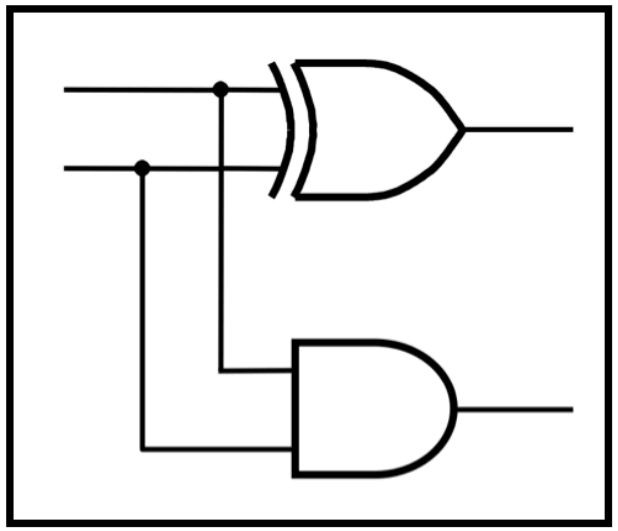


CprE 281: Digital Logic

Instructor: Alexander Stoytchev

http://www.ece.iastate.edu/~alexs/classes/

Registers and Counters

CprE 281: Digital Logic
Iowa State University, Ames, IA

Administrative Stuff

- **The second midterm is this Friday.**
- **Homework 8 is due today.**
- **Homework 9 is out. It is due on Mon Nov 6.**
- **No HW due next Monday**

Administrative Stuff

- **Midterm Exam #2**
- **When: Friday October 27 @ 4pm.**
- **Where: This classroom**
- **What: Chapters 1, 2, 3, 4 and 5.1-5.8**
- **The exam will be open book and open notes (you can bring up to 3 pages of handwritten notes).**

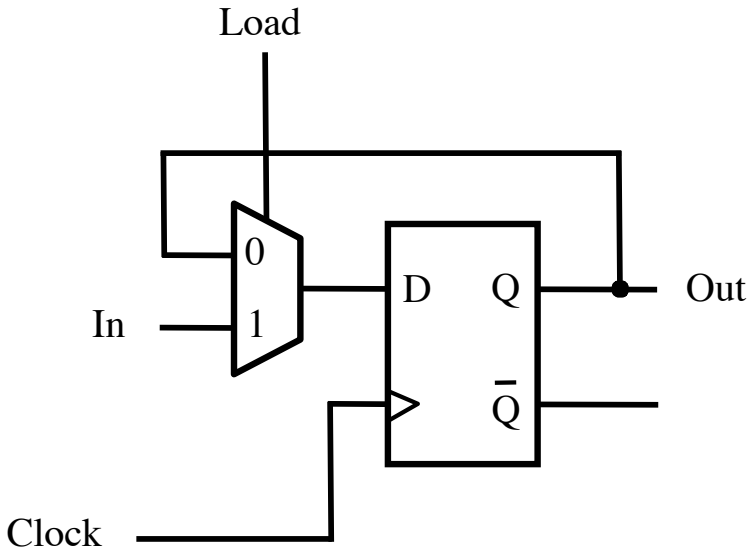
Registers

Register
(Definition)

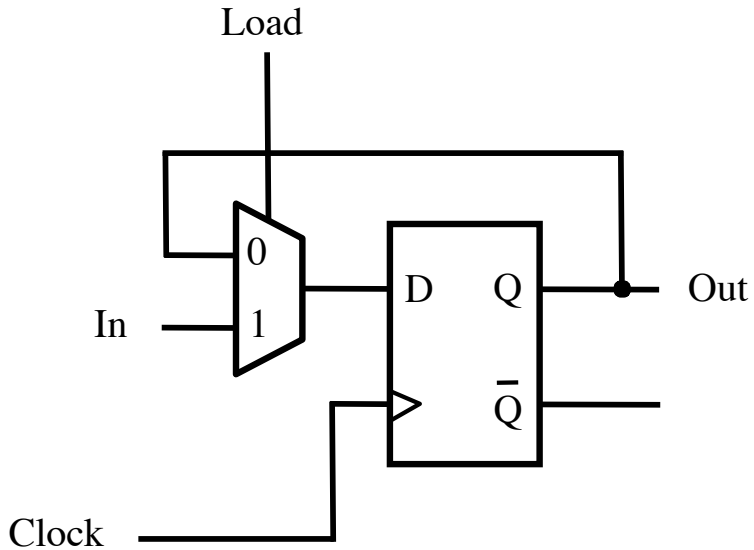
An n-bit structure consisting of flip-flops

Parallel-Access Register

1-Bit Parallel-Access Register



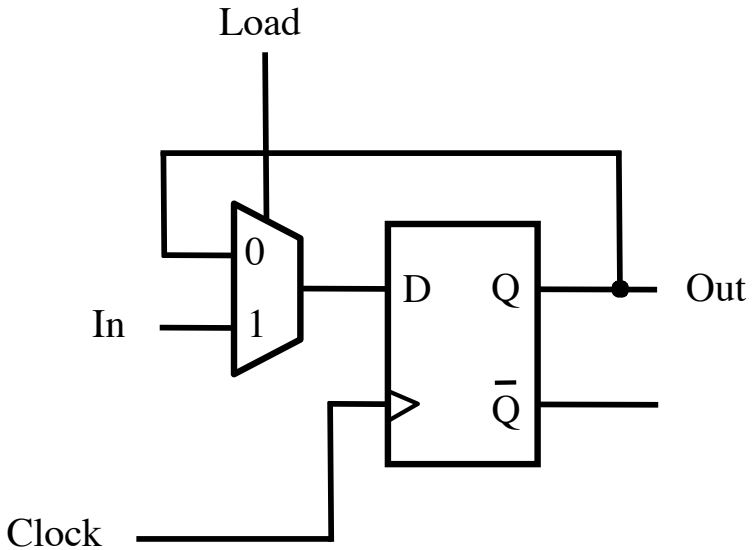
1-Bit Parallel-Access Register



The 2-to-1 multiplexer is used to select whether to load a new value into the D flip-flop or to retain the old value.

The output of this circuit is the Q output of the flip-flop.

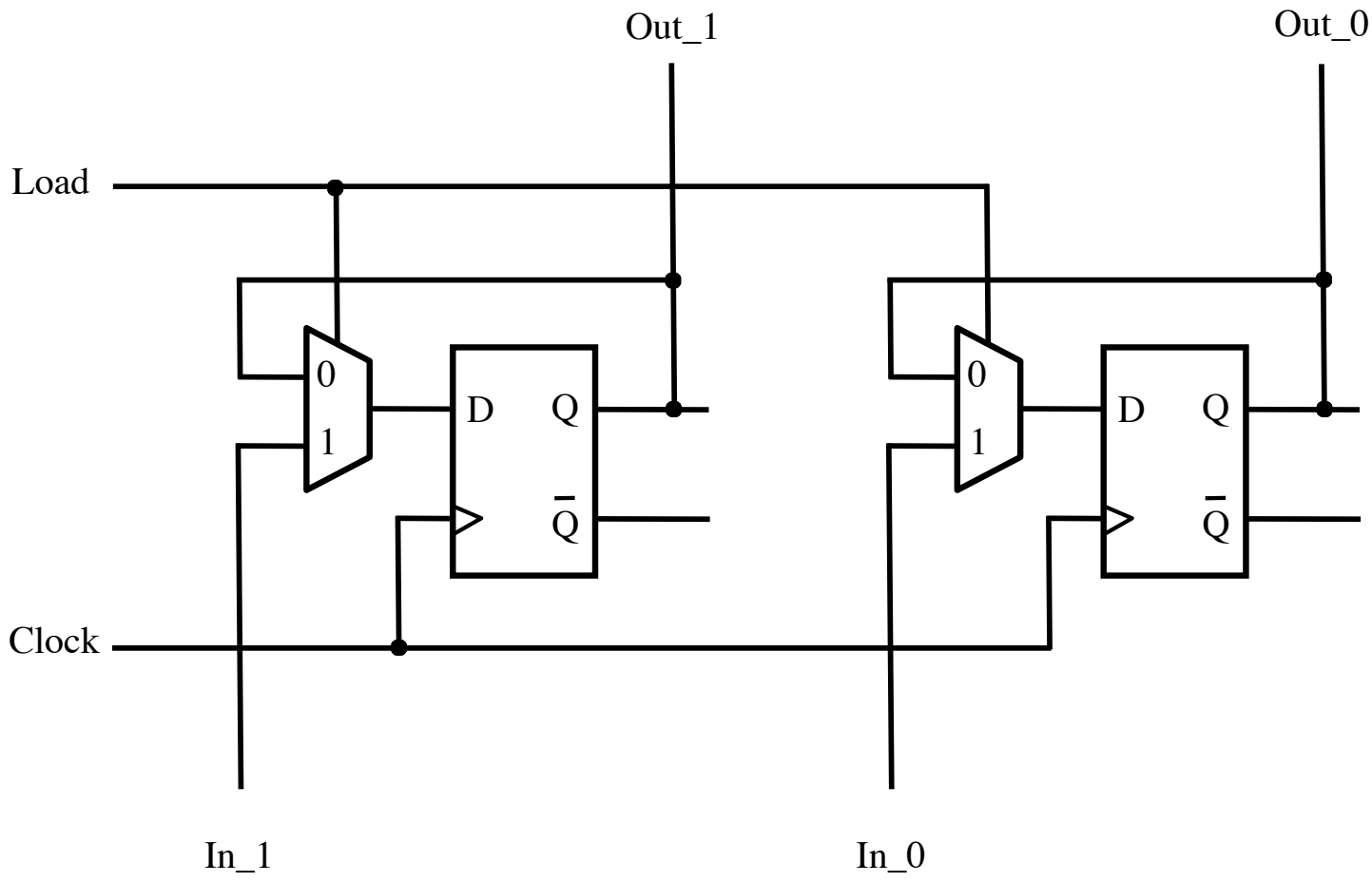
1-Bit Parallel-Access Register



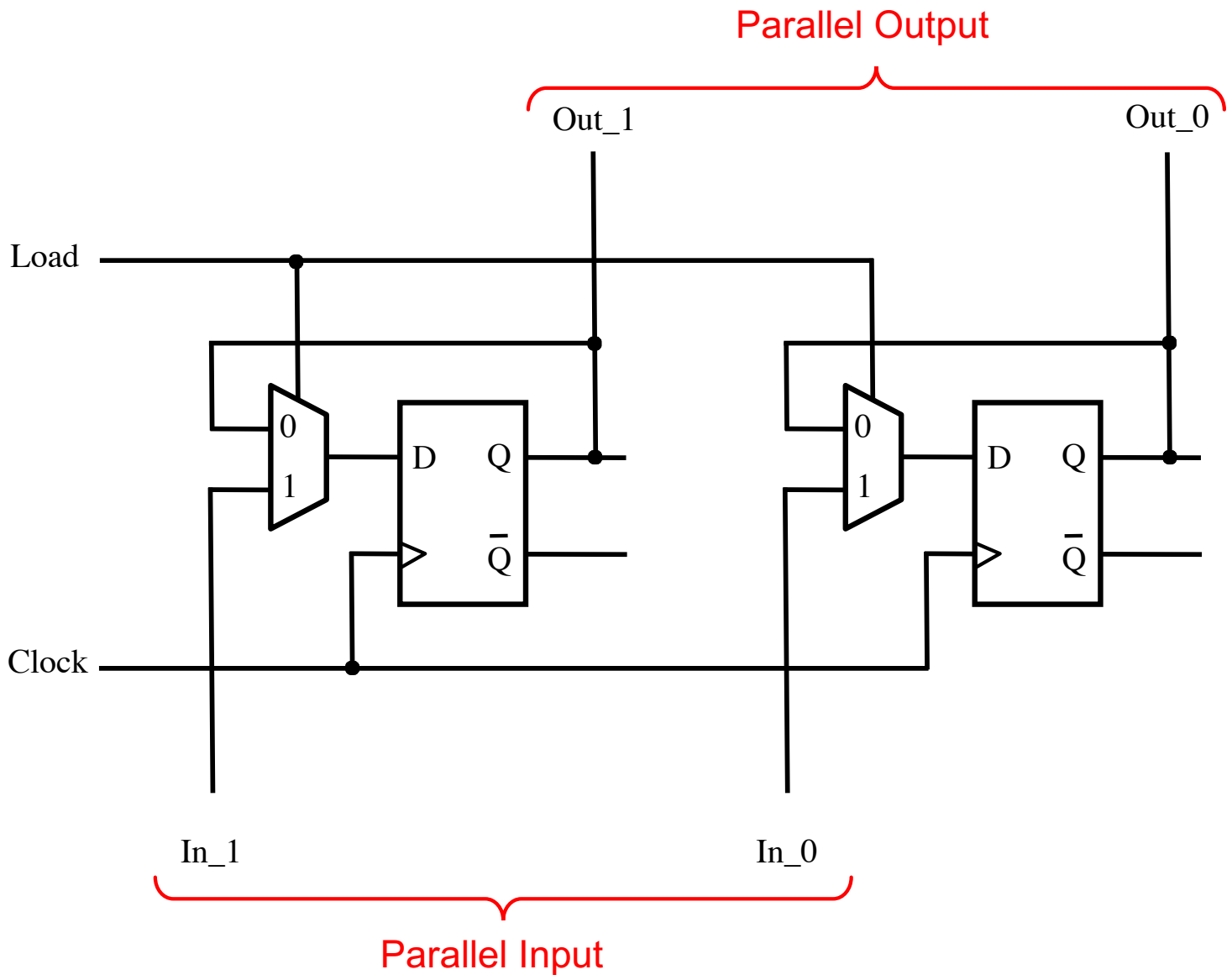
If Load = 0, then retain the old value.

If Load = 1, then load the new value from In.

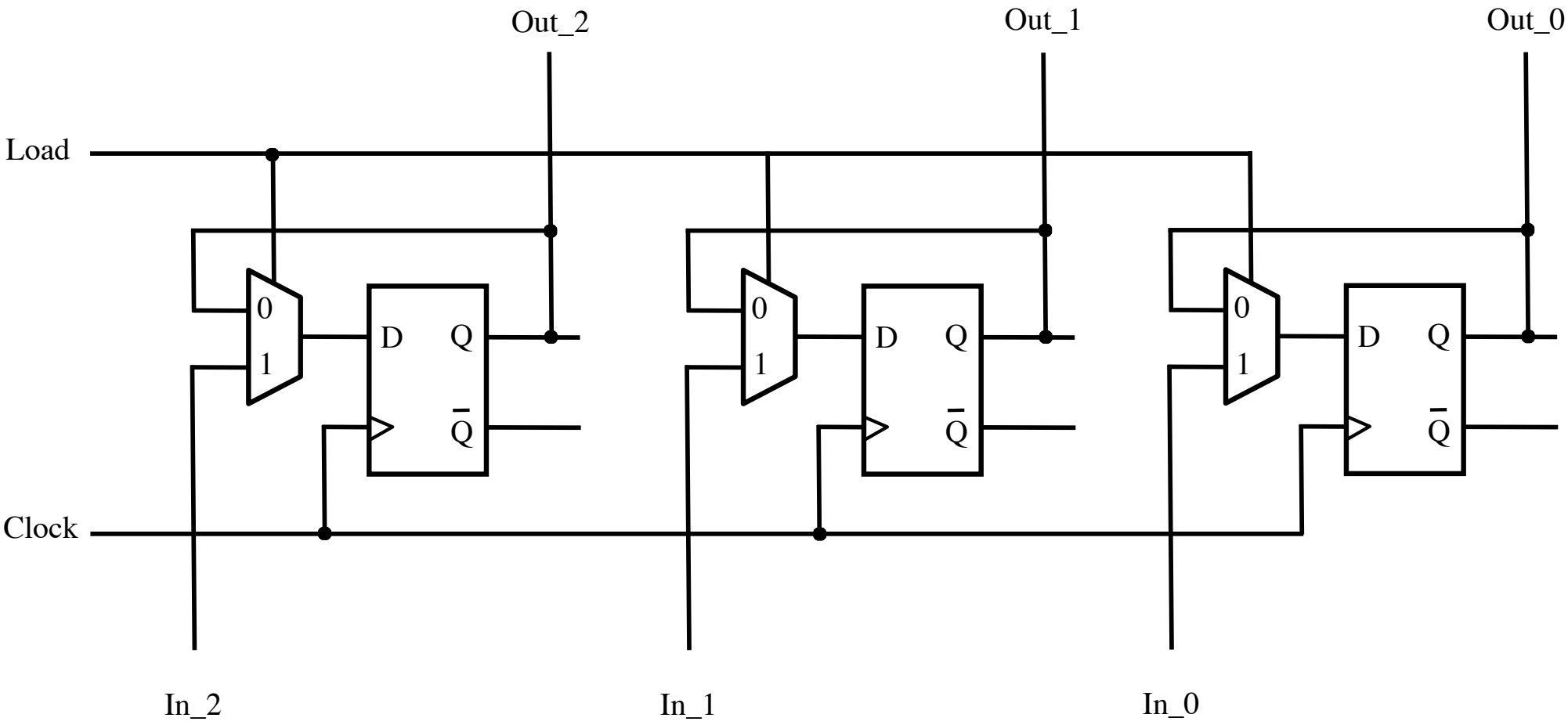
2-Bit Parallel-Access Register



2-Bit Parallel-Access Register

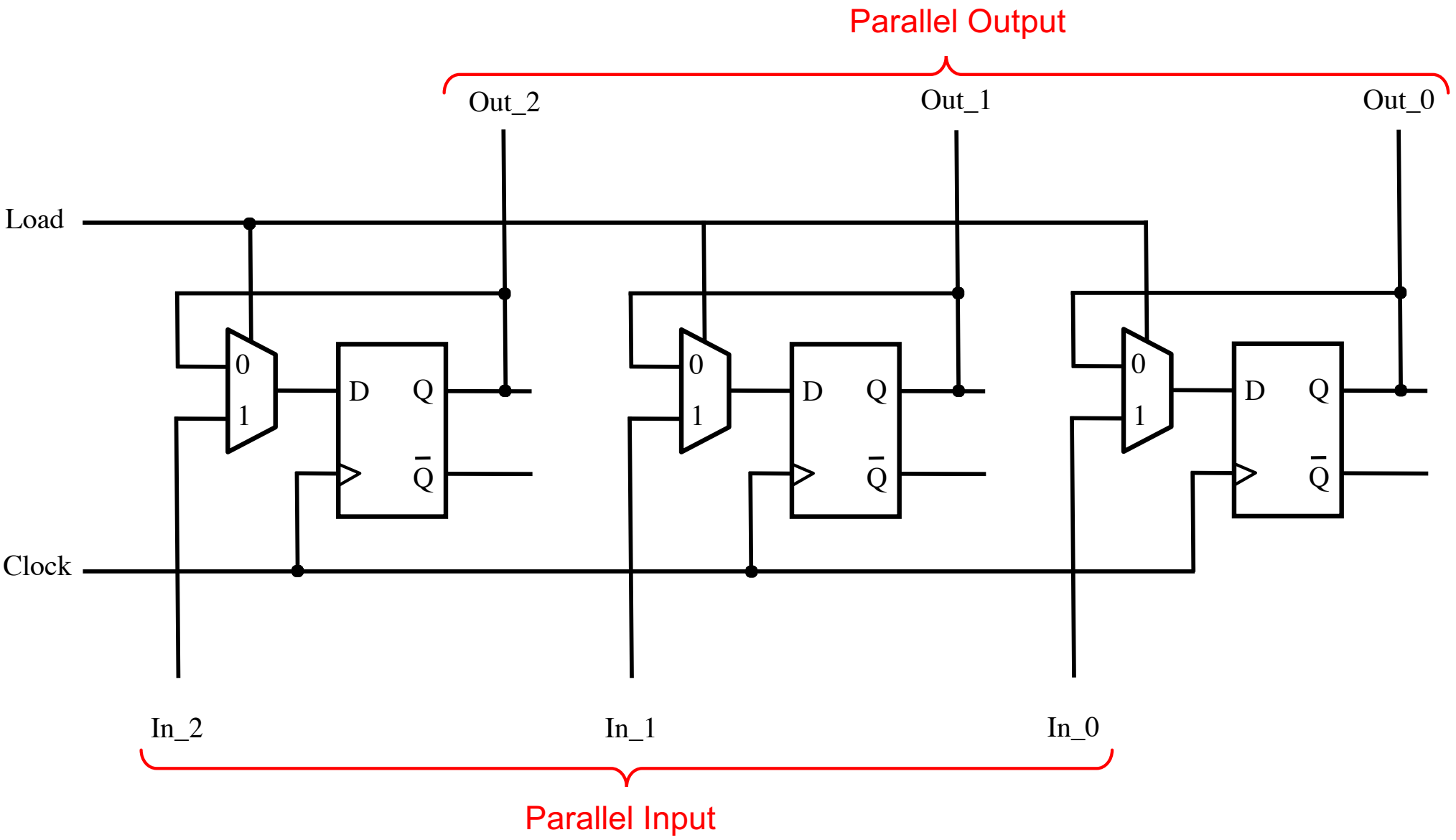


3-Bit Parallel-Access Register

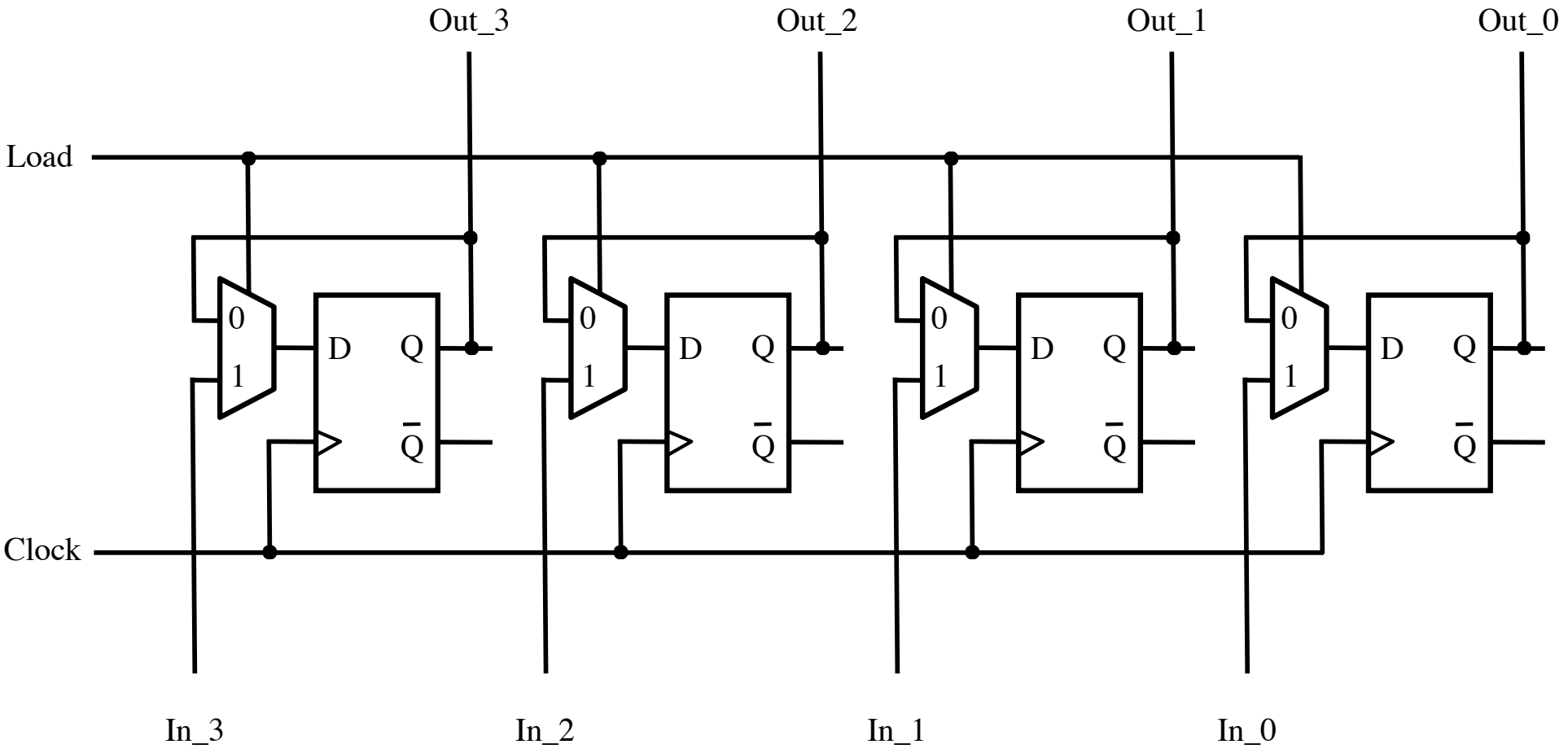


Notice that all flip-flops are on the same clock cycle.

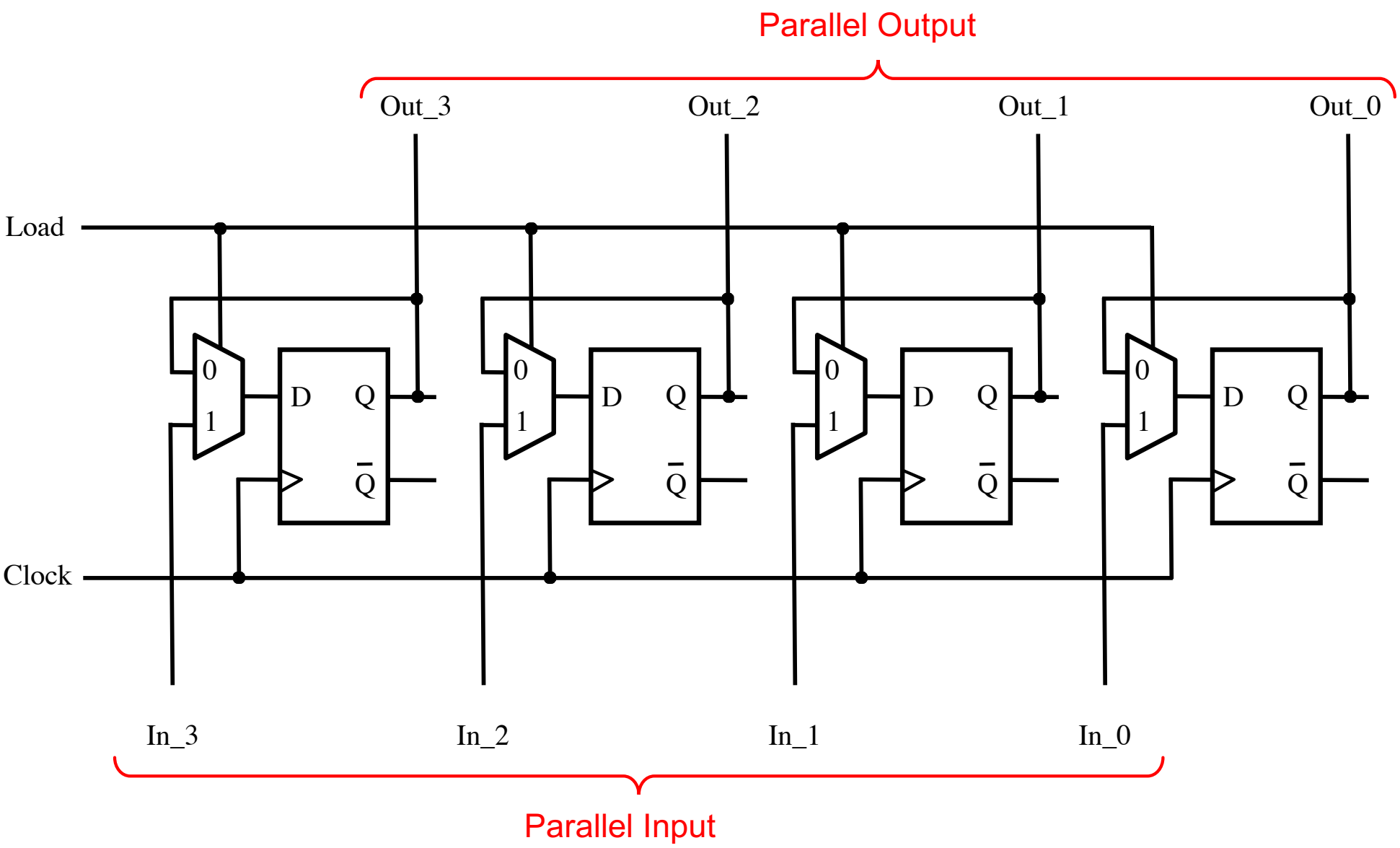
3-Bit Parallel-Access Register



4-Bit Parallel-Access Register

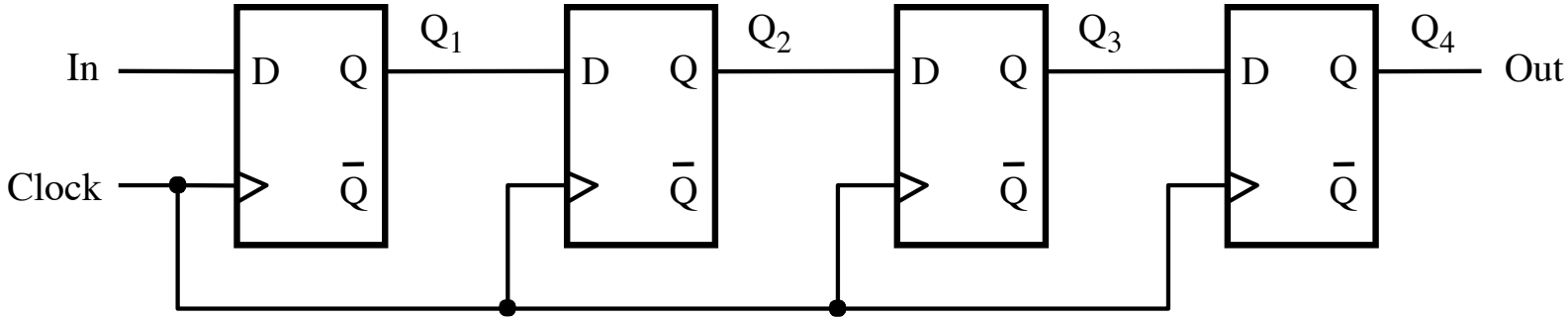


4-Bit Parallel-Access Register



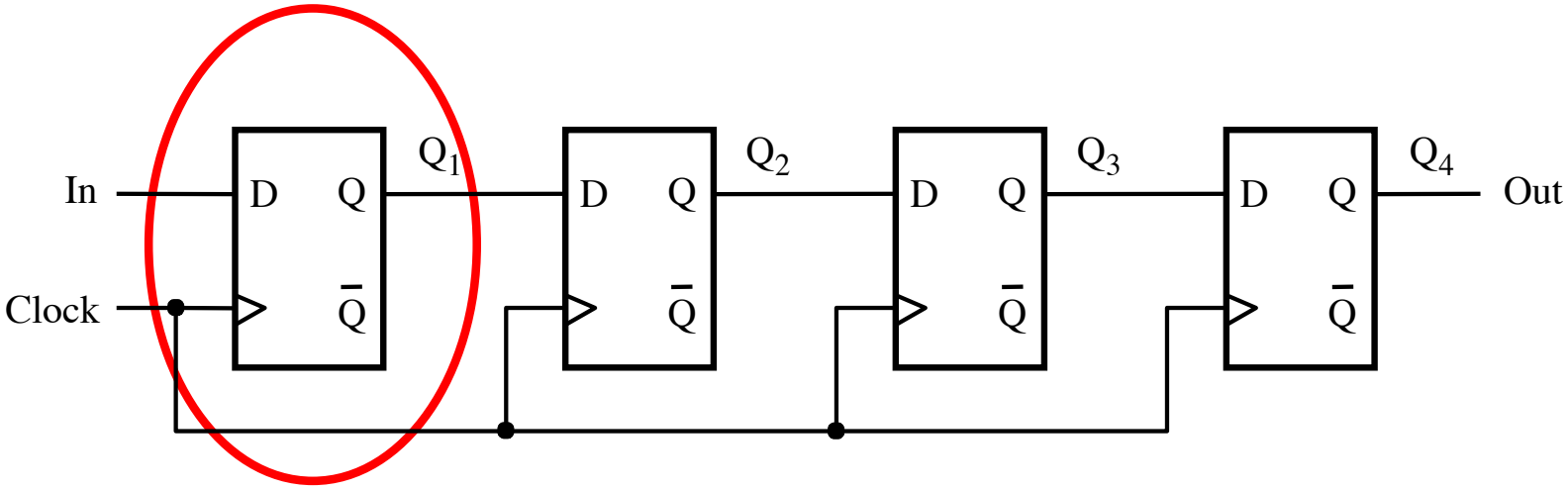
Shift Register

A simple shift register



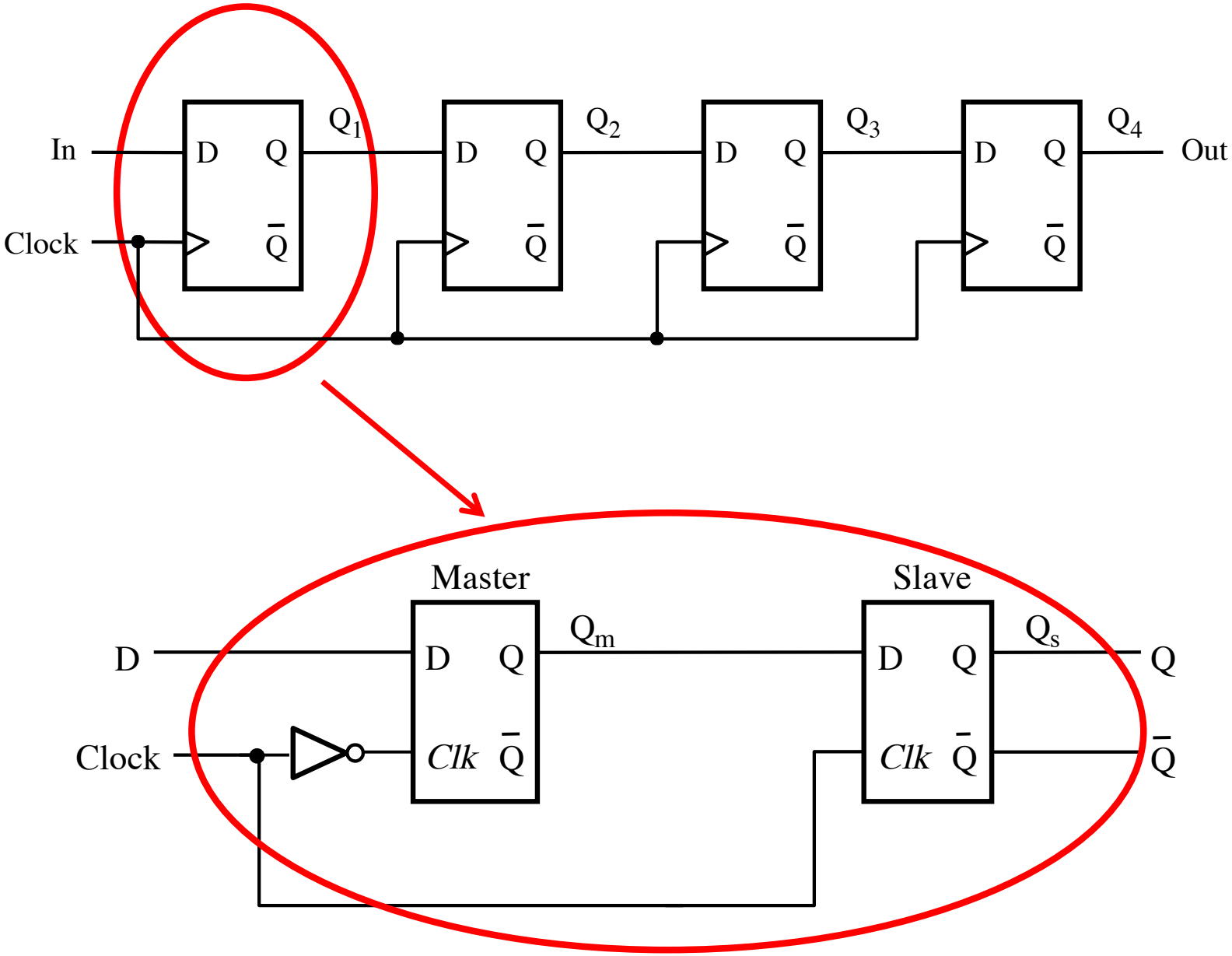
[Figure 5.17a from the textbook]

A simple shift register

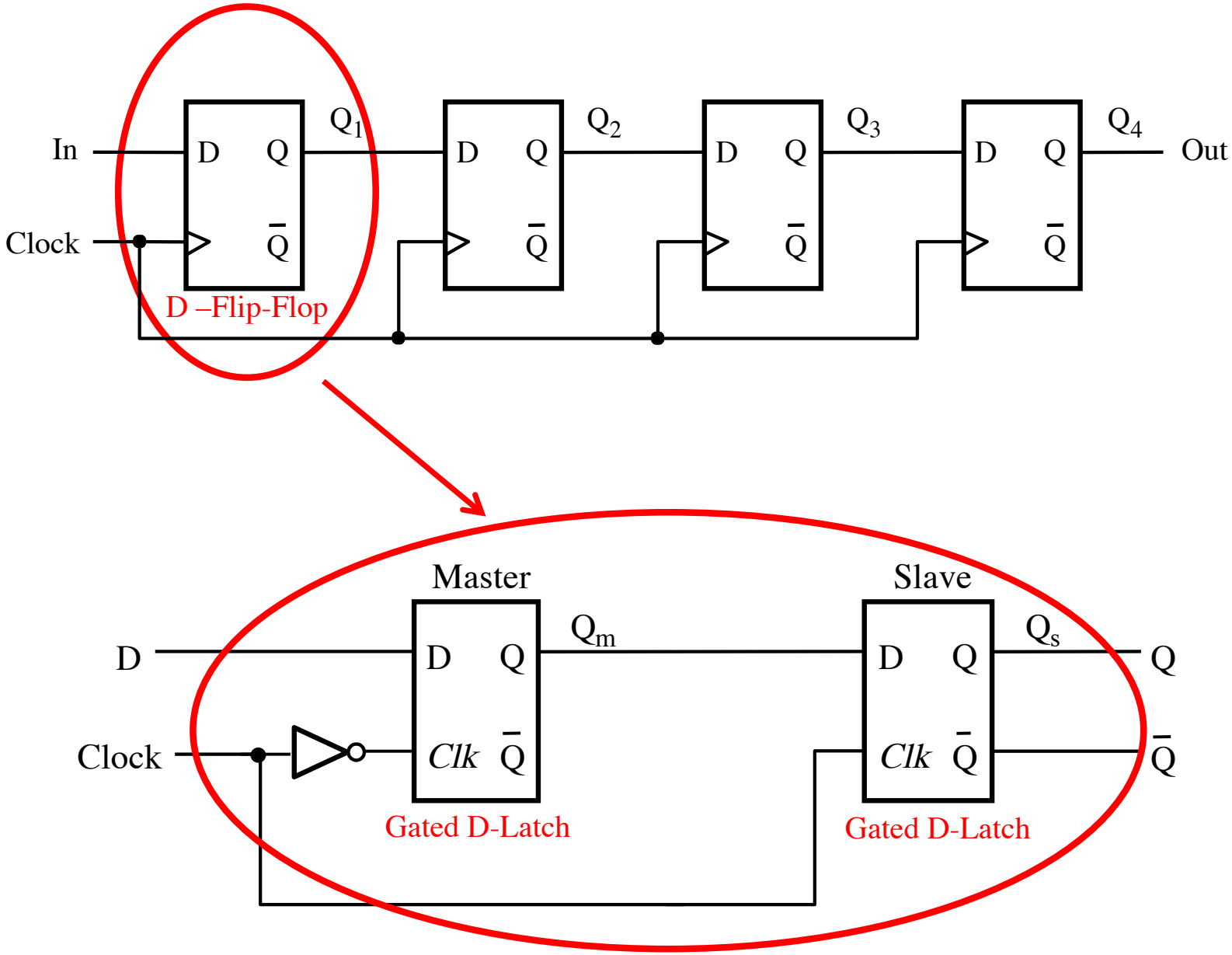


Positive-edge-triggered
D Flip-Flop

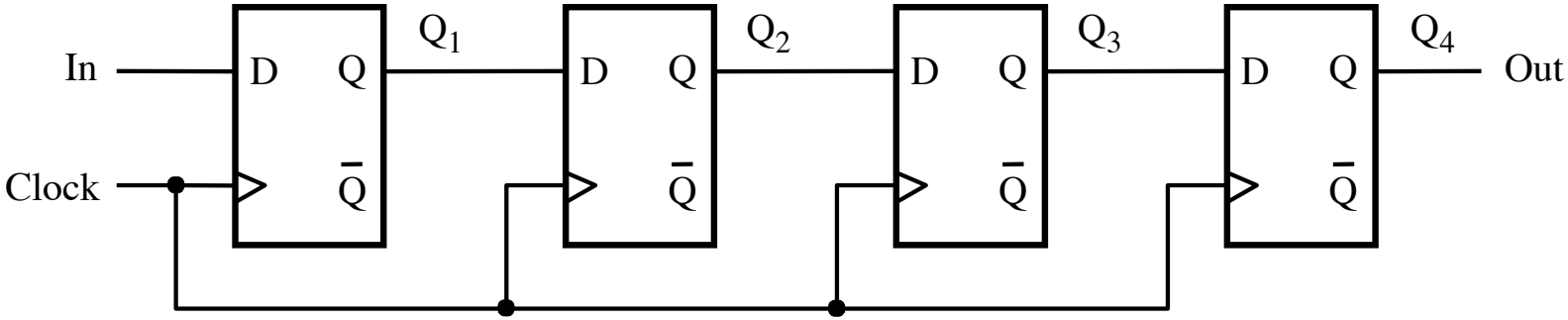
A simple shift register



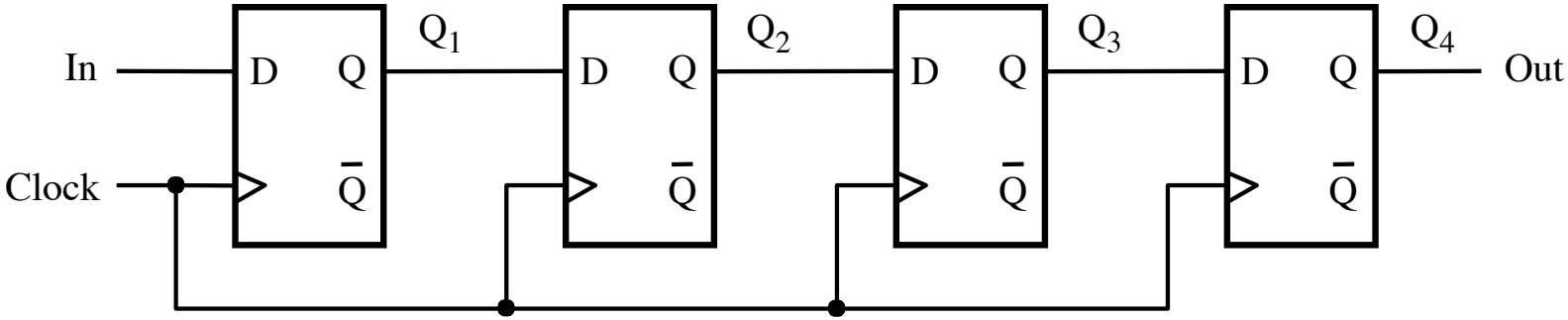
A simple shift register

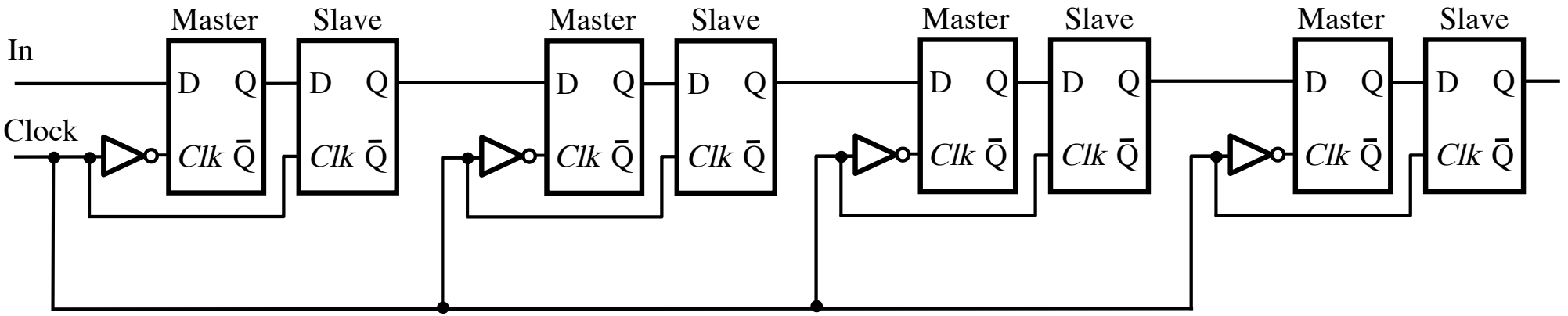


A simple shift register

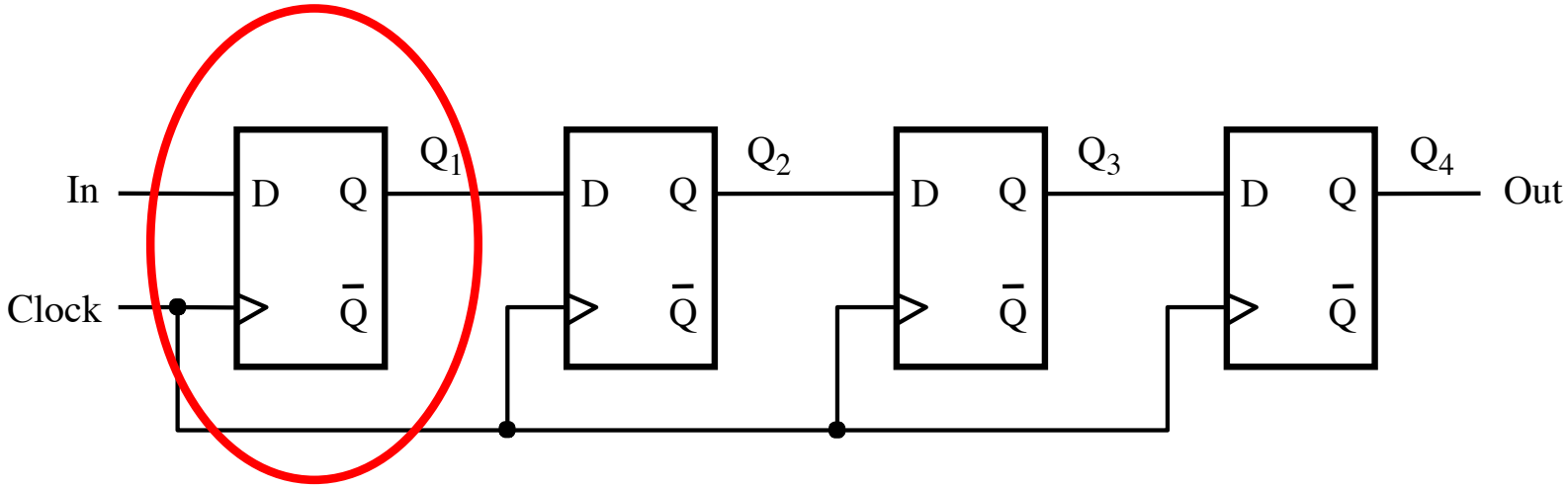


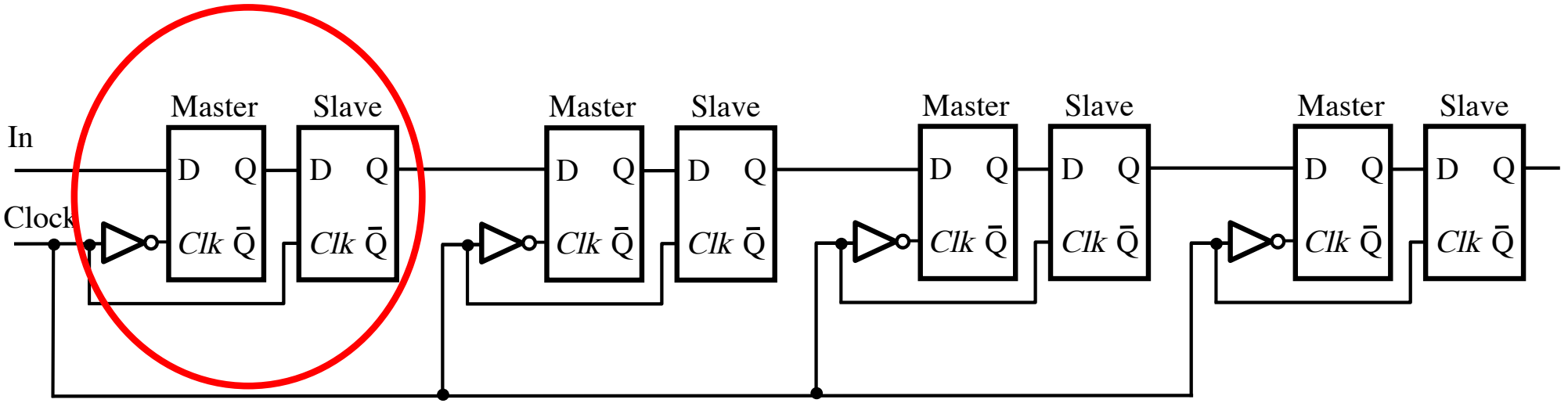
A simple shift register



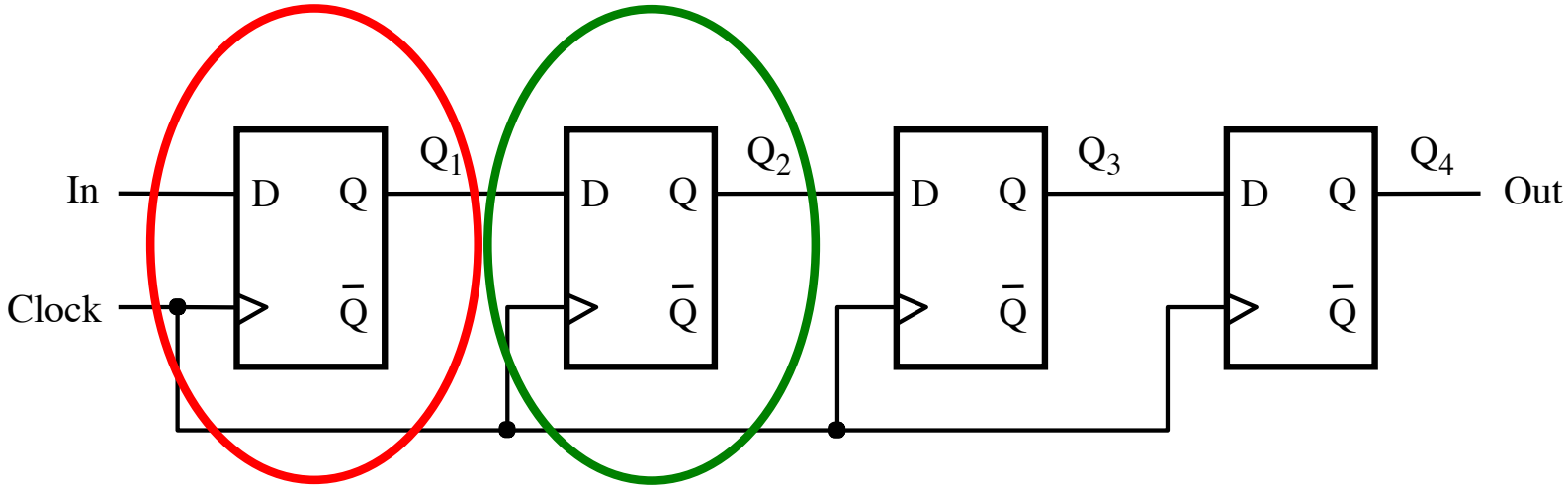


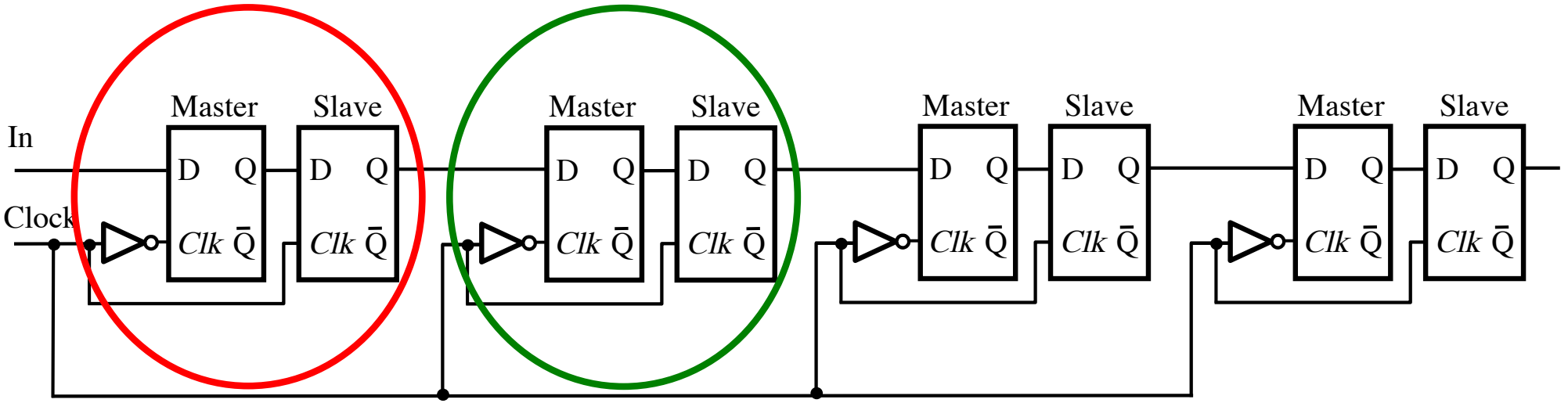
A simple shift register



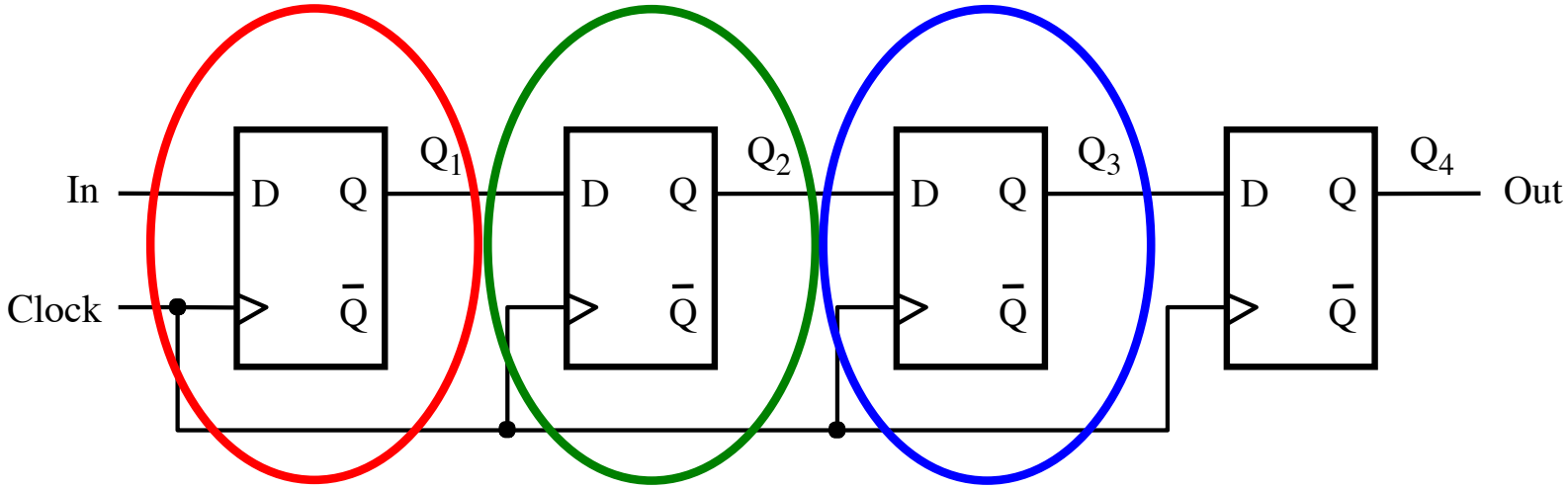


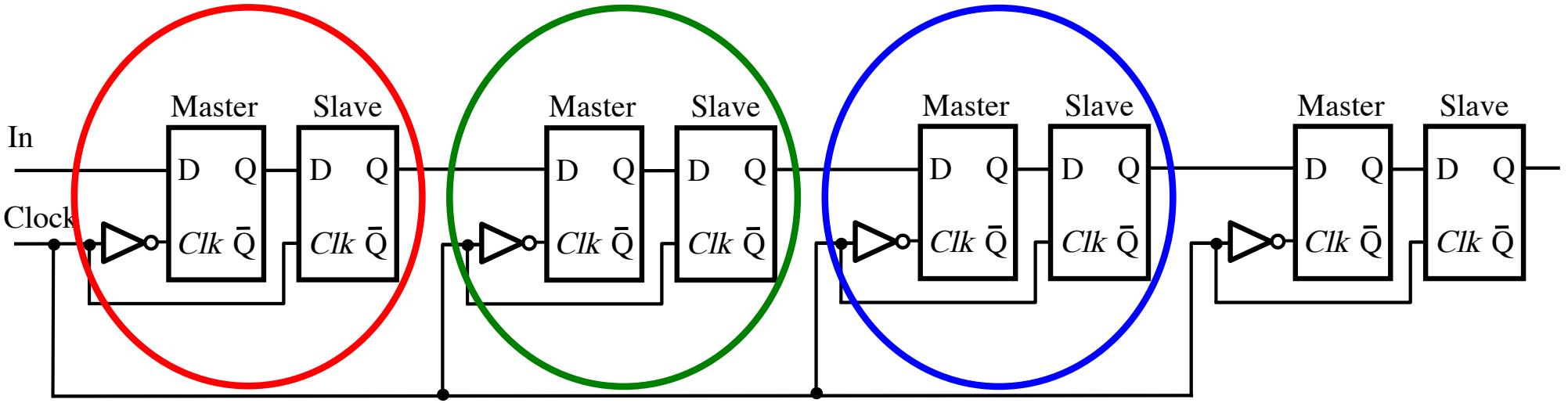
A simple shift register



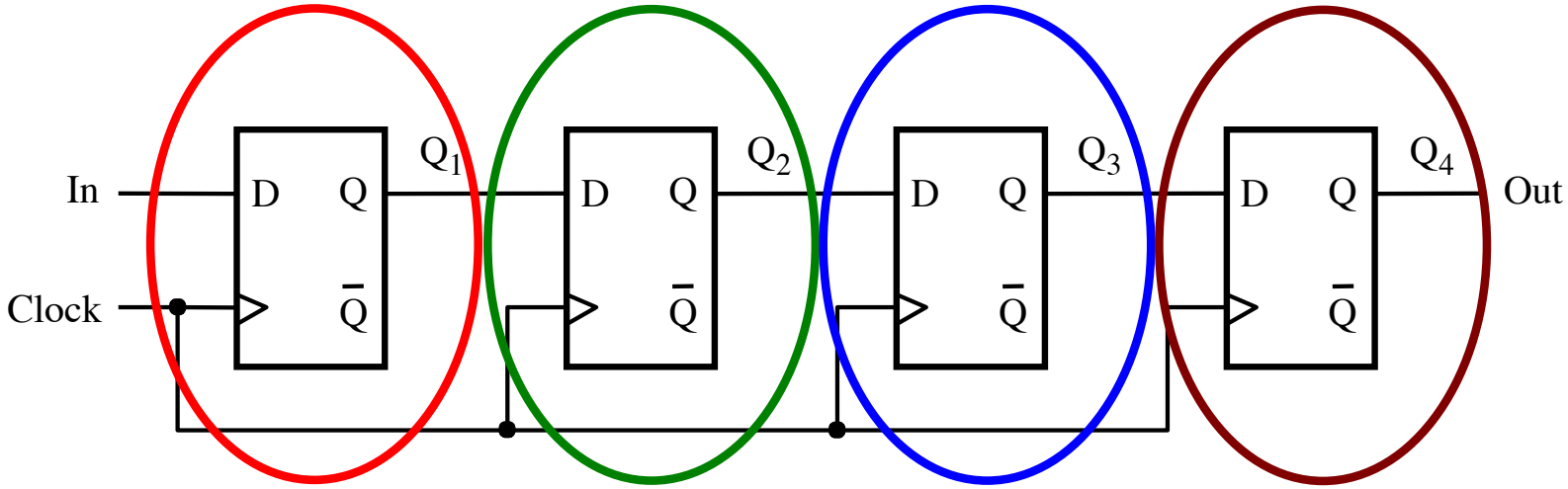


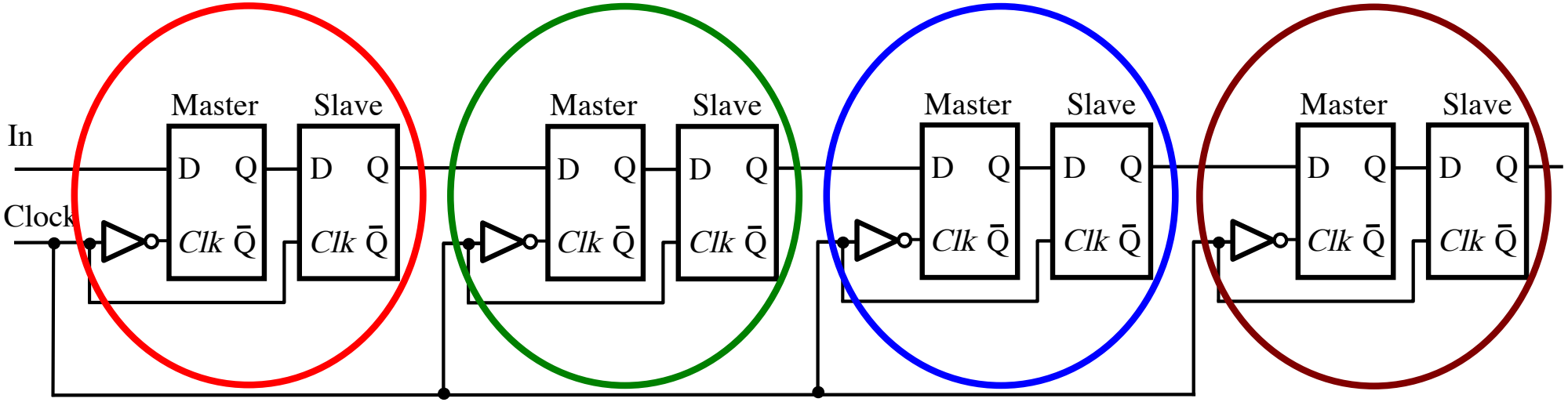
A simple shift register



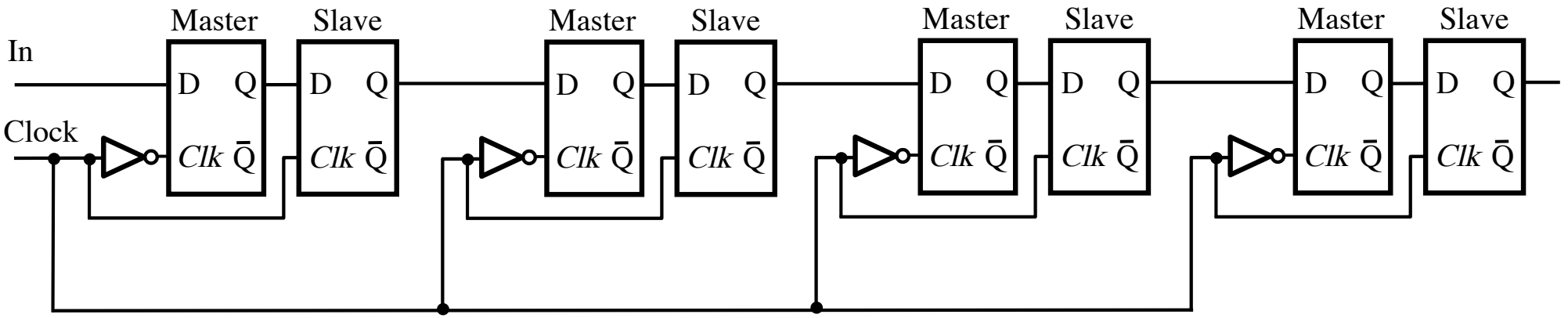


A simple shift register

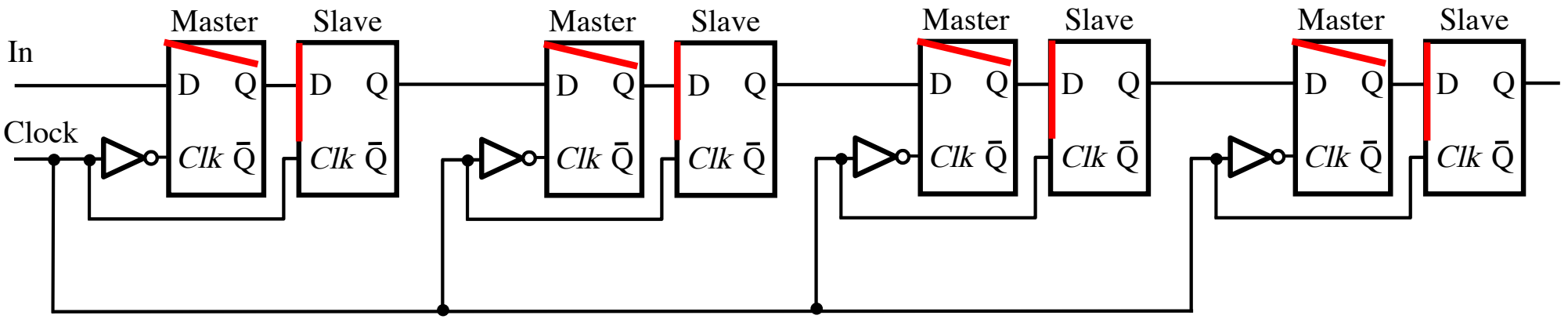




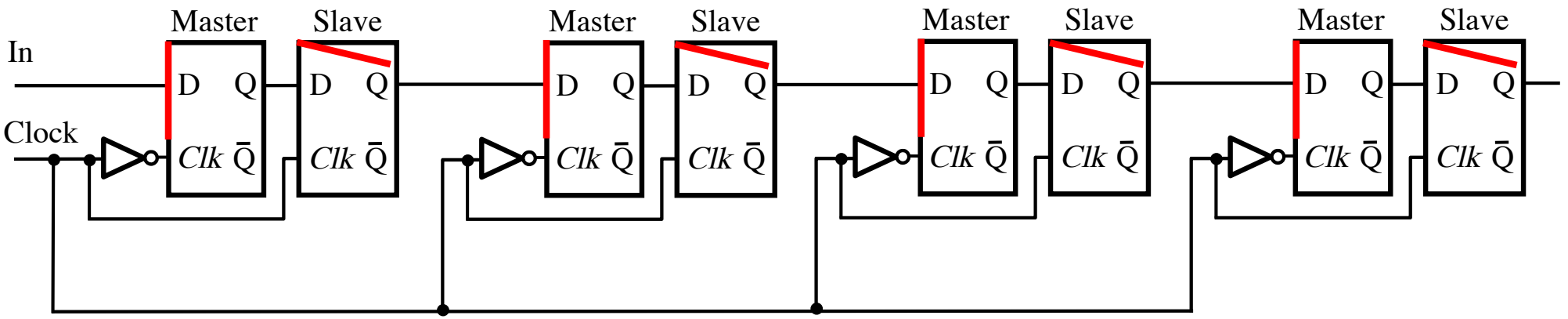
A simple shift register



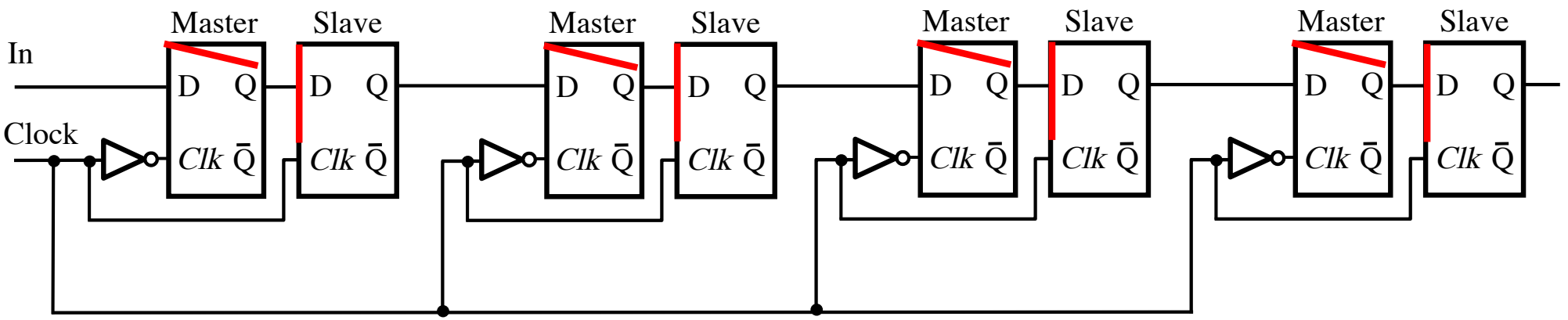
A simple shift register



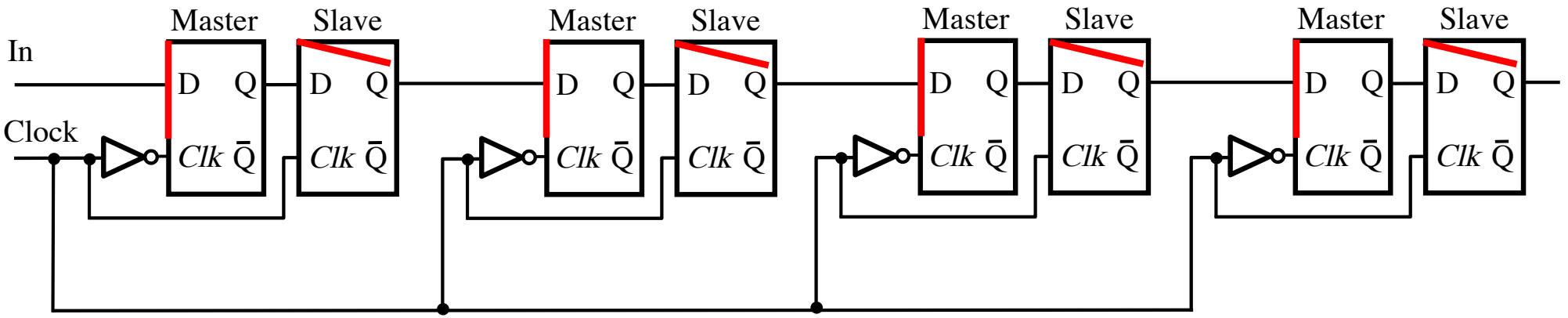
A simple shift register



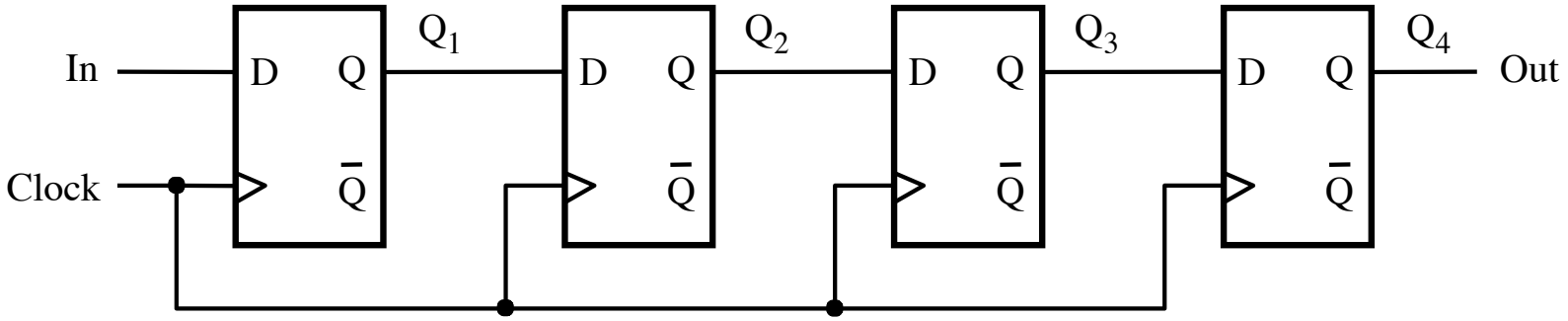
A simple shift register



A simple shift register



A simple shift register



(a) Circuit

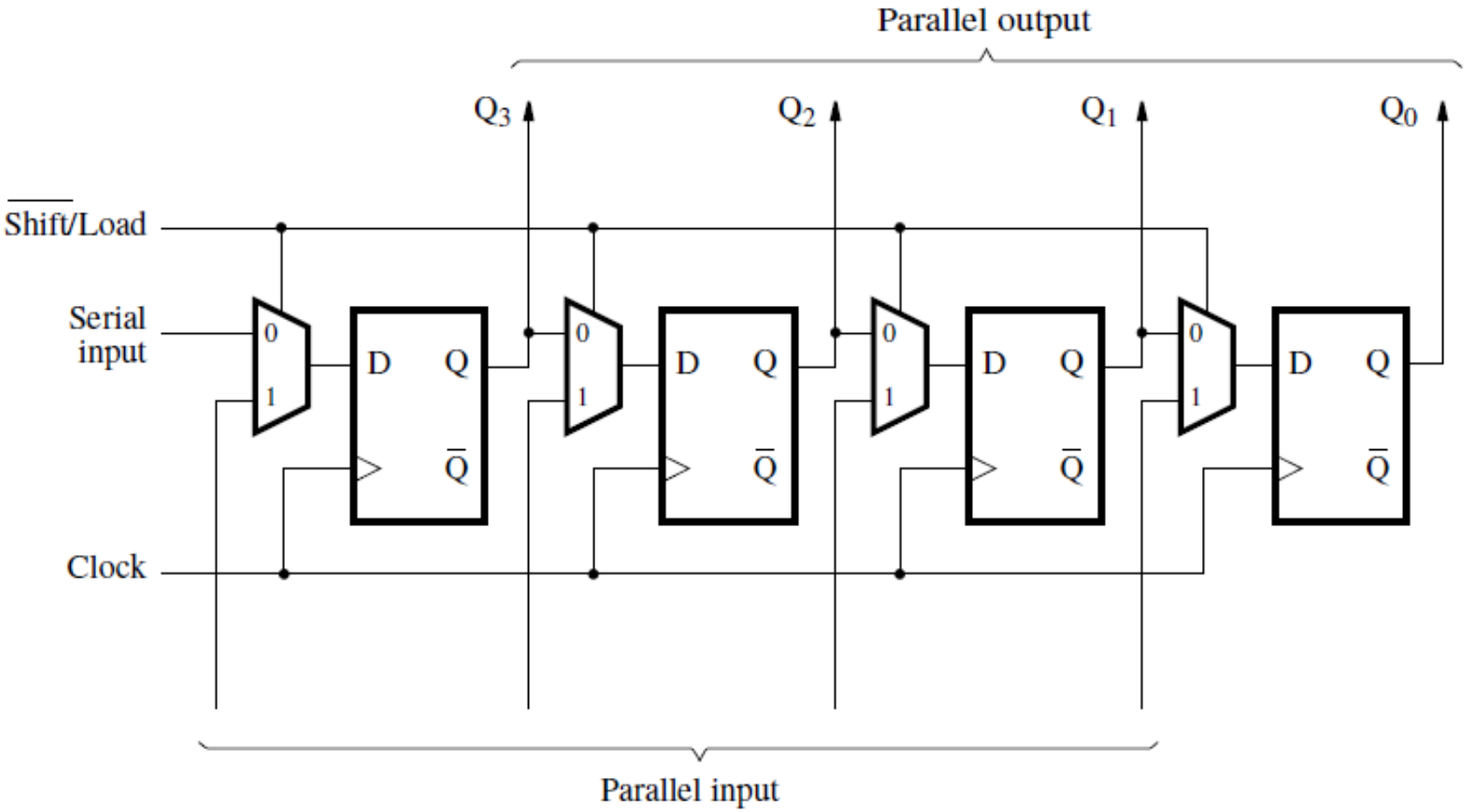
	In	Q_1	Q_2	Q_3	Q_4 = Out
t_0	1	0	0	0	0
t_1	0	1	0	0	0
t_2	1	0	1	0	0
t_3	1	1	0	1	0
t_4	1	1	1	0	1
t_5	0	1	1	1	0
t_6	0	0	1	1	1
t_7	0	0	0	1	1

(b) A sample sequence

[Figure 5.17 from the textbook]

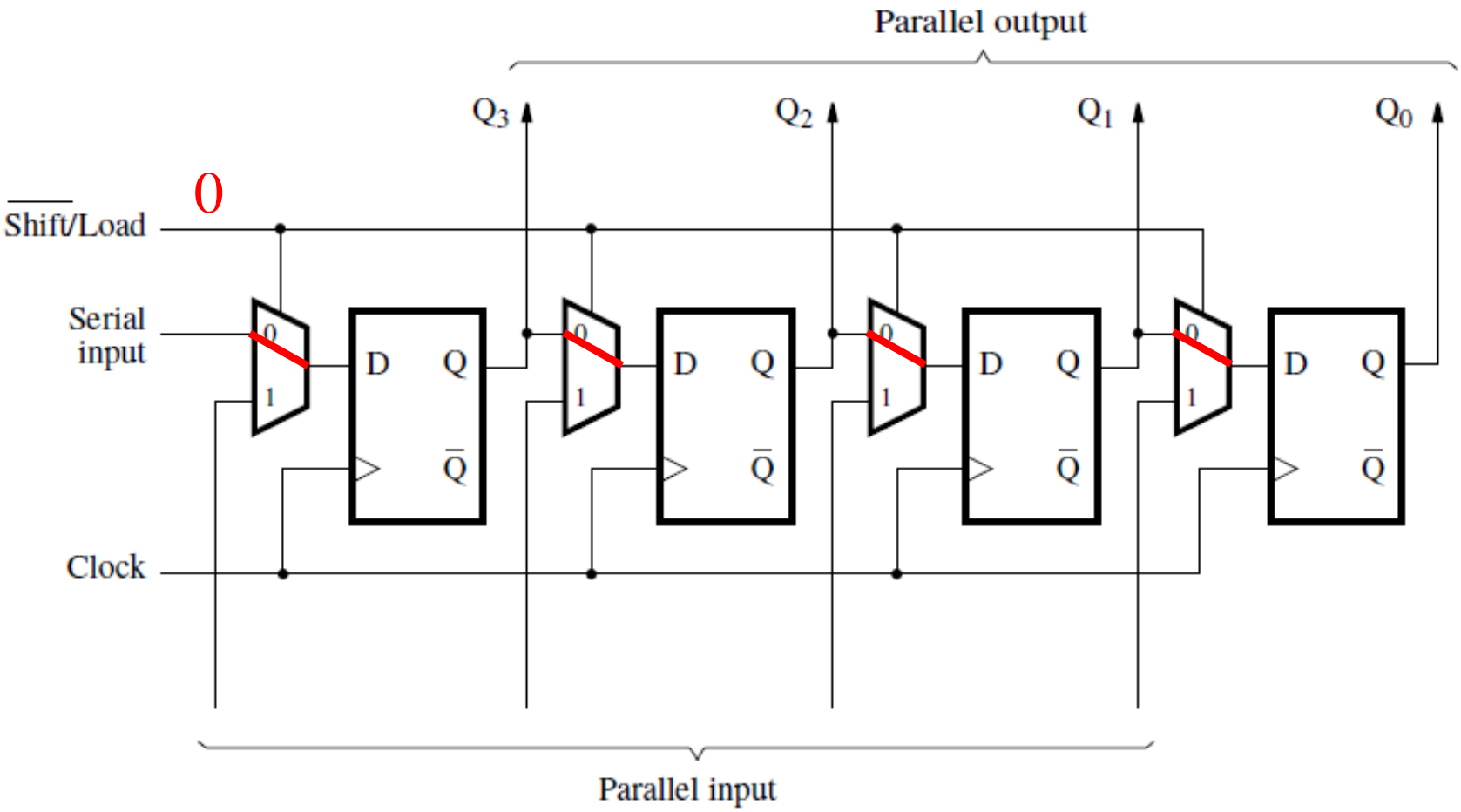
Parallel-Access Shift Register

Parallel-access shift register



[Figure 5.18 from the textbook]

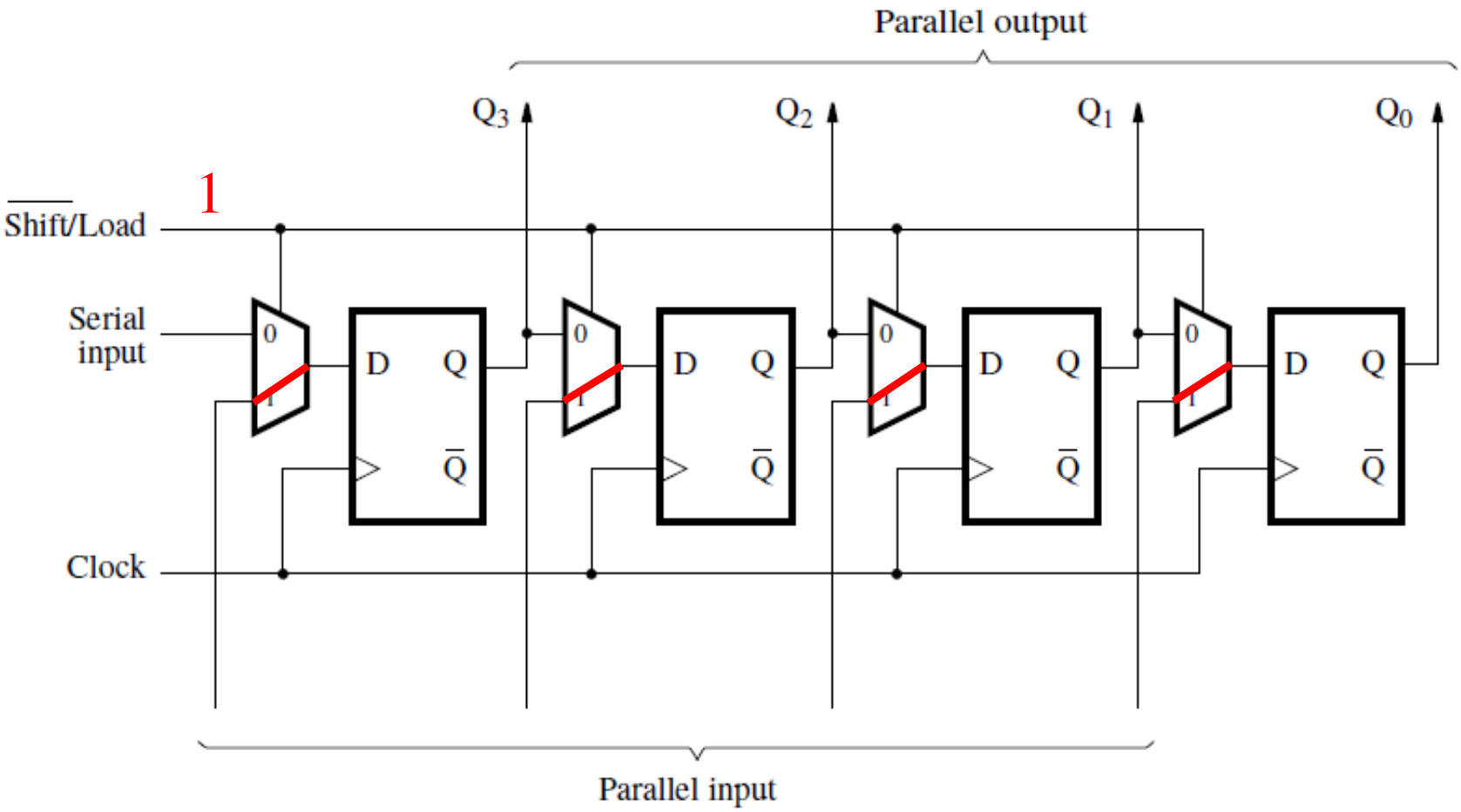
Parallel-access shift register



When Load=0, this behaves like a shift register.

[Figure 5.18 from the textbook]

Parallel-access shift register

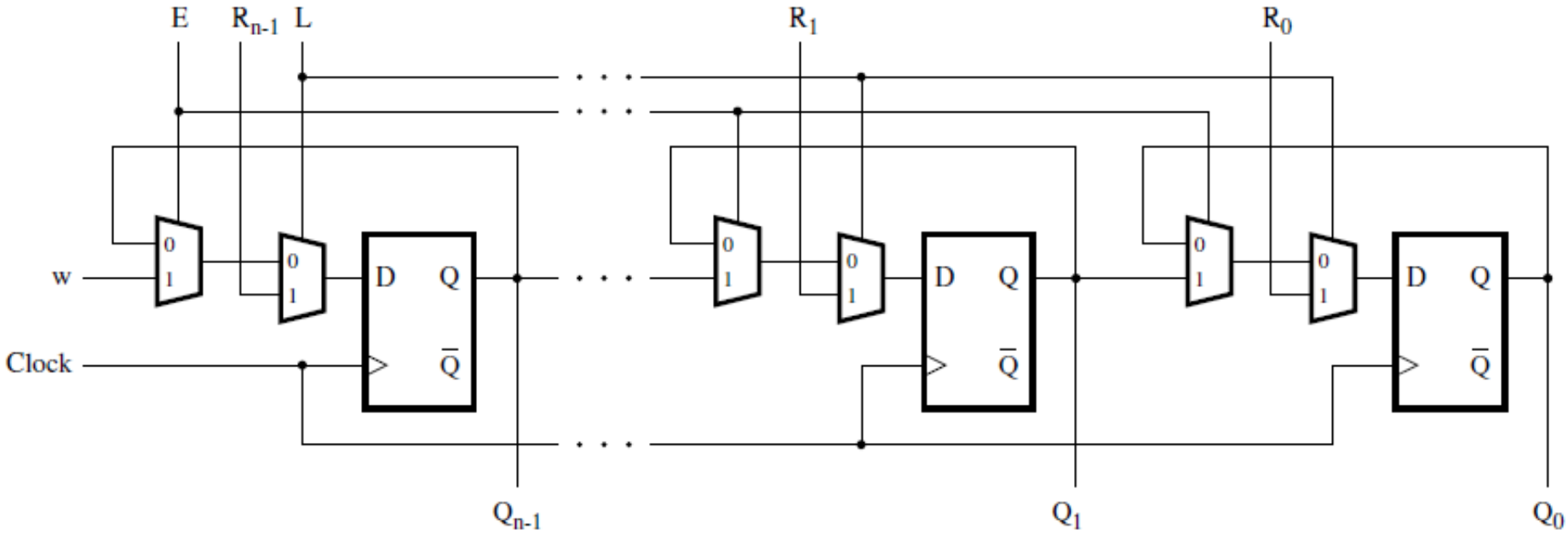


When Load=1, this behaves like a parallel-access register.

[Figure 5.18 from the textbook]

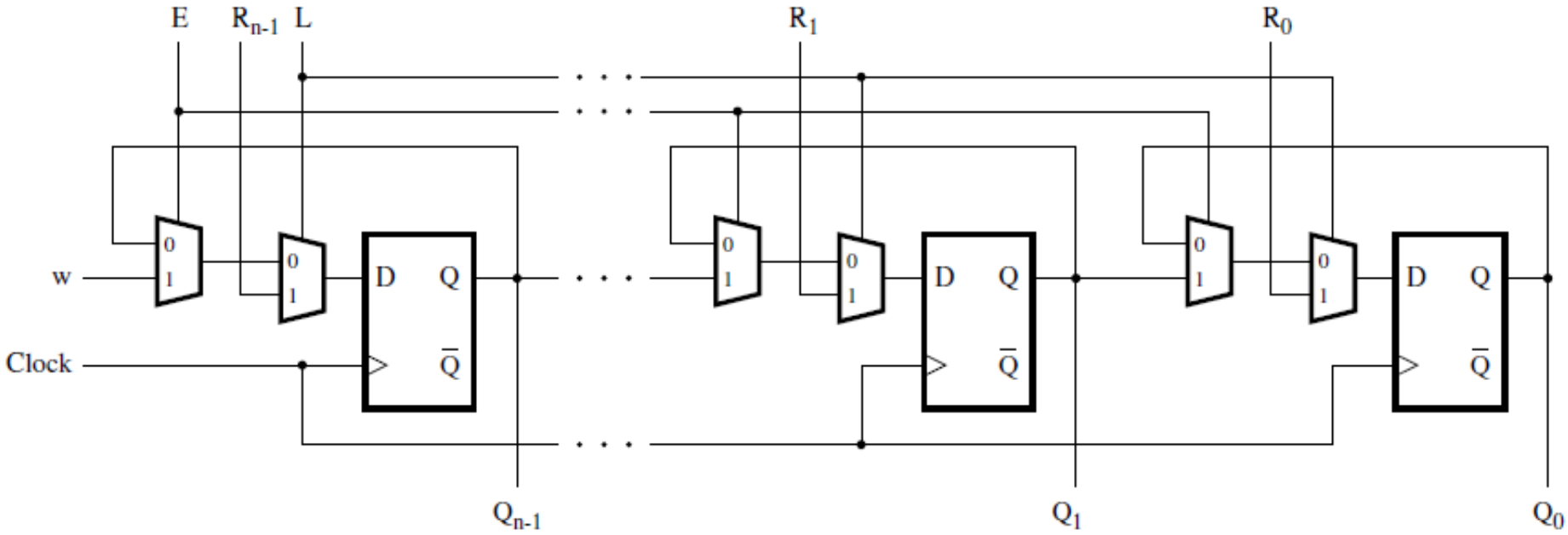
Shift Register With Parallel Load and Enable

A shift register with parallel load and enable control inputs



[Figure 5.59 from the textbook]

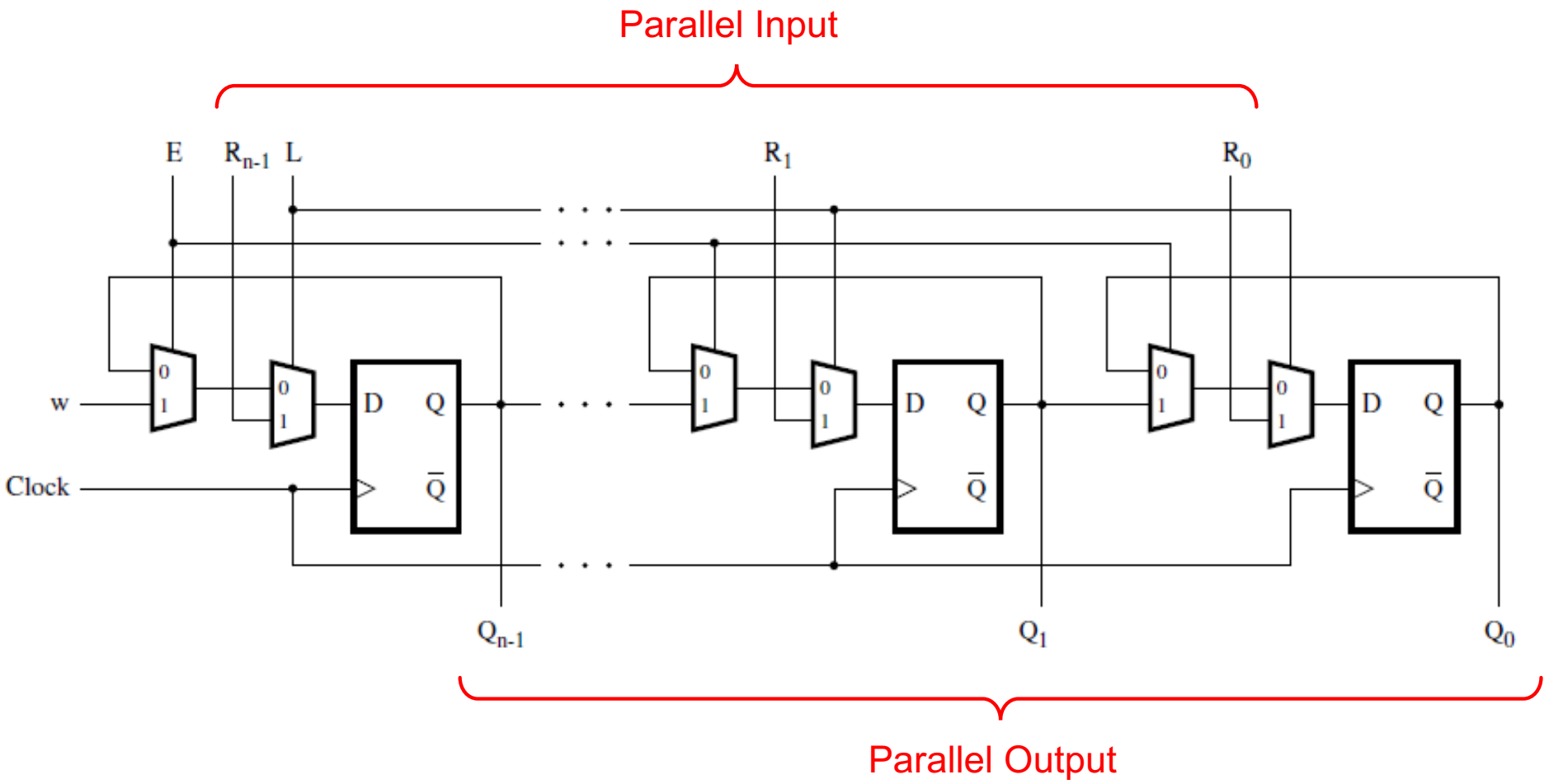
A shift register with parallel load and enable control inputs



The directions of the input and output lines are switched relative to the previous slides.

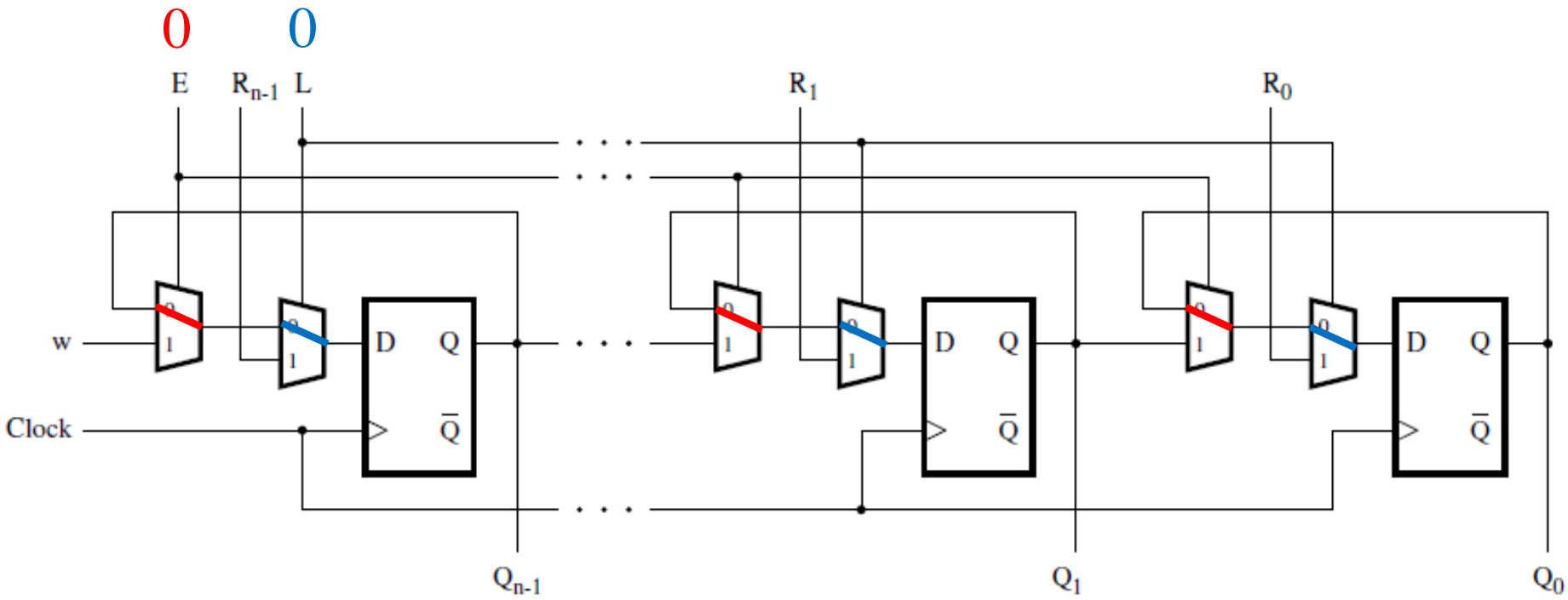
[Figure 5.59 from the textbook]

A shift register with parallel load and enable control inputs



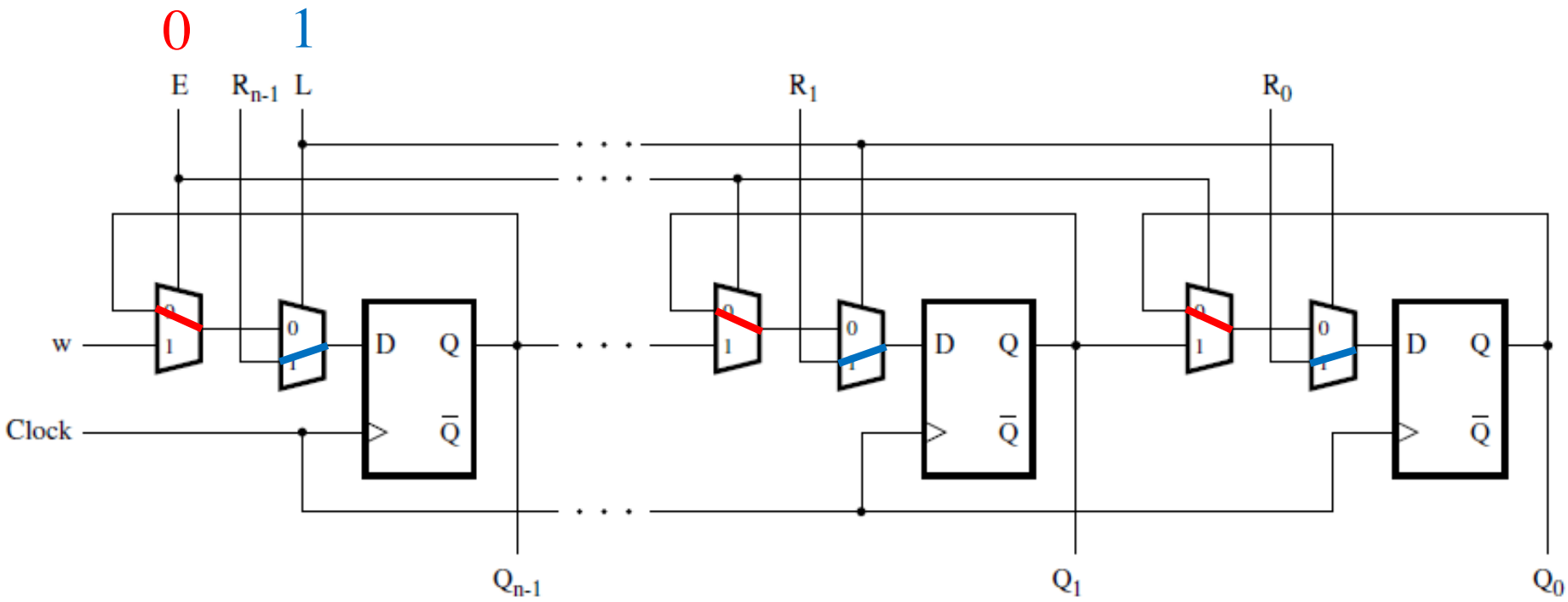
[Figure 5.59 from the textbook]

A shift register with parallel load and enable control inputs



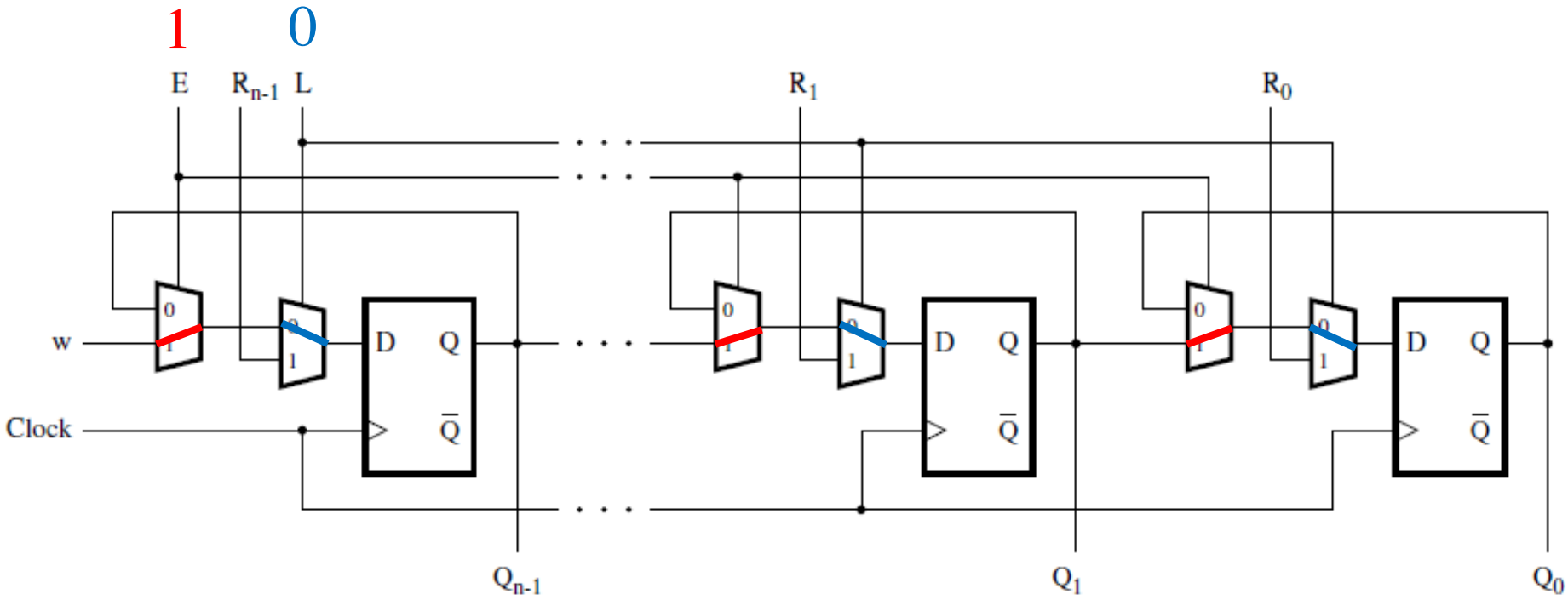
[Figure 5.59 from the textbook]

A shift register with parallel load and enable control inputs



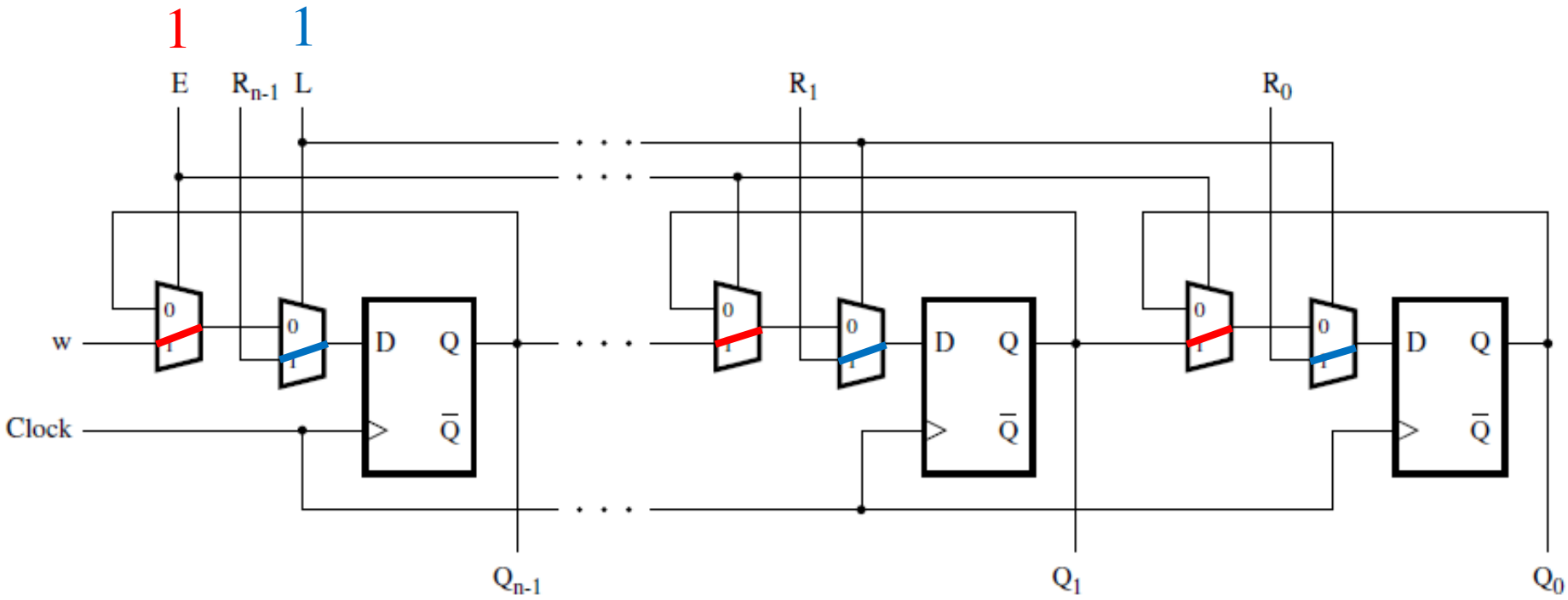
[Figure 5.59 from the textbook]

A shift register with parallel load and enable control inputs



[Figure 5.59 from the textbook]

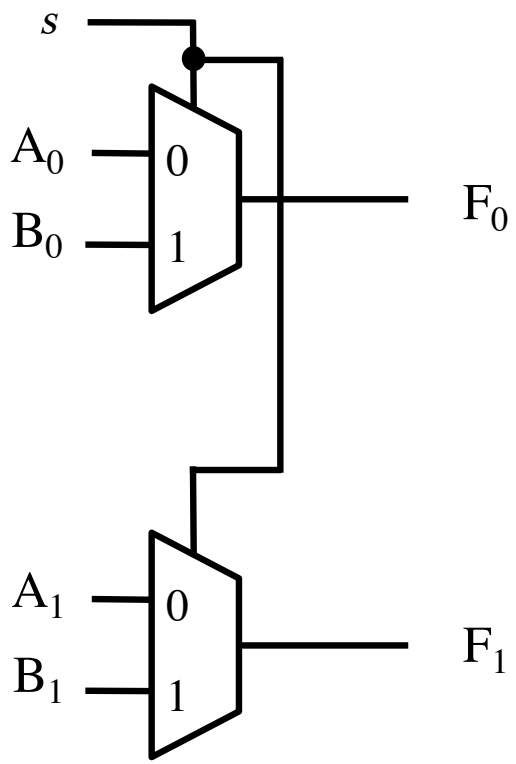
A shift register with parallel load and enable control inputs



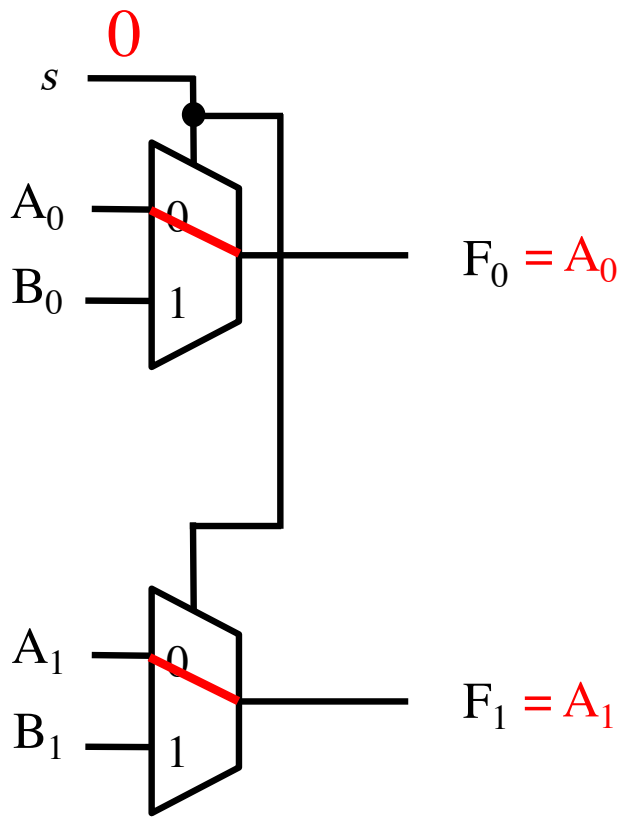
[Figure 5.59 from the textbook]

Multiplexer Tricks
(select one of two 2-bit numbers)

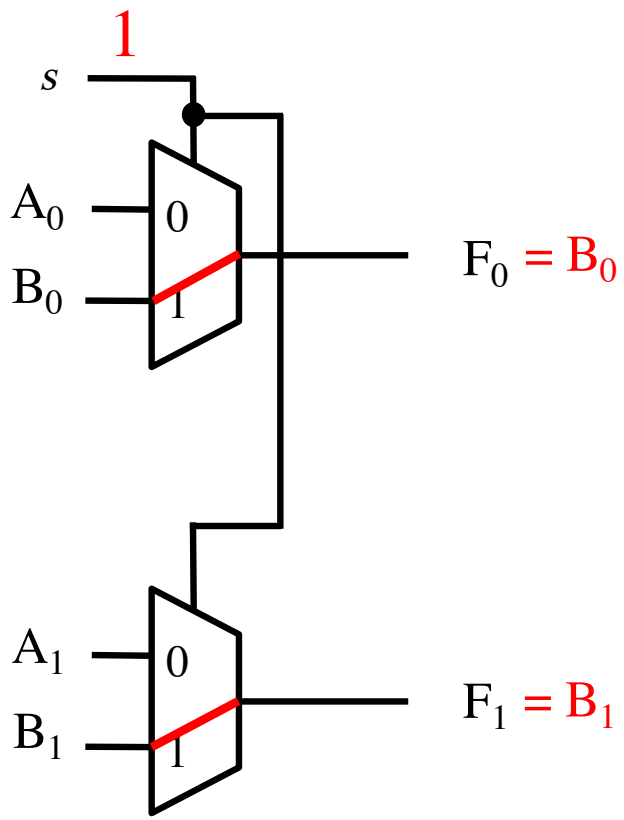
Select Either $A=A_1A_0$ or $B=B_1B_0$



Select Either $A=A_1A_0$ or $B=B_1B_0$

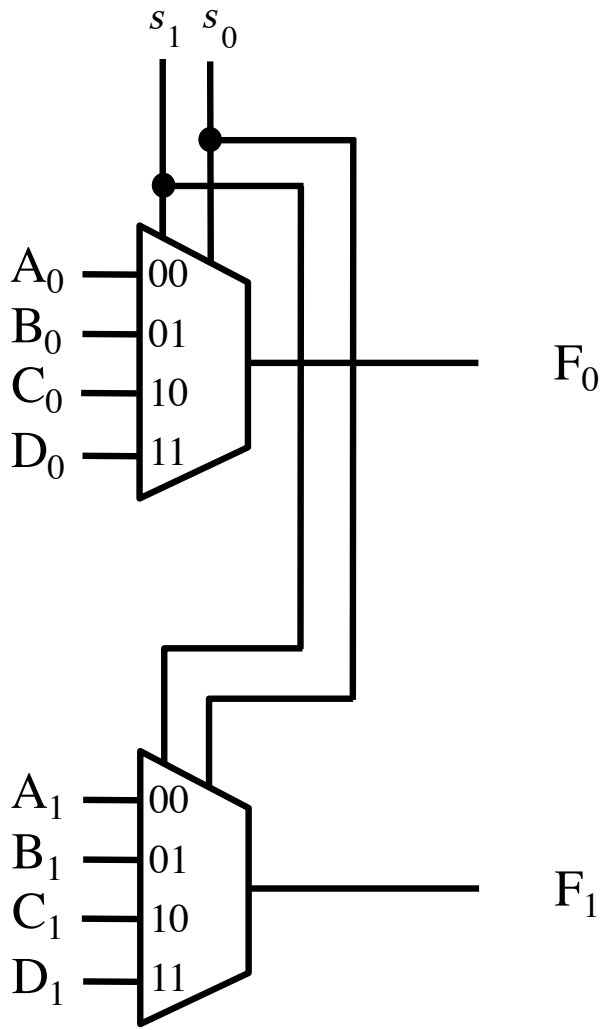


Select Either $A=A_1A_0$ or $B=B_1B_0$

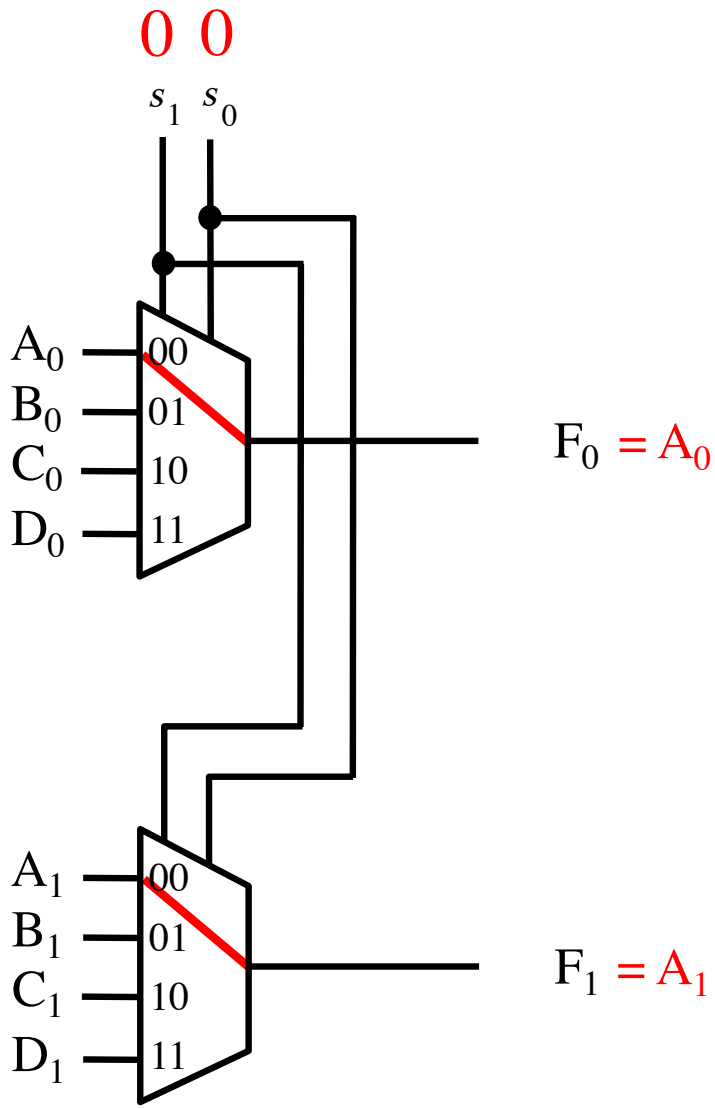


Multiplexer Tricks
(select one of four 2-bit numbers)

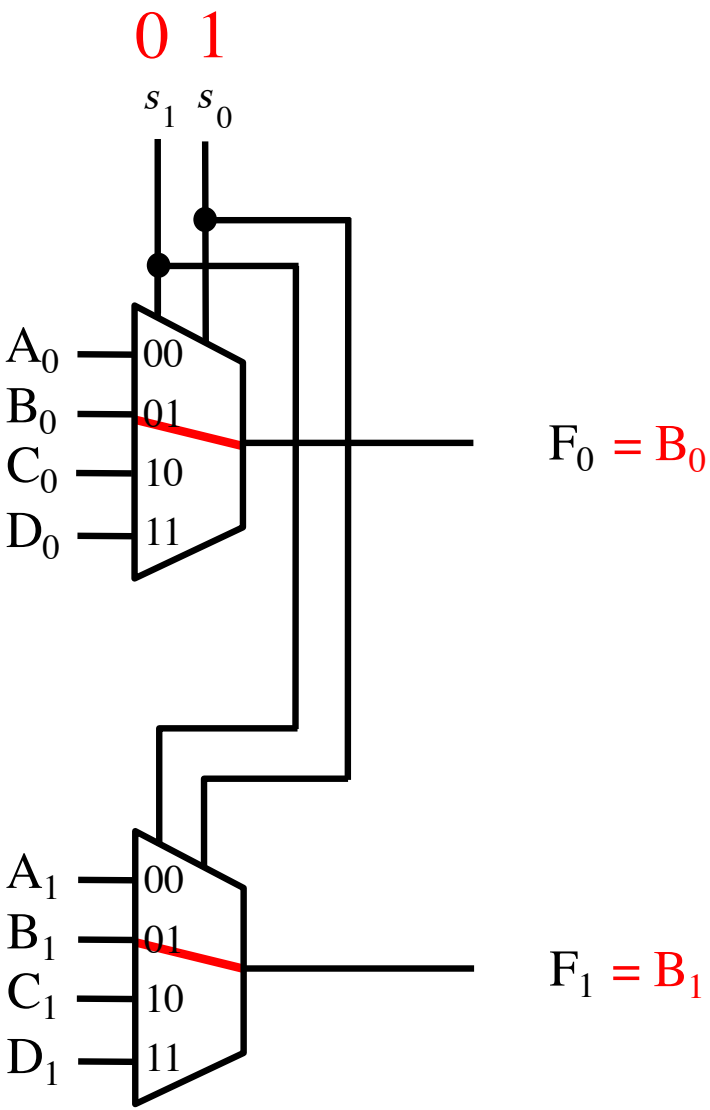
Select $A=A_1A_0$ or $B=B_1B_0$ or $C=C_1C_0$ or $D=D_1D_0$



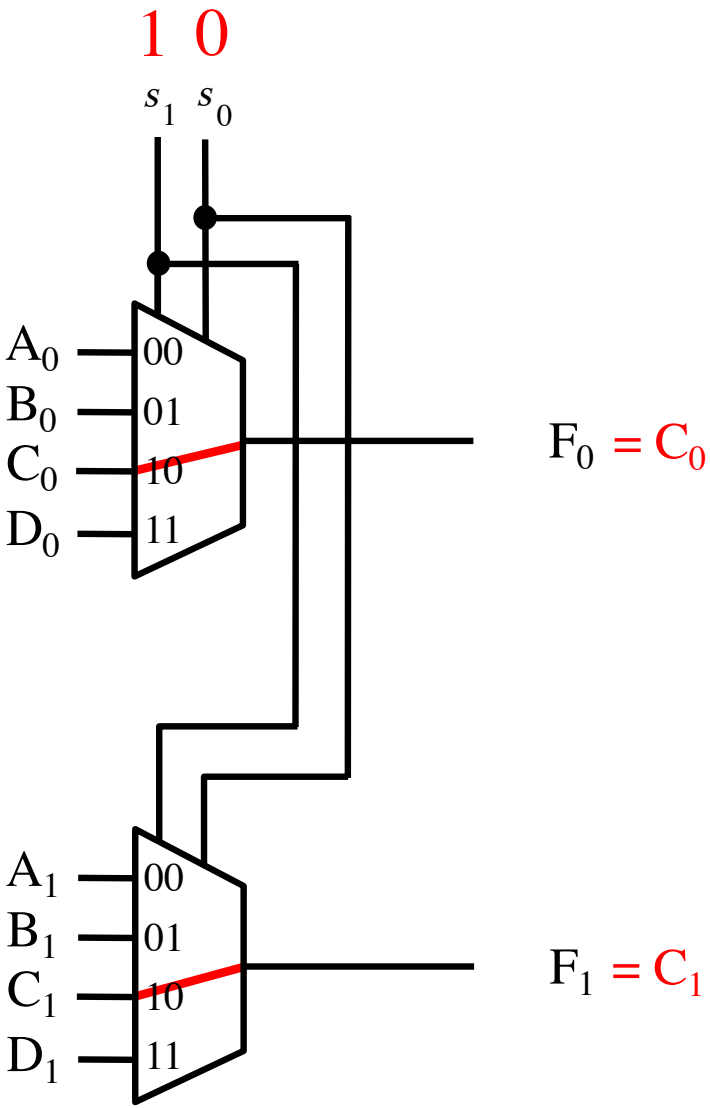
Select $A=A_1A_0$ or $B=B_1B_0$ or $C=C_1C_0$ or $D=D_1D_0$



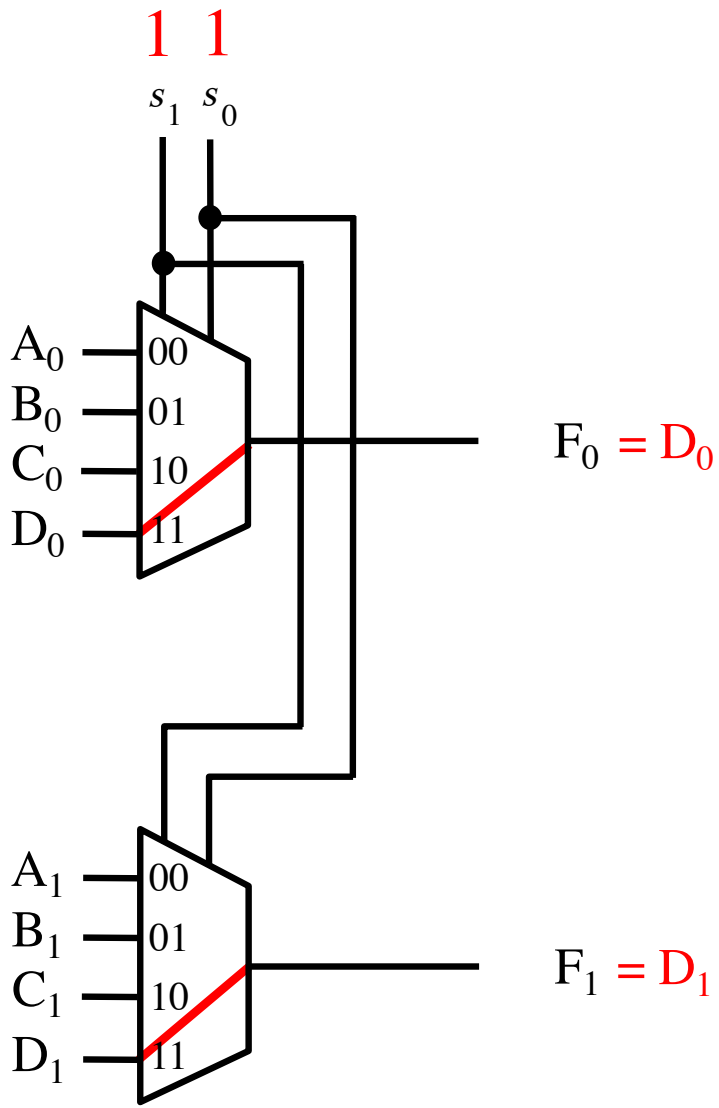
Select $A=A_1A_0$ or $B=B_1B_0$ or $C=C_1C_0$ or $D=D_1D_0$



Select $A=A_1A_0$ or $B=B_1B_0$ or $C=C_1C_0$ or $D=D_1D_0$

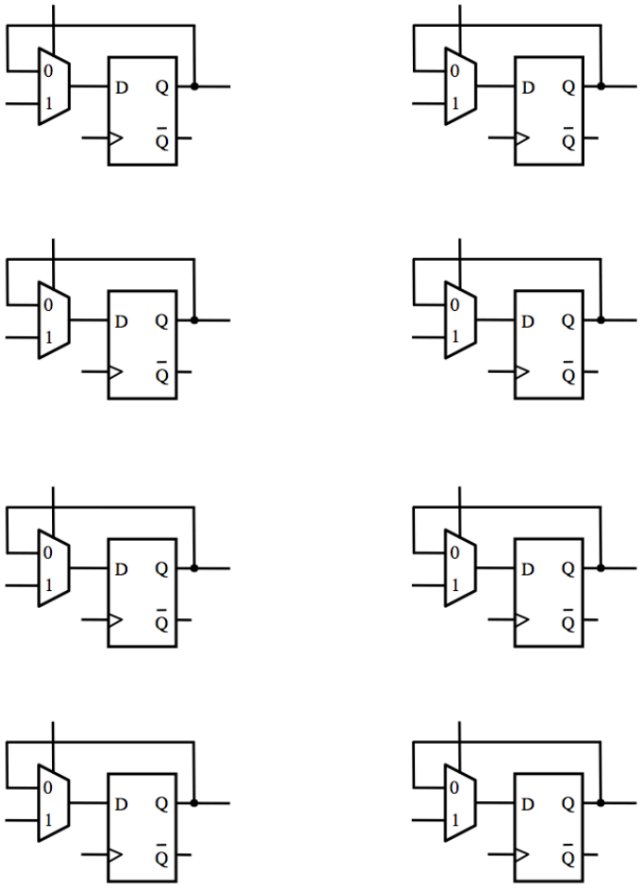


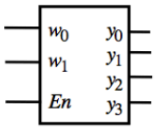
Select $A=A_1A_0$ or $B=B_1B_0$ or $C=C_1C_0$ or $D=D_1D_0$

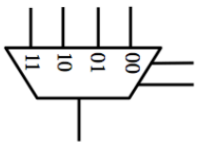


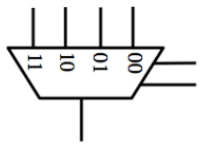
Register File

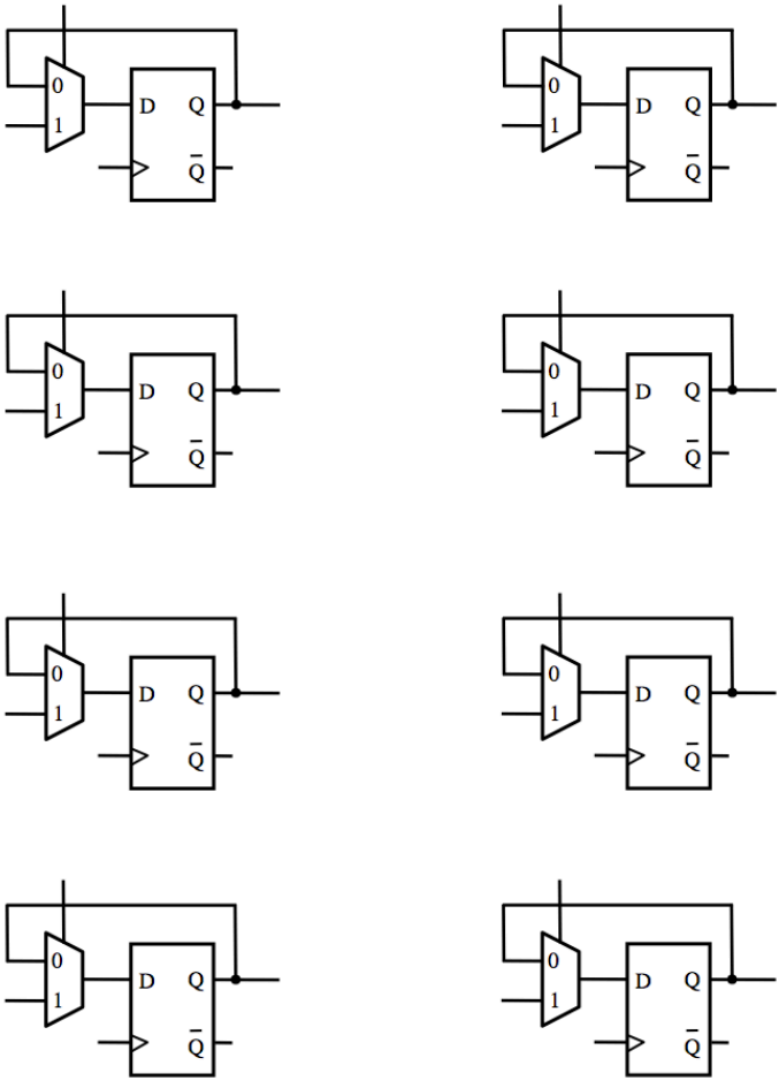
Complete the following circuit diagram to implement a register file with four 2-bit registers, one write port, one read port, and one write enable line.

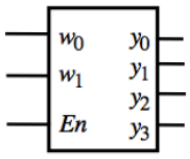


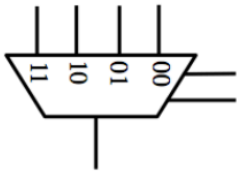


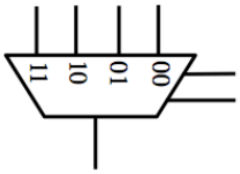


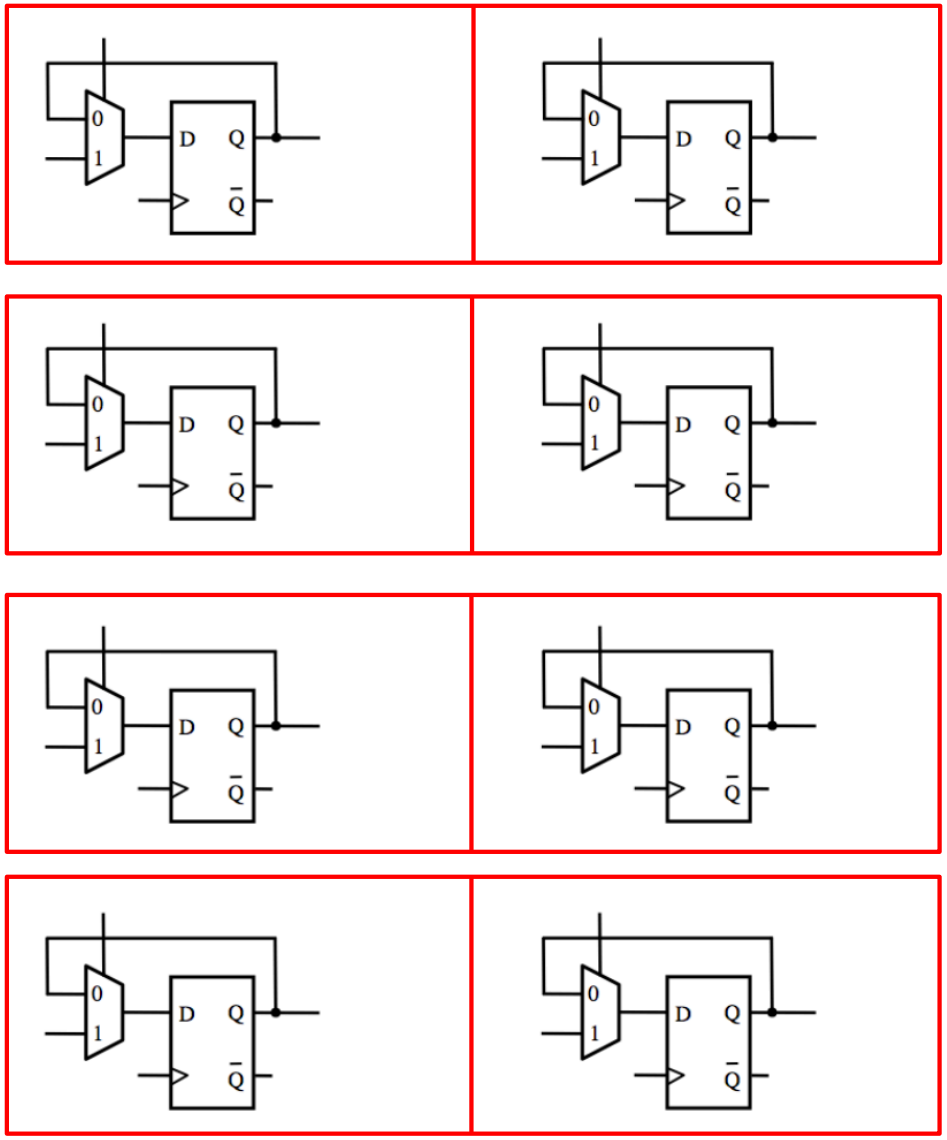


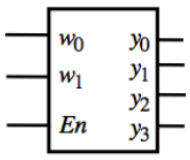

0
1
D
Q
Q

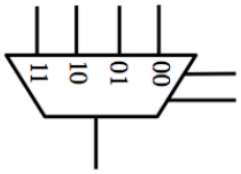

w_0
w_1
En
y_0
y_1
y_2
y_3

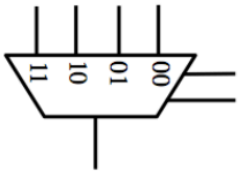

11
10
01
00

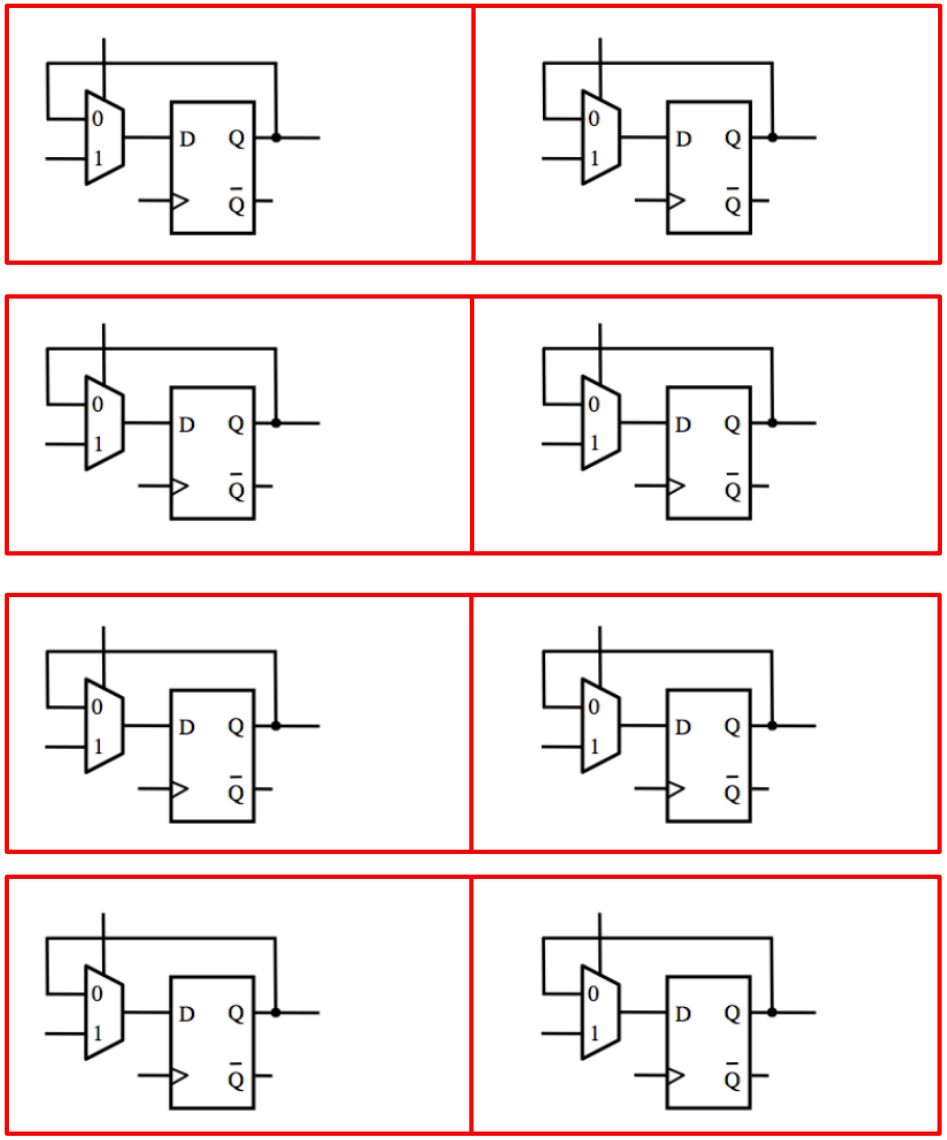

11
10
01
00

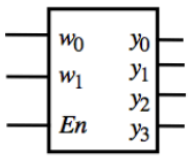

Register 0
Register 1
Register 2
Register 3
0
1
D
Q
Q̄

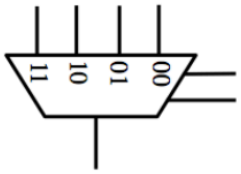

w0
w1
En
y0
y1
y2
y3

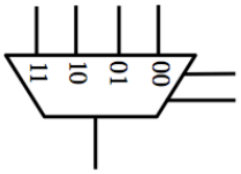

11
10
01
00

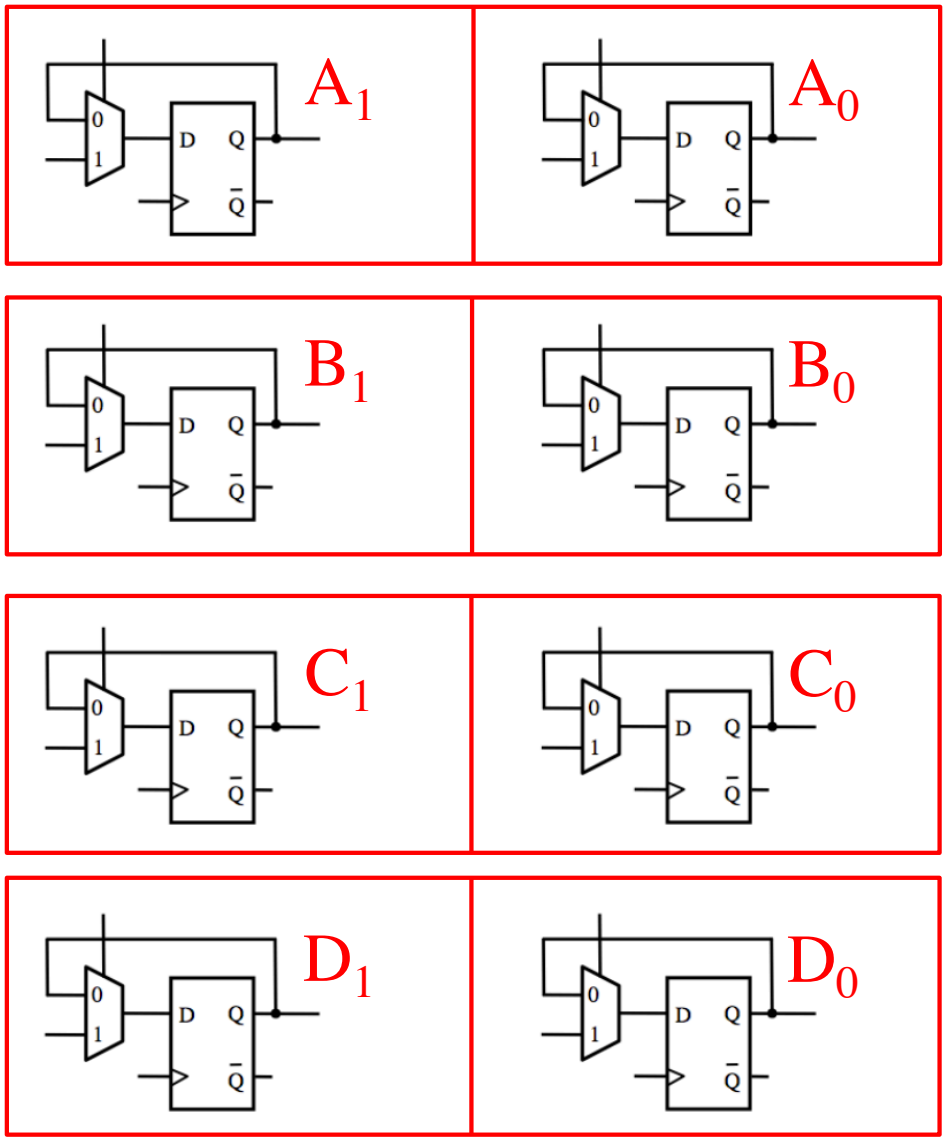

11
10
01
00

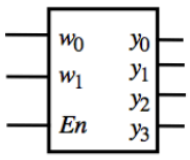

Register A
Register B
Register C
Register D

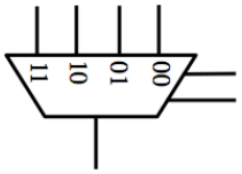

w_0
w_1
En
y_0
y_1
y_2
y_3

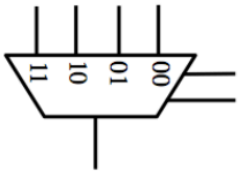

11
10
01
00

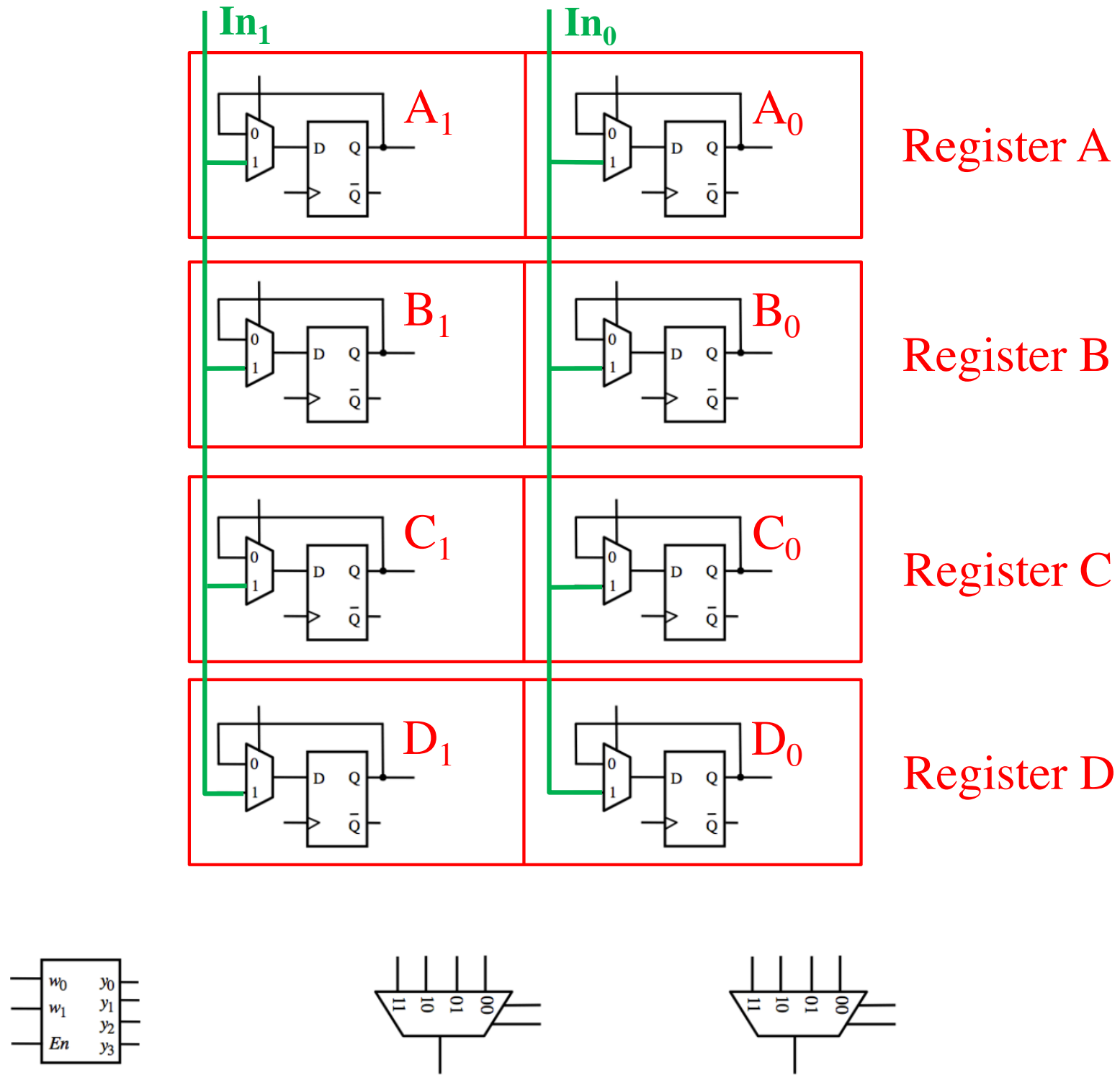

11
10
01
00

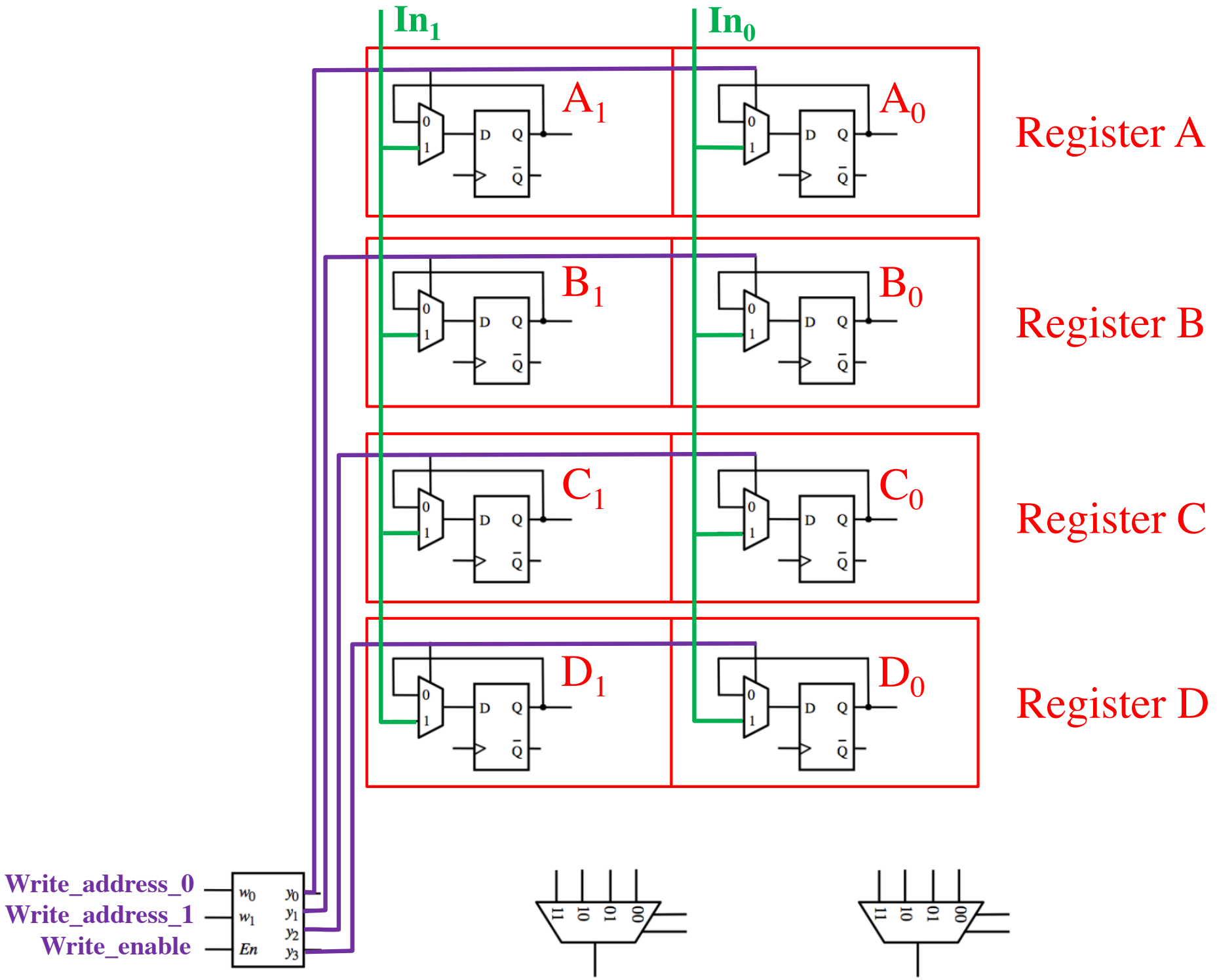

A1
A0
Register A
B1
B0
Register B
C1
C0
Register C
D1
D0
Register D
D
Q
0
1

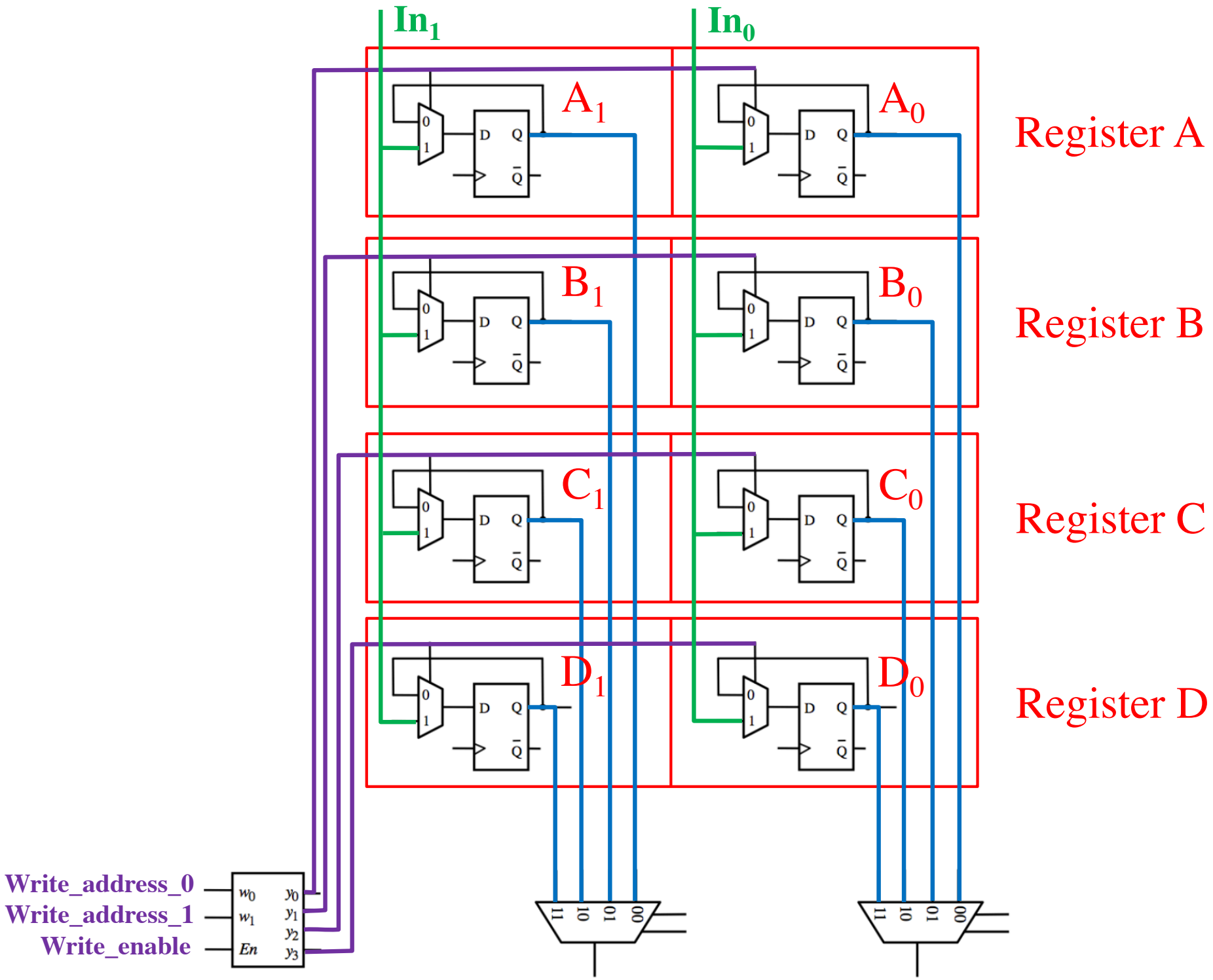

w0
w1
En
y0
y1
y2
y3

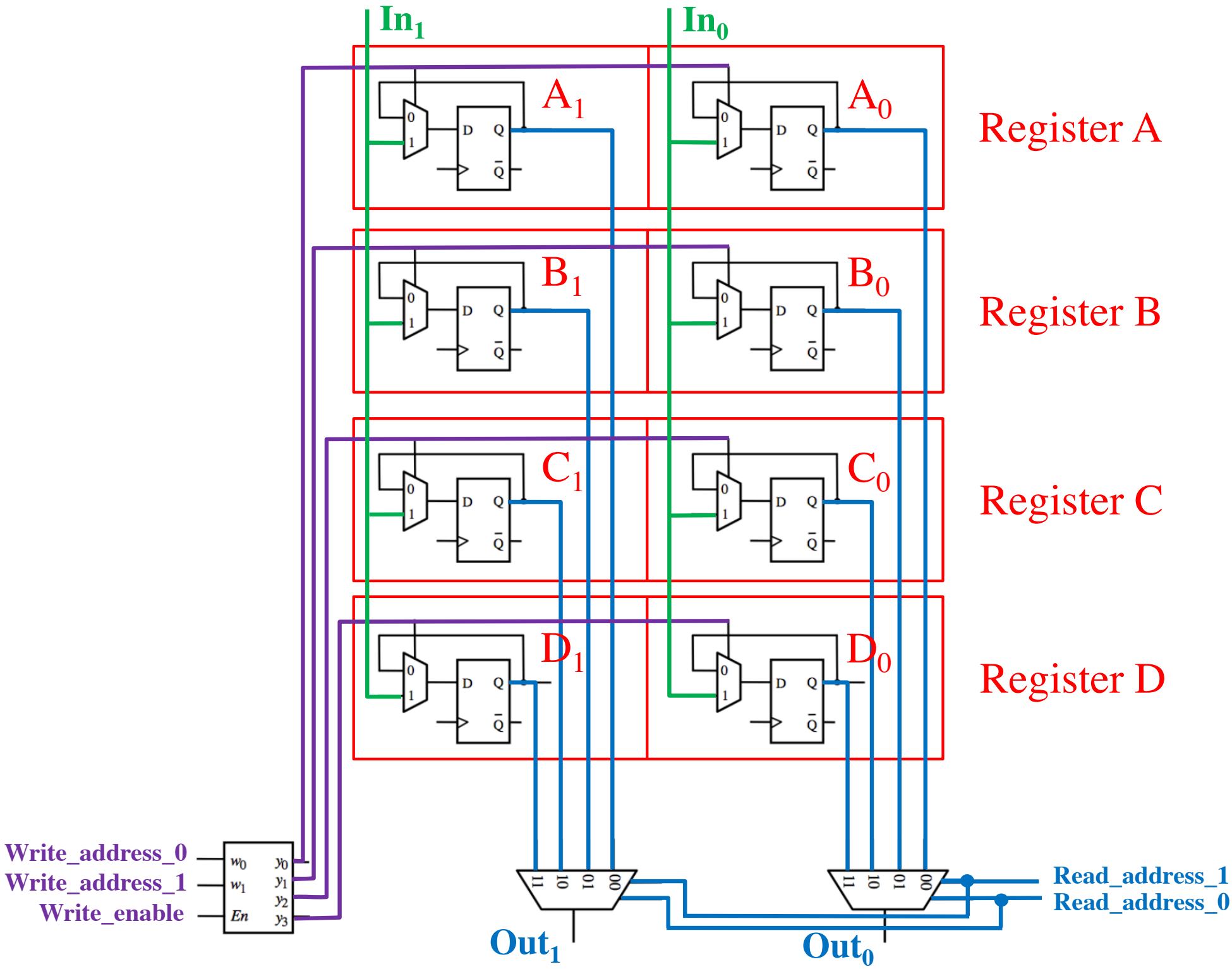

11
10
01
00

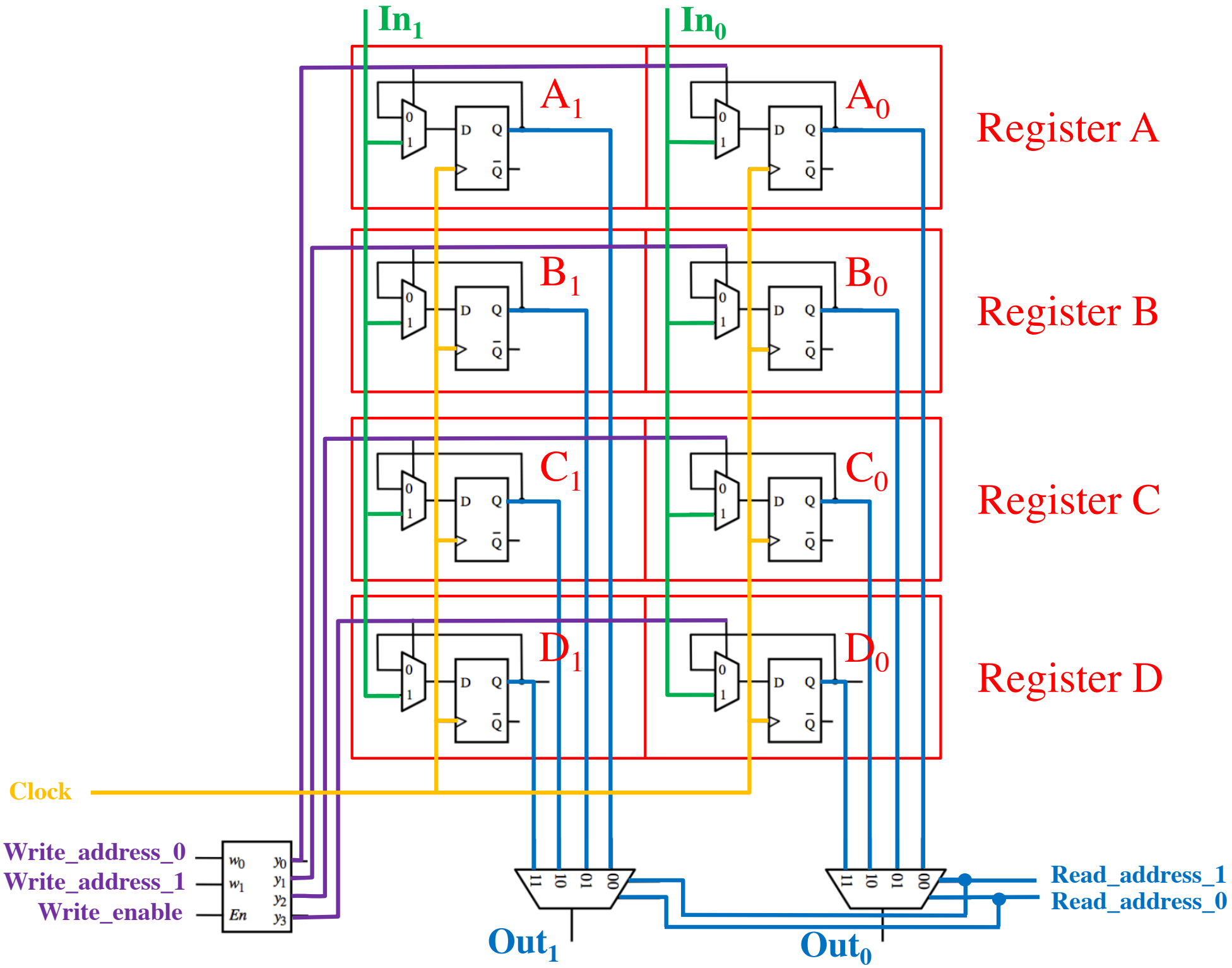

11
10
01
00

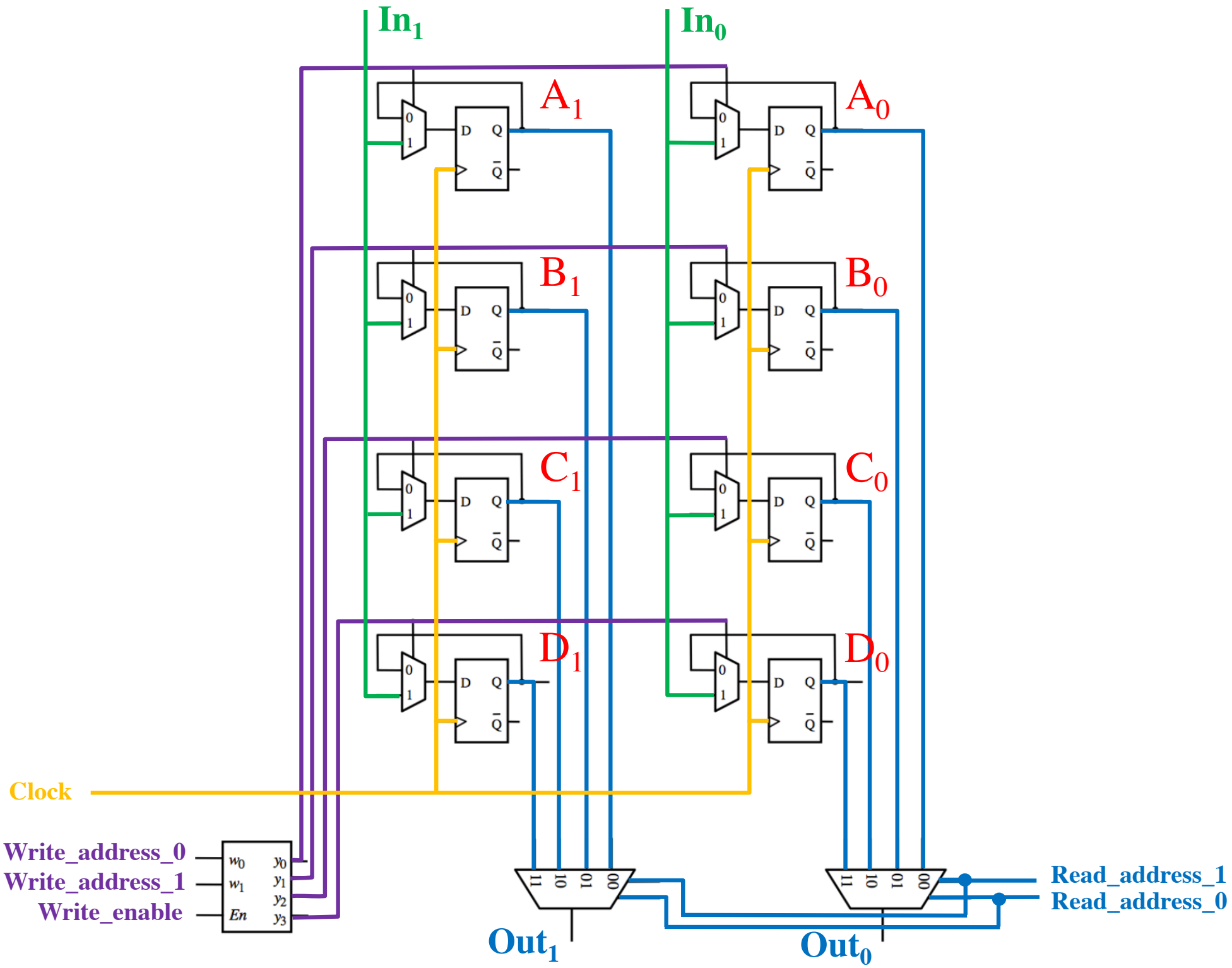

In1
In0
A1
A0
B1
B0
C1
C0
D1
D0
Register A
Register B
Register C
Register D
D
Q
0
1
w0
w1
En
y0
y1
y2
y3
11
10
01
00


In1
In0
A1
A0
B1
B0
C1
C0
D1
D0
Register A
Register B
Register C
Register D
Write_address_0
Write_address_1
Write_enable
w0
w1
En
y0
y1
y2
y3
11
10
01
00
11
10
01
00


In1
In0
A1
A0
B1
B0
C1
C0
D1
D0
Register A
Register B
Register C
Register D
Write_address_0
Write_address_1
Write_enable
w0
w1
En
y0
y1
y2
y3
D
Q
Q̄
0
1
11
10
01
00


In1
In0
A1
A0
B1
B0
C1
C0
D1
D0
Register A
Register B
Register C
Register D
D
Q
Q̄
0
1
Write_address_0
Write_address_1
Write_enable
w0
w1
En
y0
y1
y2
y3
11
10
01
00
Out1
Out0
Read_address_1
Read_address_0

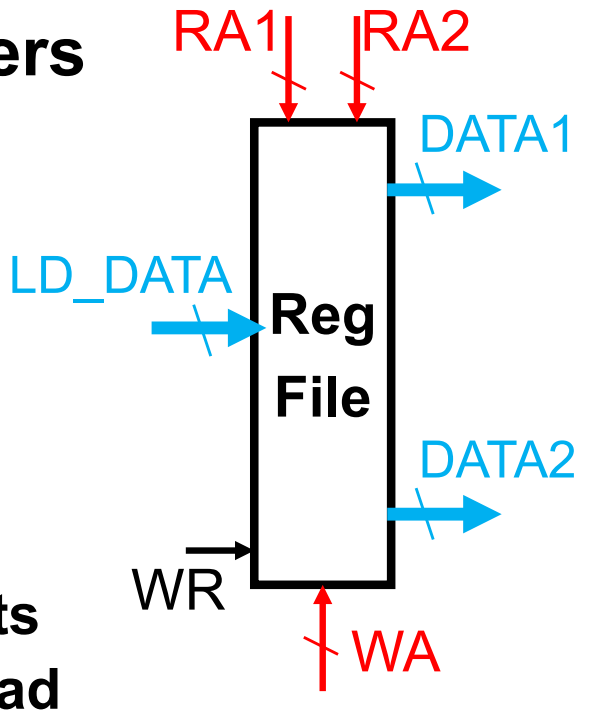

In1
In0
A1
A0
B1
B0
C1
C0
D1
D0
Register A
Register B
Register C
Register D
Clock
Write_address_0
Write_address_1
Write_enable
w0
w1
En
y0
y1
y2
y3
11
10
01
00
Out1
Out0
Read_address_1
Read_address_0


In1
In0
A1
A0
B1
B0
C1
C0
D1
D0
D
Q
Clock
Write_address_0
Write_address_1
Write_enable
w0
w1
En
y0
y1
y2
y3
11
10
01
00
Out1
Out0
Read_address_1
Read_address_0

Another Register File

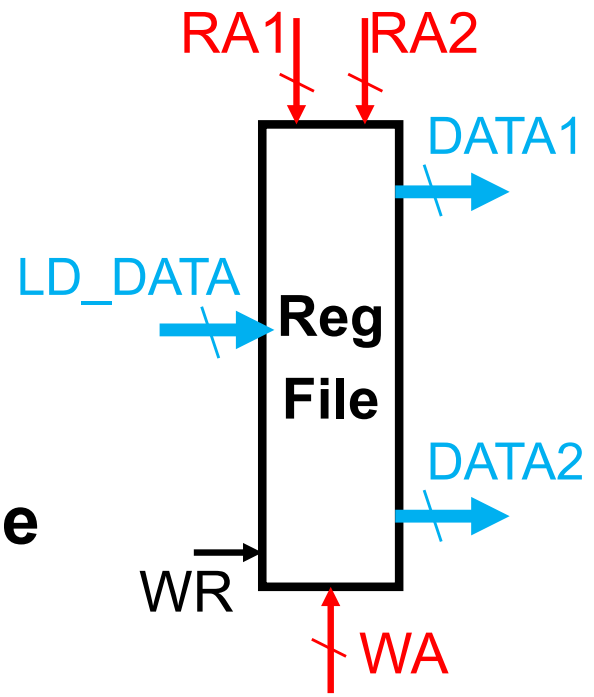
Register File

- **Register file is a unit containing r registers**
  - **r can be 4, 8, 16, 32, etc.**
- **Each register has n bits**
  - **n can be 4, 8, 16, 32, etc.**
  - **n defines the data path width**
- **Output ports (DATA1 and DATA2) are used for reading the register file**
  - **Any register can be read from any of the ports**
  - **Each port needs a $\log_2 r$ bits to specify the read address (RA1 and RA2)**
- **Input port (LD_DATA) is used for writing data to the register file**
  - **Write address is also specified by $\log_2 r$ bits (WA)**
  - **Writing is enabled by a 1-bit signal (WR)**



Register File: Exercise

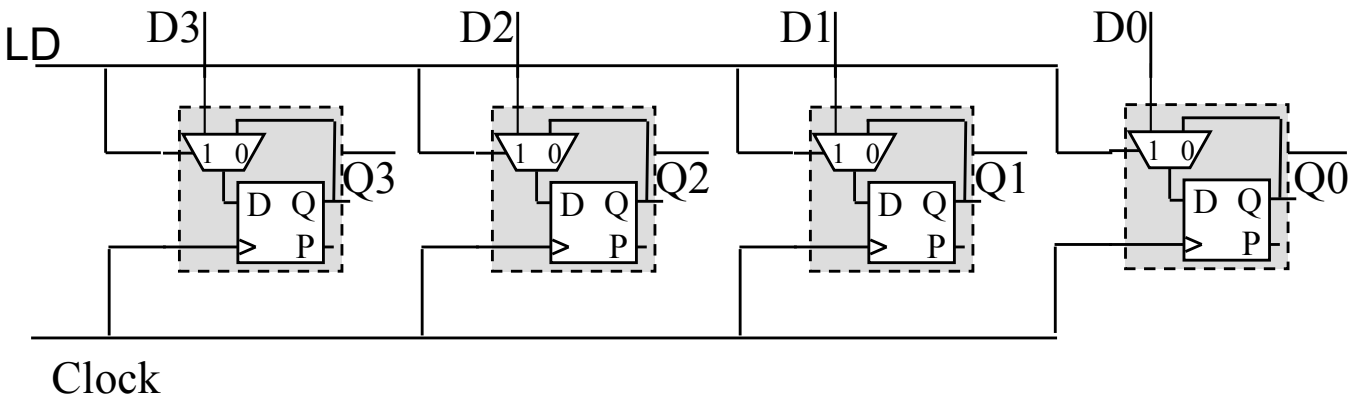
- **Suppose that a register file**
  - **contains 32 registers**
  - **width of data path is 16 bits (i.e., each register has 16 bits)**

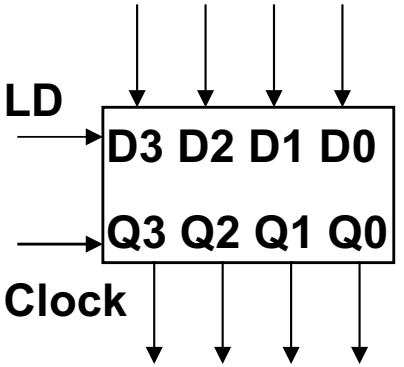


- **How many bits are there for each of the signals?**
  - **RA1** **5**
  - **RA2** **5**
  - **DATA1** **16**
  - **DATA2** **16**
  - **WA** **5**
  - **LD_DATA** **16**
  - **WR** **1**

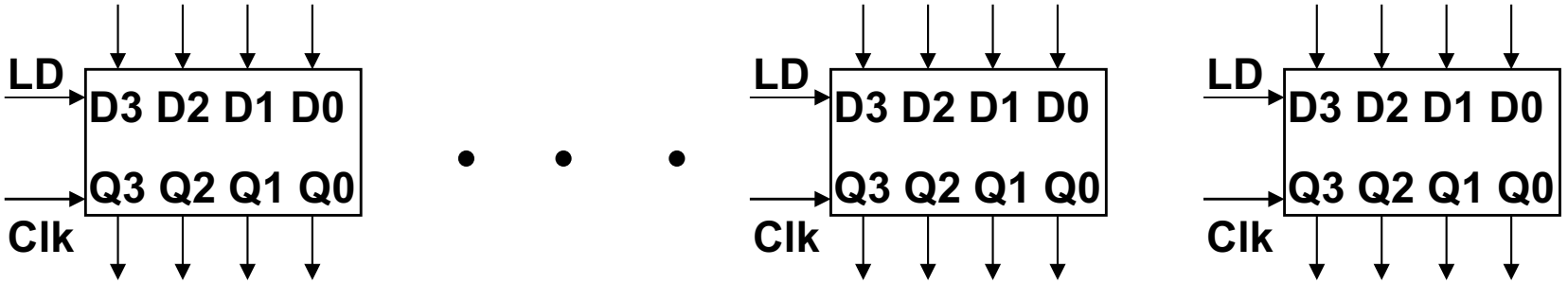
Register file design

- We will design an eight-register file with 4-bit wide registers
- A single 4-bit register and its abstraction are shown below





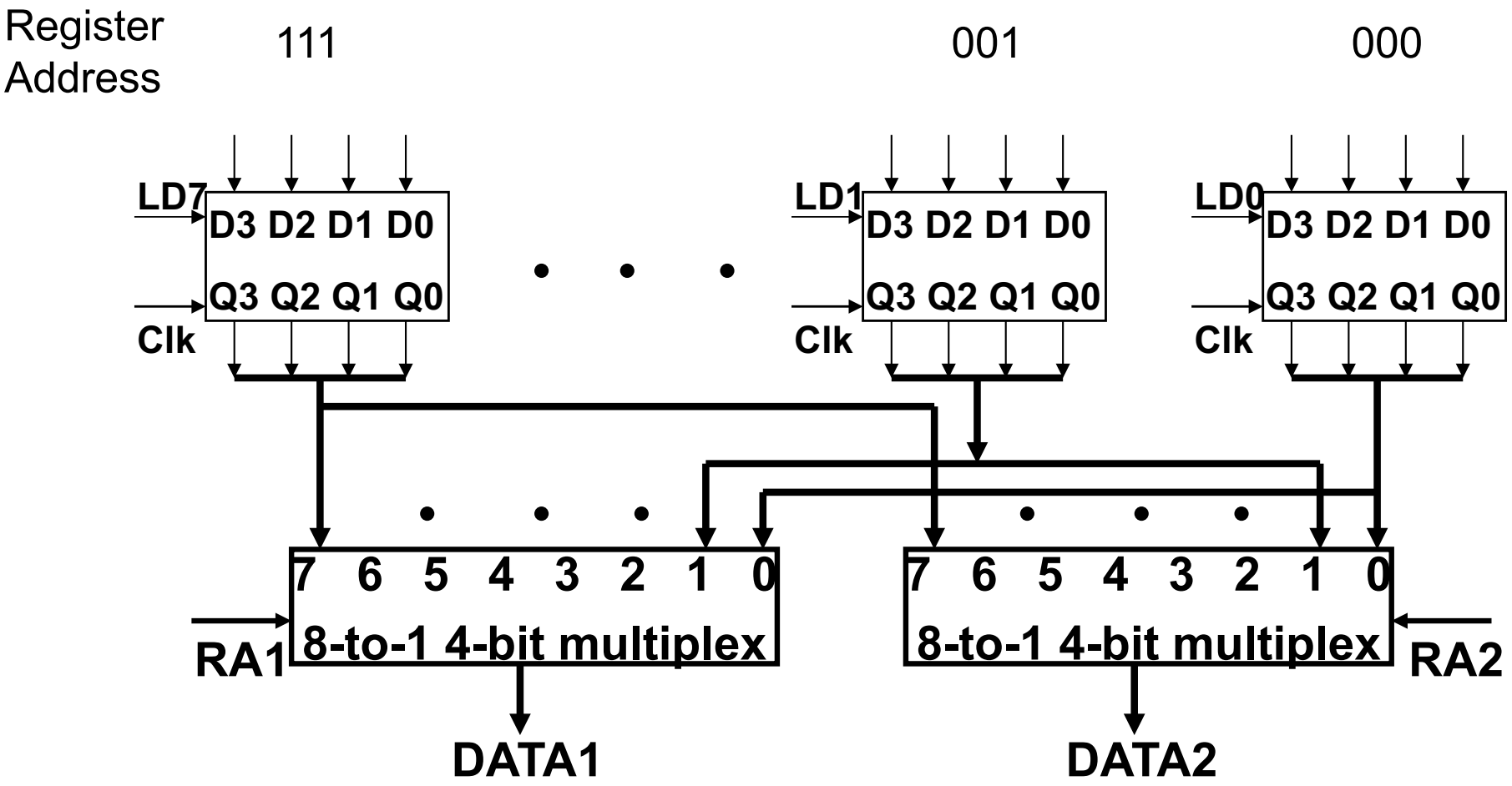
- We have to use eight such registers to make an eight register file



- How many bits are required to specify a register address?

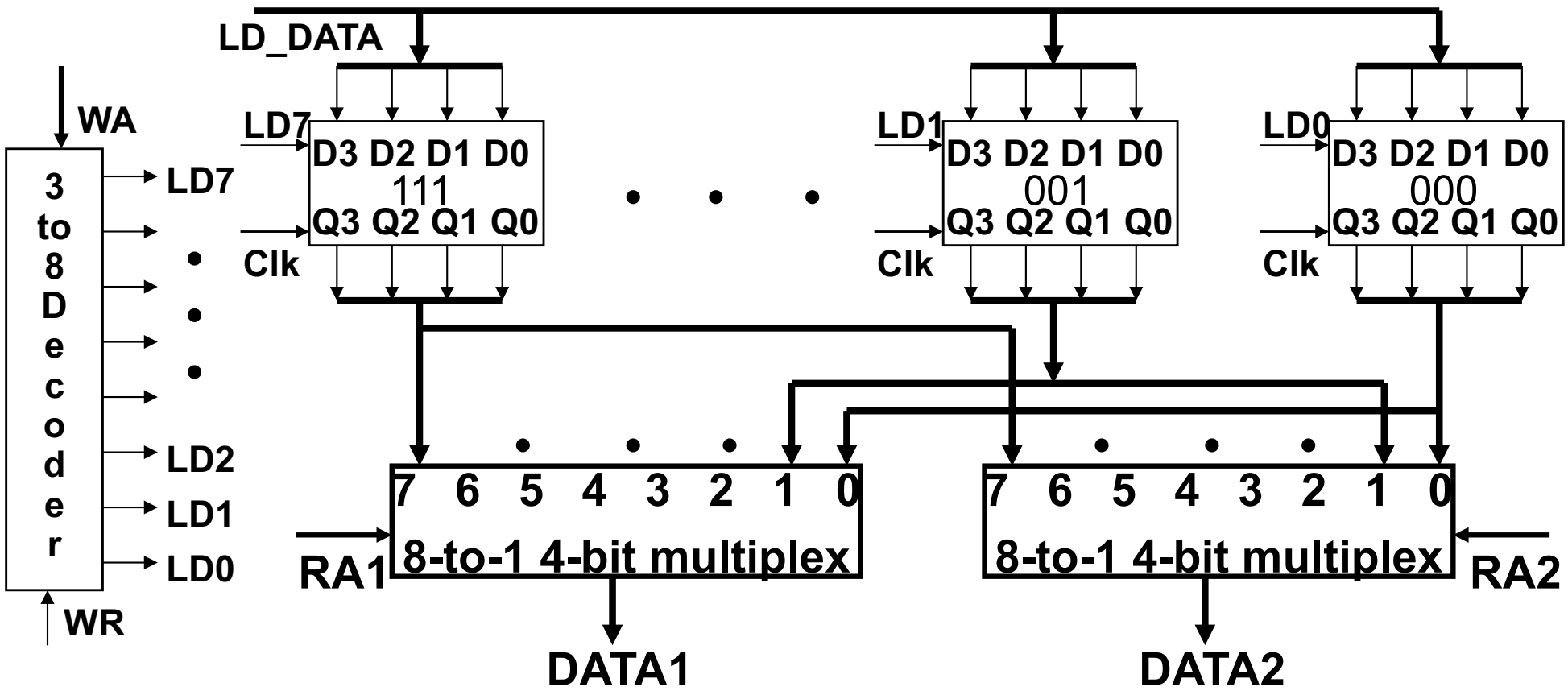
Reading Circuit

- **A 3-bit register address, RA, specifies which register is to be read**
- **For each output port, we need one 8-to-1 4-bit multiplier**



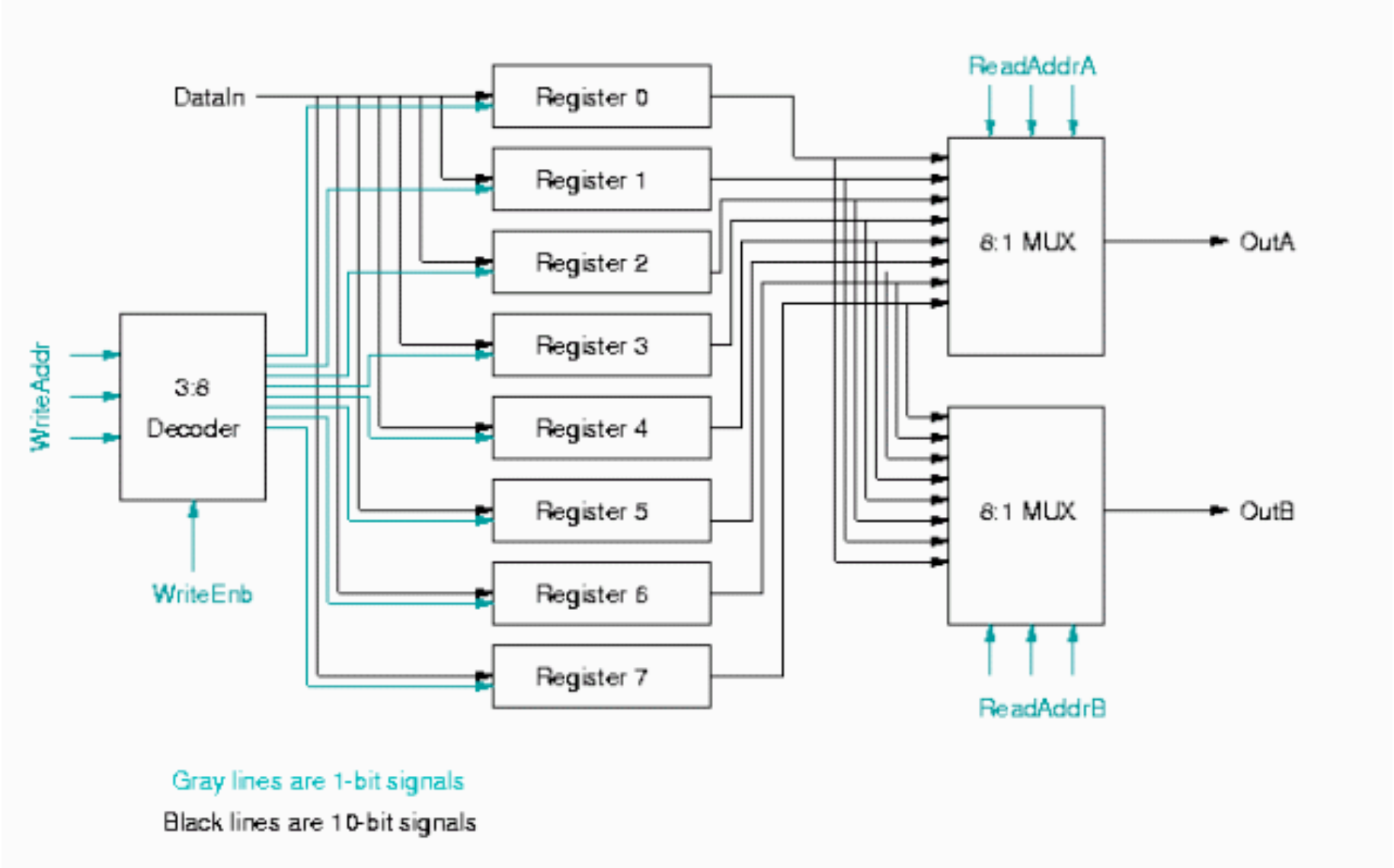
Adding write control to register file

- To write to any register, we need the register's address (WA) and a write register signal (WR)
- A 3-bit write address is decoded if write register signal is present
- One of the eight registers gets a LD signal from the decoder

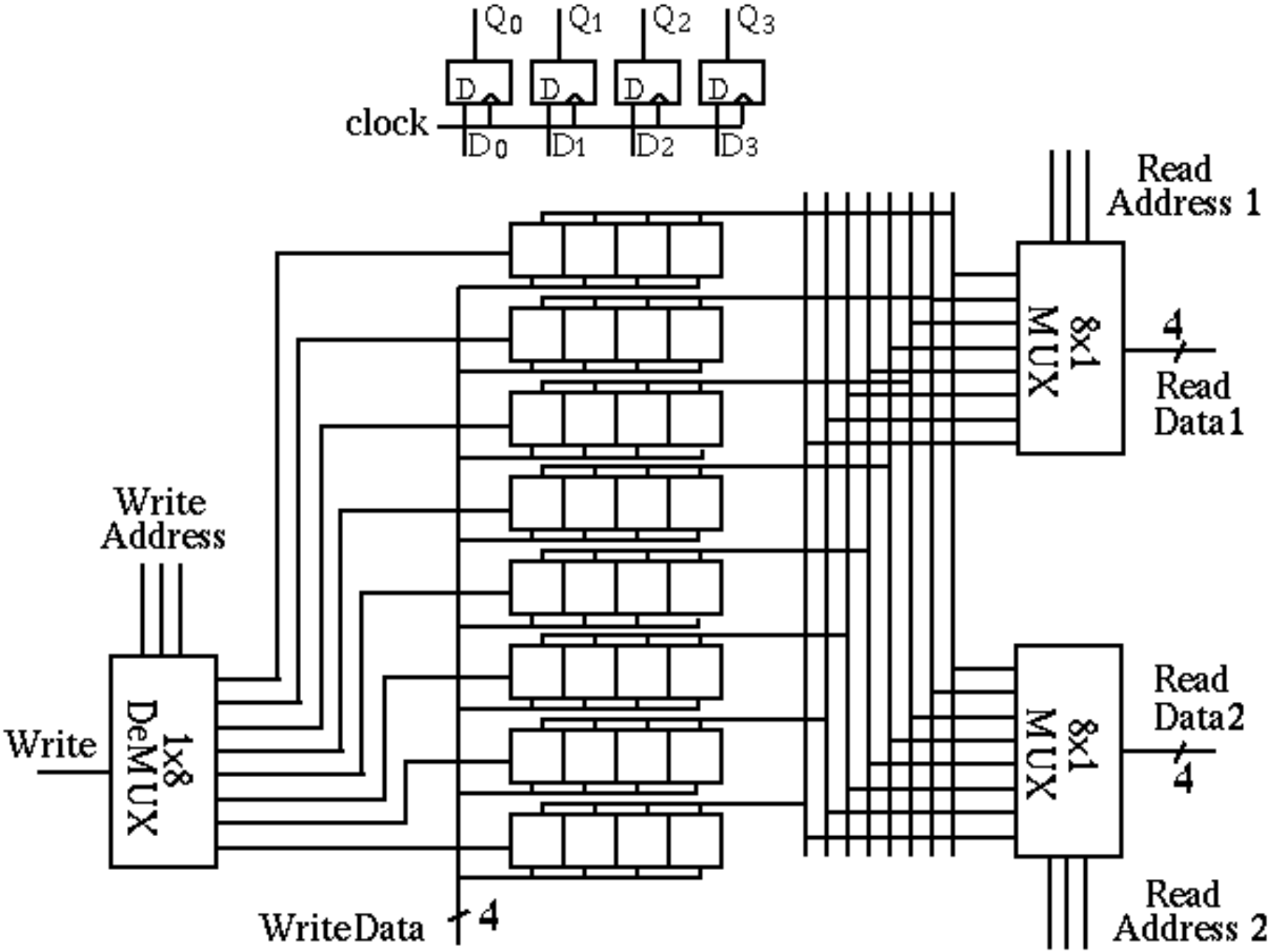


Register File
(More Examples)

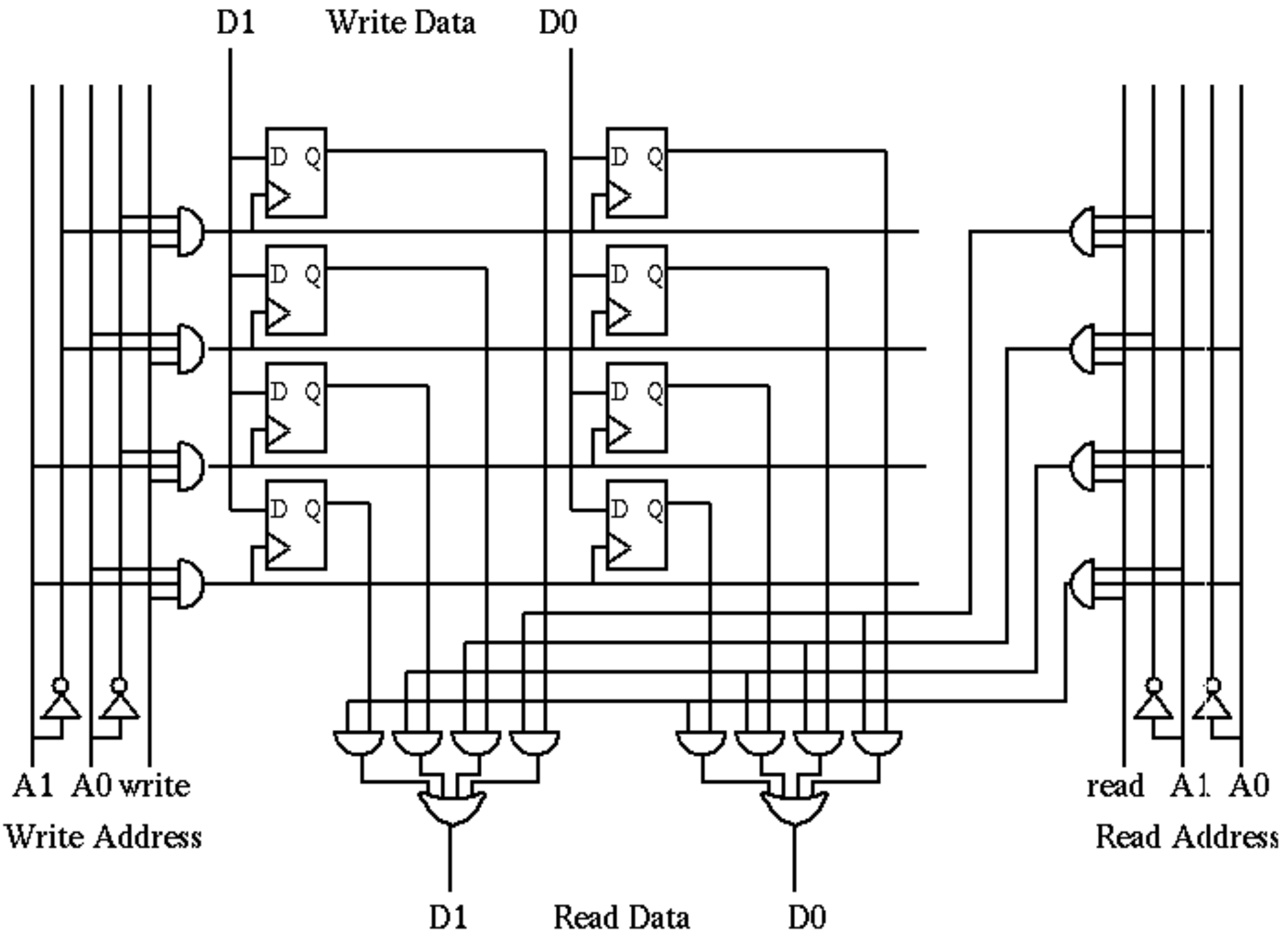
Register File



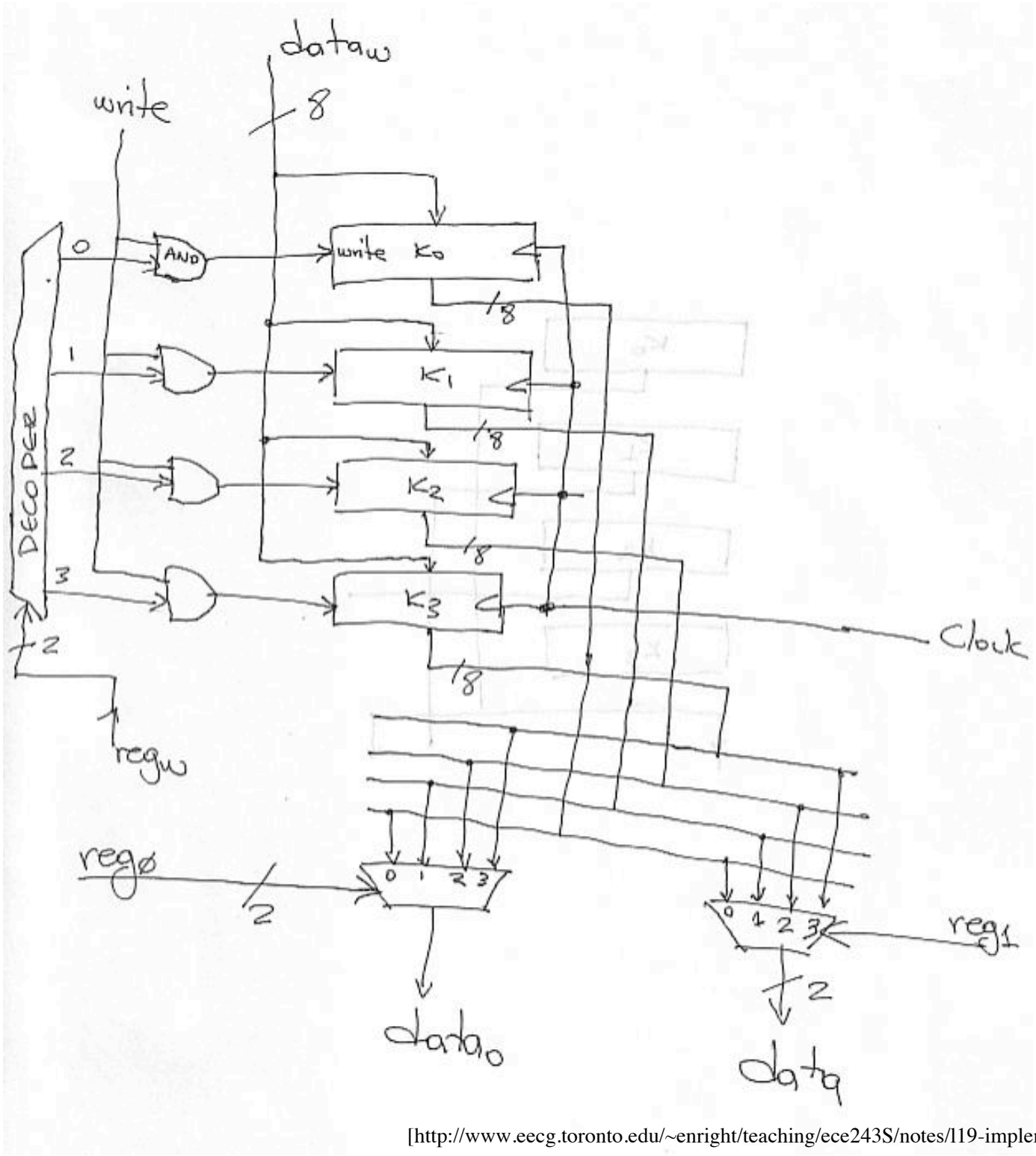
[https://jindongpu.wordpress.com/2012/03/07/register-file/]



[http://fourier.eng.hmc.edu/e85_old/lectures/digital_logic/node19.html]



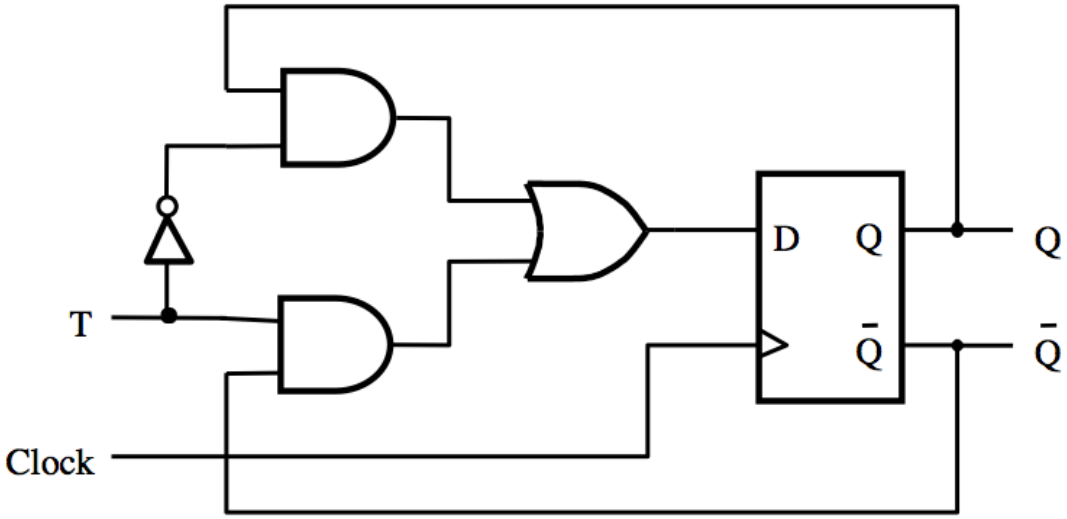
[http://fourier.eng.hmc.edu/e85_old/lectures/digital_logic/node19.html]

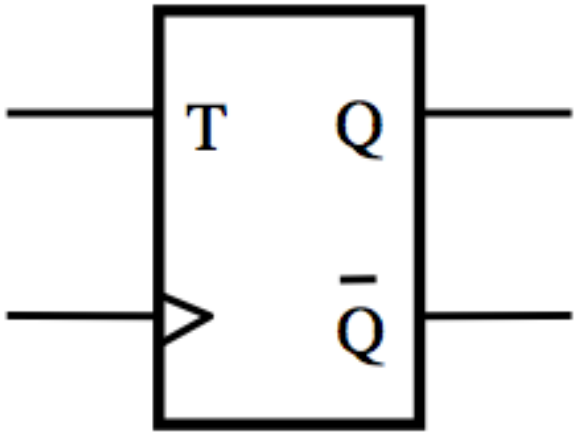


[http://www.eecg.toronto.edu/~enright/teaching/ece243S/notes/l19-implemenation-single-cycle.html]

Counters

T Flip-Flop
(circuit and graphical symbol)

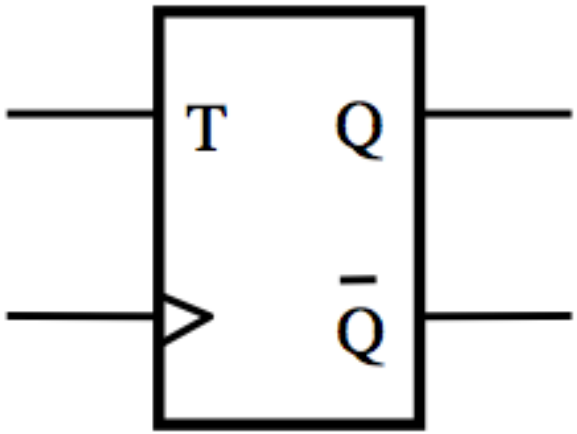




[Figure 5.15a,c from the textbook]

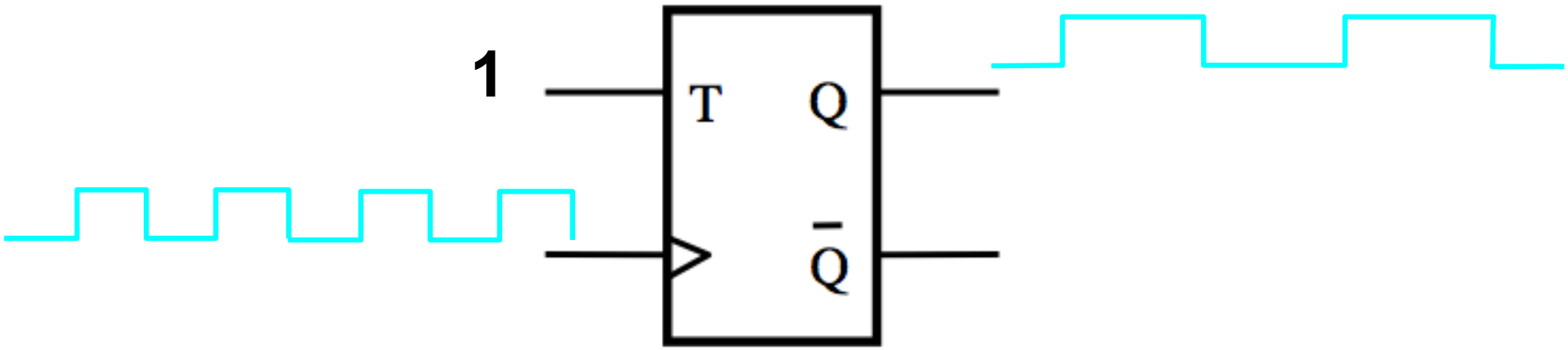
The output of the T Flip-Flop

divides the frequency of the clock by 2

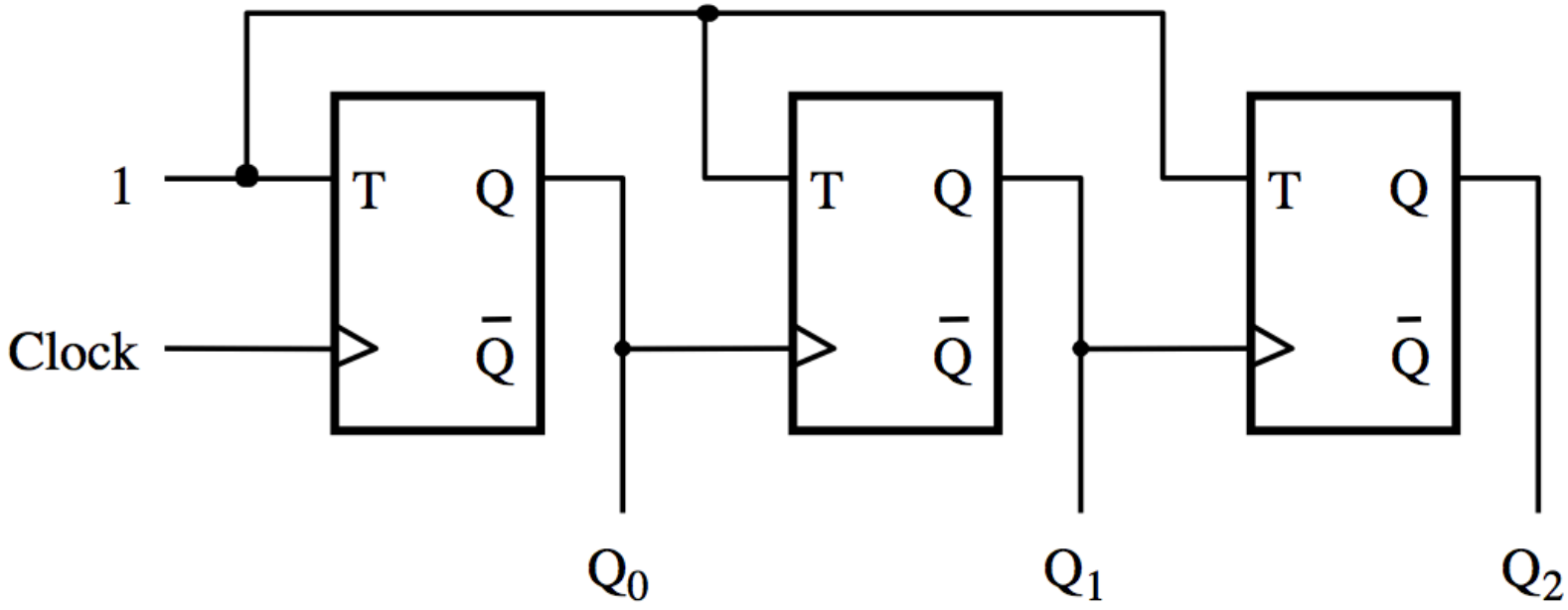


The output of the T Flip-Flop

divides the frequency of the clock by 2

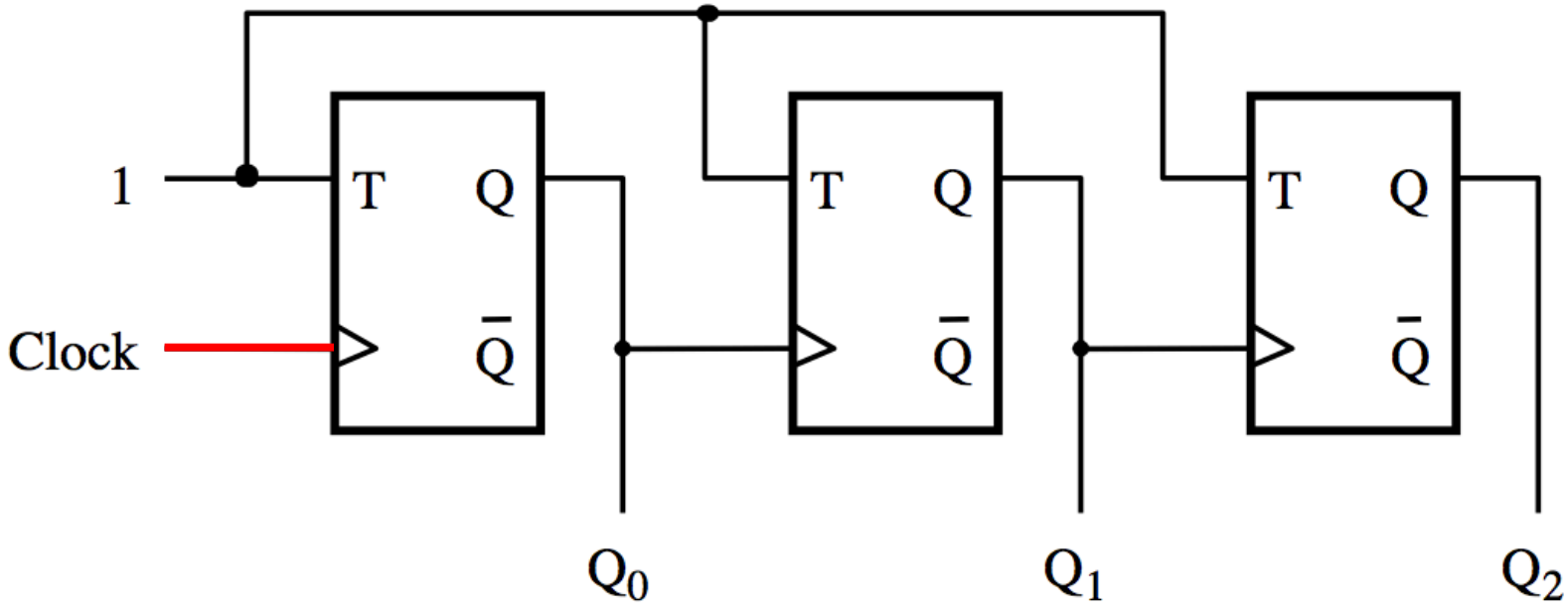


A three-bit down-counter



[Figure 5.20 from the textbook]

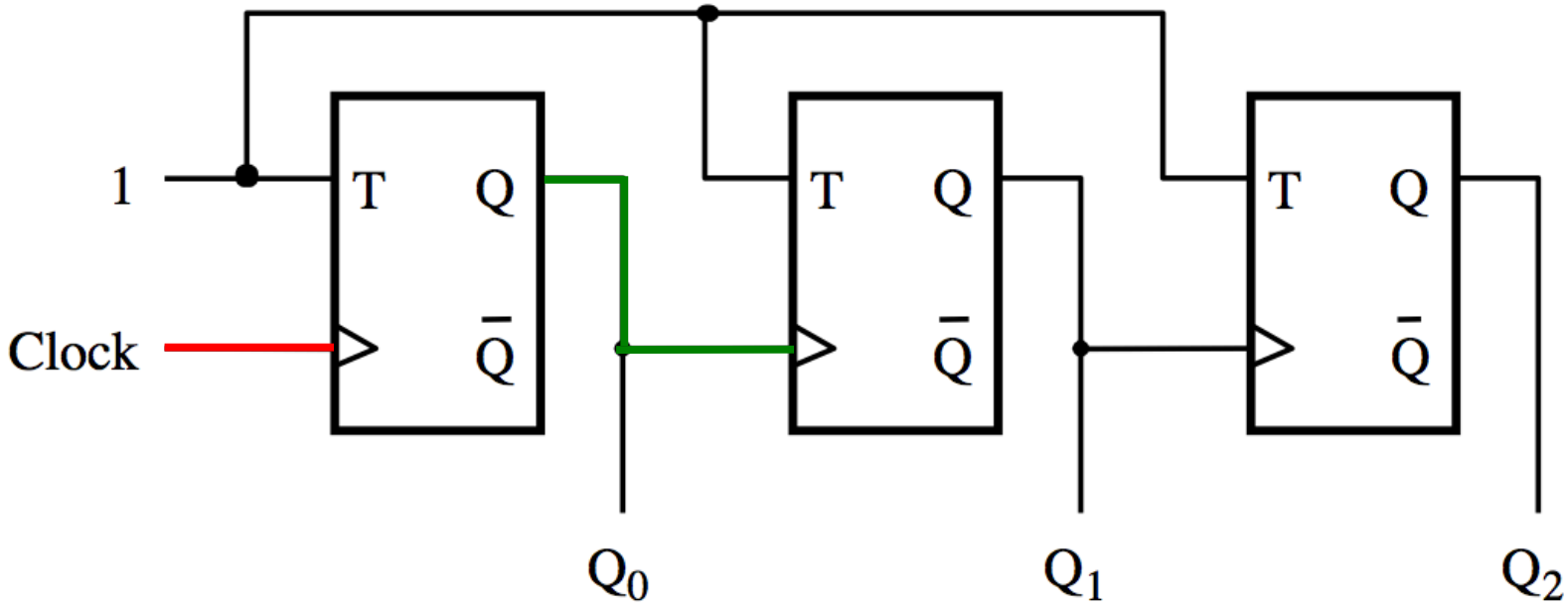
A three-bit down-counter



The first flip-flop changes
on the positive edge of the clock

[Figure 5.20 from the textbook]

A three-bit down-counter

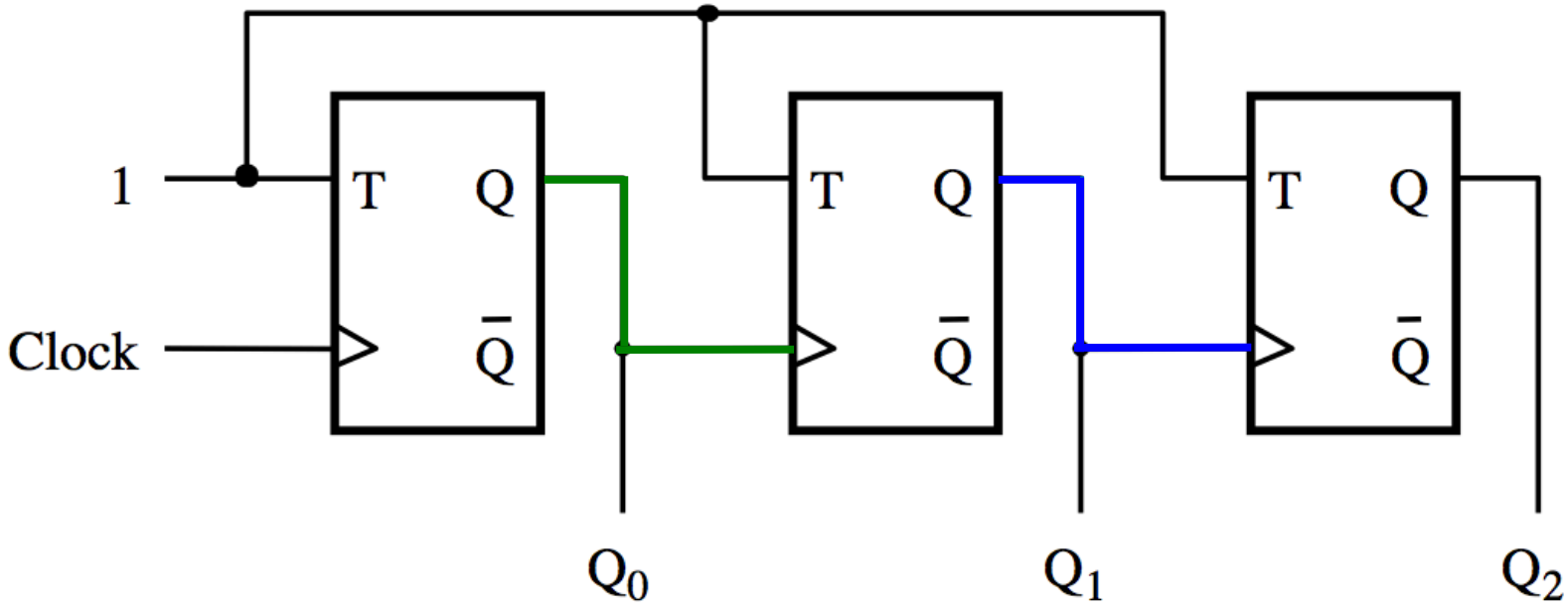


The first flip-flop changes on the positive edge of the clock

The second flip-flop changes on the positive edge of Q_0

[Figure 5.20 from the textbook]

A three-bit down-counter



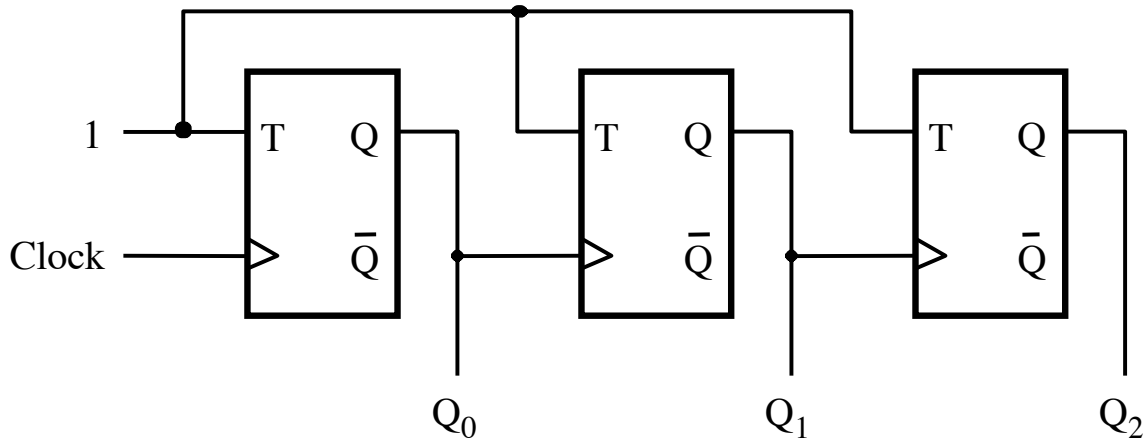
The first flip-flop changes on the positive edge of the clock

The second flip-flop changes on the positive edge of Q_0

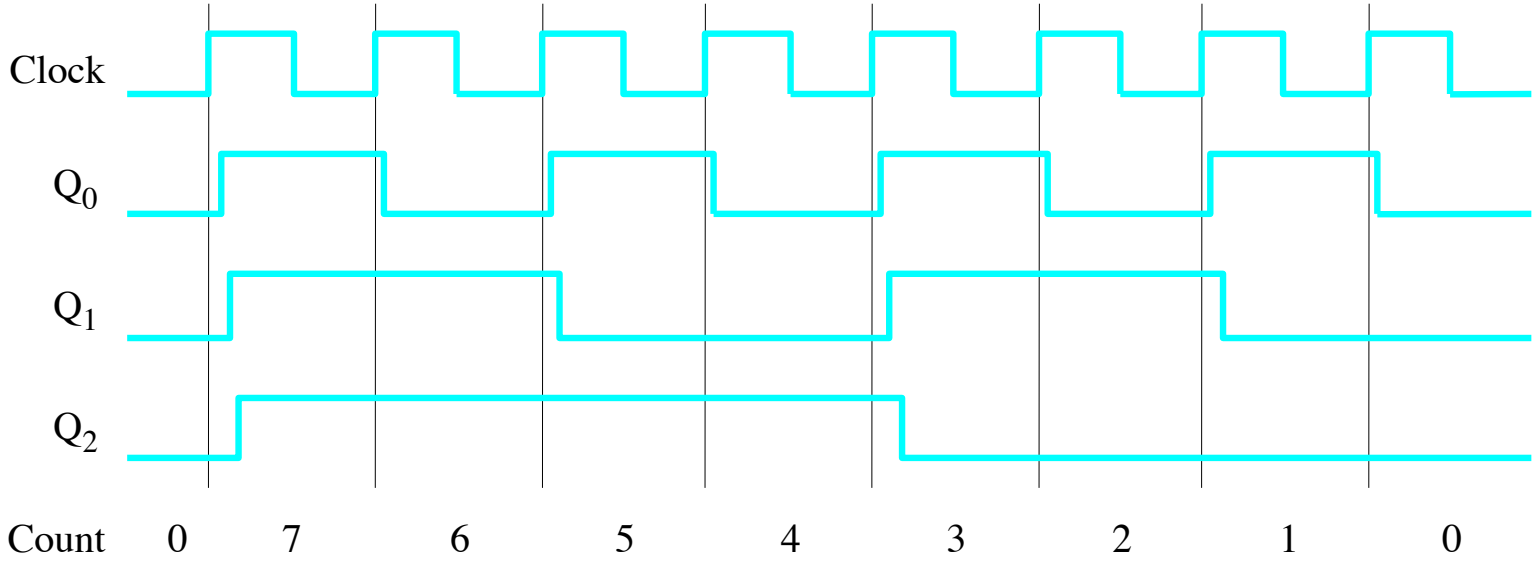
The third flip-flop changes on the positive edge of Q_1

[Figure 5.20 from the textbook]

A three-bit down-counter



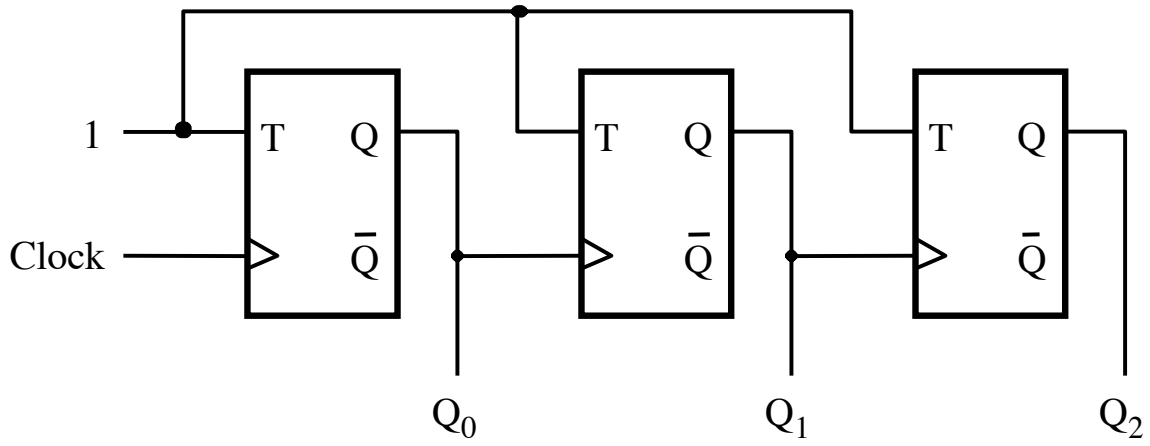
(a) Circuit



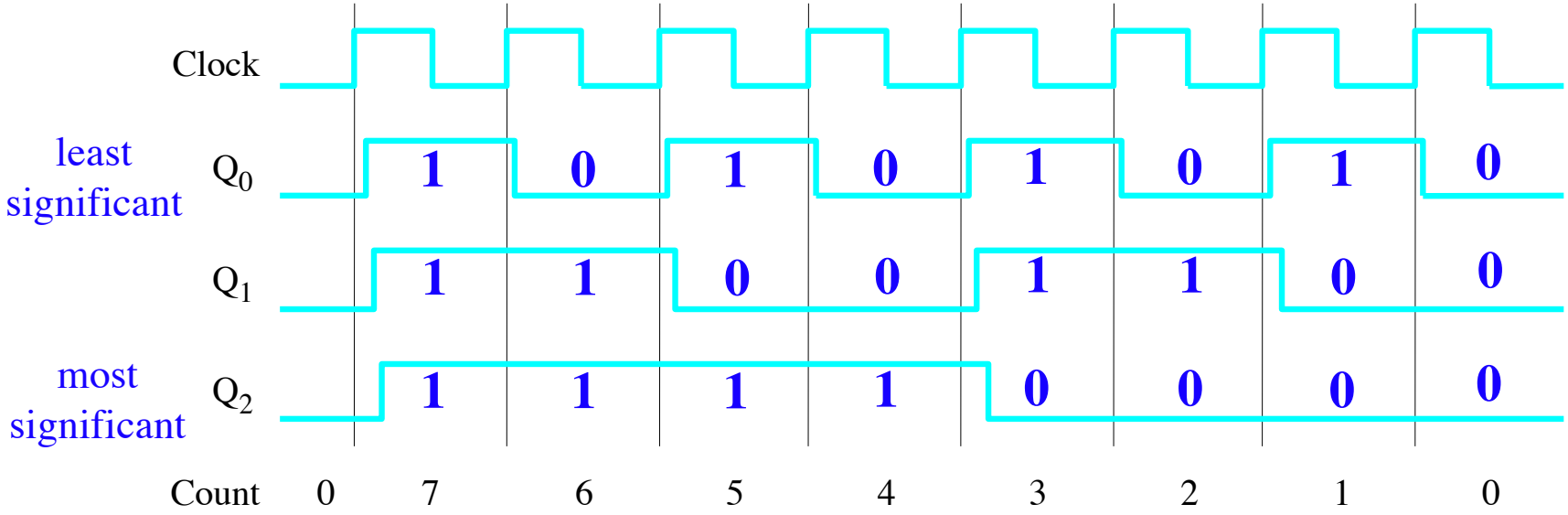
(b) Timing diagram

[Figure 5.20 from the textbook]

A three-bit down-counter

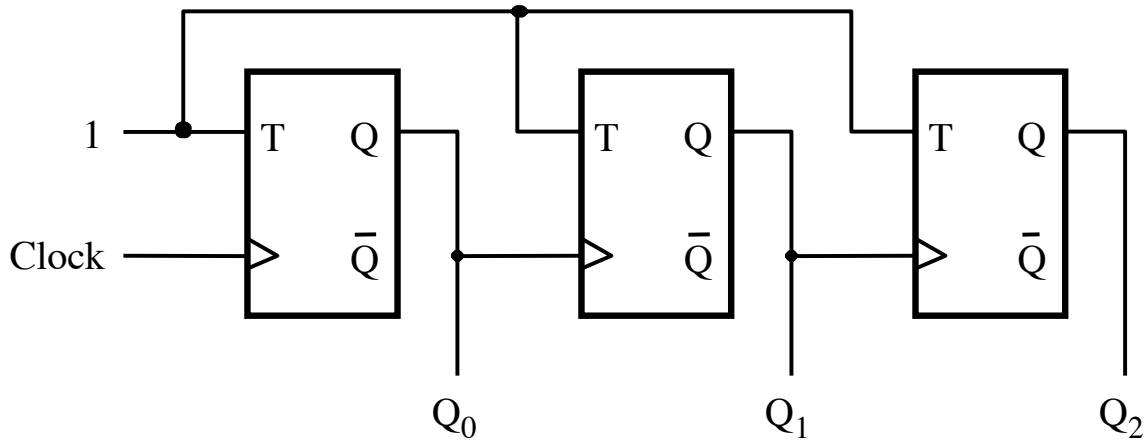


(a) Circuit

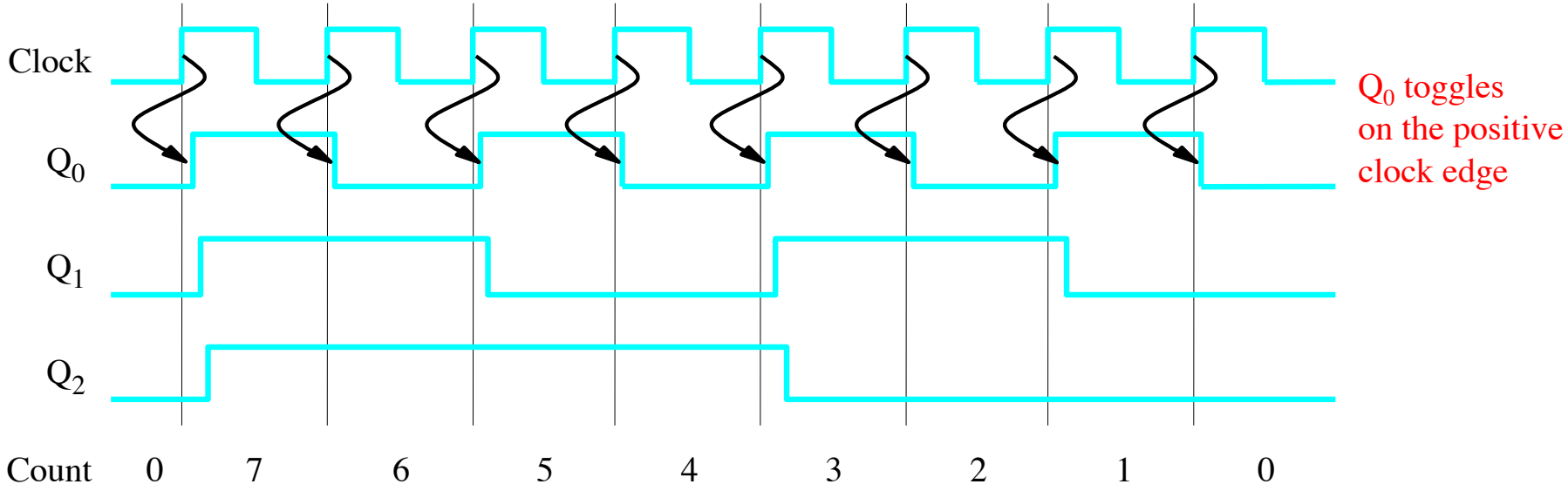


(b) Timing diagram

A three-bit down-counter

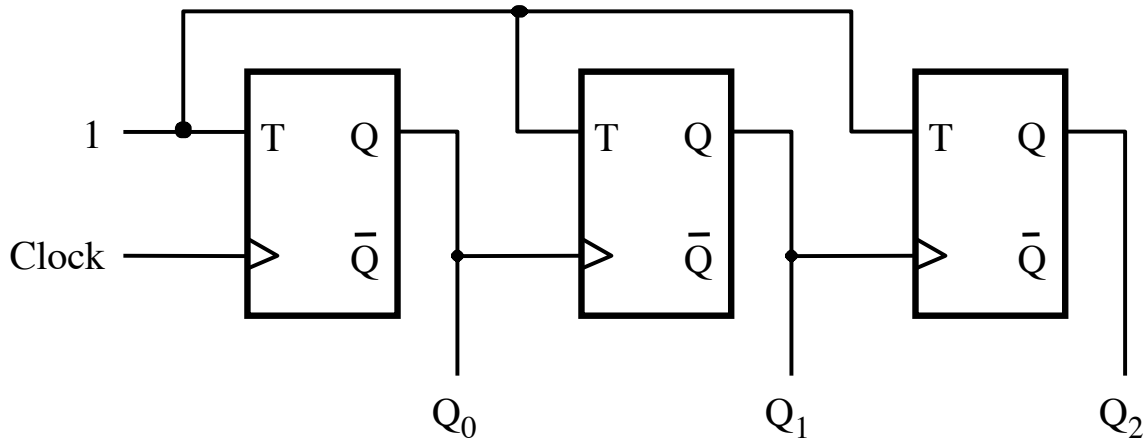


(a) Circuit

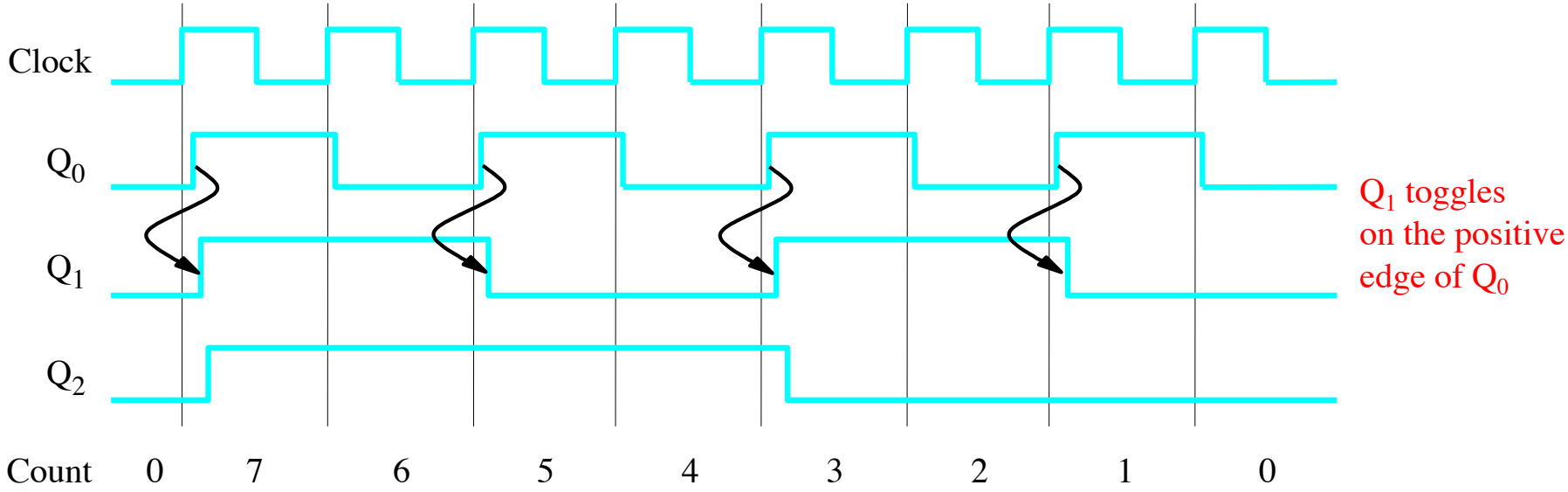


(b) Timing diagram

A three-bit down-counter

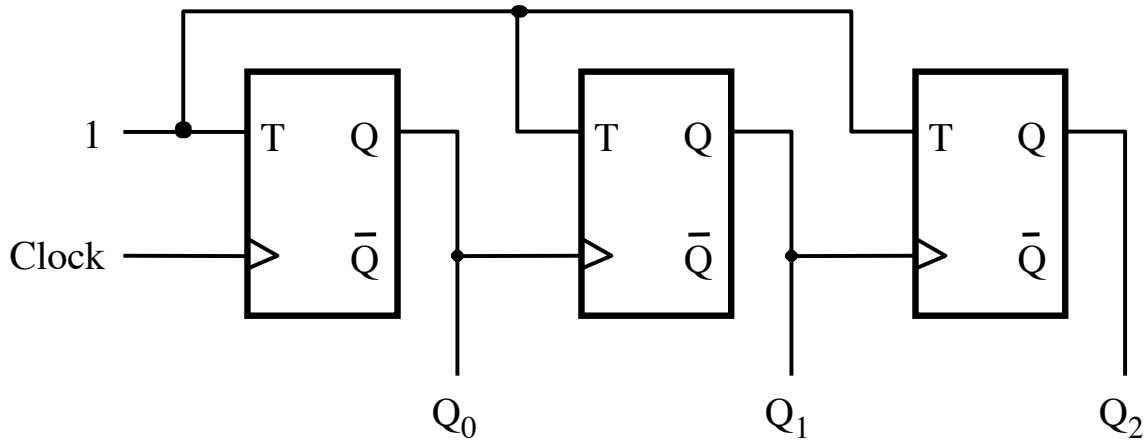


(a) Circuit

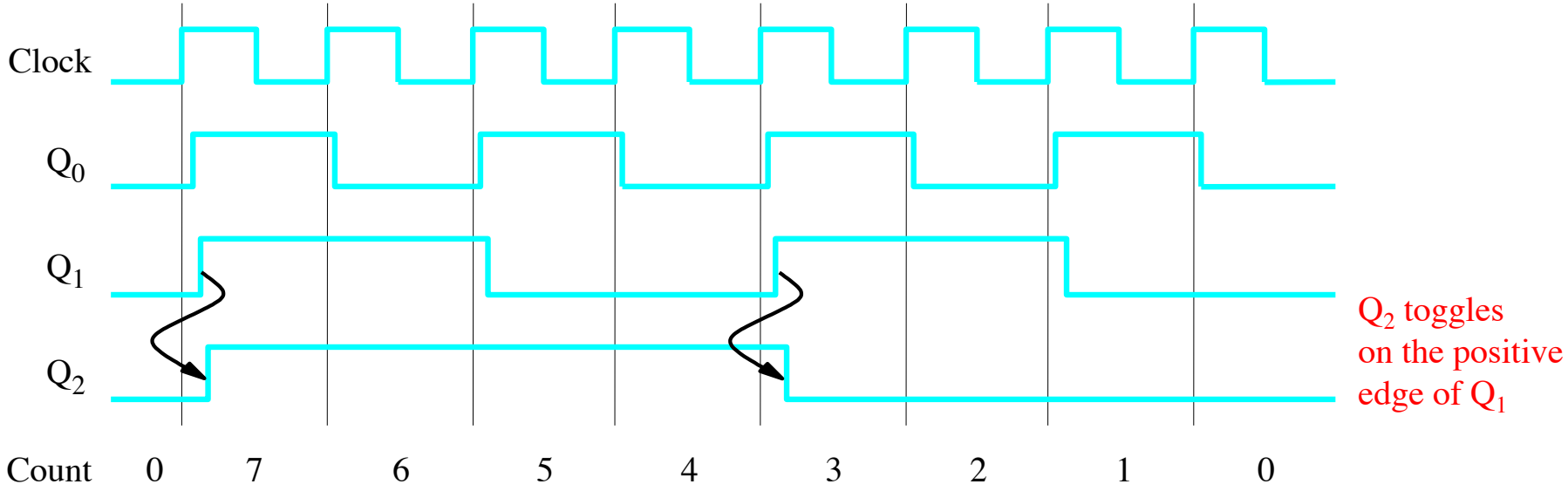


(b) Timing diagram

A three-bit down-counter

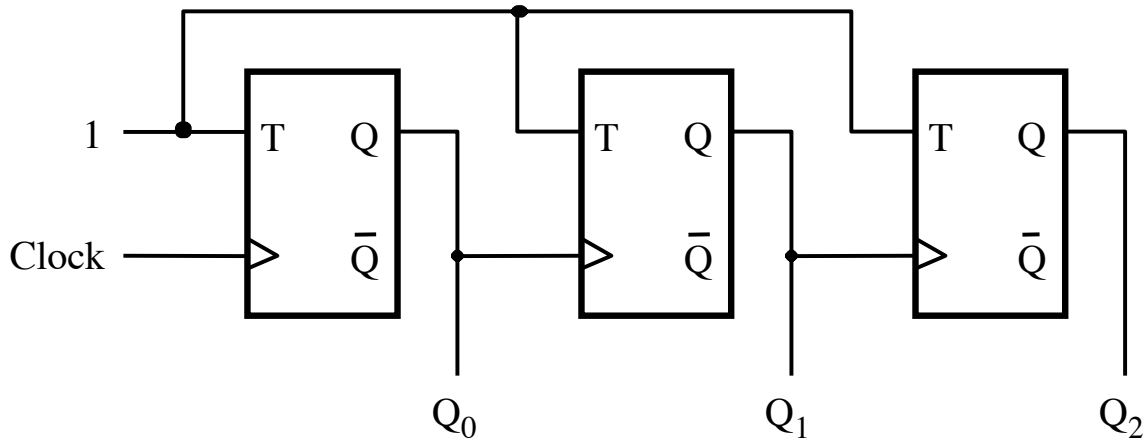


(a) Circuit

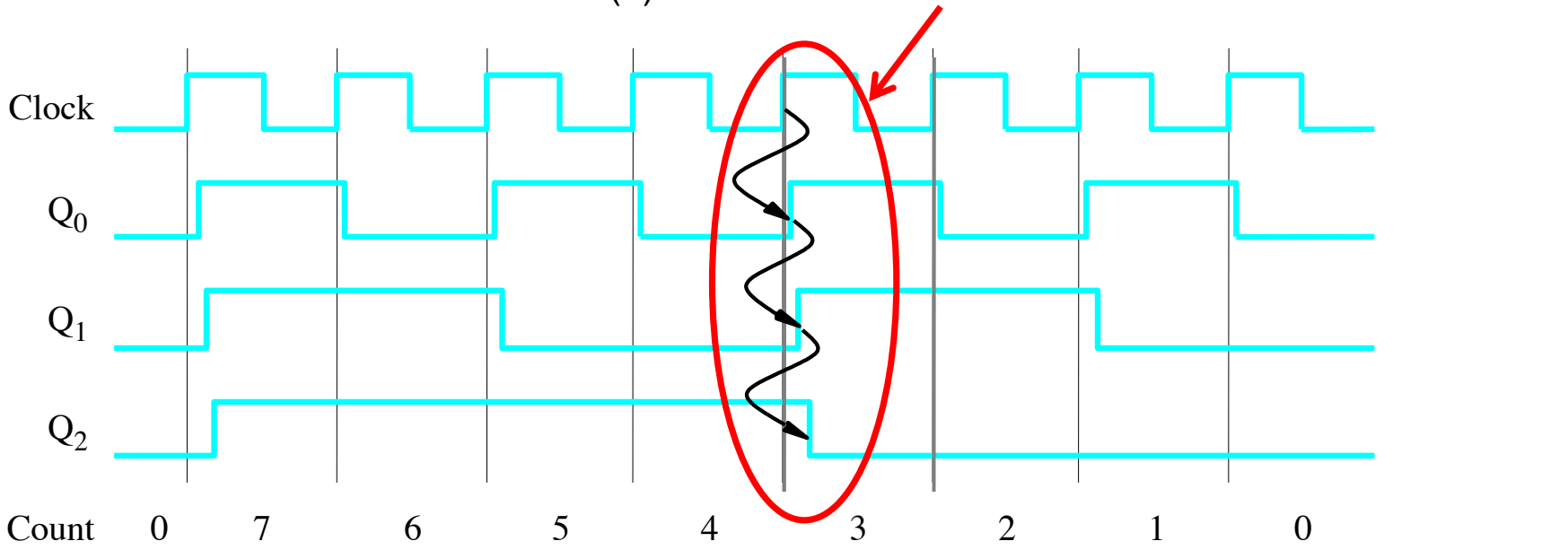


(b) Timing diagram

A three-bit down-counter

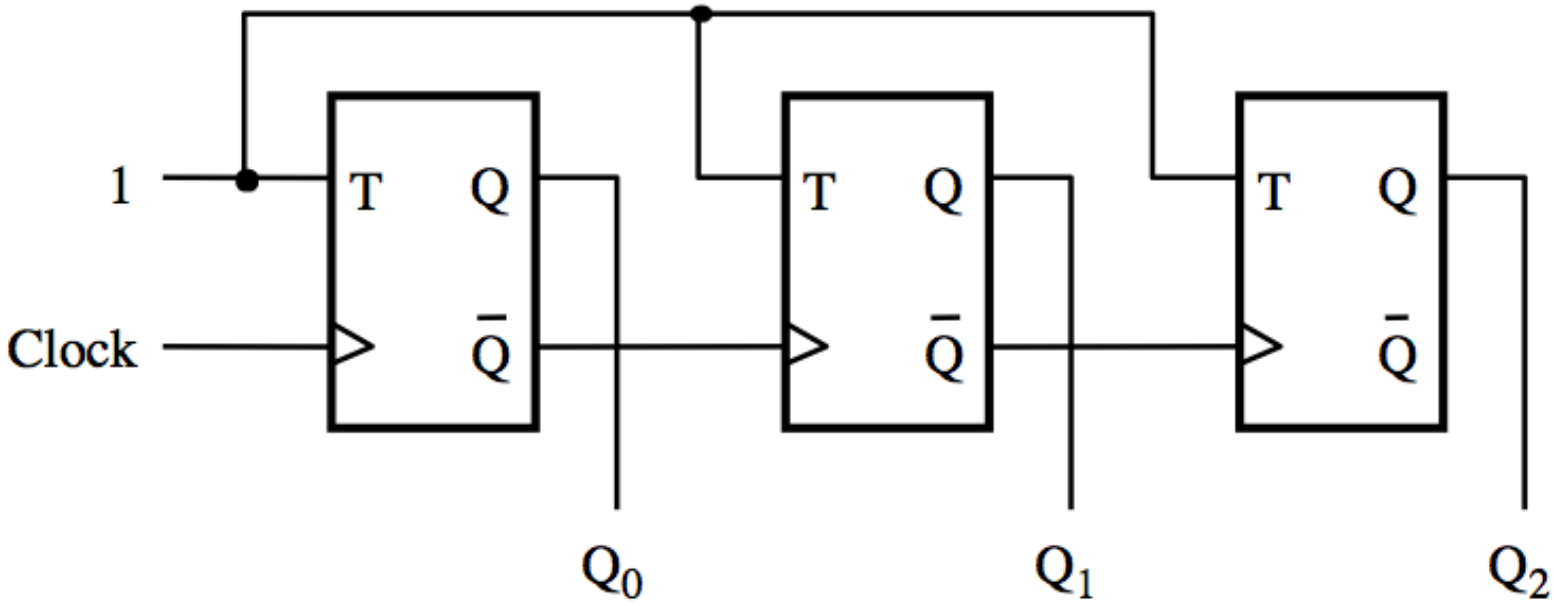


(a) Circuit



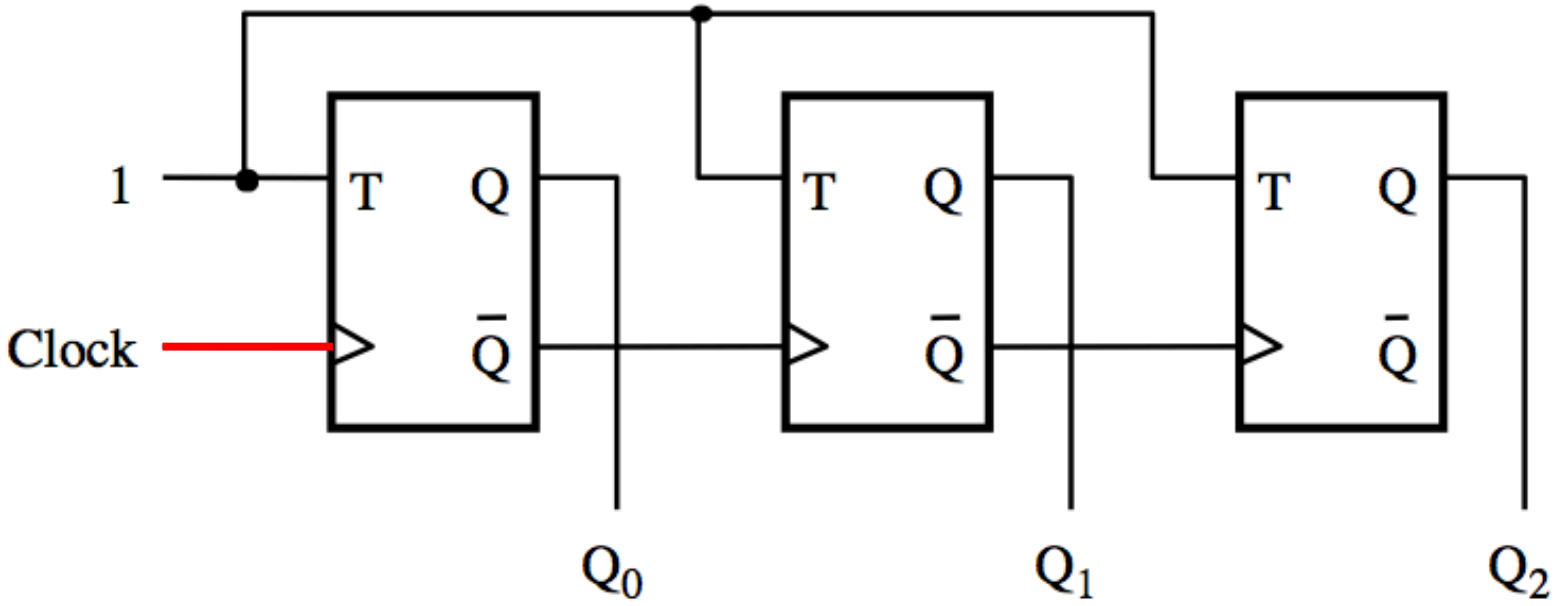
(b) Timing diagram

A three-bit up-counter



[Figure 5.19 from the textbook]

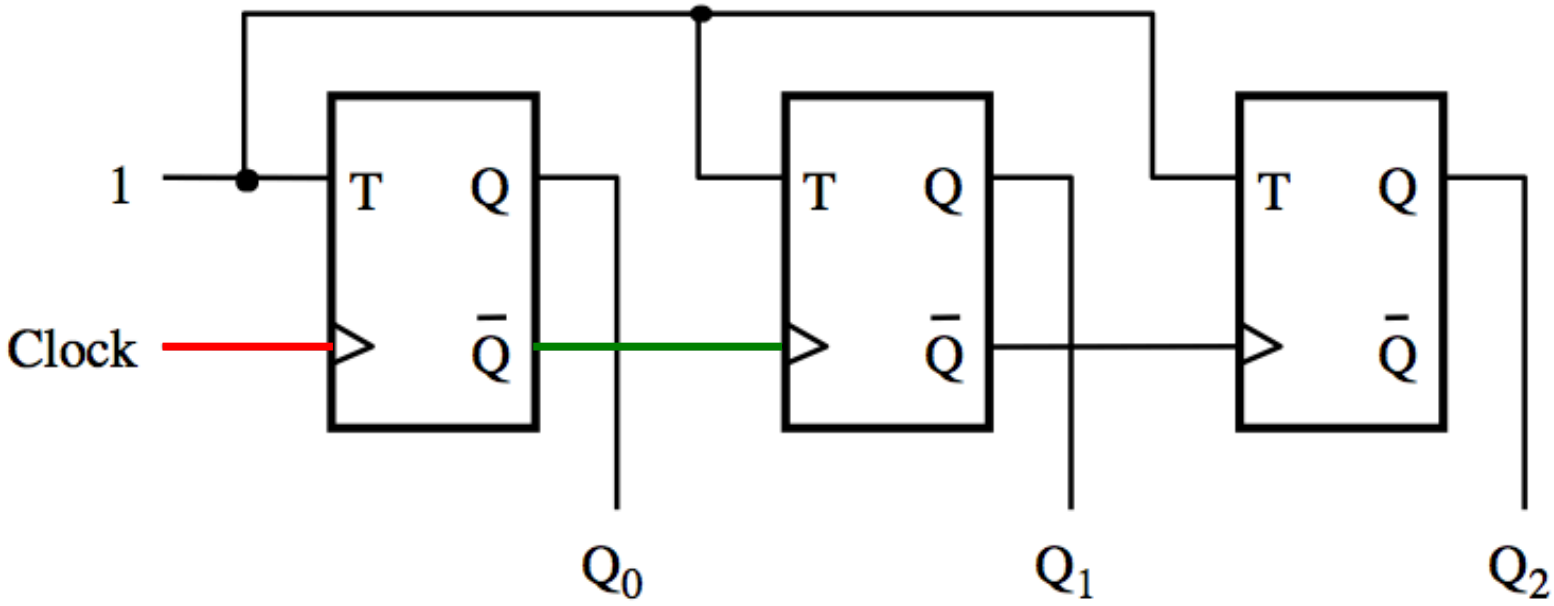
A three-bit up-counter



The first flip-flop changes
on the positive edge of the clock

[Figure 5.19 from the textbook]

A three-bit up-counter

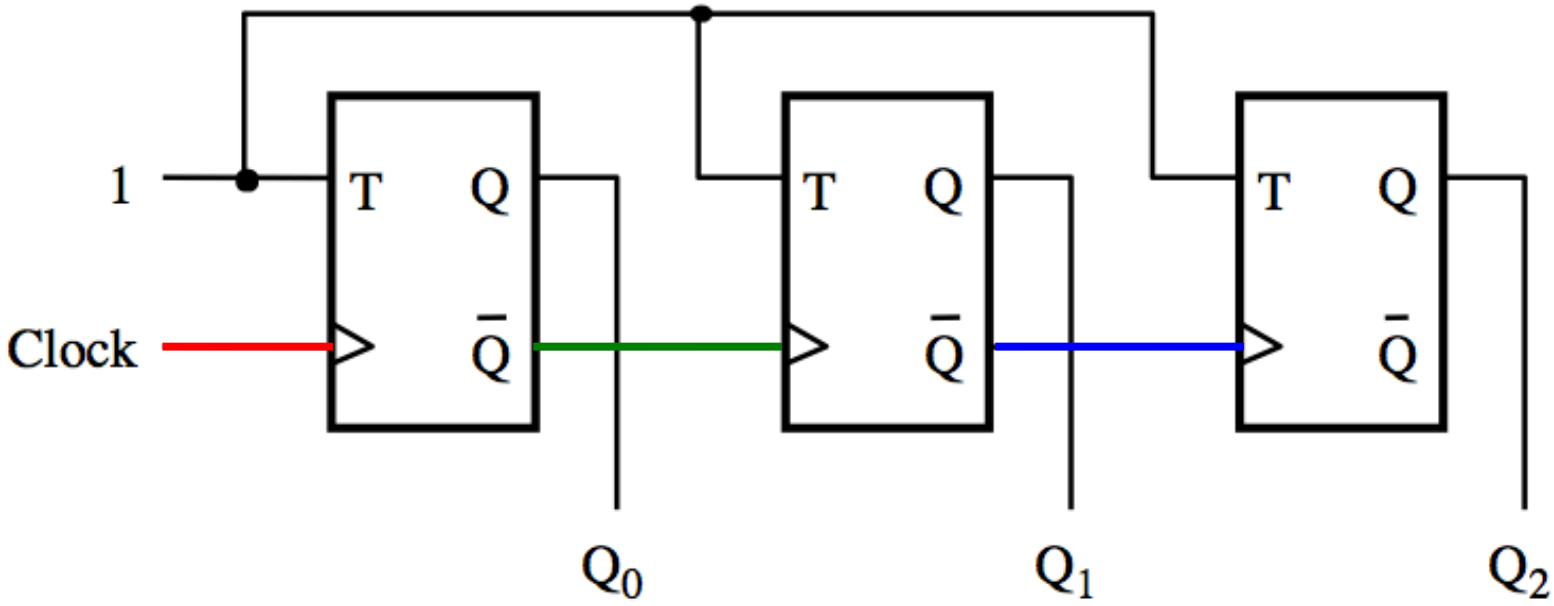


The first flip-flop changes
on the positive edge of the clock

The second flip-flop changes
on the positive edge of $\overline{Q}_0$

[Figure 5.19 from the textbook]

A three-bit up-counter



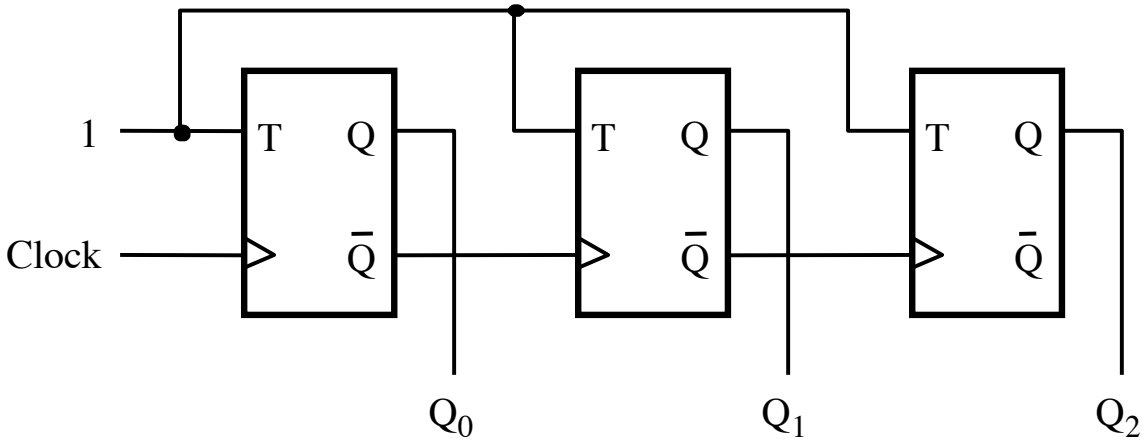
The first flip-flop changes on the positive edge of the clock

The second flip-flop changes on the positive edge of $\overline{Q}_0$

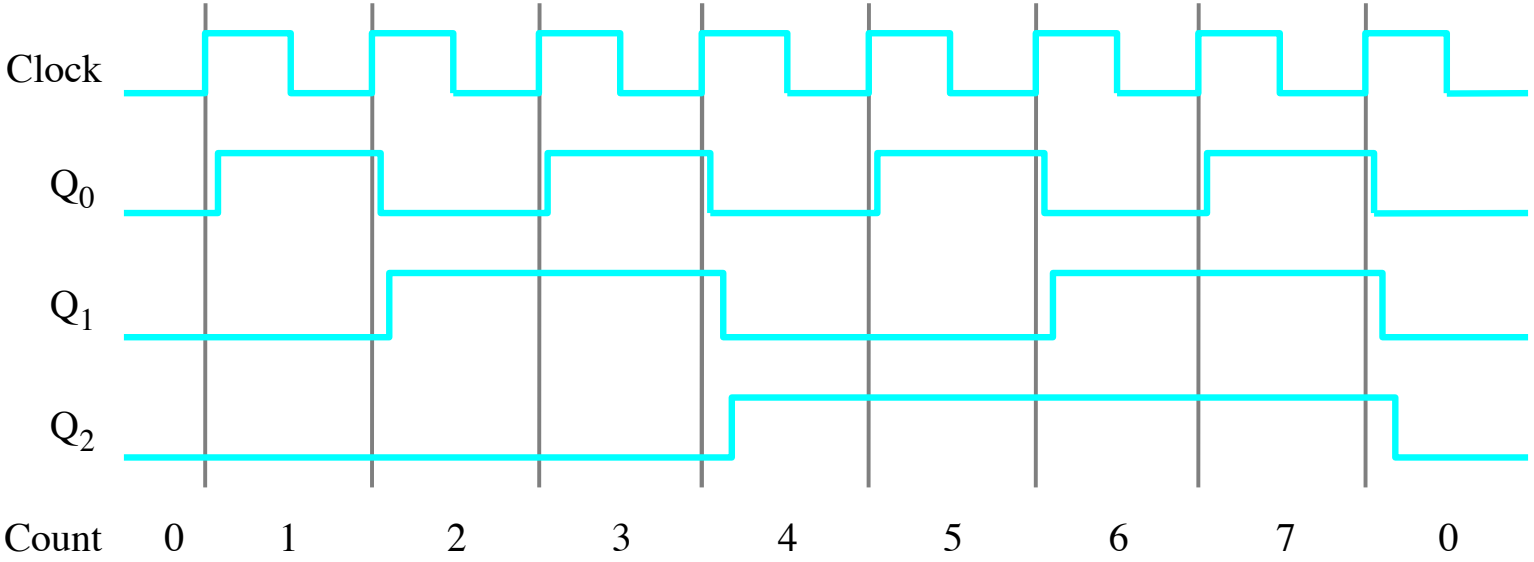
The third flip-flop changes on the positive edge of $\overline{Q}_1$

[Figure 5.19 from the textbook]

A three-bit up-counter



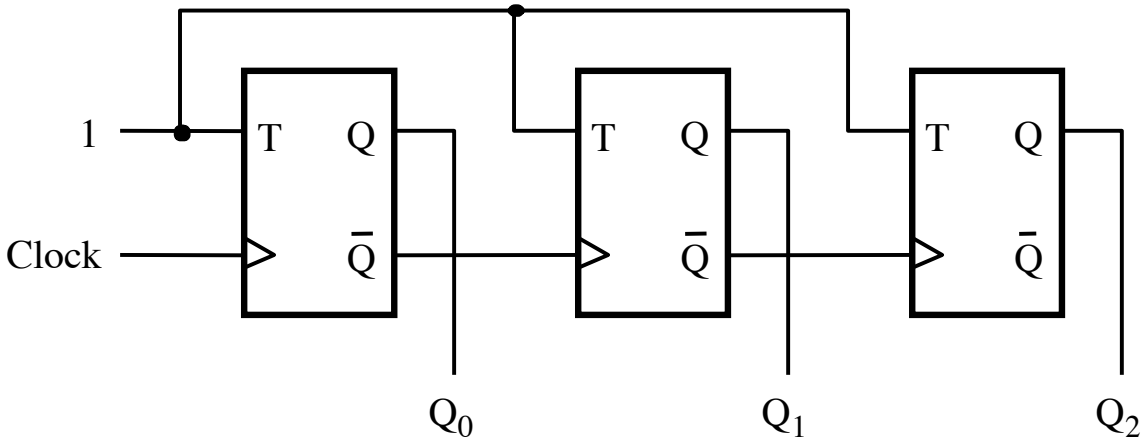
(a) Circuit



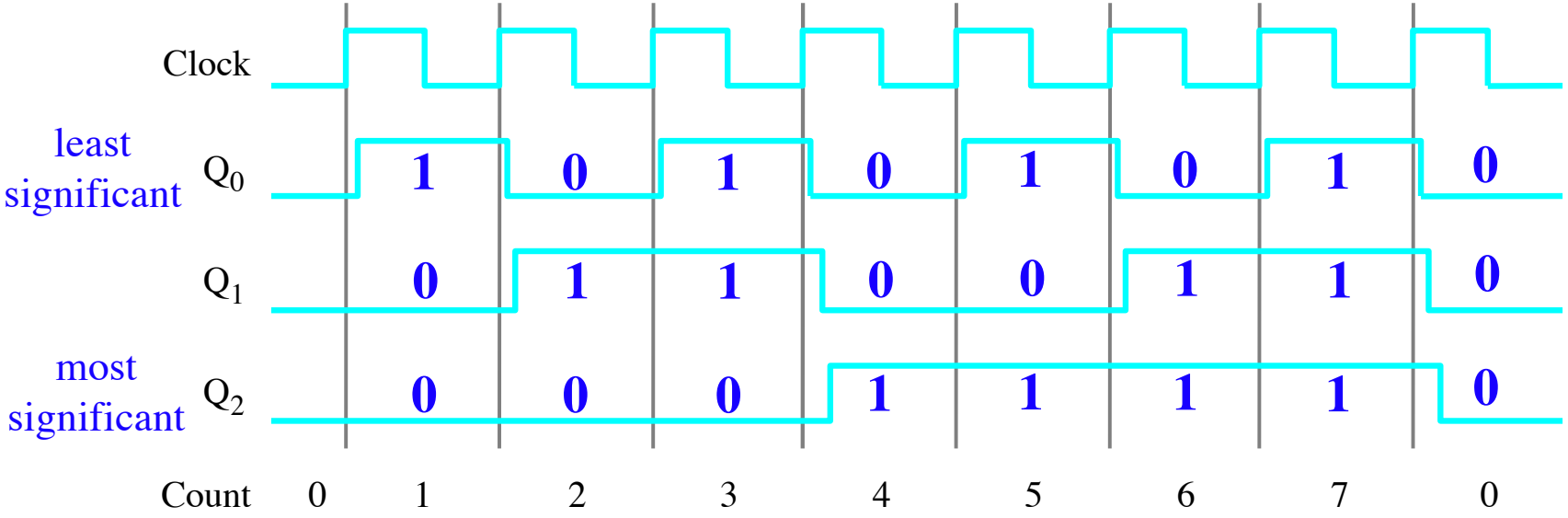
(b) Timing diagram

[Figure 5.19 from the textbook]

A three-bit up-counter



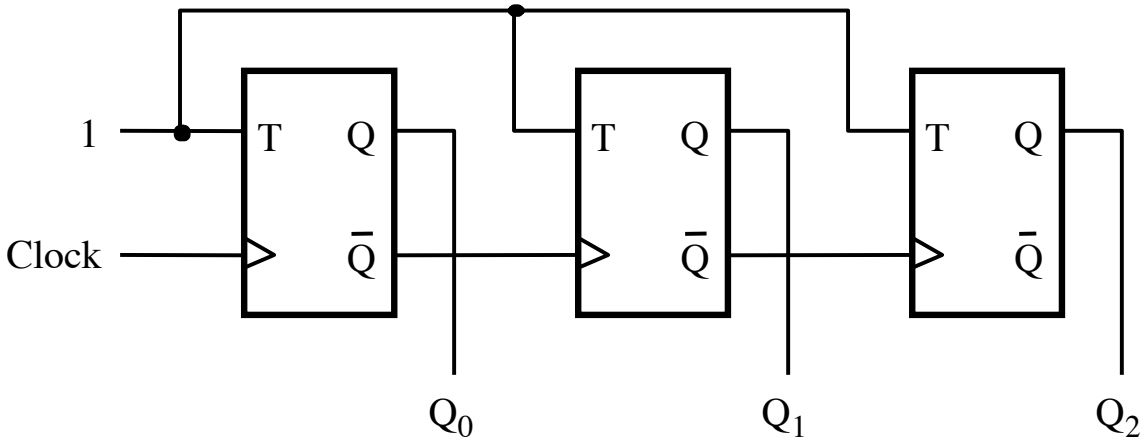
(a) Circuit



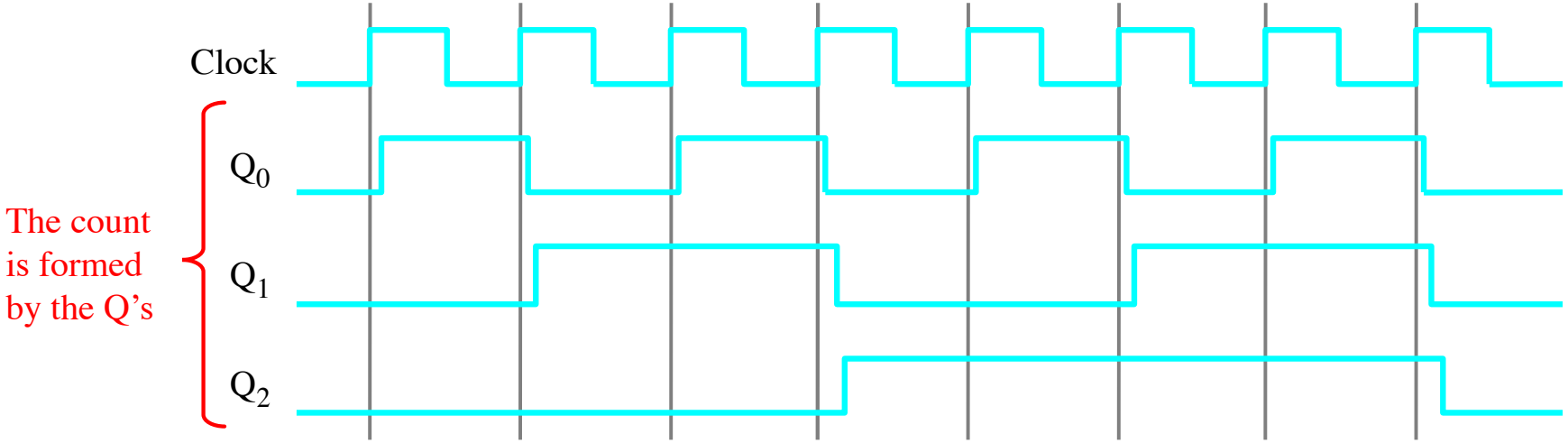
(b) Timing diagram

[Figure 5.19 from the textbook]

A three-bit up-counter



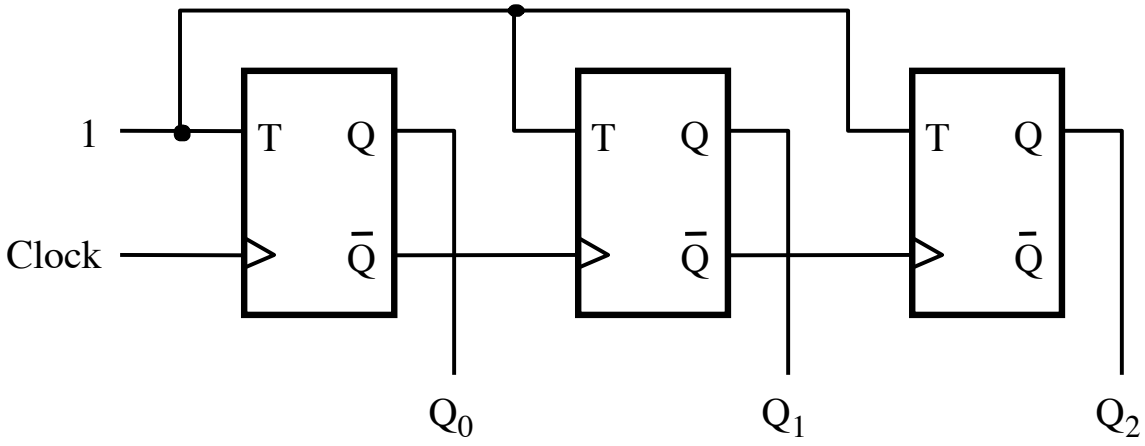
(a) Circuit



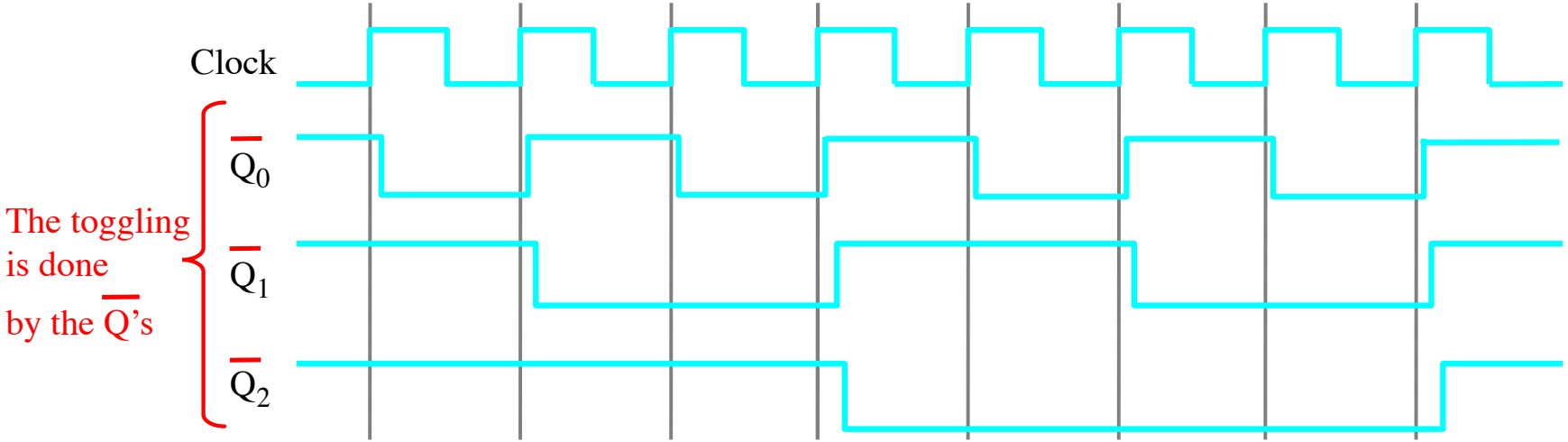
(b) Timing diagram

[Figure 5.19 from the textbook]

A three-bit up-counter

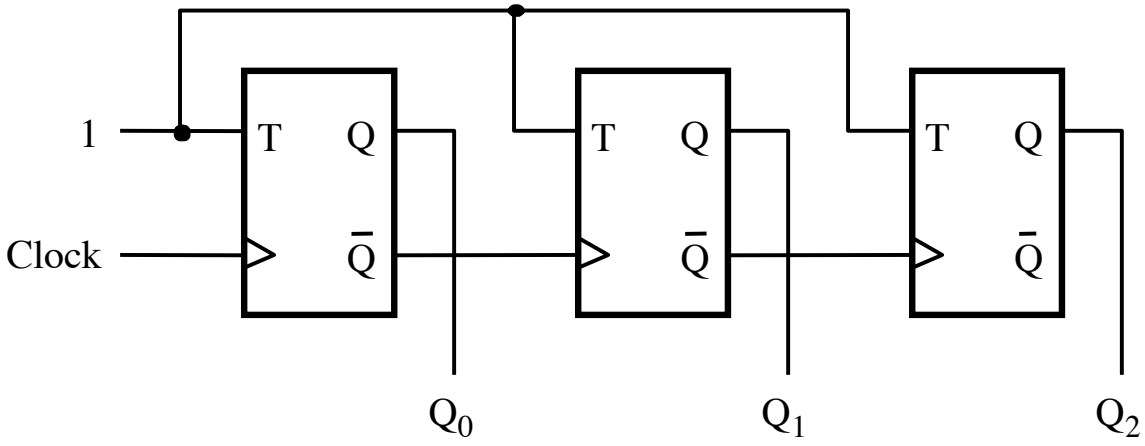


(a) Circuit

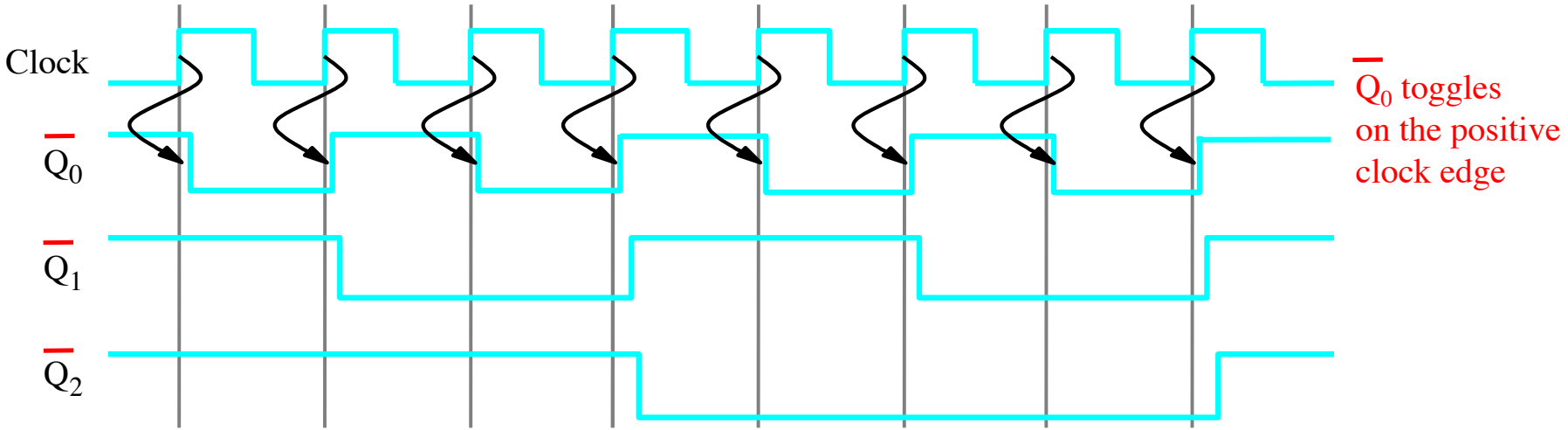


(b) Timing diagram

A three-bit up-counter

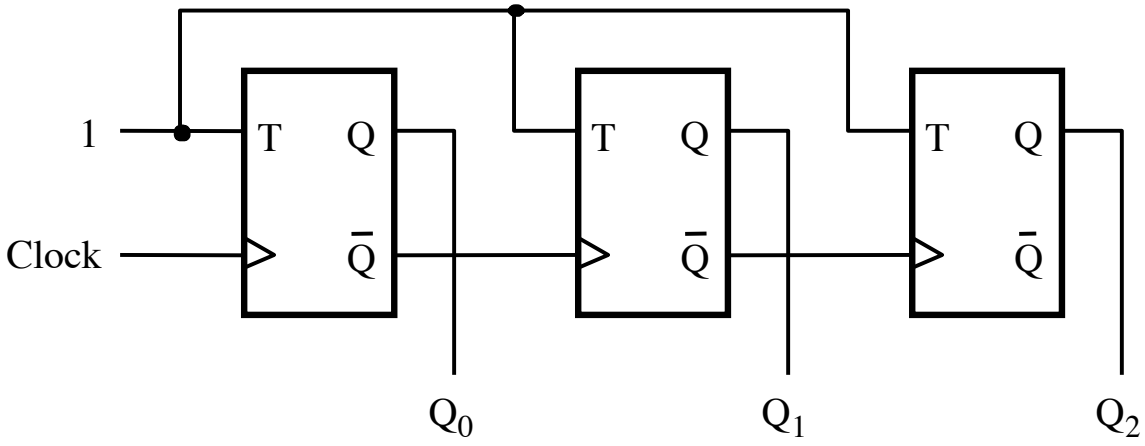


(a) Circuit

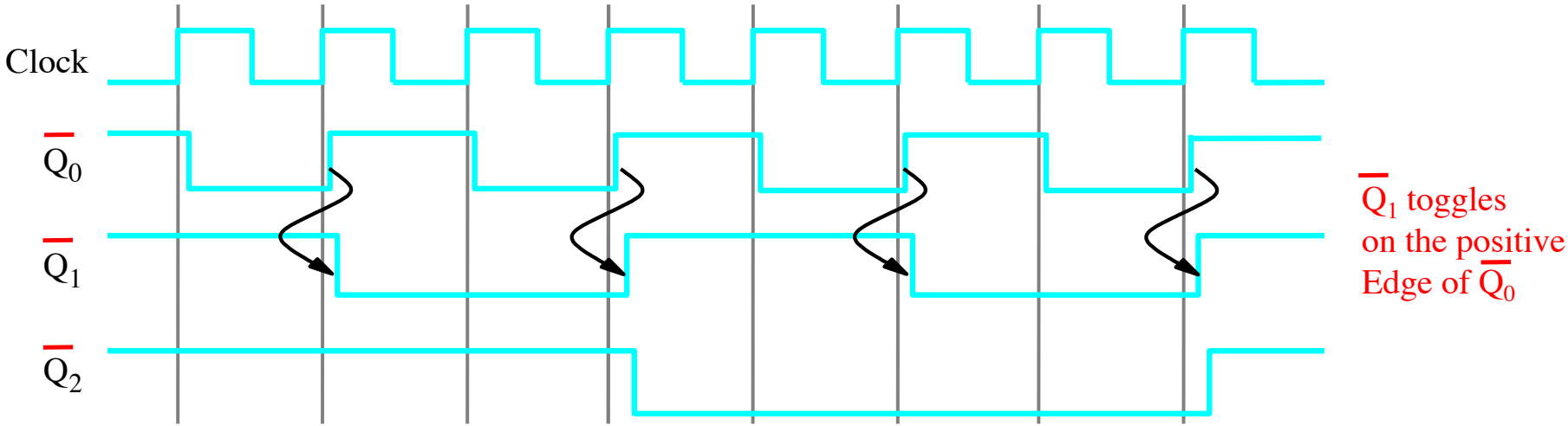


(b) Timing diagram

A three-bit up-counter

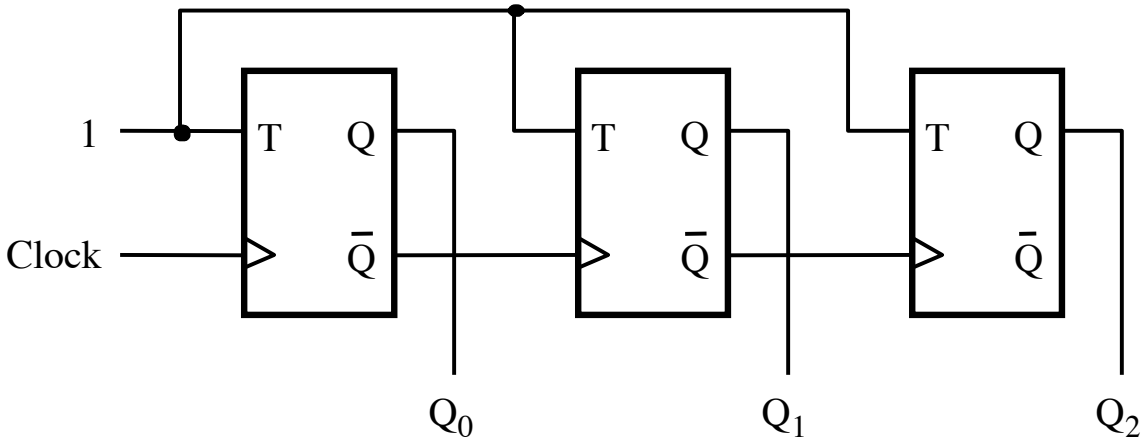


(a) Circuit

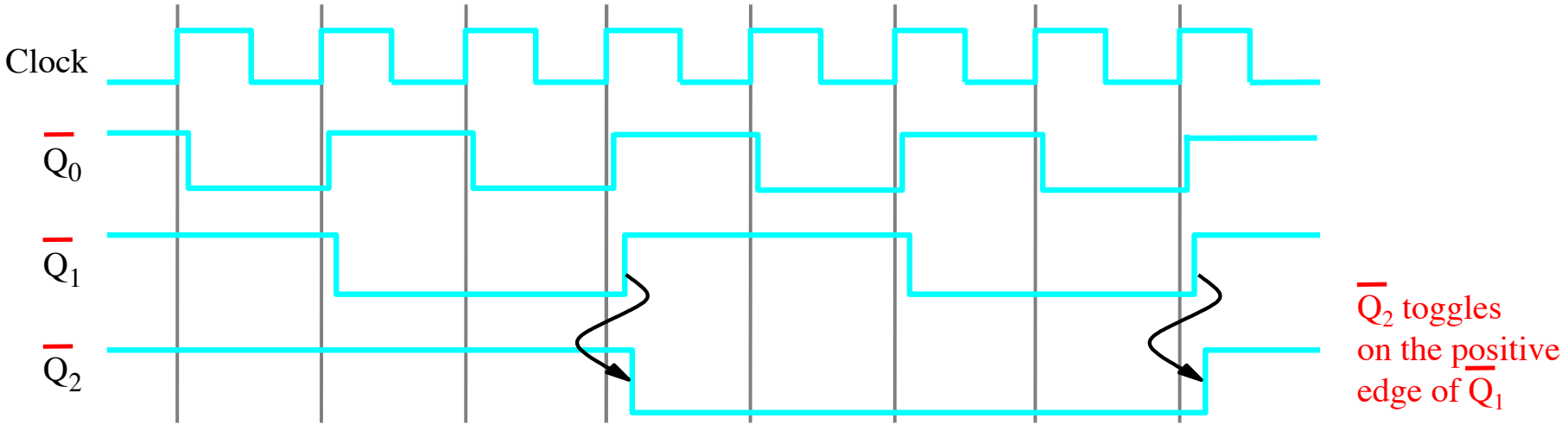


(b) Timing diagram

A three-bit up-counter

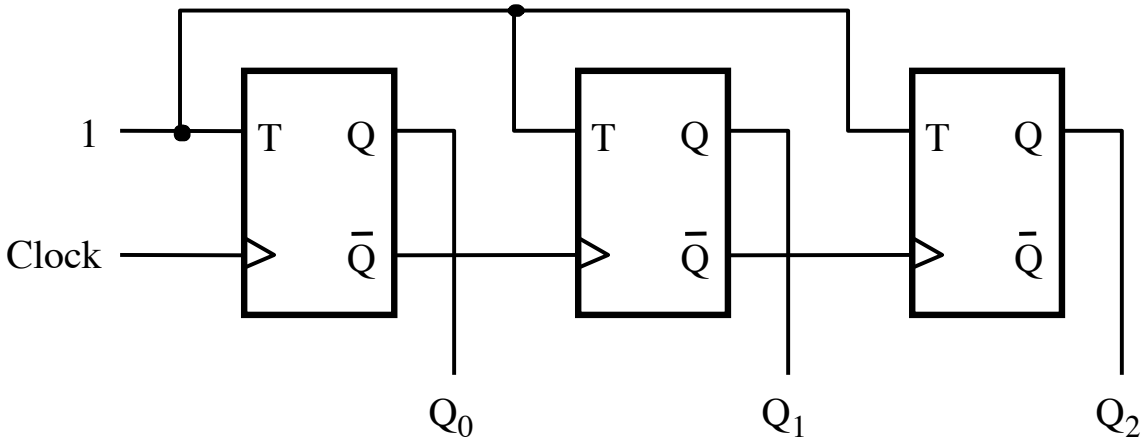


(a) Circuit



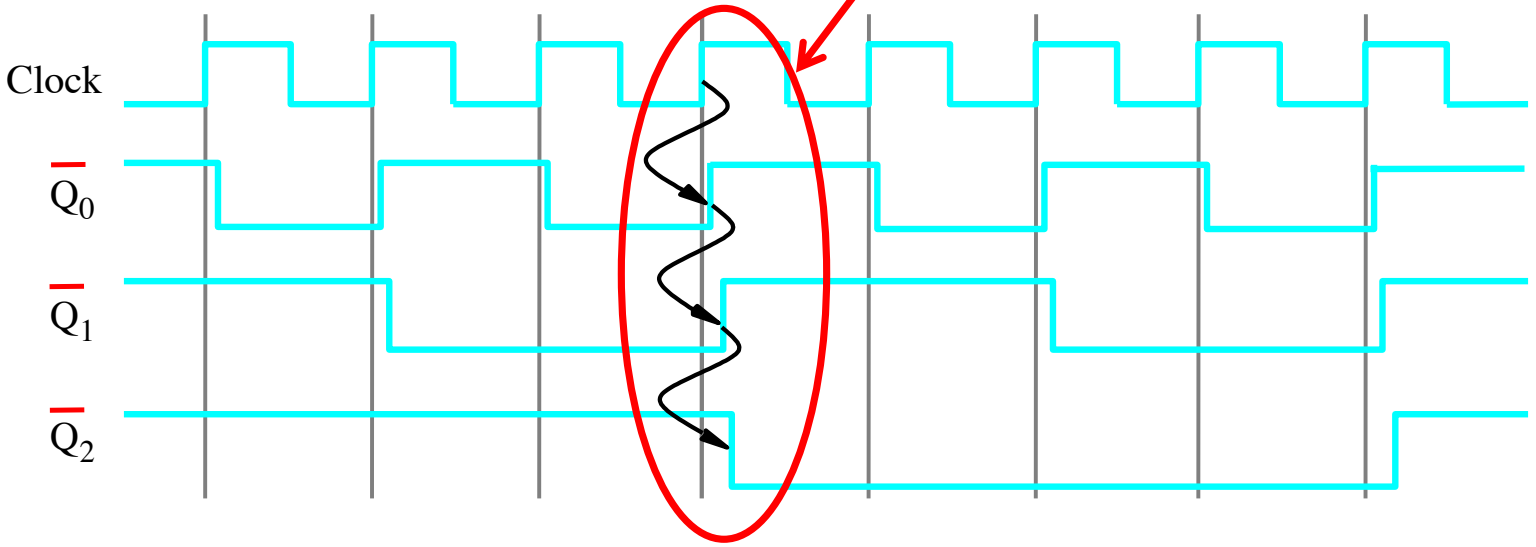
(b) Timing diagram

A three-bit up-counter



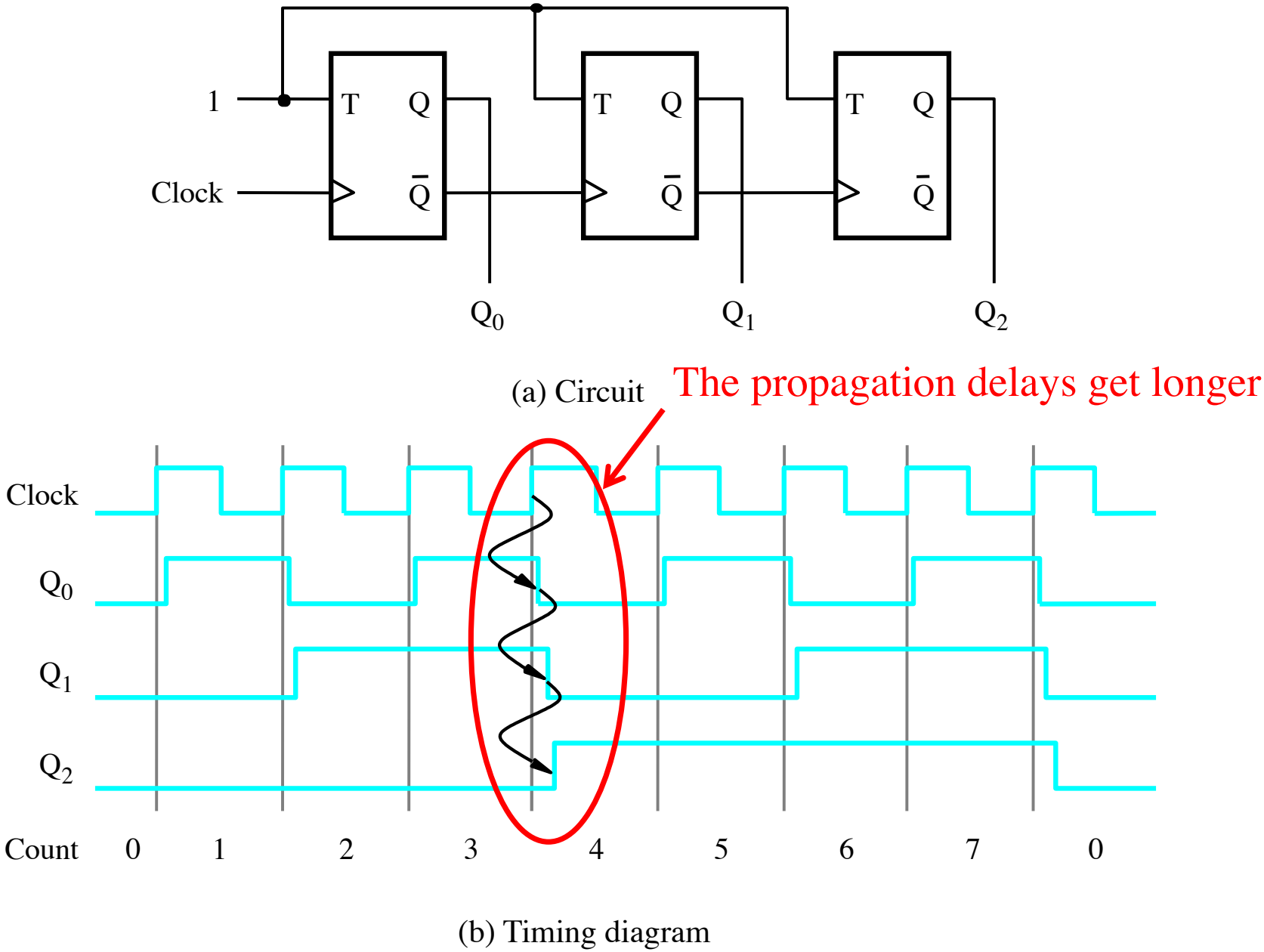
(a) Circuit

The propagation delays get longer



(b) Timing diagram

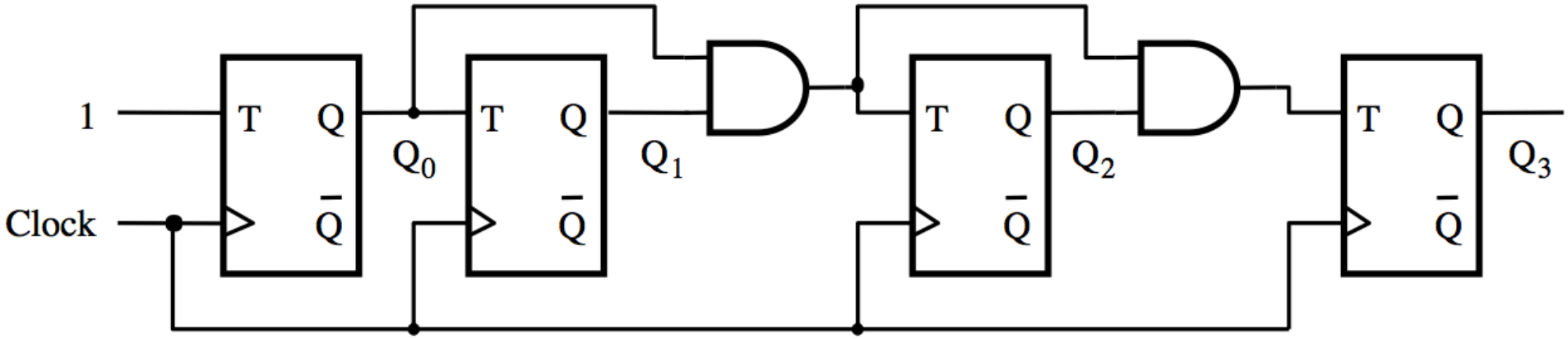
A three-bit up-counter



[Figure 5.19 from the textbook]

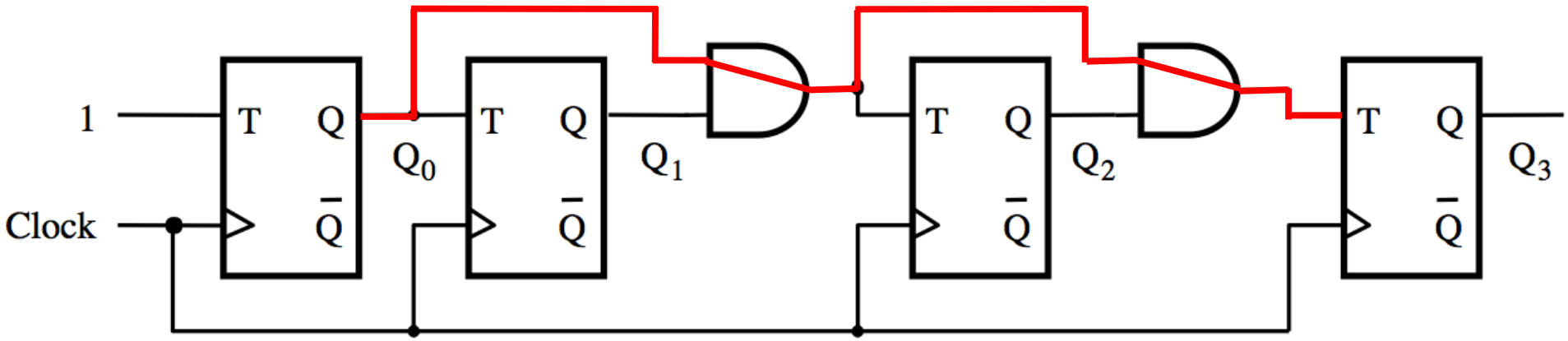
Synchronous Counters

A four-bit synchronous up-counter



[Figure 5.21 from the textbook]

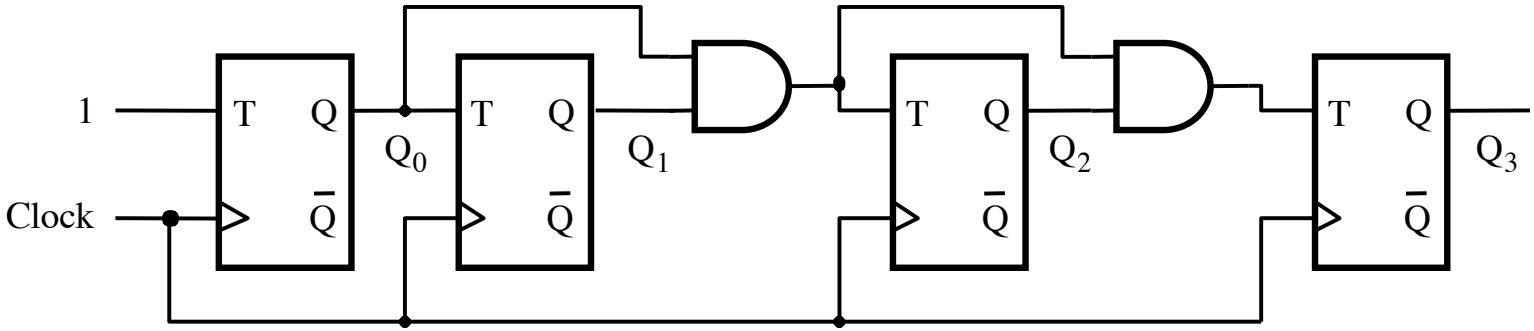
A four-bit synchronous up-counter



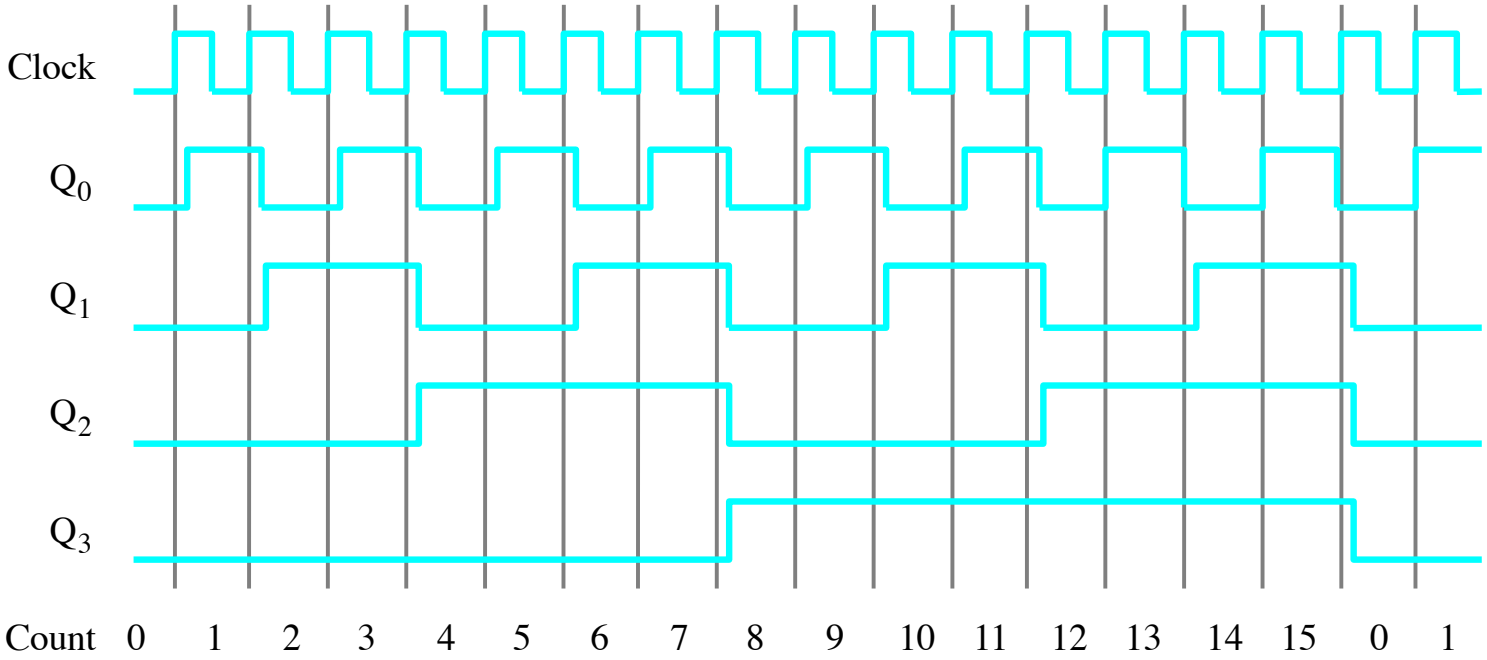
The propagation delay through all AND gates combined must not exceed the clock period minus the setup time for the flip-flops

[Figure 5.21 from the textbook]

A four-bit synchronous up-counter



(a) Circuit

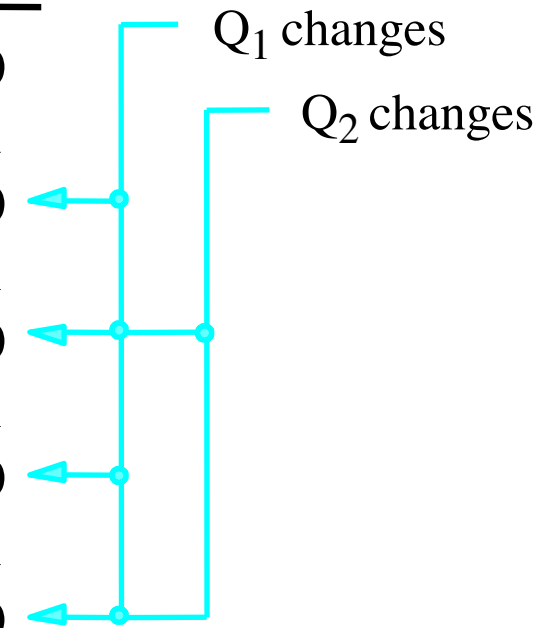


(b) Timing diagram

[Figure 5.21 from the textbook]

Derivation of the synchronous up-counter

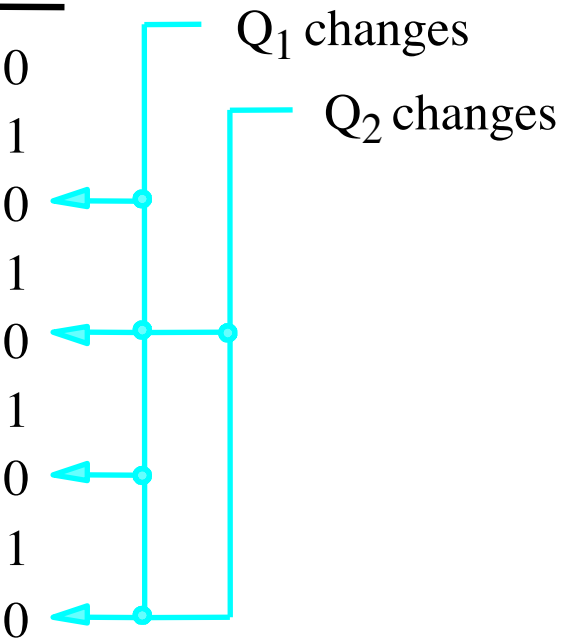
Clock cycle	Q_2	Q_1	Q_0
0	0	0	0
1	0	0	1
2	0	1	0
3	0	1	1
4	1	0	0
5	1	0	1
6	1	1	0
7	1	1	1
8	0	0	0



[Table 5.1 from the textbook]

Derivation of the synchronous up-counter

Clock cycle	Q_2	Q_1	Q_0
0	0	0	0
1	0	0	1
2	0	1	0
3	0	1	1
4	1	0	0
5	1	0	1
6	1	1	0
7	1	1	1
8	0	0	0



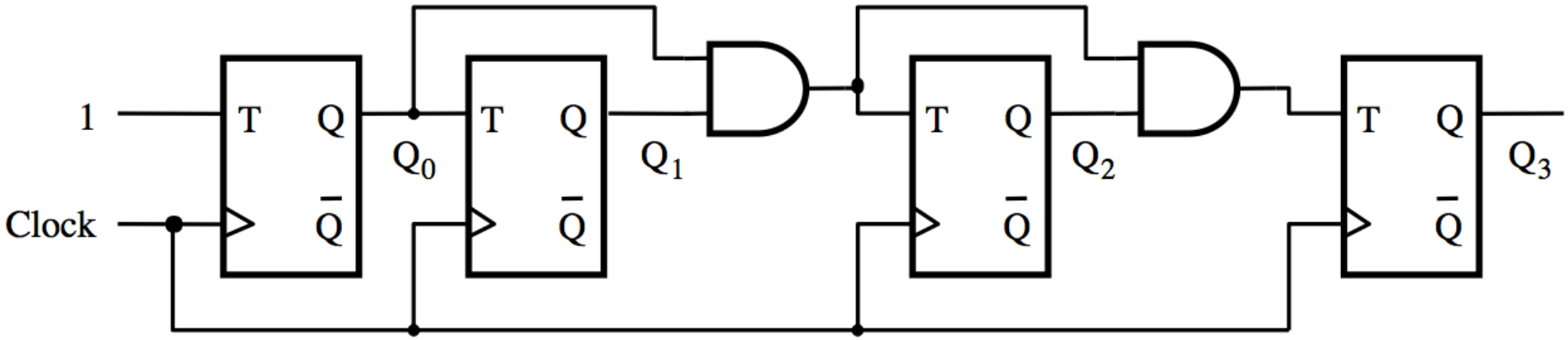
$T_0 = 1$

$T_1 = Q_0$

$T_2 = Q_0 Q_1$

[Table 5.1 from the textbook]

A four-bit synchronous up-counter



$T_0 = 1$

$T_1 = Q_0$

$T_2 = Q_0 Q_1$

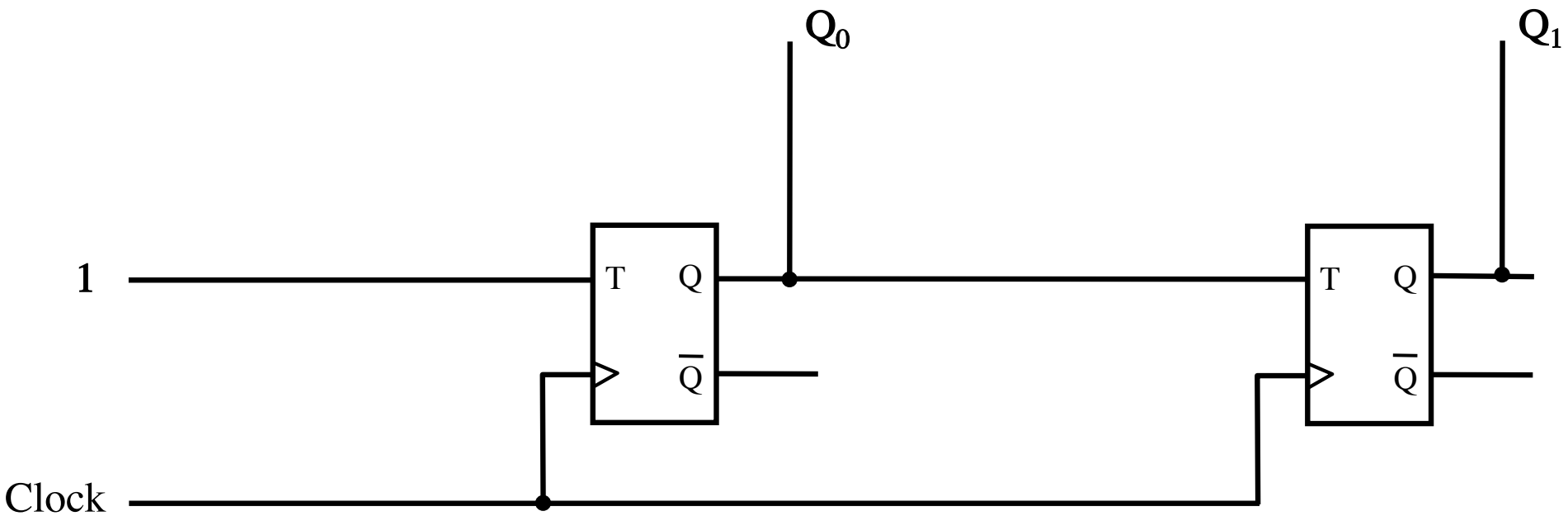
[Figure 5.21 from the textbook]

In general we have

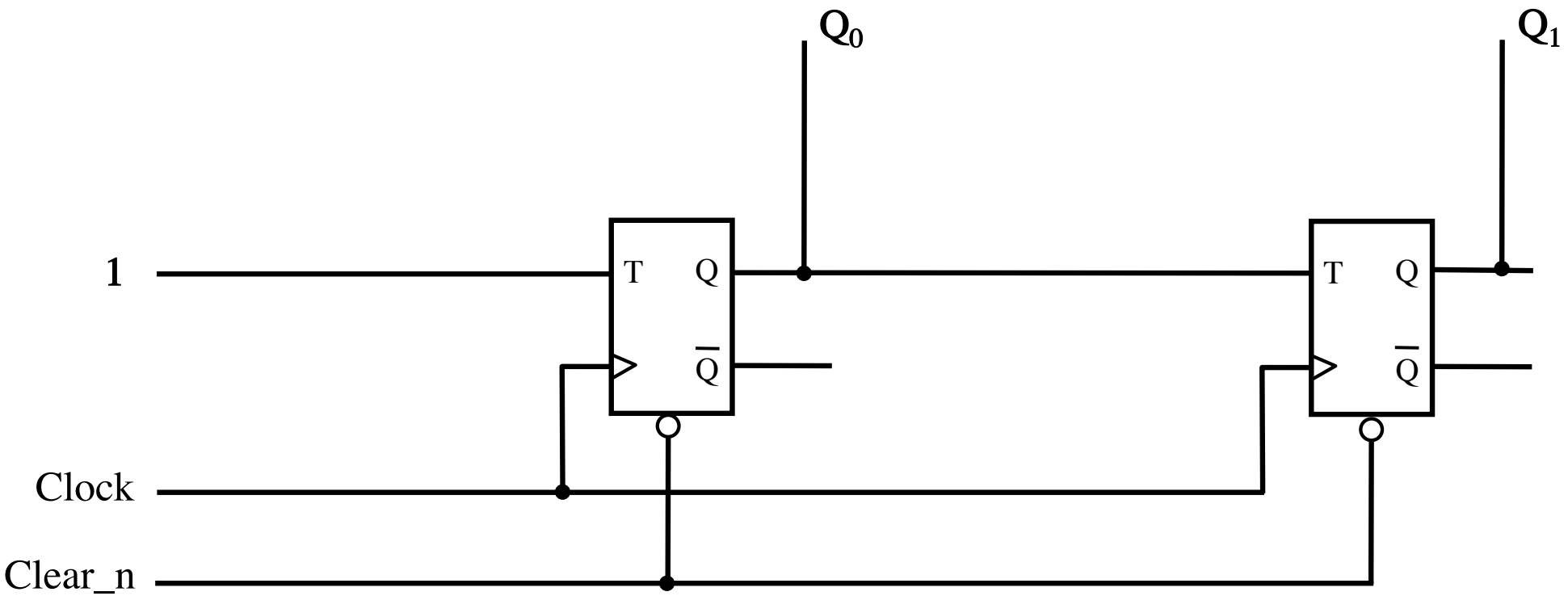
$$T_0 = 1$$
$$T_1 = Q_0$$
$$T_2 = Q_0\, Q_1$$
$$T_3 = Q_0\, Q_1\, Q_2$$
$$\dots$$
$$T_n = Q_0\, Q_1\, Q_2 \dots Q_{n-1}$$

Synchronous v.s. Asynchronous Clear

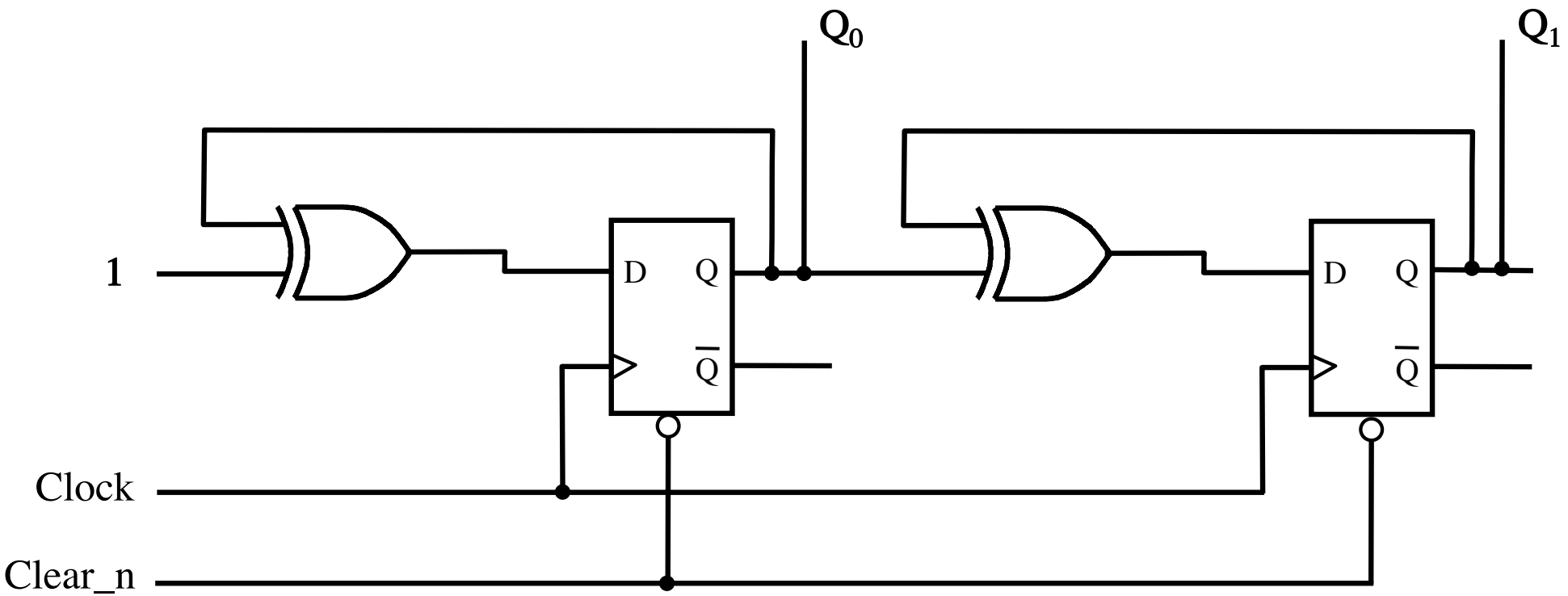
2-Bit Synchronous Up-Counter (without clear capability)



2-Bit Synchronous Up-Counter (with asynchronous clear)

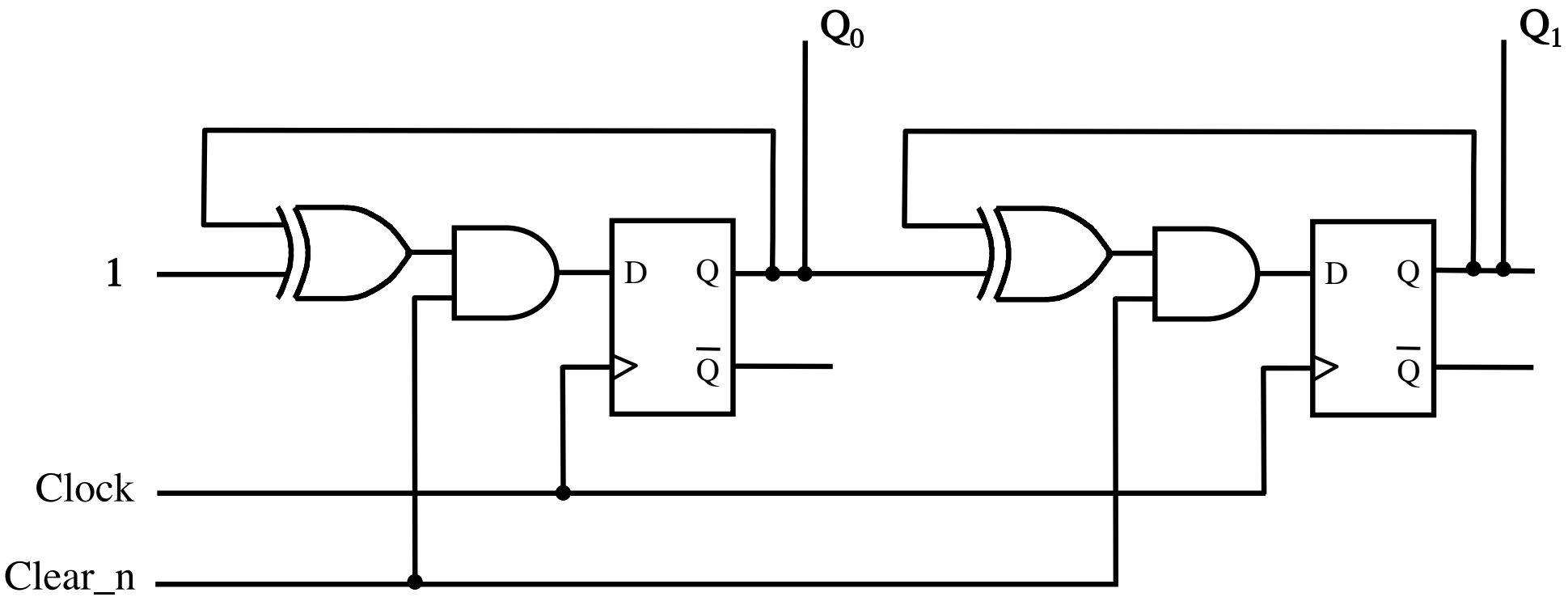


2-Bit Synchronous Up-Counter (with asynchronous clear)



This is the same circuit but uses D Flip-Flops.

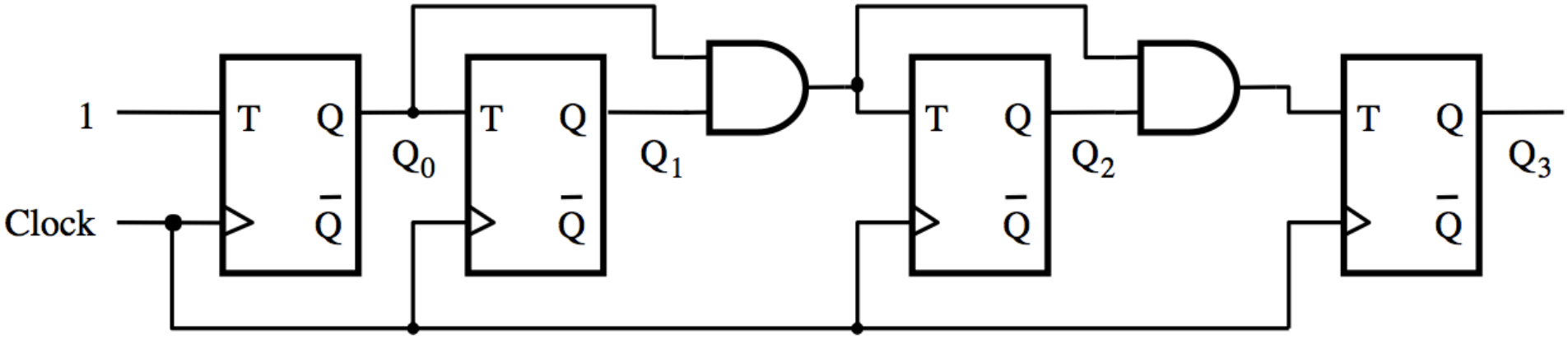
2-Bit Synchronous Up-Counter (with synchronous clear)



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

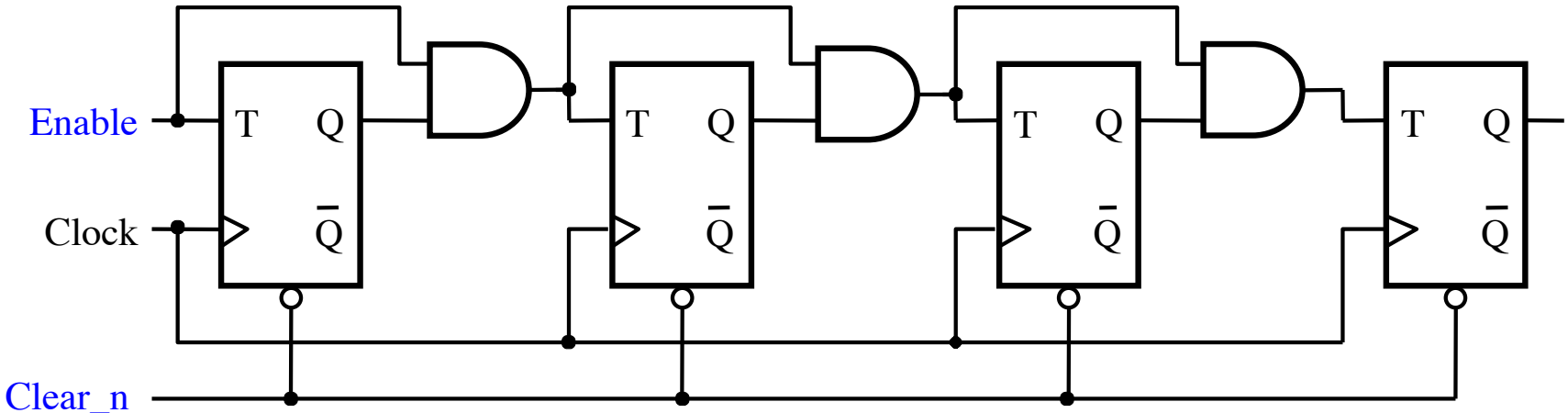
Adding Enable Capability

A four-bit synchronous up-counter



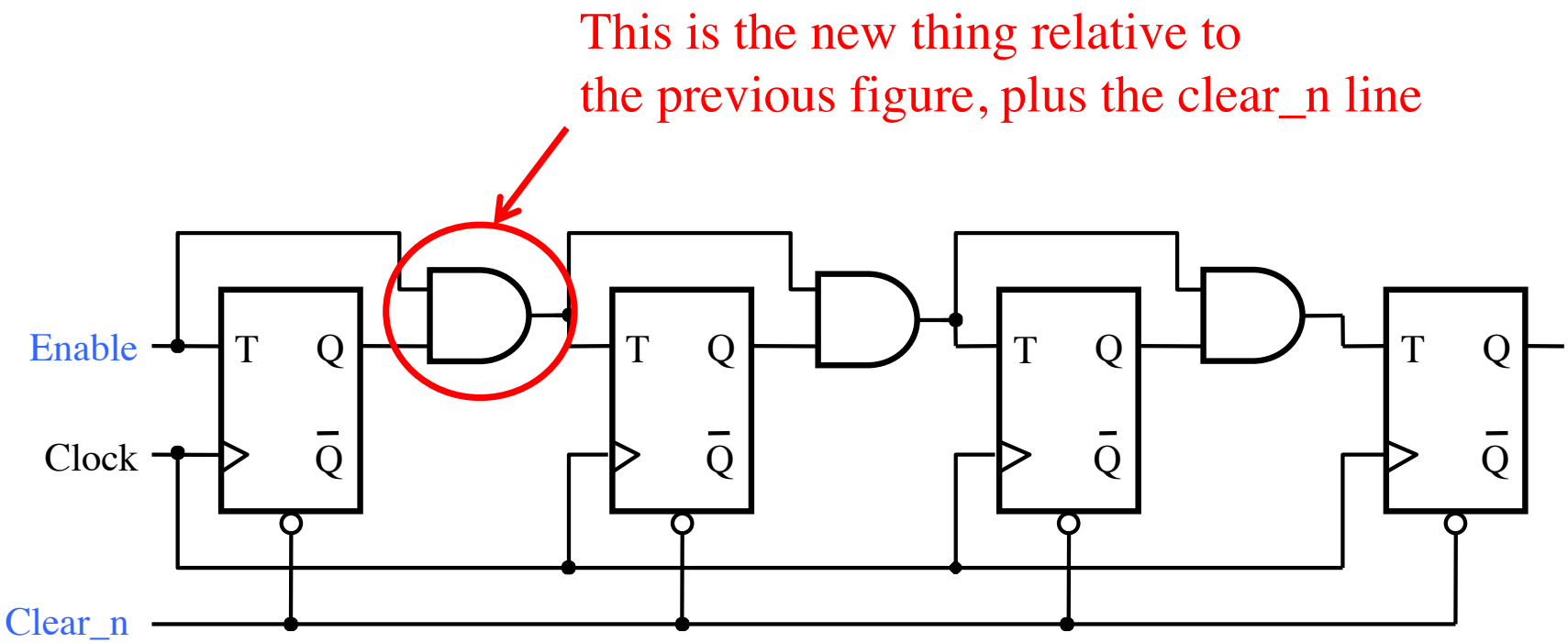
[Figure 5.21 from the textbook]

Inclusion of Enable and Clear Capability



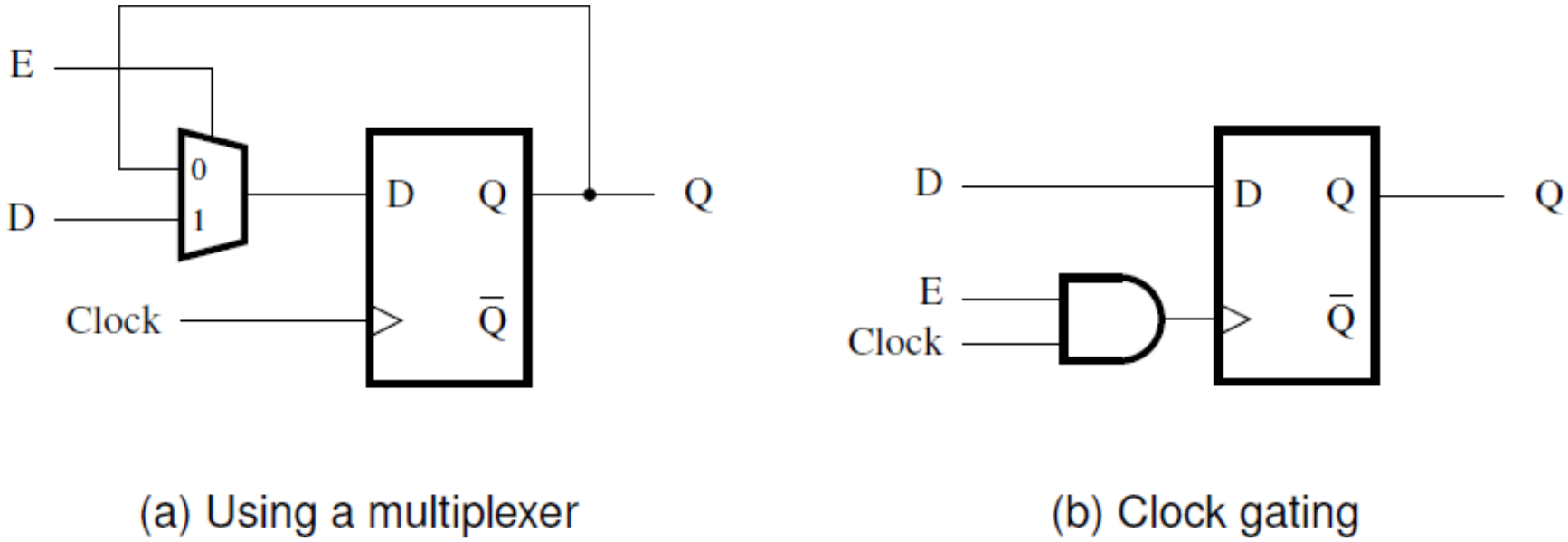
[Figure 5.22 from the textbook]

Inclusion of Enable and Clear Capability



[Figure 5.22 from the textbook]

Providing an enable input for a D flip-flop



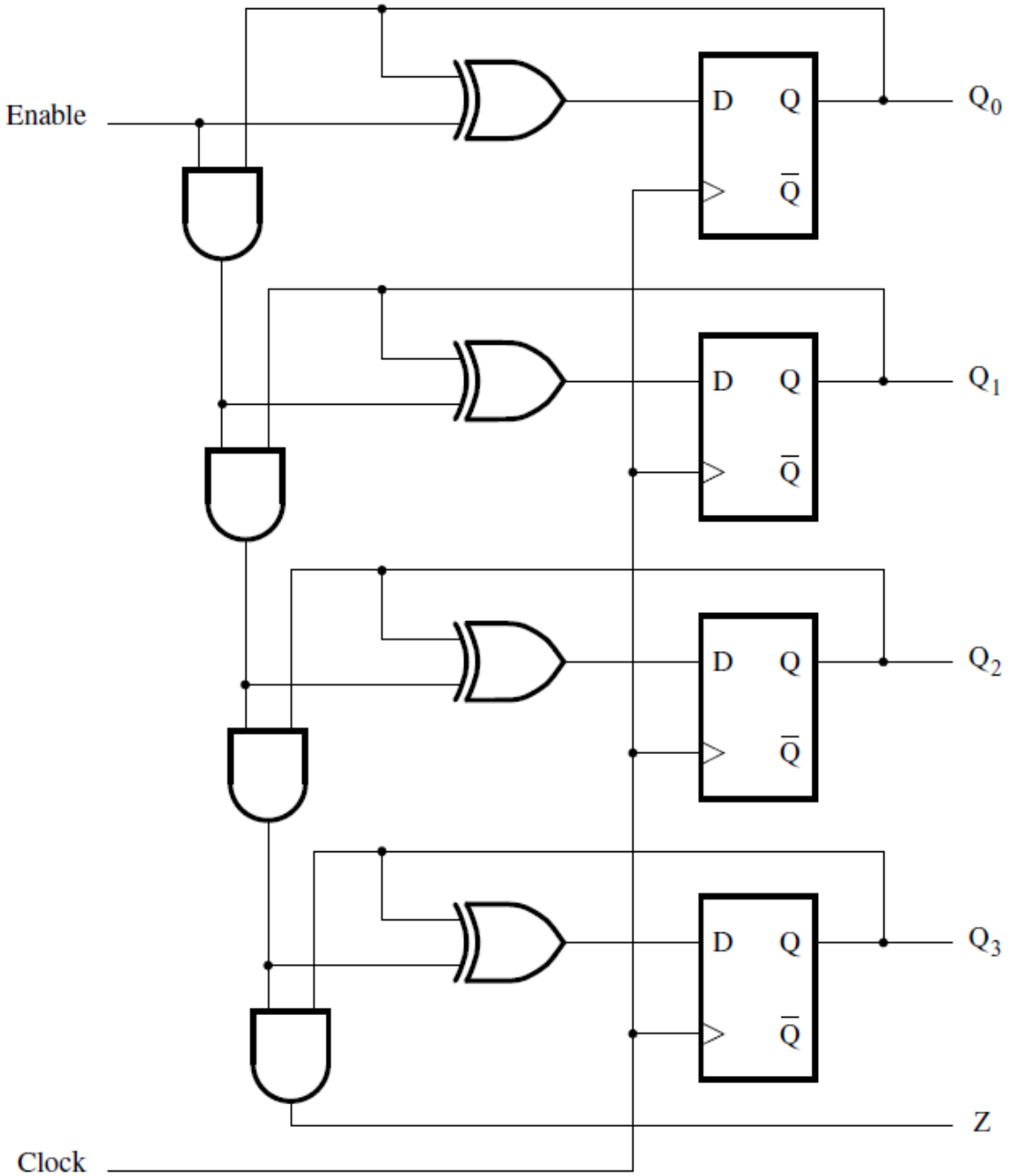
(a) Using a multiplexer

(b) Clock gating

[Figure 5.56 from the textbook]

Synchronous Counter (with D Flip-Flops)

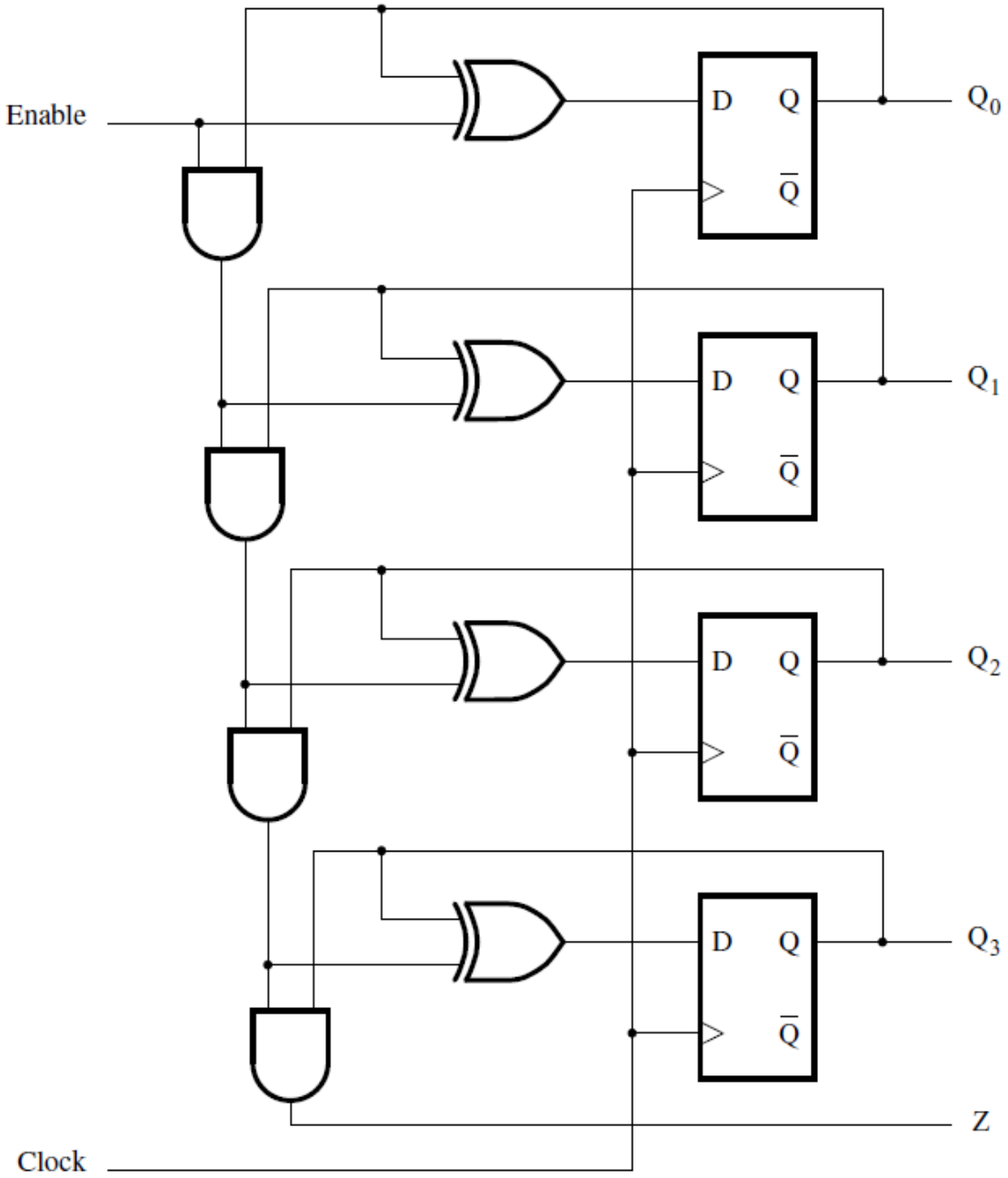
A four-bit counter with D flip-flops



[Figure 5.23 from the textbook]

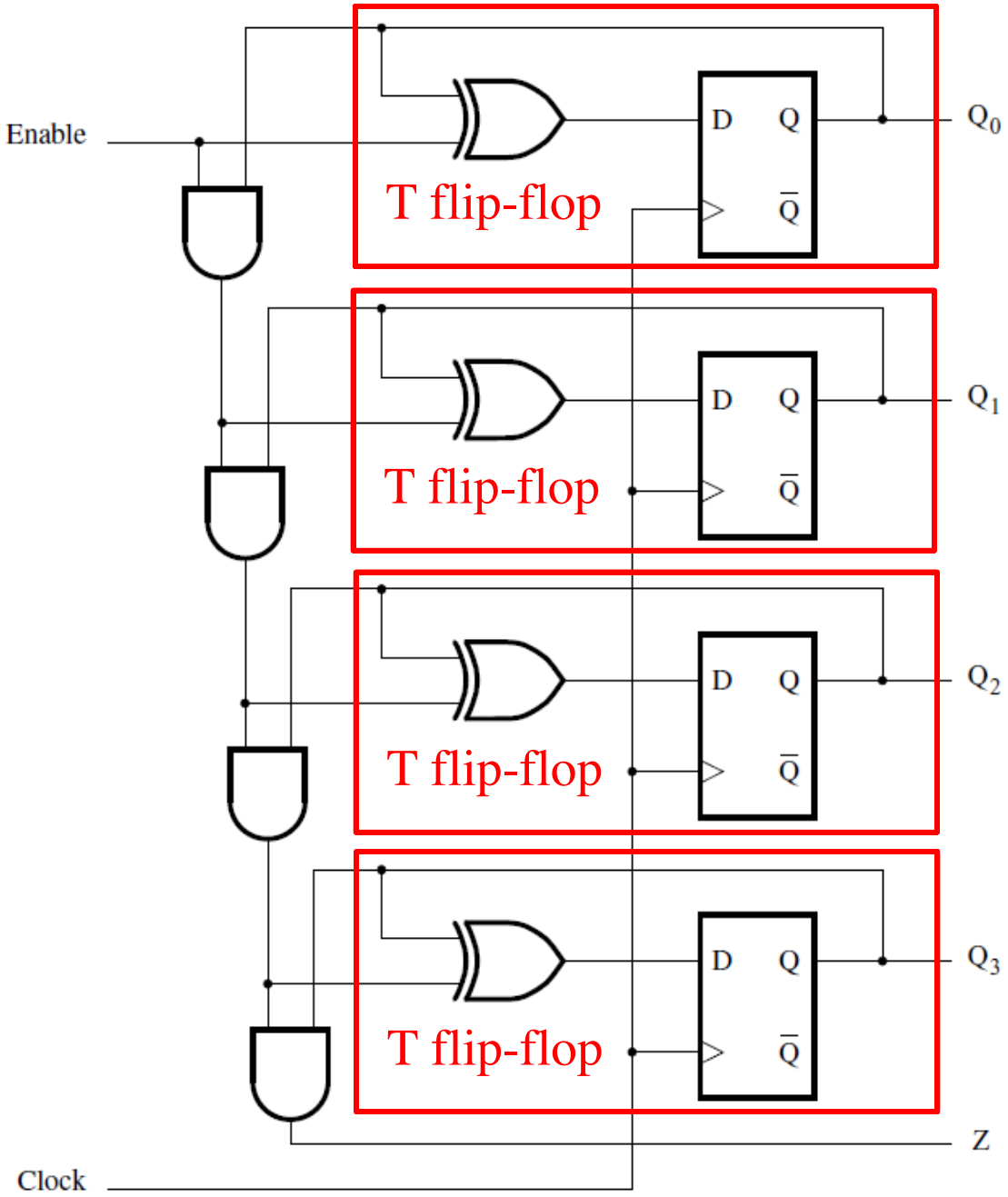
Counters with Parallel Load

A 4-bit up-counter with D flip-flops



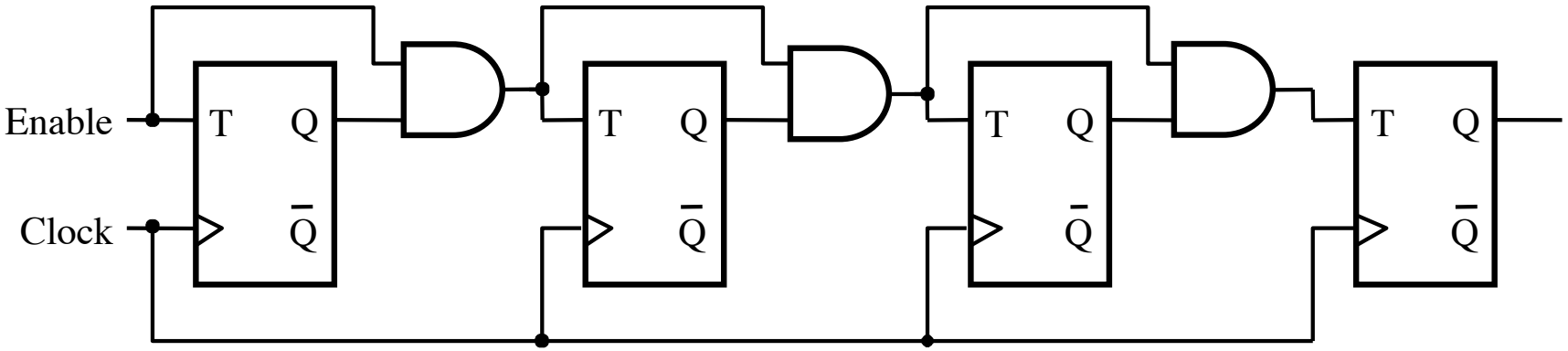
[Figure 5.23 from the textbook]

A 4-bit up-counter with D flip-flops

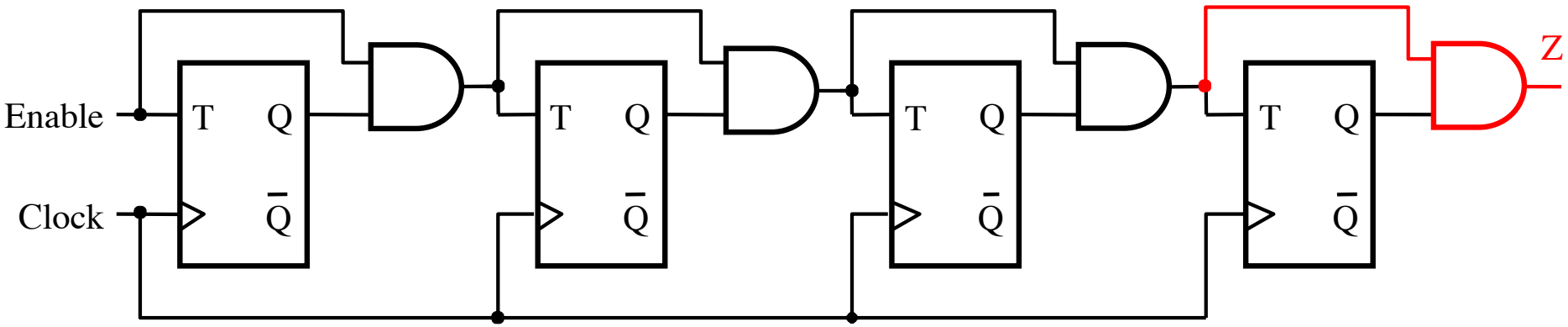


[Figure 5.23 from the textbook]

Equivalent to this circuit with T flip-flops



Equivalent to this circuit with T flip-flops

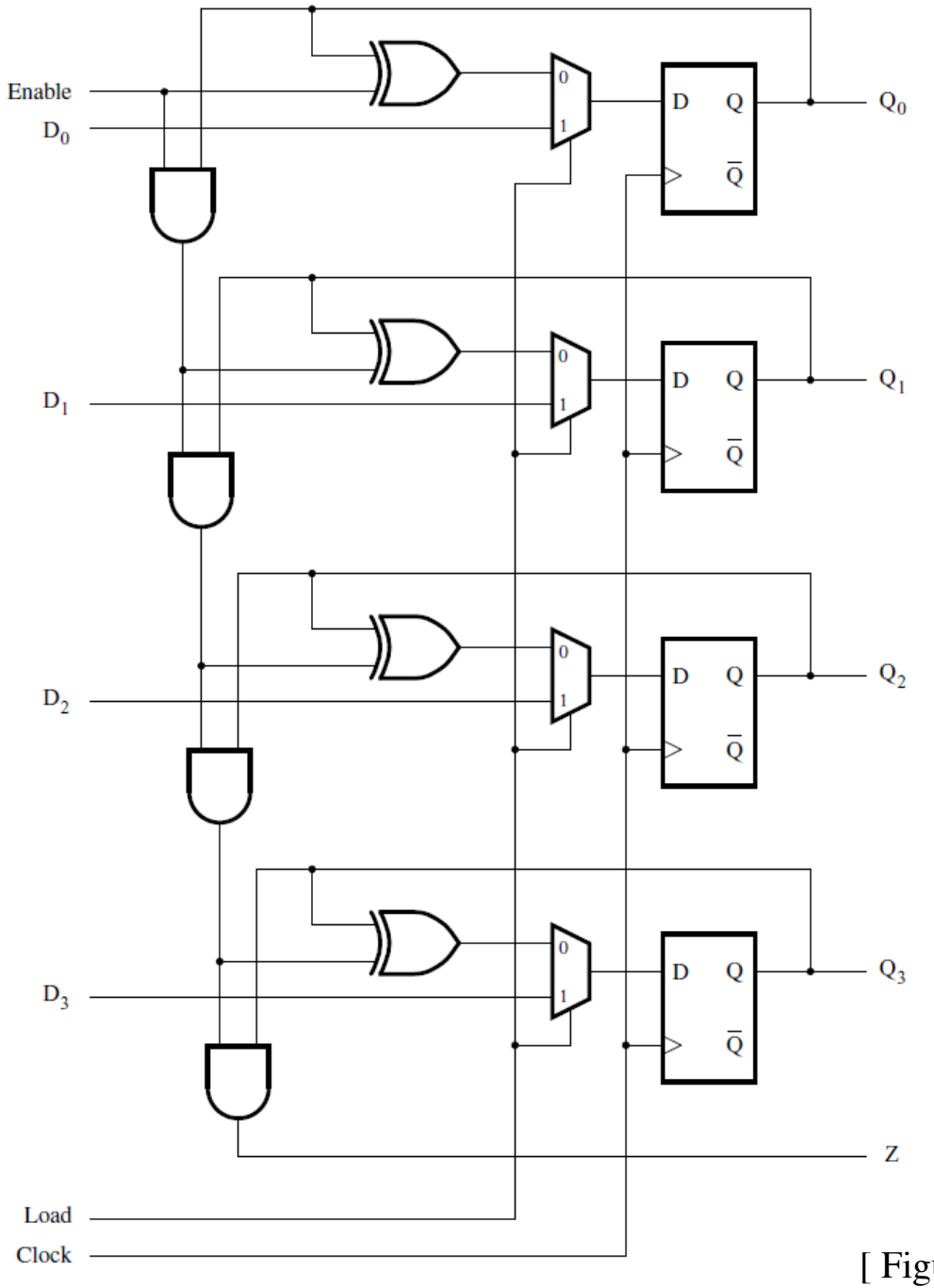


But has one extra output called Z, which can be used to connect two 4-bit counters to make an 8-bit counter.

When Z=1 the counter will go 0000 on the next clock edge, i.e., the outputs of all flip-flops are currently 1 (maximum count value).

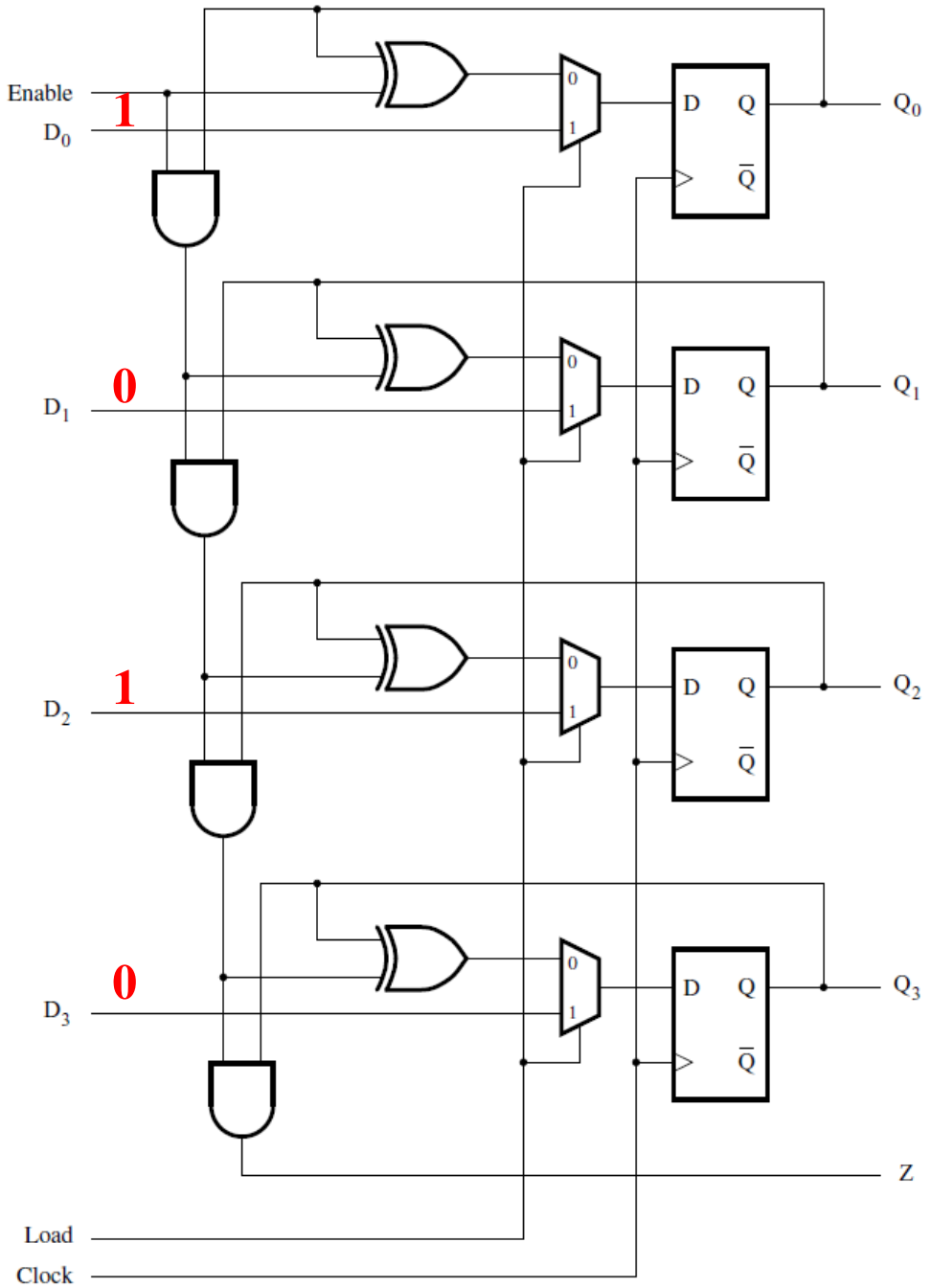
Counters with Parallel Load

A counter with parallel-load capability



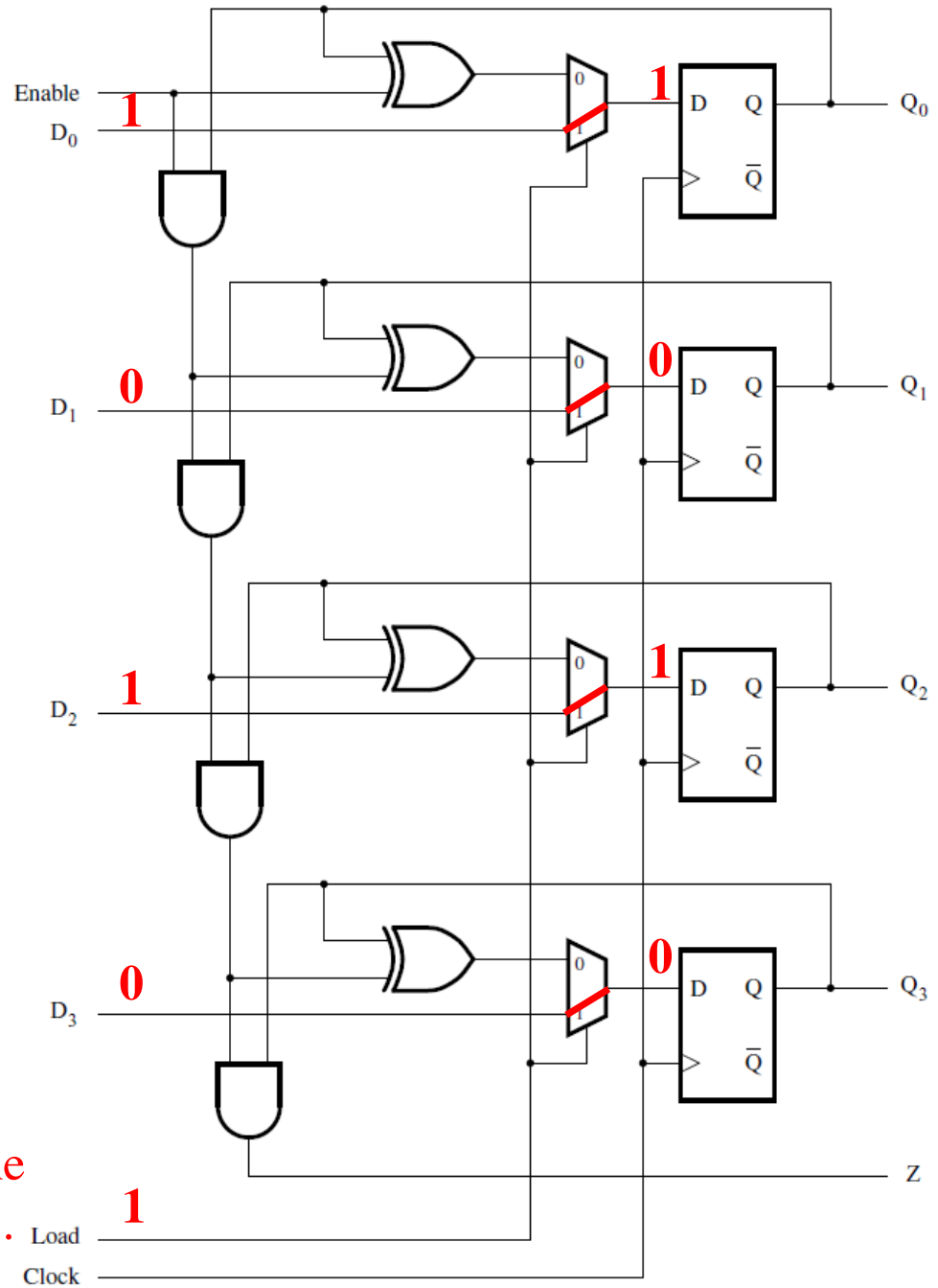
[Figure 5.24 from the textbook]

How to load the initial count value



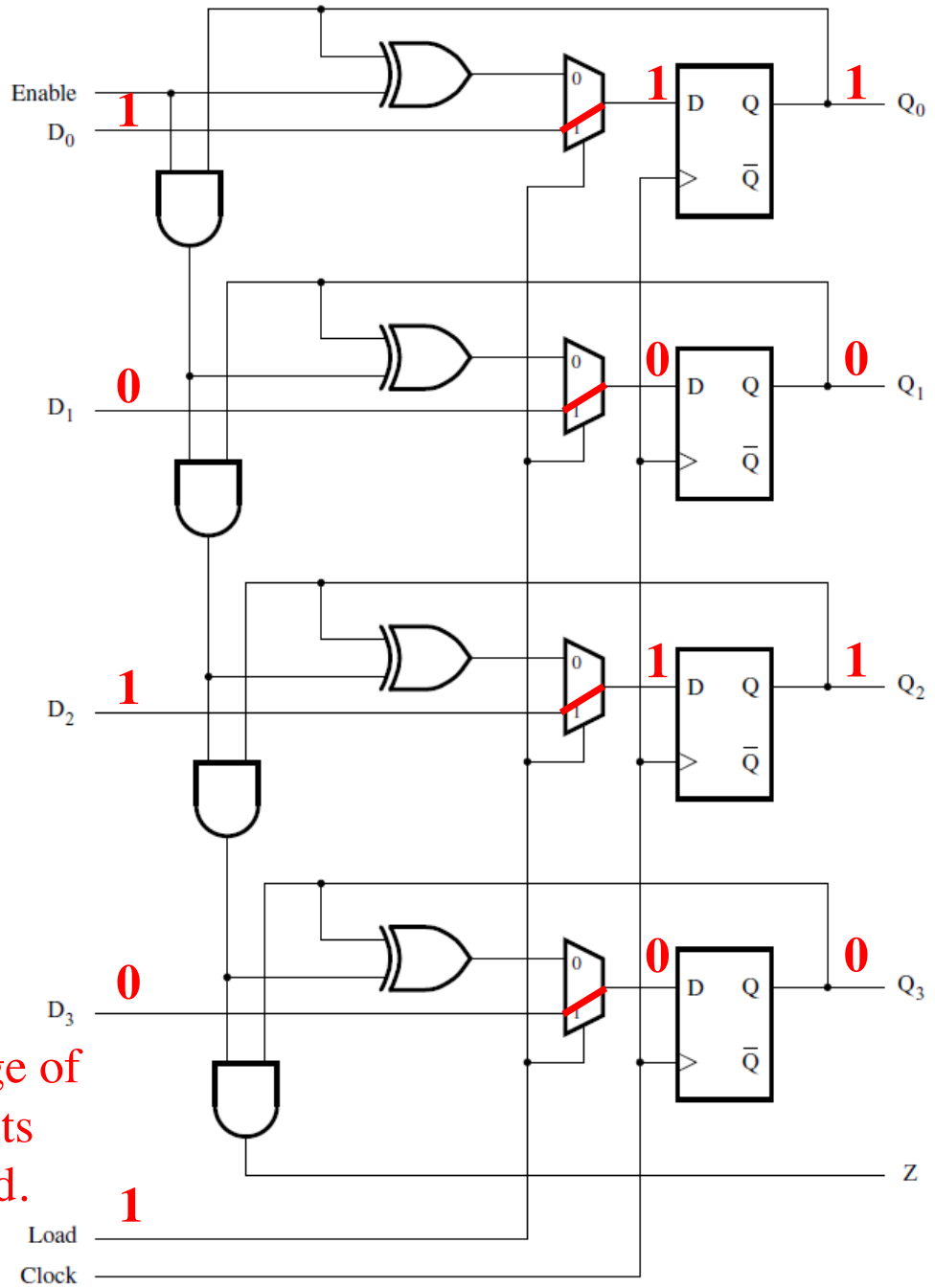
Set the initial count on the parallel load lines (in this case 5).

How to zero a counter



Set "Load" to 1, to open the "1" line of the multiplexers.

How to zero a counter



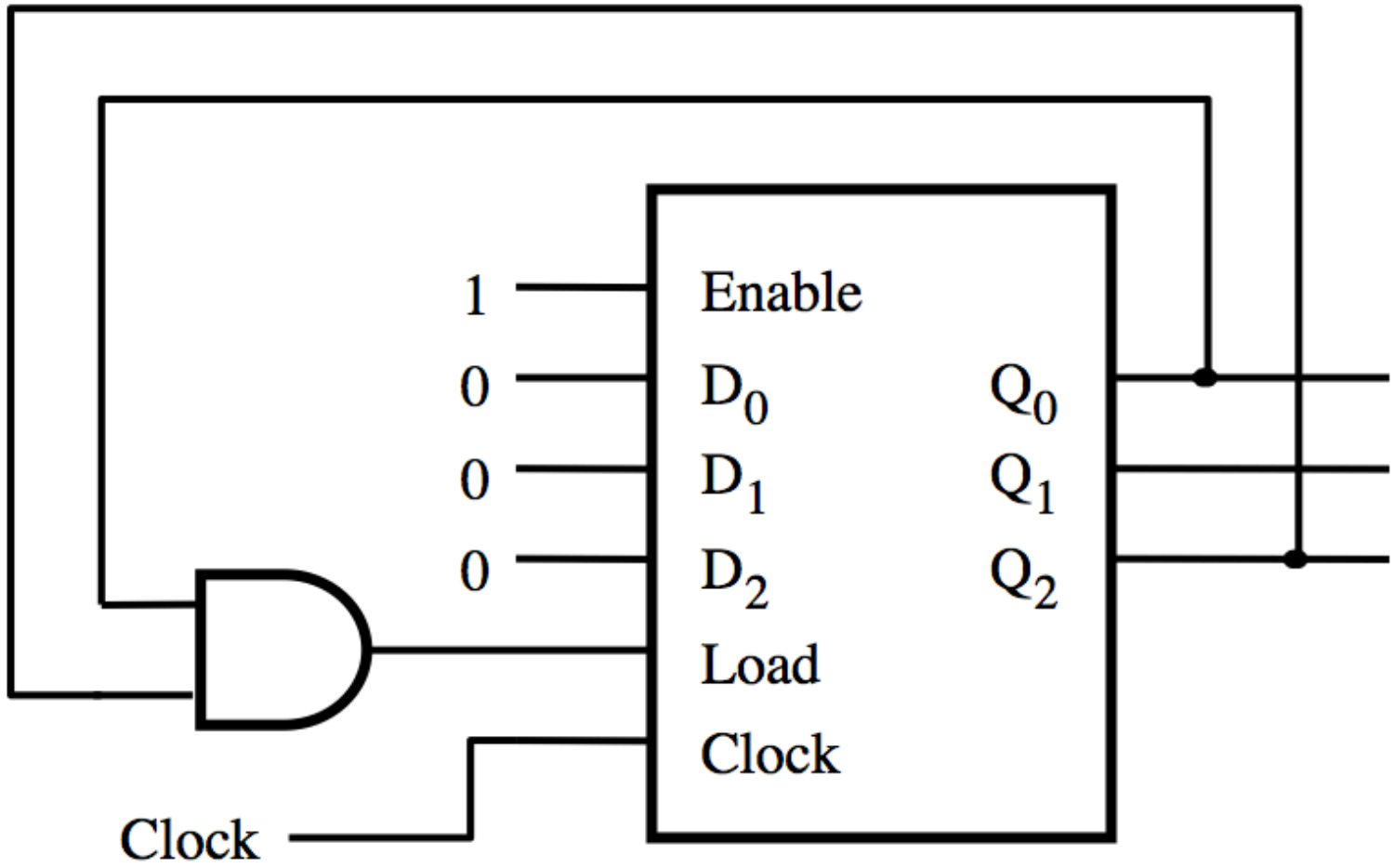
When the next positive edge of the clock arrives, the outputs of the flip-flops are updated.

Reset Synchronization

Motivation

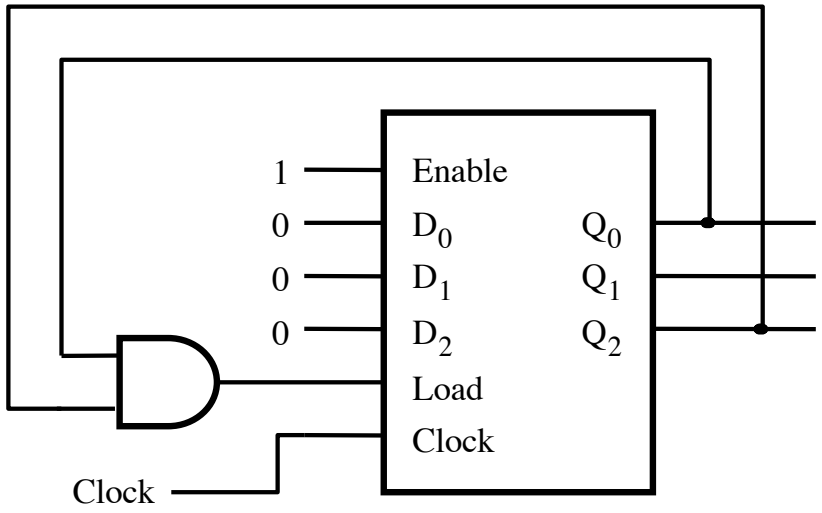
- An n-bit counter counts from 0, 1, …, 2^n-1
- For example a 3-bit counter counts up as follow
  - 0, 1, 2, 3, 4, 5, 6, 7, 0, 1, 2, …
- What if we want it to count like this
  - 0, 1, 2, 3, 4, 5, 0, 1, 2, 3, 4, 5, 0, 1, …
- In other words, what is the cycle is not a power of 2?

What does this circuit do?

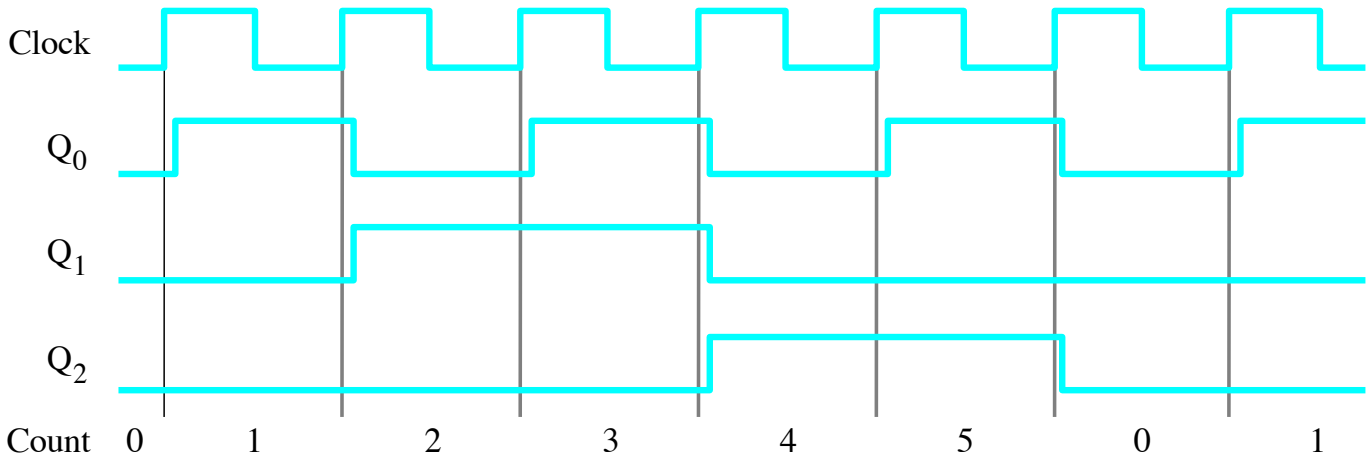


[Figure 5.25a from the textbook]

A modulo-6 counter with synchronous reset



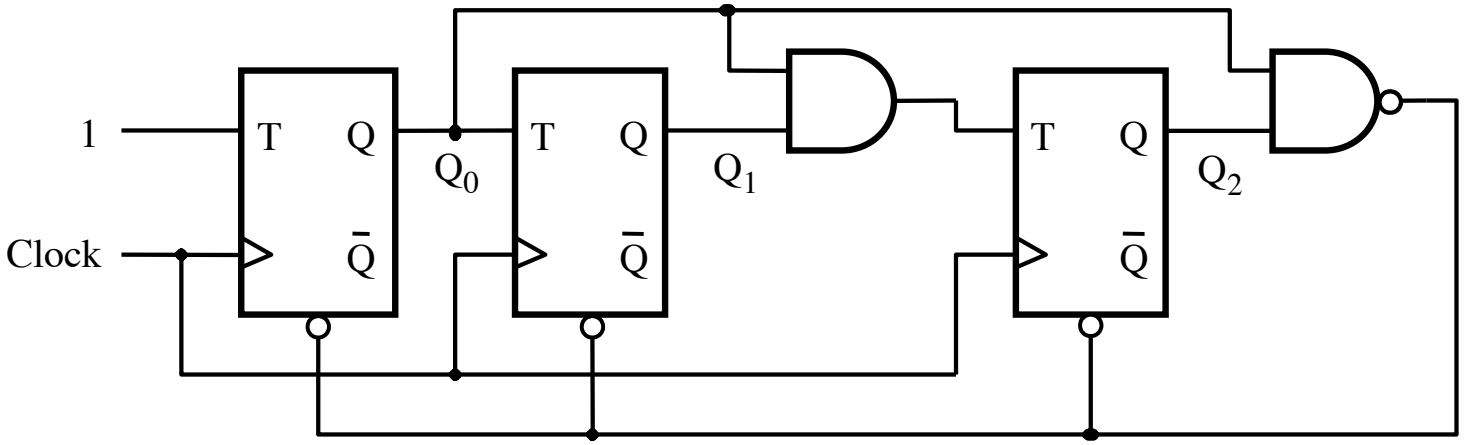
(a) Circuit



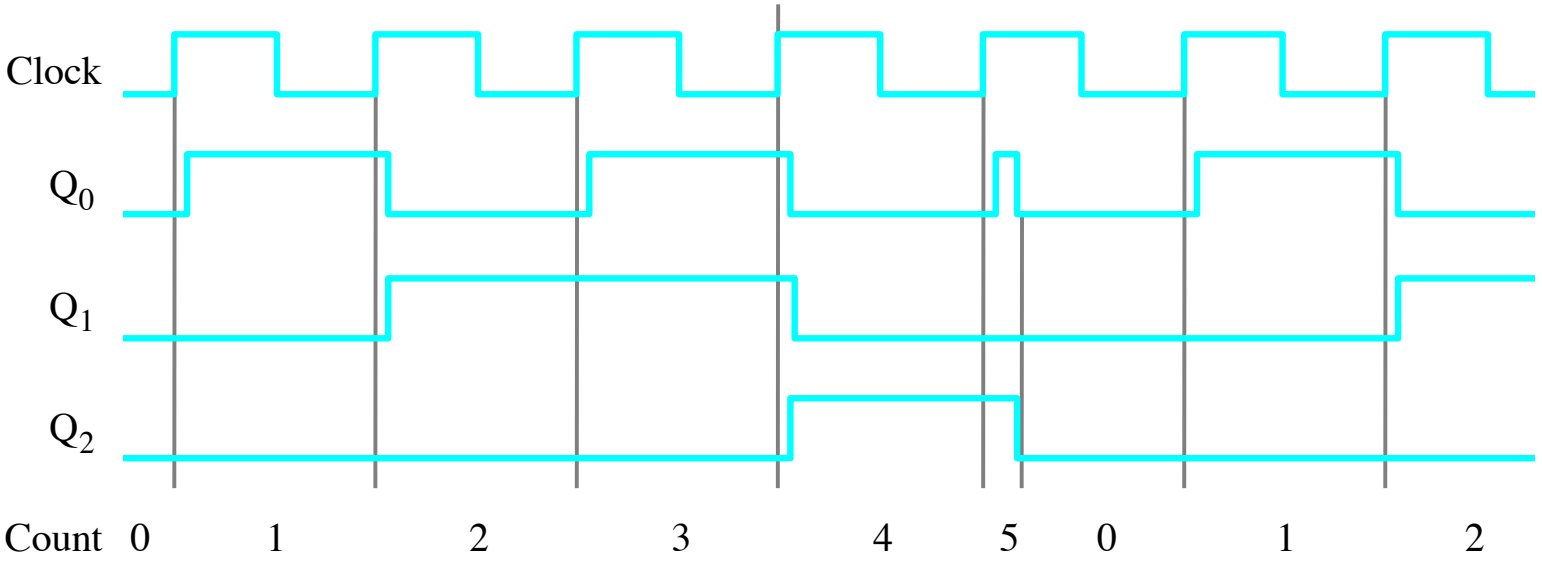
(b) Timing diagram

[Figure 5.25 from the textbook]

A modulo-6 counter with asynchronous reset



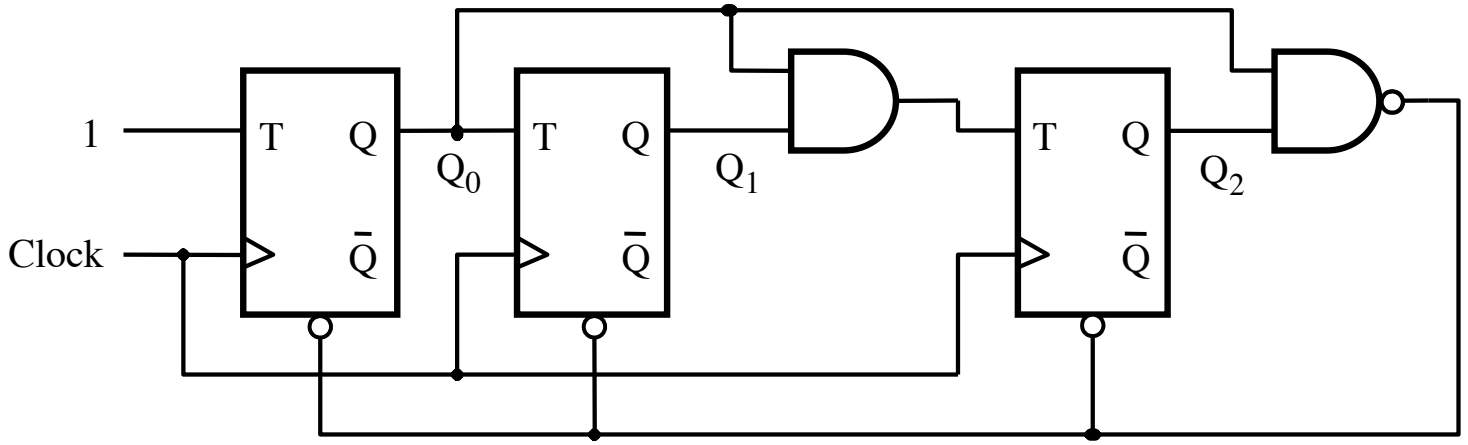
(a) Circuit



(b) Timing diagram

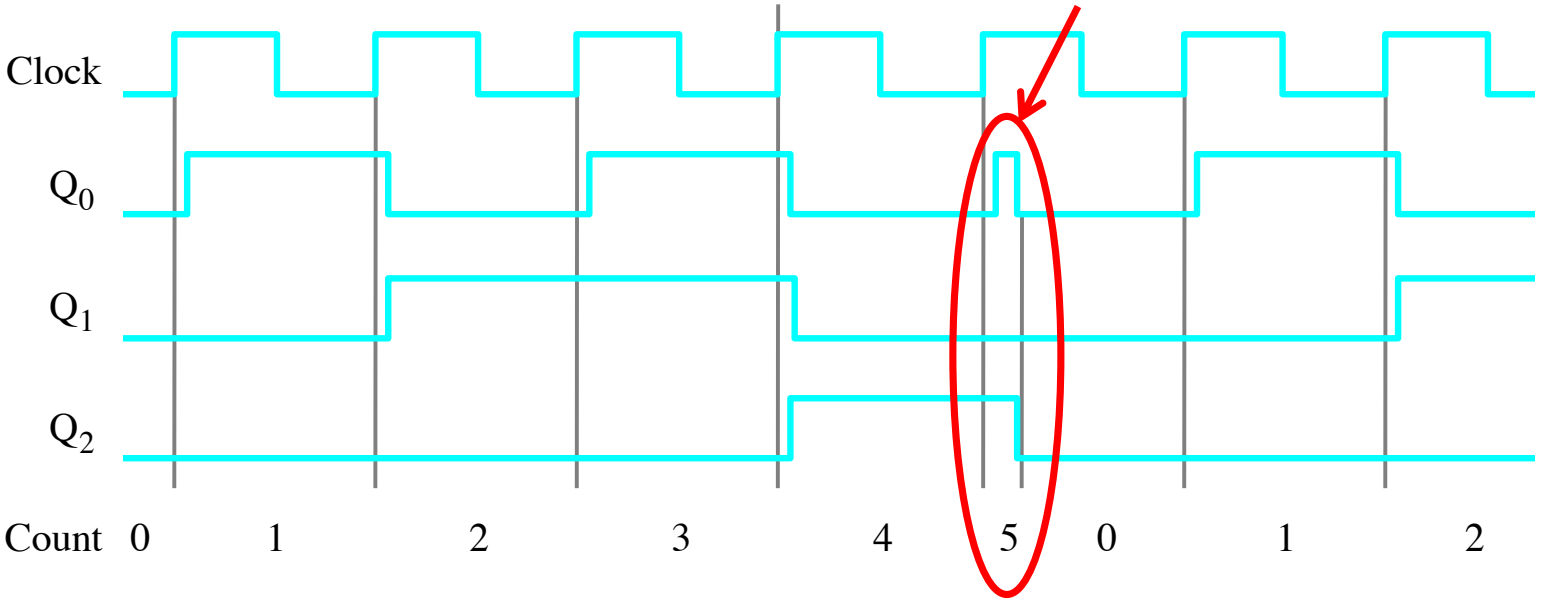
[Figure 5.26 from the textbook]

A modulo-6 counter with asynchronous reset



(a) Circuit

The number 5 is displayed for a very short amount of time



(b) Timing diagram

[Figure 5.26 from the textbook]

Questions?

THE END