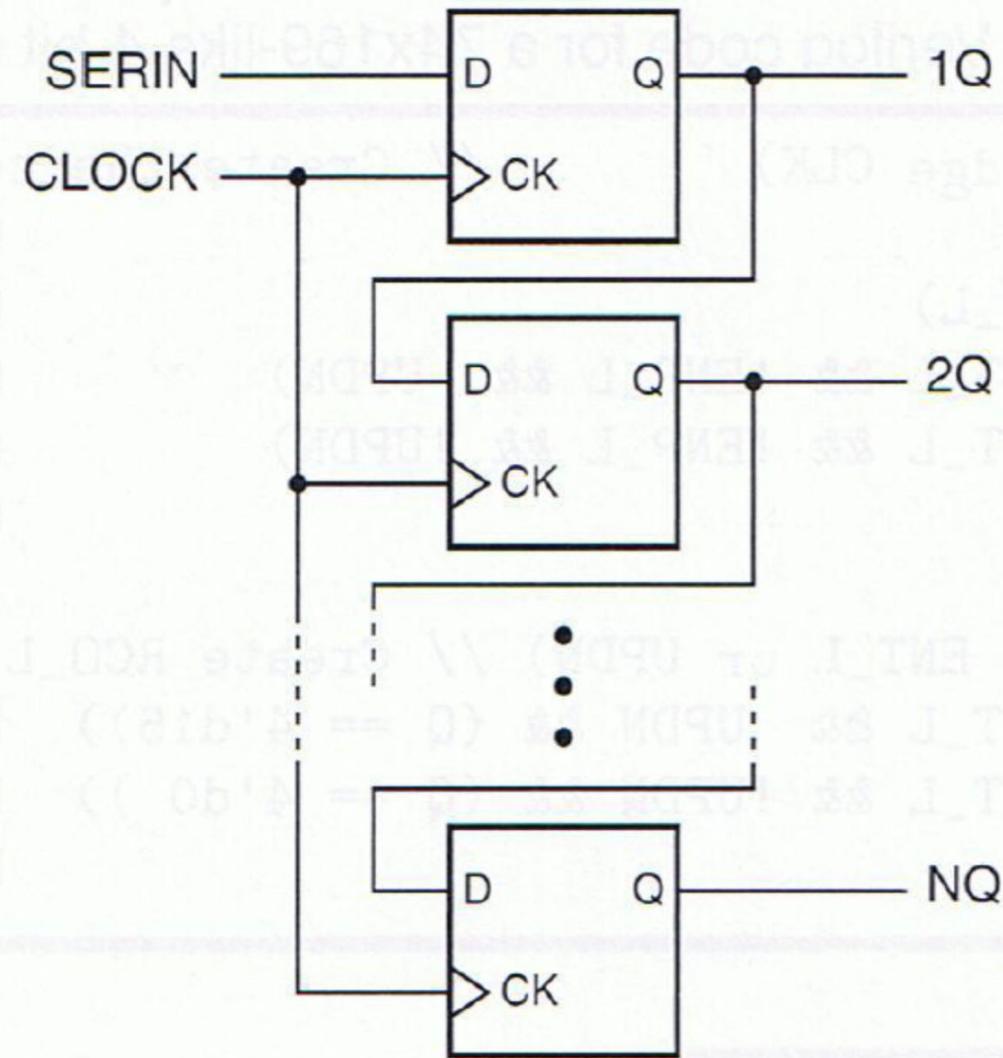


Figure 8-38
Structure of a
serial-in, parallel-out
shift register.

Shift Registers (Parallel-in, Serial-out)

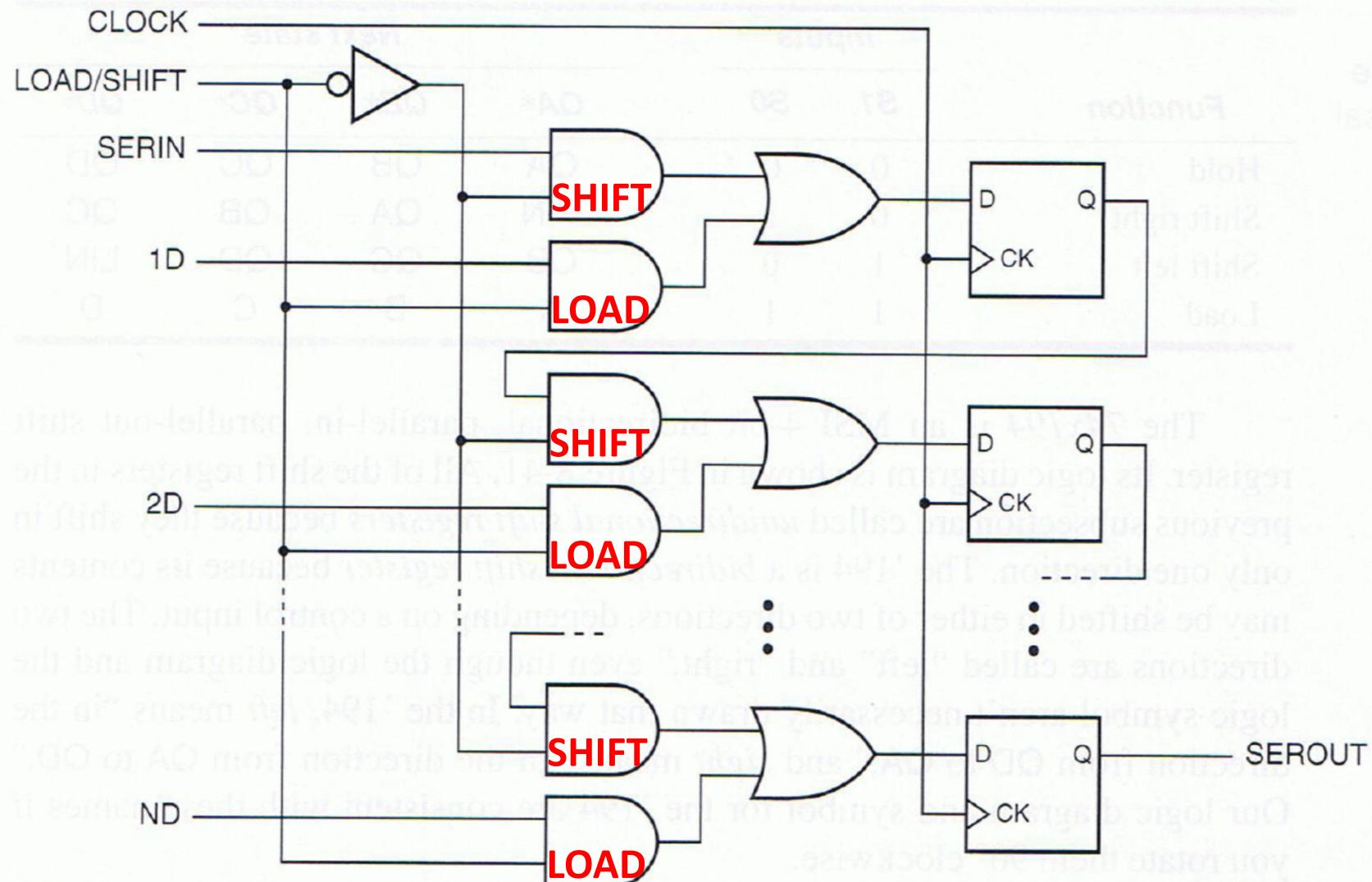


Figure 8-39 Structure of a parallel-in, serial-out shift register.

Shift Registers (Parallel-in, Parallel-out)

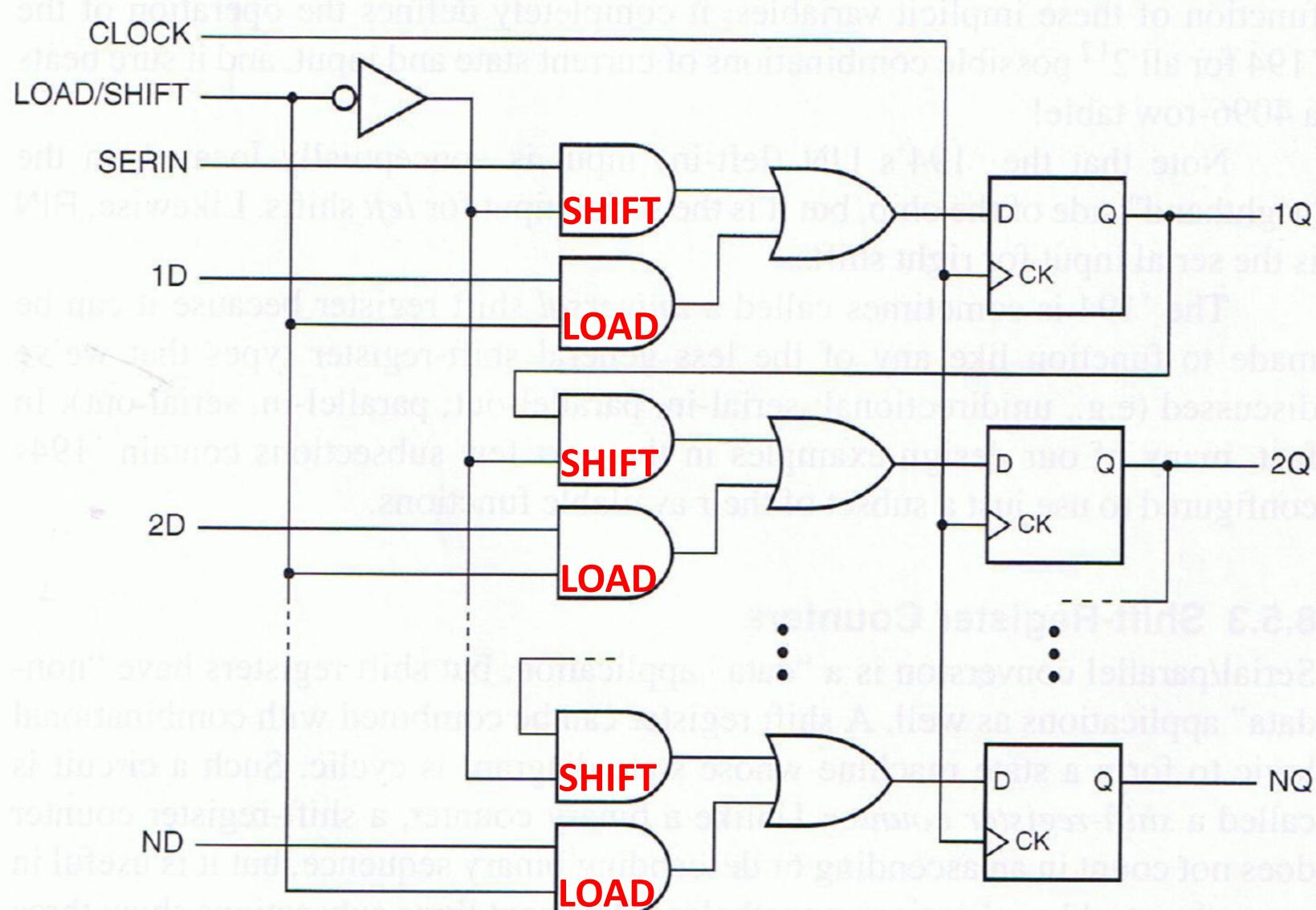
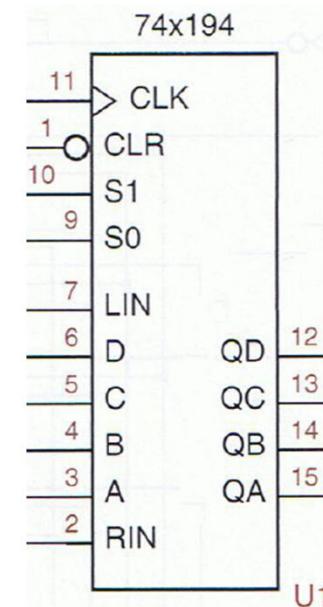
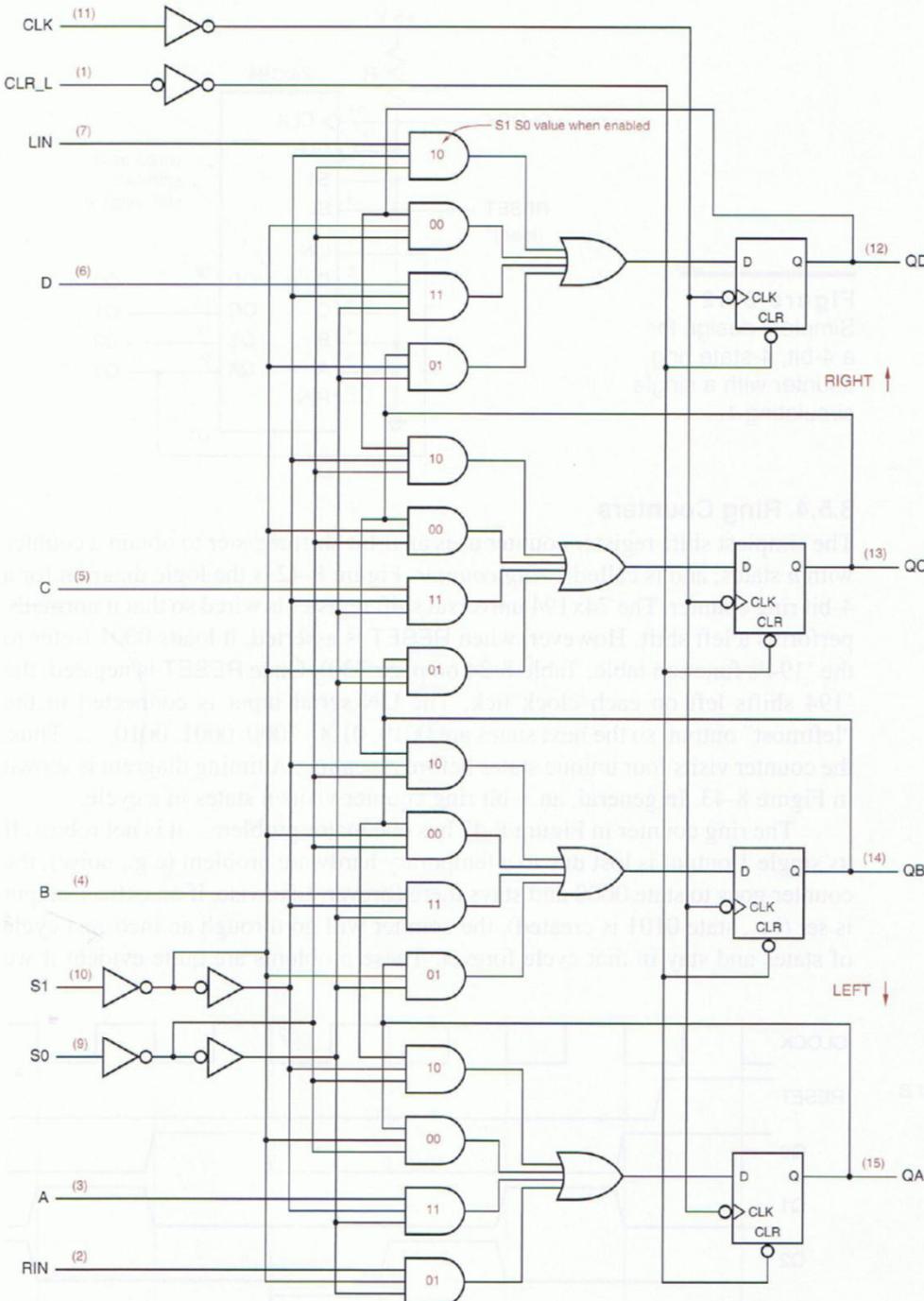


Figure 8-40 Structure of a parallel-in, parallel-out shift register.



74x194 Universal Shift Register

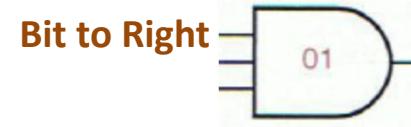
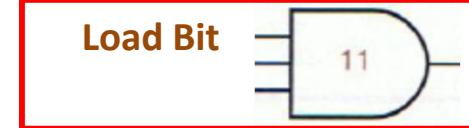
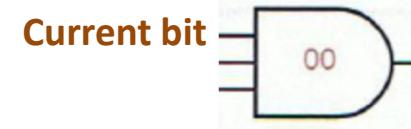
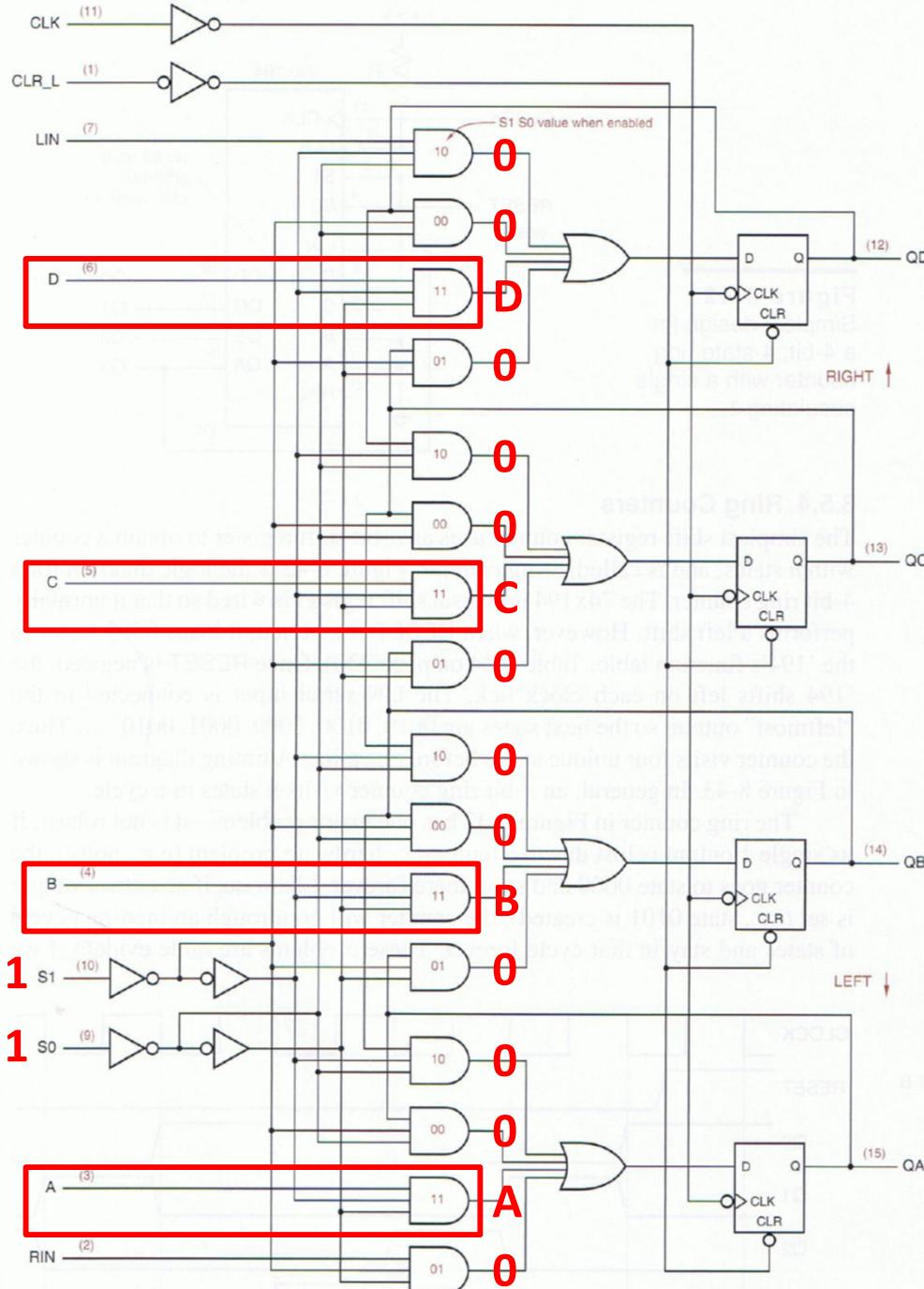


Function	Inputs		Next state			
	S1	S0	QA*	QB*	QC*	QD*
Hold	0	0	QA	QB	QC	QD
Shift right	0	1	RIN	QA	QB	QC
Shift left	1	0	QB	QC	QD	LIN
Load	1	1	A	B	C	D

Figure 8-41 Logic diagram for the 74x194 4-bit universal shift register, including pin numbers for a standard 16-pin dual in-line package.



74x194 Universal Shift Register (Load)



Function	Inputs		Next state			
	S1	S0	QA*	QB*	QC*	QD*
Hold	0	0	QA	QB	QC	QD
Shift right	0	1	RIN	QA	QB	QC
Shift left	1	0	QB	QC	QD	LIN
Load	1	1	A	B	C	D

Figure 8-41 Logic diagram for the 74x194 4-bit universal shift register, including pin numbers for a standard 16-pin dual in-line package.



74x194 Universal Shift Register (Hold)

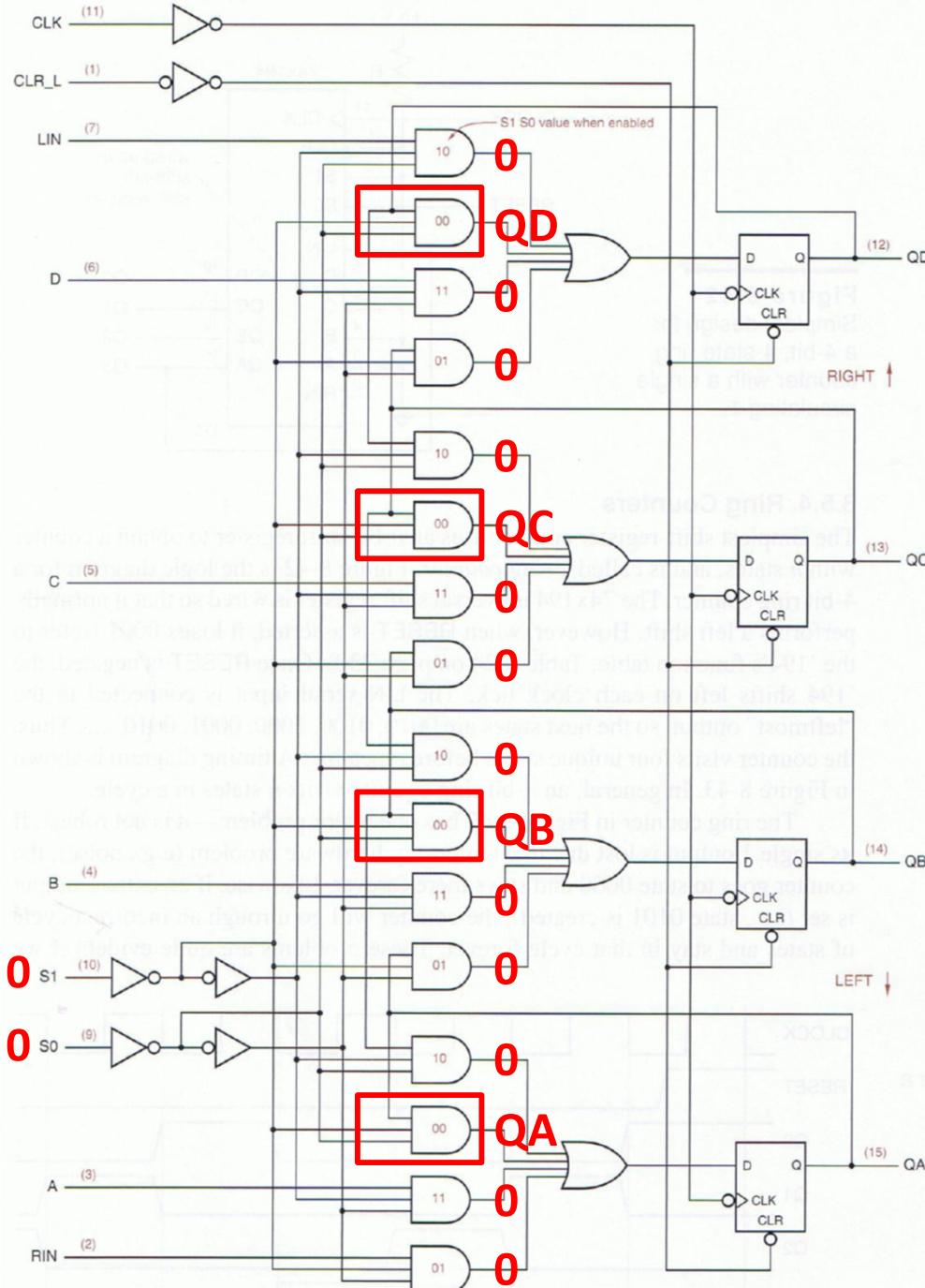
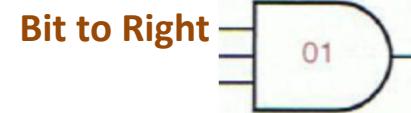
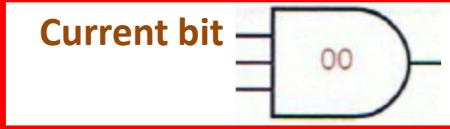
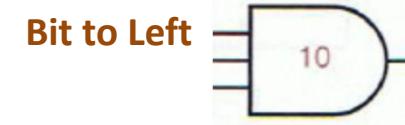


Figure 8-41 Logic diagram for the 74x194 4-bit universal shift register, including pin numbers for a standard 16-pin dual in-line package.



Function	Inputs		Next state			
	S1	S0	QA*	QB*	QC*	QD*
Hold	0	0	QA	QB	QC	QD
Shift right	0	1	RIN	QA	QB	QC
Shift left	1	0	QB	QC	QD	LIN
Load	1	1	A	B	C	D



74x194 Universal Shift Register (Shift Right)

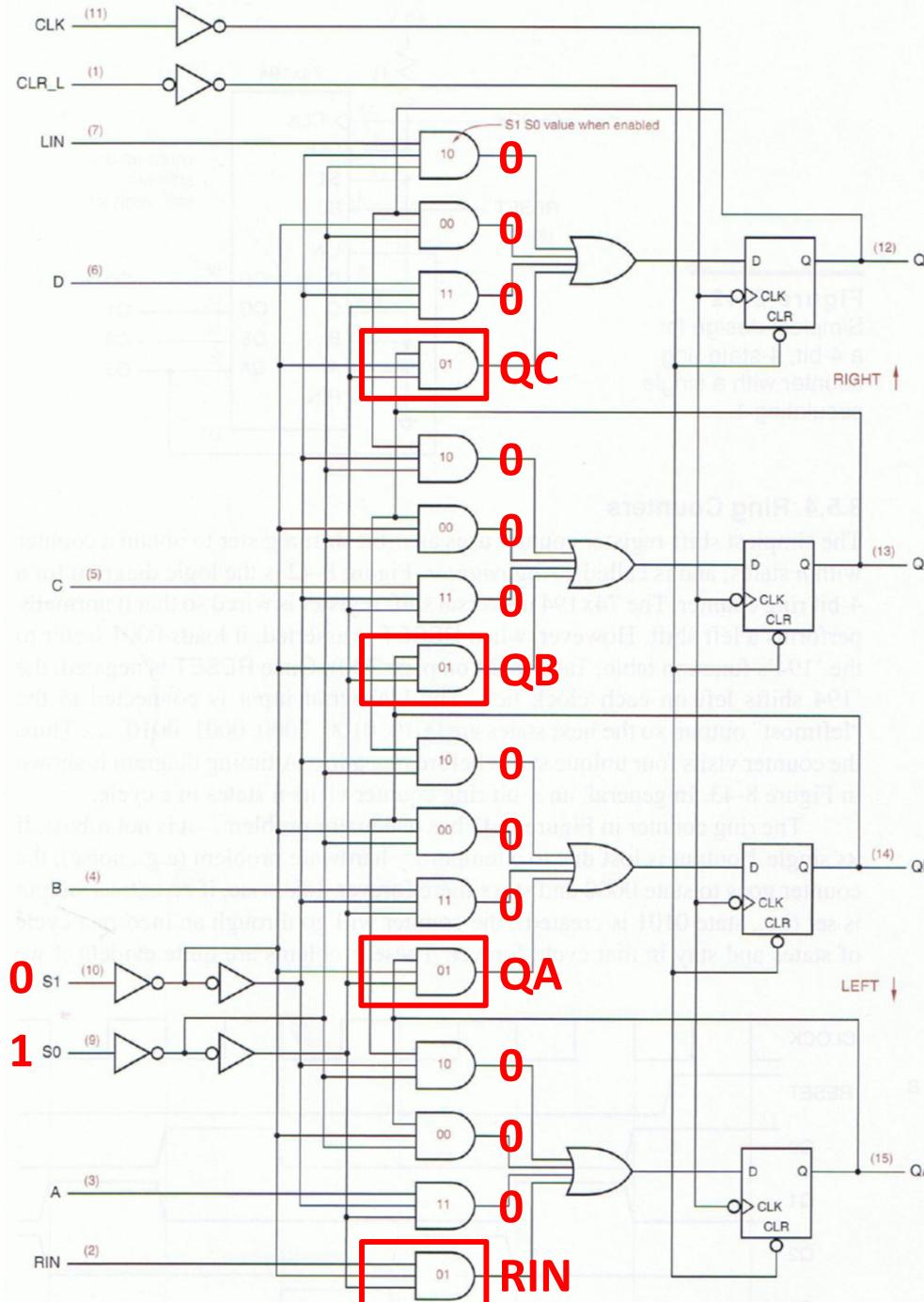
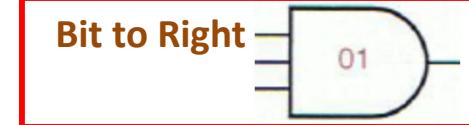
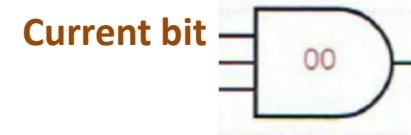
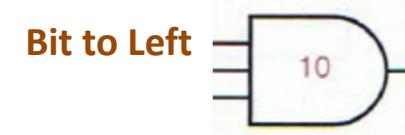


Figure 8-41 Logic diagram for the 74x194 4-bit universal shift register, including pin numbers for a standard 16-pin dual in-line package.



Function	Inputs		Next state			
	S1	S0	QA*	QB*	QC*	QD*
Hold	0	0	QA	QB	QC	QD
Shift right	0	1	RIN	QA	QB	QC
Shift left	1	0	QB	QC	QD	LIN
Load	1	1	A	B	C	D



74x194 Universal Shift Register (Shift Left)

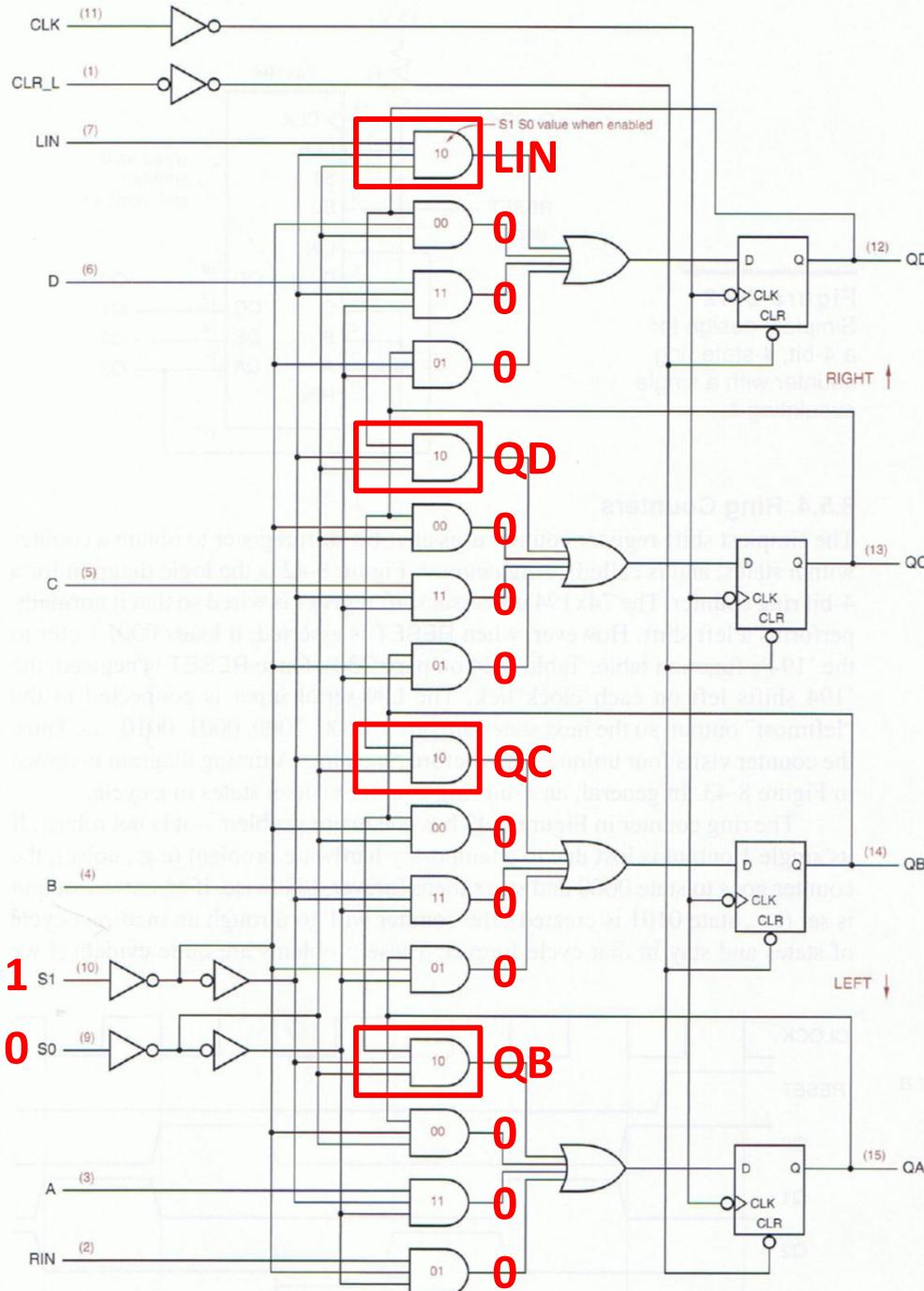
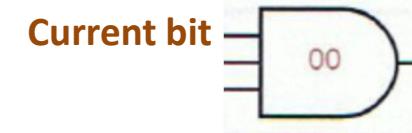
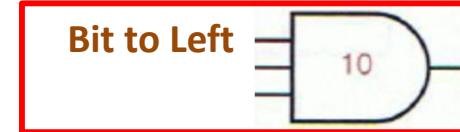


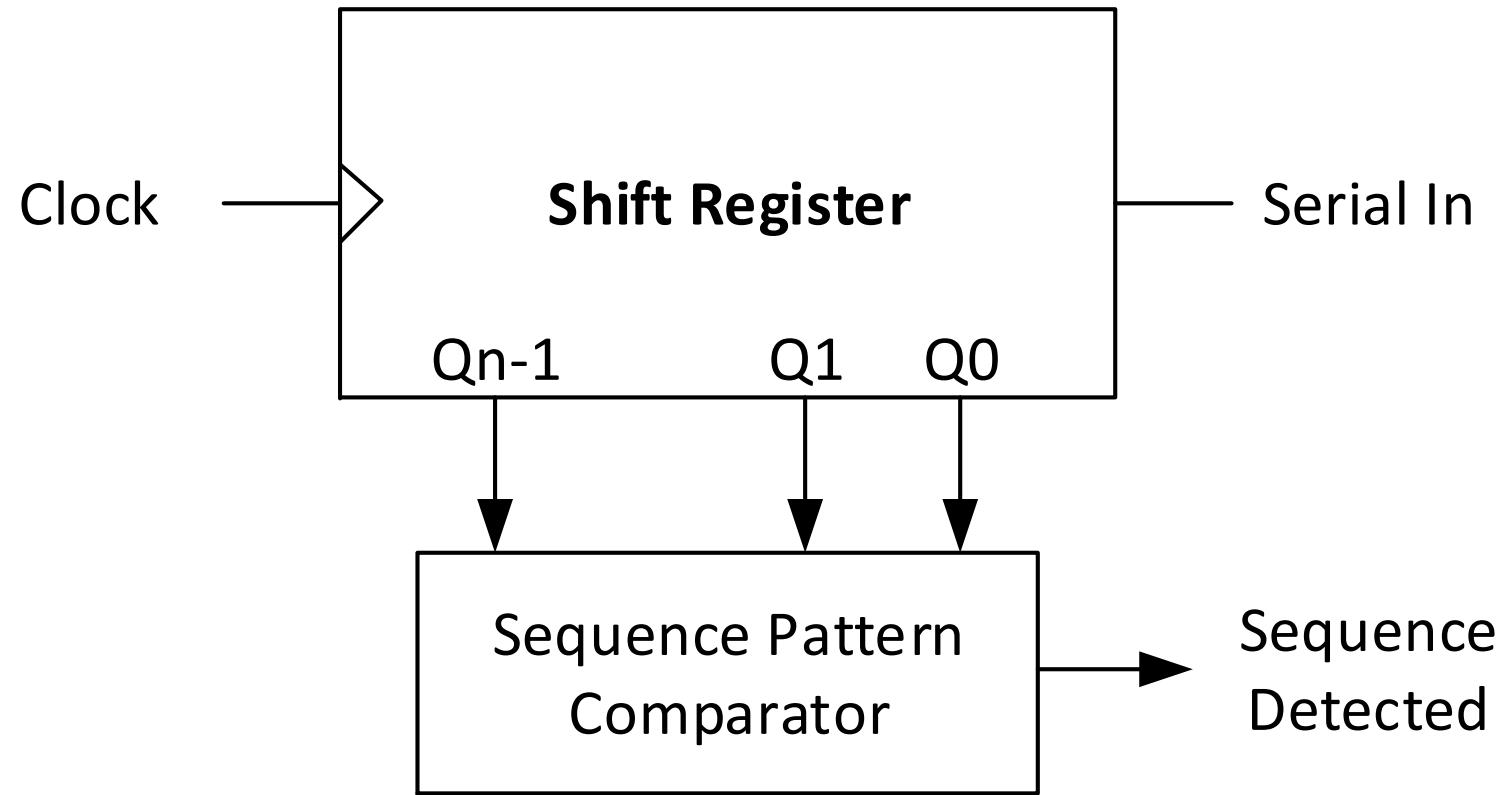
Figure 8-41 Logic diagram for the 74x194 4-bit universal shift register, including pin numbers for a standard 16-pin dual in-line package.



Function	Inputs		Next state			
	S1	S0	QA*	QB*	QC*	QD*
Hold	0	0	QA	QB	QC	QD
Shift right	0	1	RIN	QA	QB	QC
Shift left	1	0	QB	QC	QD	LIN
Load	1	1	A	B	C	D



Building Sequence Detectors with Shift Registers (overlapping sequences)



How to implement efficiently the sequence pattern comparator?

Ring Counters

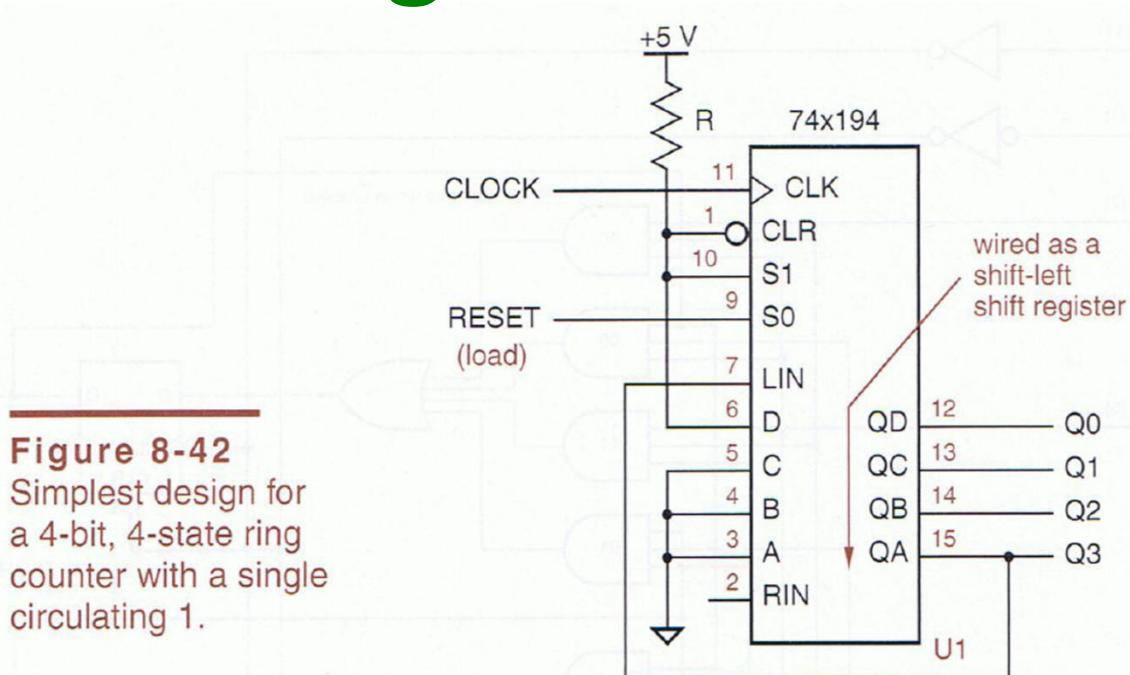
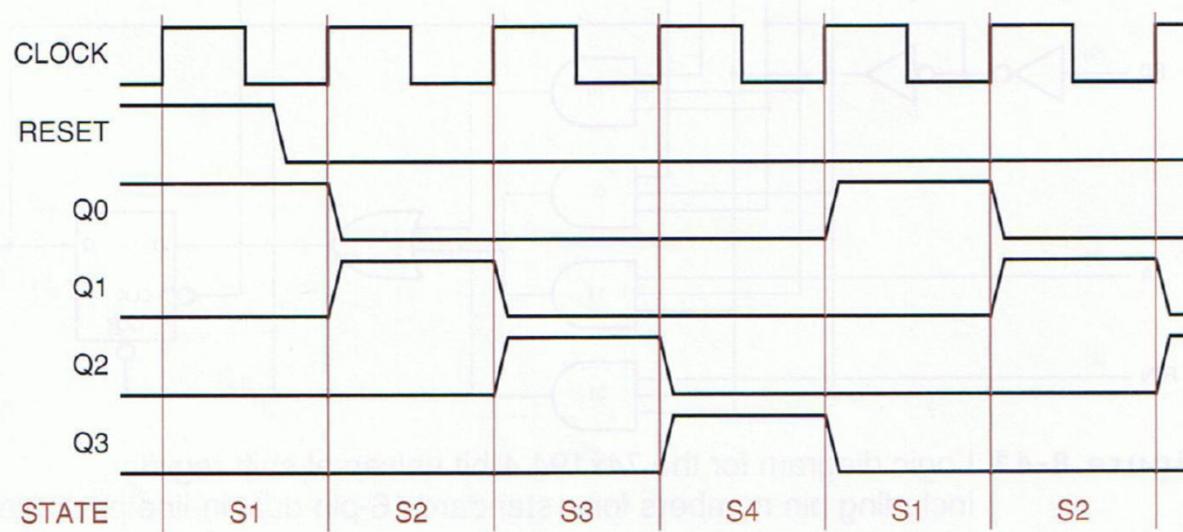


Figure 8-42
Simplest design for
a 4-bit, 4-state ring
counter with a single
circulating 1.

Figure 8-43
Timing diagram for a
4-bit ring counter.



Ring Counter State Diagram

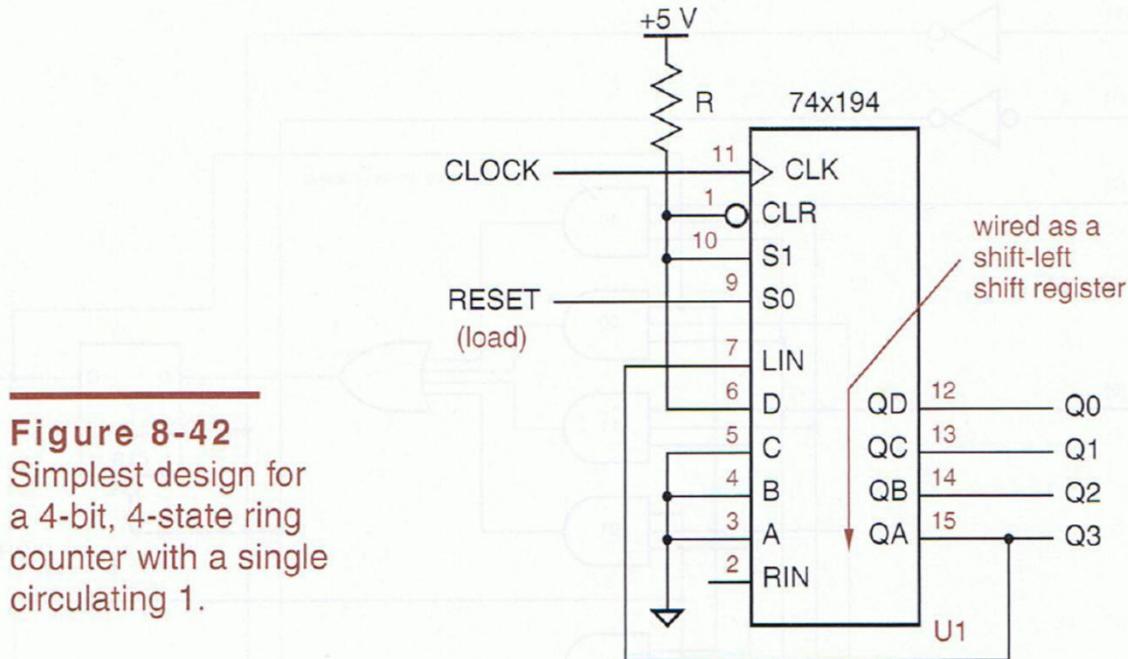


Figure 8-42
Simplest design for
a 4-bit, 4-state ring
counter with a single
circulating 1.

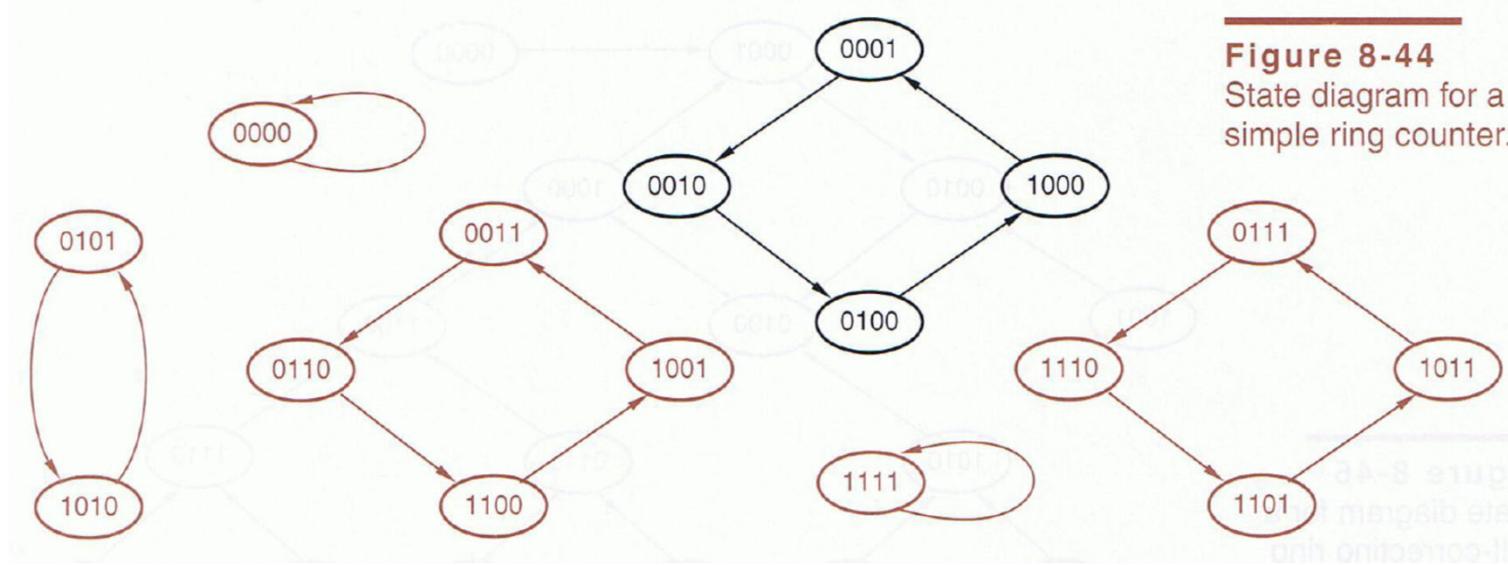


Figure 8-44
State diagram for a
simple ring counter.

Self-correcting Ring Counter

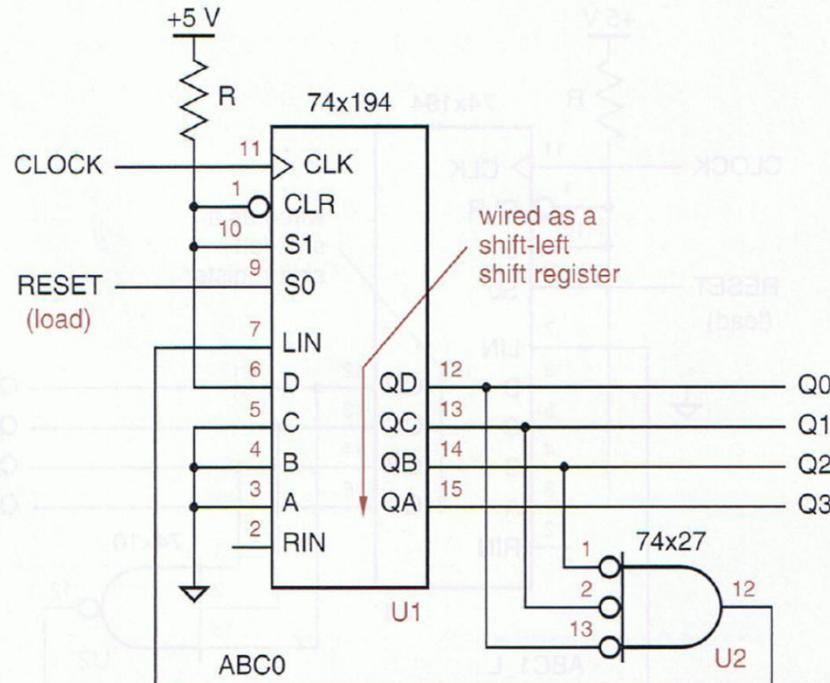


Figure 8-45

Self-correcting 4-bit, 4-state ring counter with a single circulating 1.

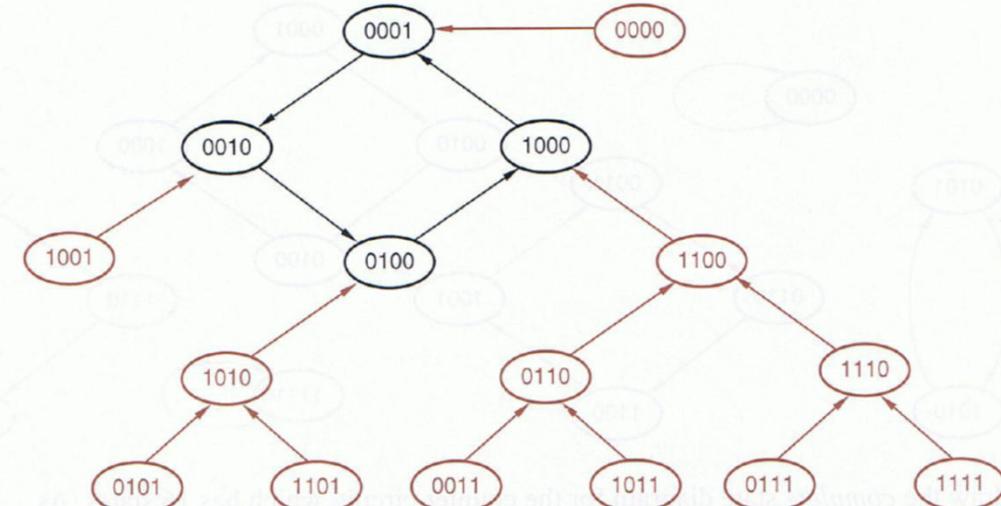


Figure 8-46

State diagram for a self-correcting ring counter.



Johnson Counter (twisted ring)

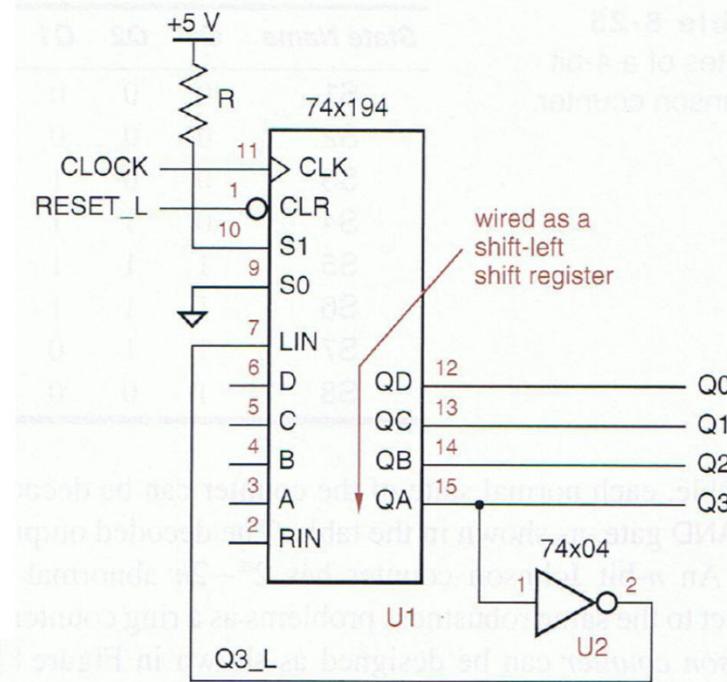
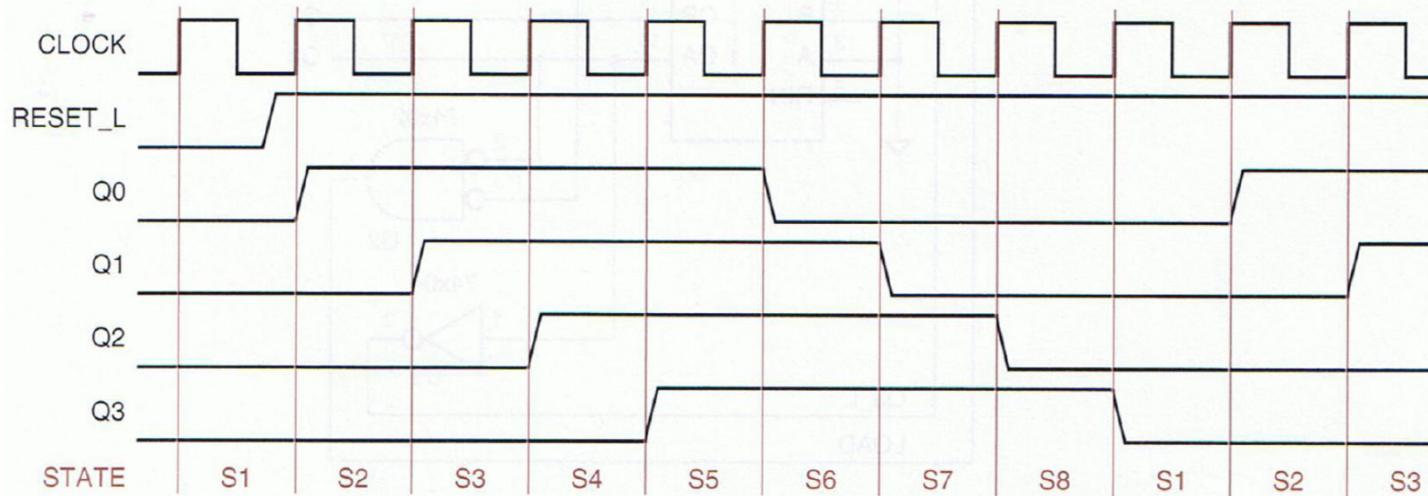


Figure 8-48
Basic 4-bit, 8-state
Johnson counter.

Figure 8-49 Timing diagram for a 4-bit Johnson counter.

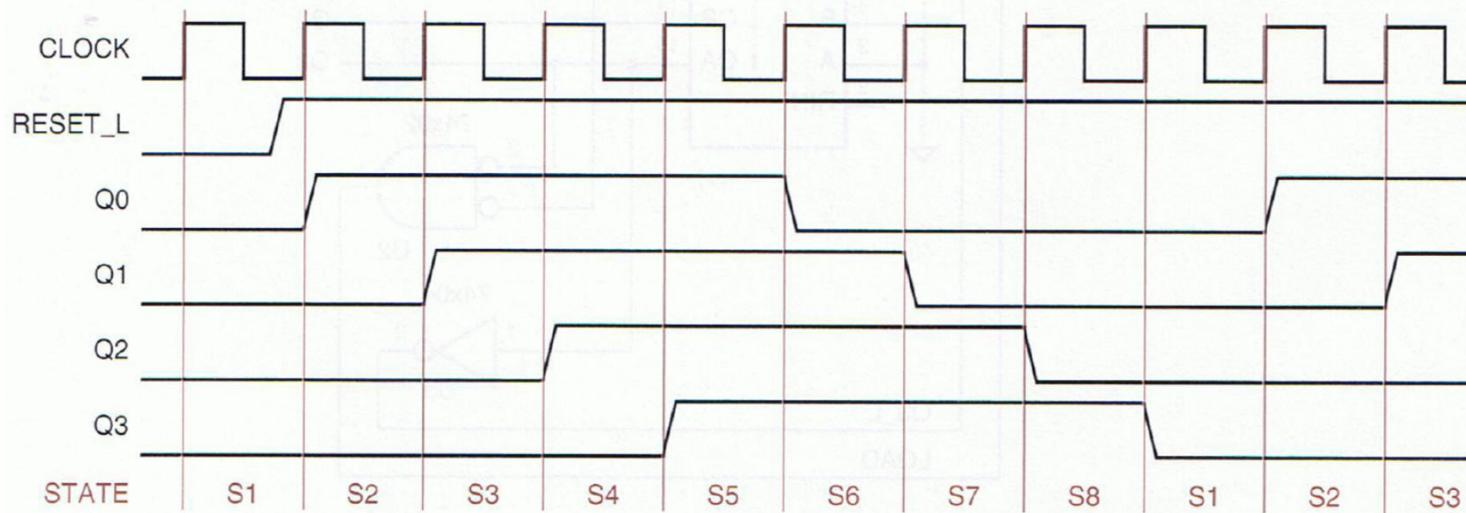


Johnson Counter (twisted ring)

Table 8-25
States of a 4-bit
Johnson counter.

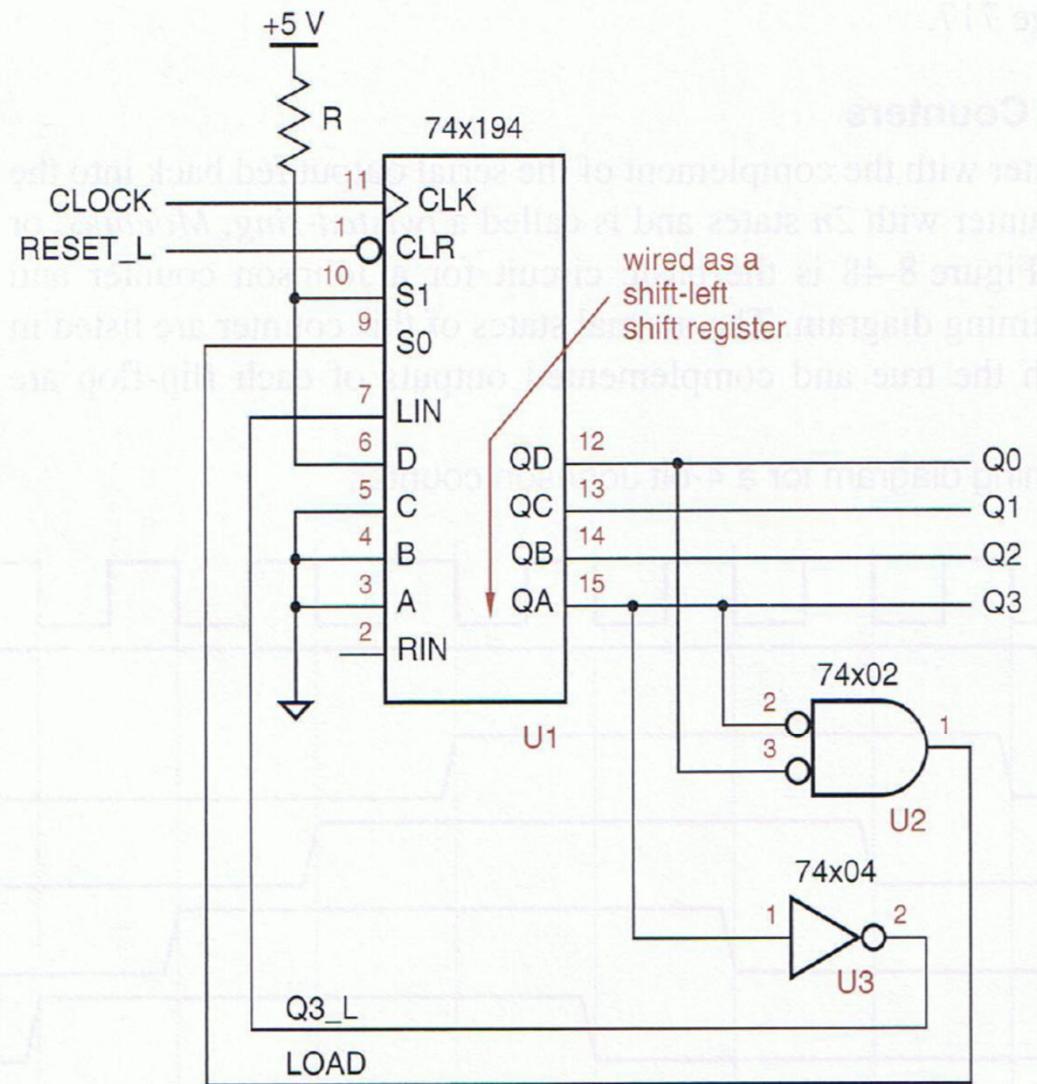
State Name	Q3	Q2	Q1	Q0	Decoding
S1	0	0	0	0	$Q3' \cdot Q0'$
S2	0	0	0	1	$Q1' \cdot Q0$
S3	0	0	1	1	$Q2' \cdot Q1$
S4	0	1	1	1	$Q3' \cdot Q2$
S5	1	1	1	1	$Q3 \cdot Q0$
S6	1	1	1	0	$Q1 \cdot Q0'$
S7	1	1	0	0	$Q2 \cdot Q1'$
S8	1	0	0	0	$Q3 \cdot Q2'$

Figure 8-49 Timing diagram for a 4-bit Johnson counter.



Self Correcting Johnson Counter

Figure 8-50
Self-correcting
4-bit, 8-state
Johnson counter.



Conclusion

- At the end of this lecture and corresponding lab, it is fundamental to know some fundamental sequential blocks / components, namely multibit registers, counters and shift registers
- Plan for the next lecture
 - Iterative vs. sequential circuits

Reading chapter 7 (4th ed.) or chapter 11 (5th ed.) of John F. Wakerly, “Digital Design – Principles and Practices”, Pearson – Prentice Hall, is highly recommended.