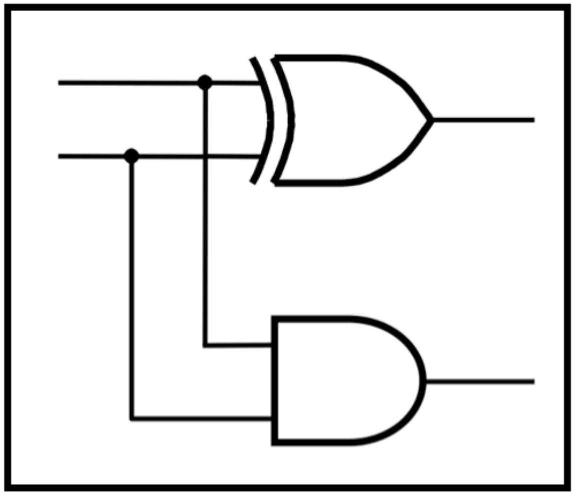


CprE 281: Digital Logic

Instructor: Alexander Stoytchev

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

Multiplication

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

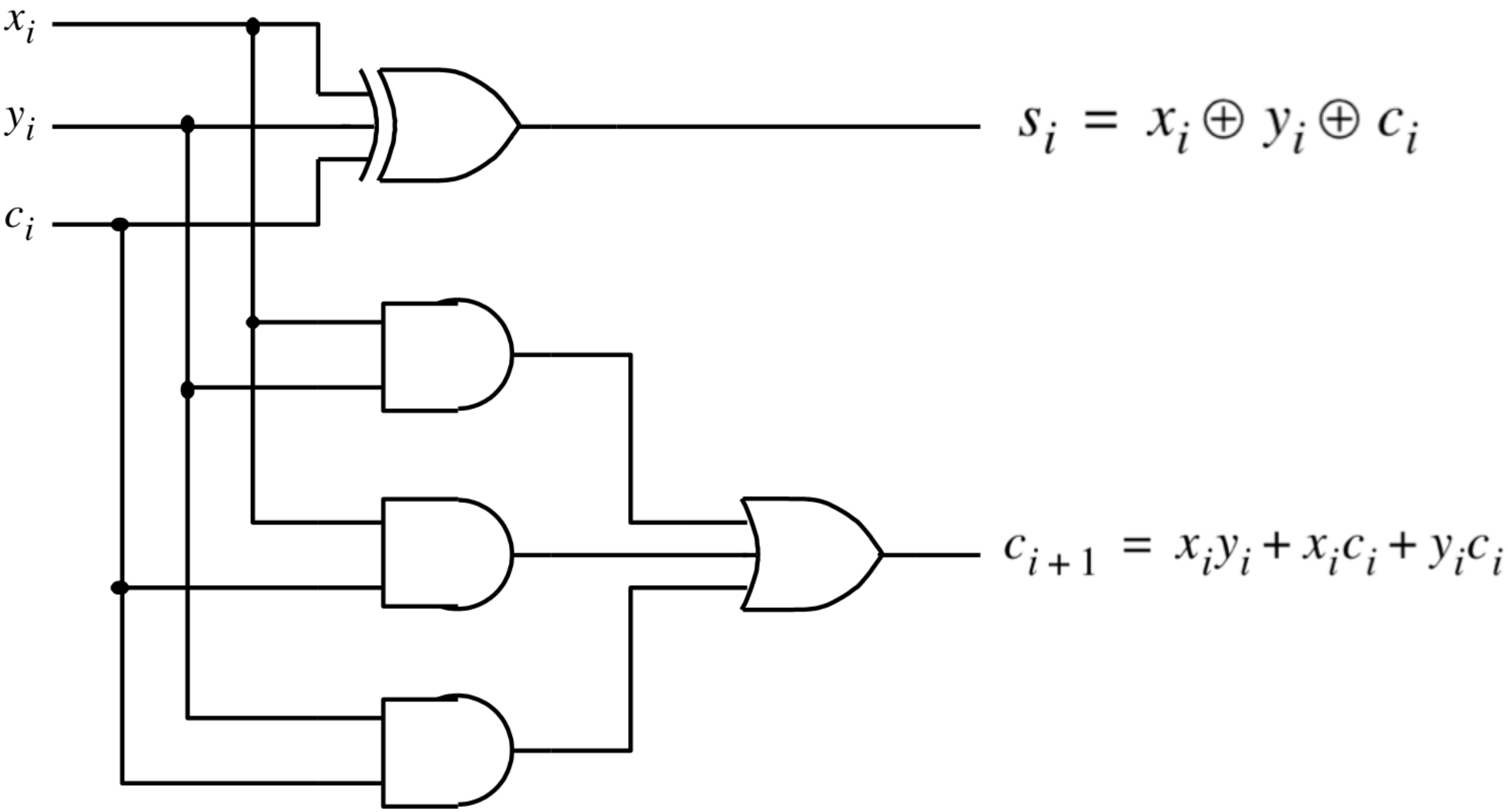
Administrative Stuff

- HW 6 is out

- It is due on Monday Oct 10 @ 4pm

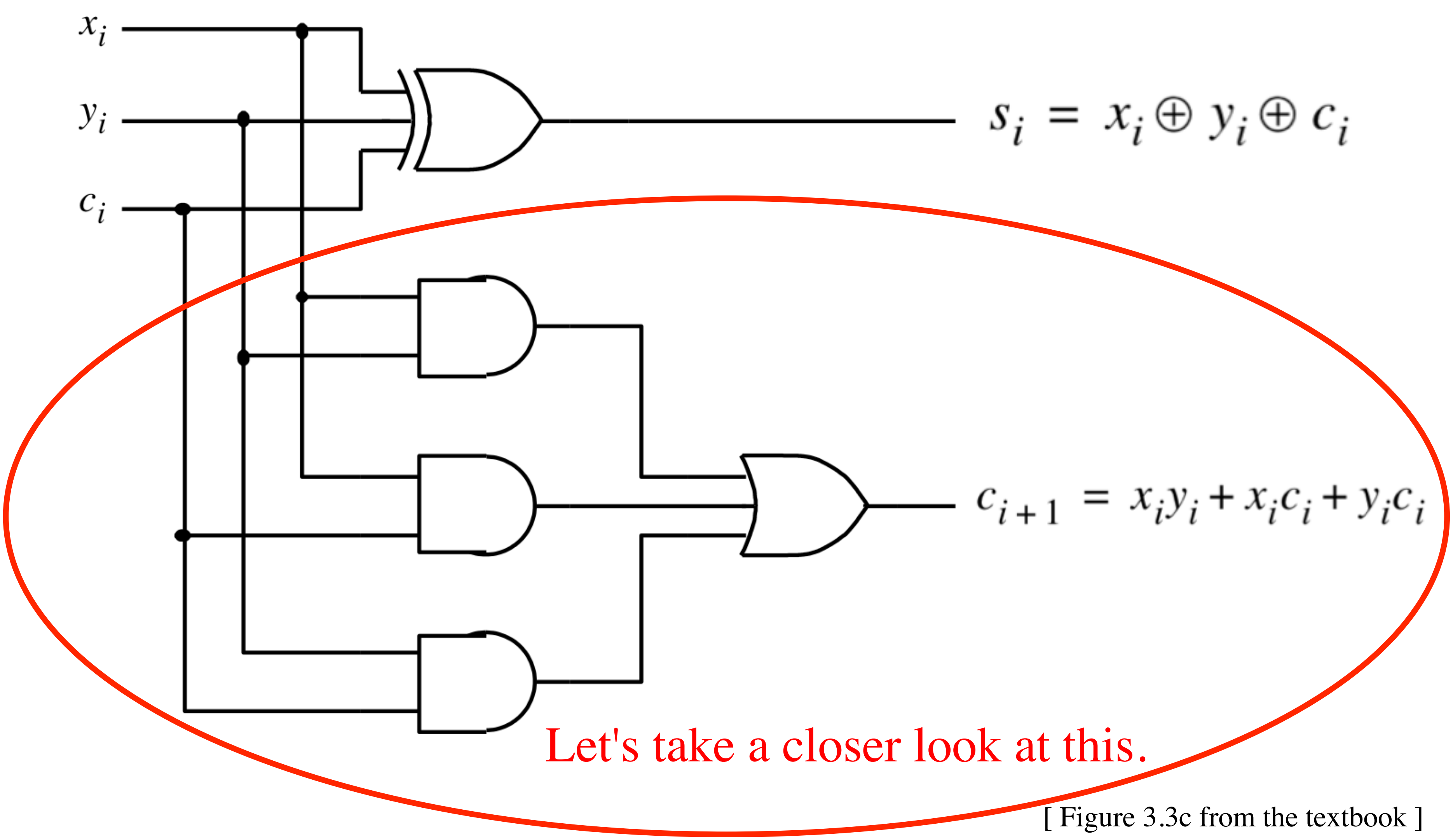
Quick Review

The Full-Adder Circuit


x_i
y_i
c_i
$s_i = x_i \oplus y_i \oplus c_i$
$c_{i+1} = x_i y_i + x_i c_i + y_i c_i$

[Figure 3.3c from the textbook]

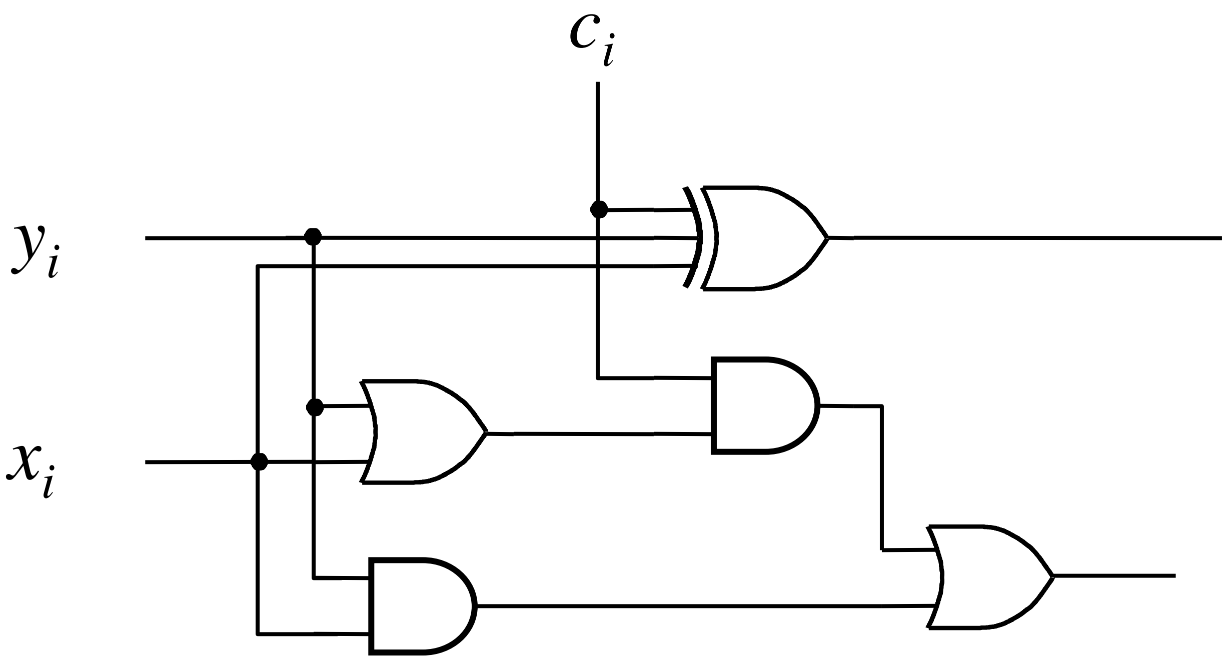
The Full-Adder Circuit


x_i
y_i
c_i
$s_i = x_i \oplus y_i \oplus c_i$
$c_{i+1} = x_iy_i + x_ic_i + y_ic_i$

Let's take a closer look at this.

[Figure 3.3c from the textbook]

Another Way to Draw the Full-Adder Circuit



$s_i = x_i \oplus y_i \oplus c_i$

$c_{i+1} = x_i\, y_i + (x_i + y_i\,)c_i$

Decomposing the Carry Expression

$$c_{i+1} = x_i\, y_i + x_i\, c_i + y_i\, c_i$$

Decomposing the Carry Expression

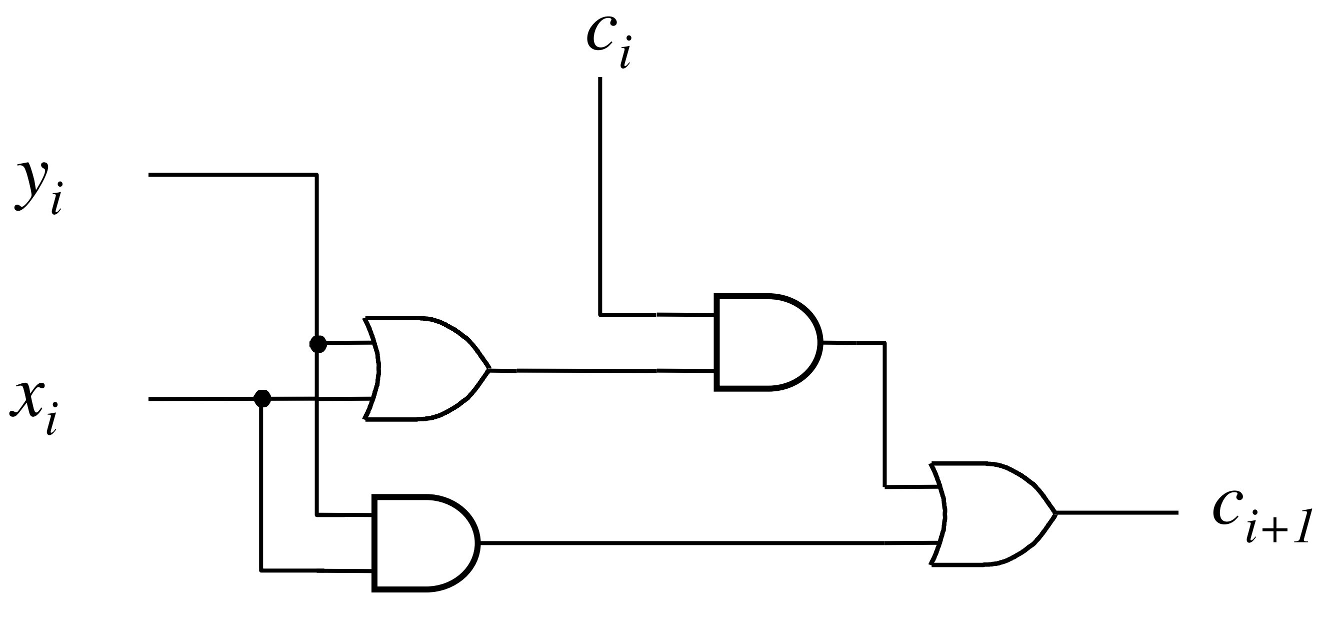
$$c_{i+1} = x_i\, y_i + x_i\, c_i + y_i\, c_i$$

$$c_{i+1} = x_i\, y_i + (x_i + y_i)c_i$$

Decomposing the Carry Expression

$$c_{i+1} = x_i\, y_i + x_i\, c_i + y_i\, c_i$$

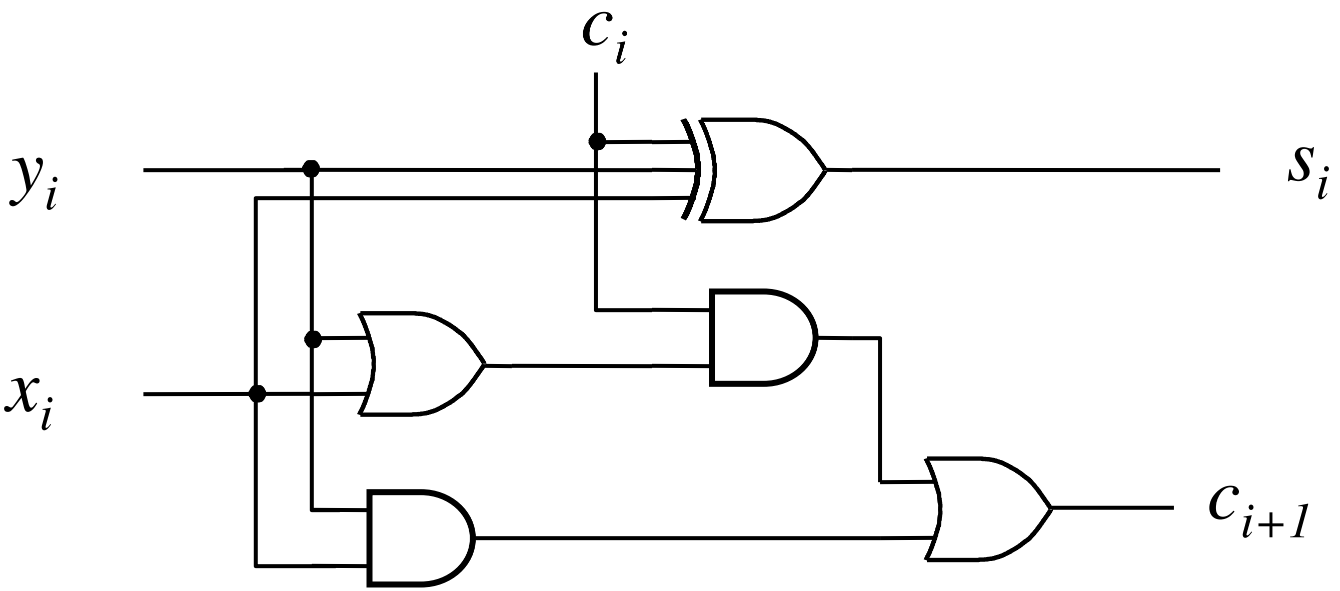
$$c_{i+1} = x_i\, y_i + (x_i + y_i)c_i$$



Another Way to Draw the Full-Adder Circuit

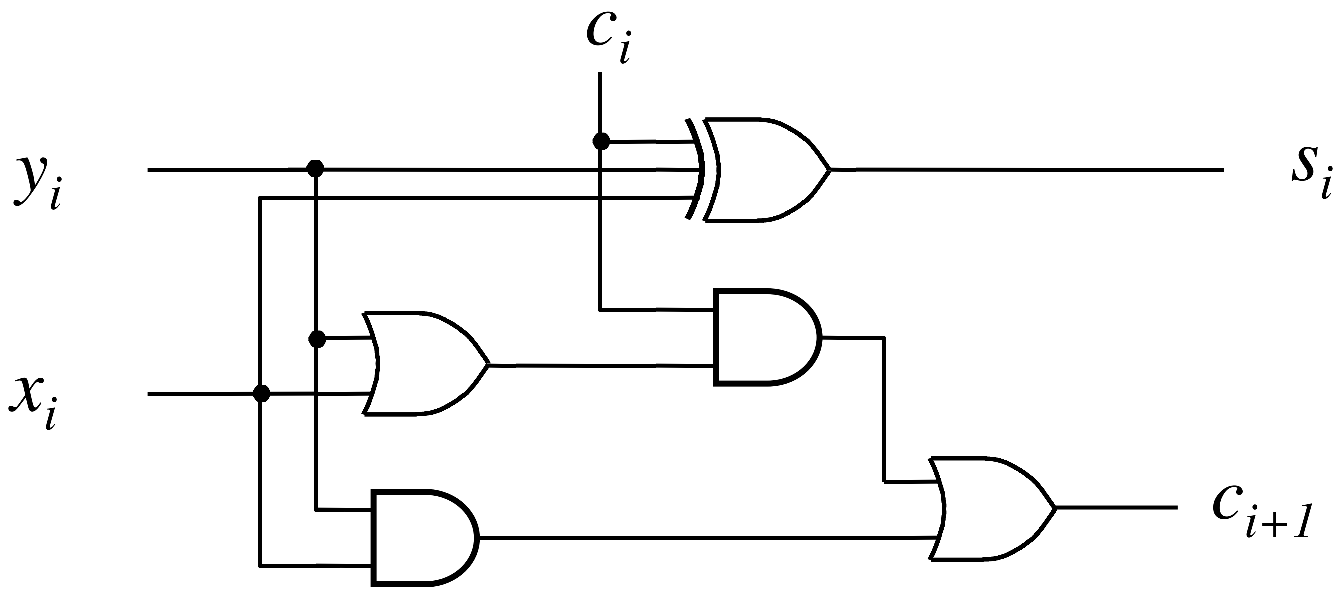
$$c_{i+1} = x_i\, y_i + x_i\, c_i + y_i\, c_i$$

$$c_{i+1} = x_i\, y_i + (x_i + y_i)c_i$$



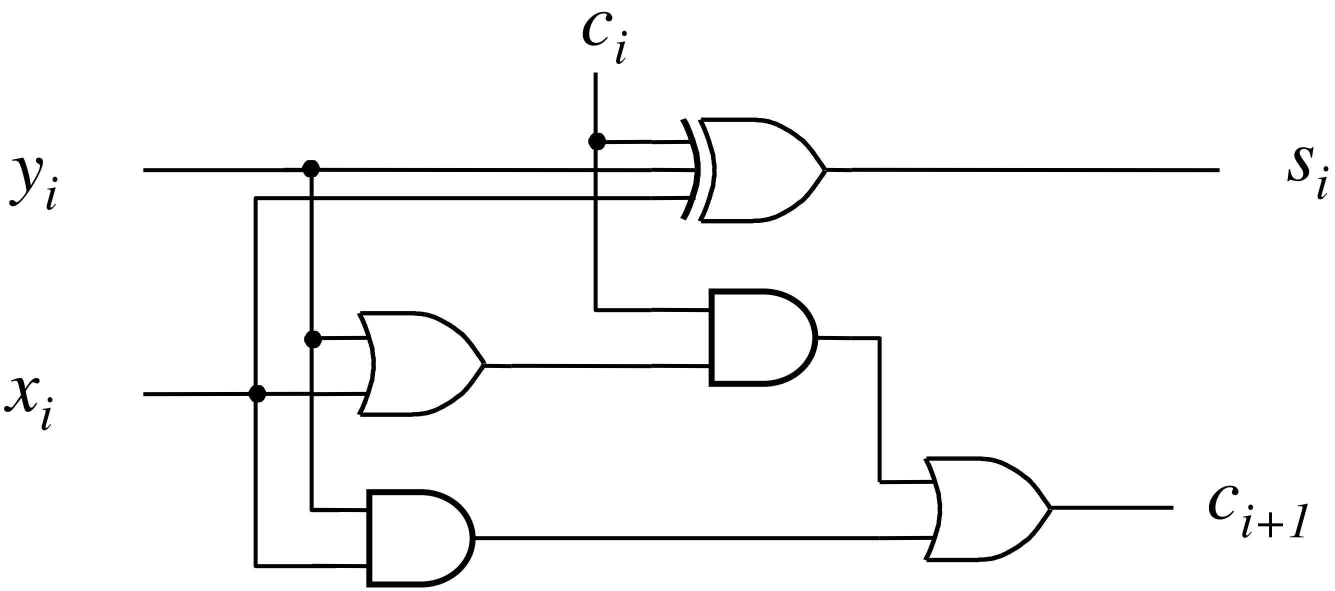
Another Way to Draw the Full-Adder Circuit

$$c_{i+1} = x_i\, y_i + (x_i + y_i)c_i$$



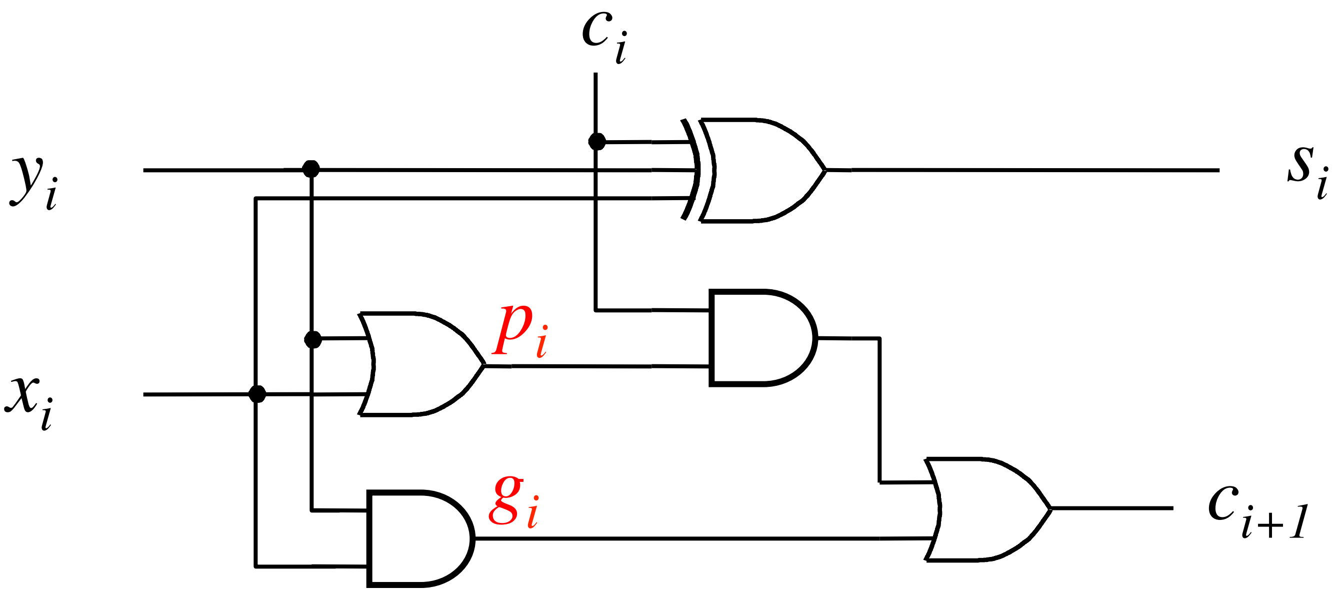
Another Way to Draw the Full-Adder Circuit

$$c_{i+1} = \underbrace{x_i\, y_i}_{g_i} + \underbrace{(x_i + y_i)}_{p_i} c_i$$

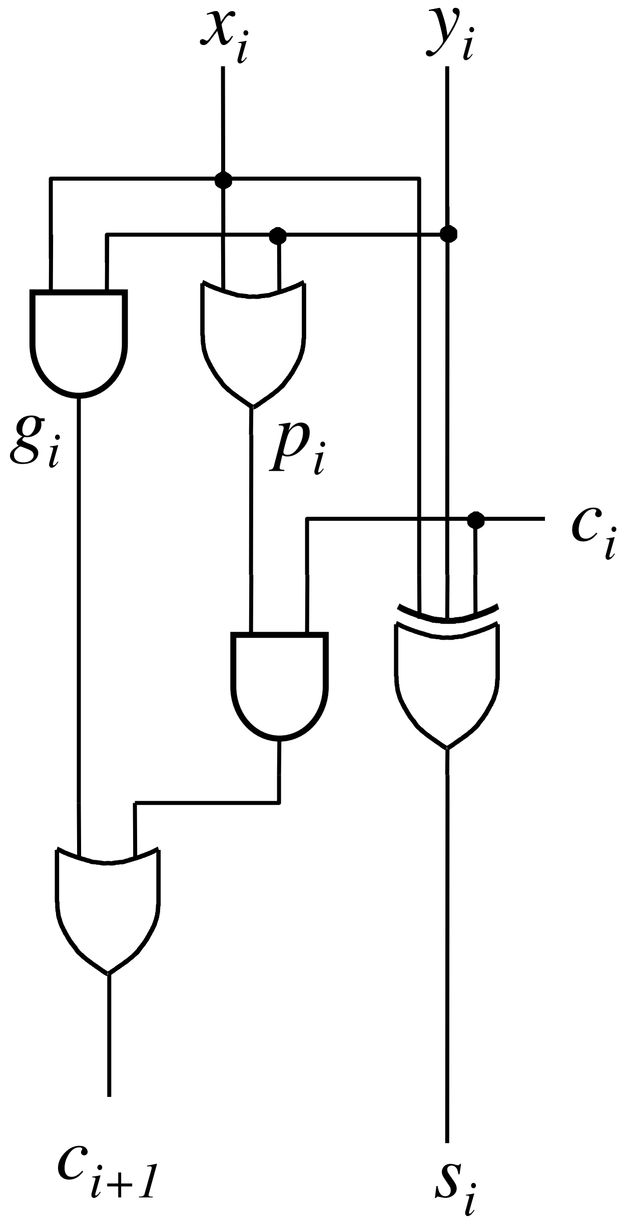


Another Way to Draw the Full-Adder Circuit

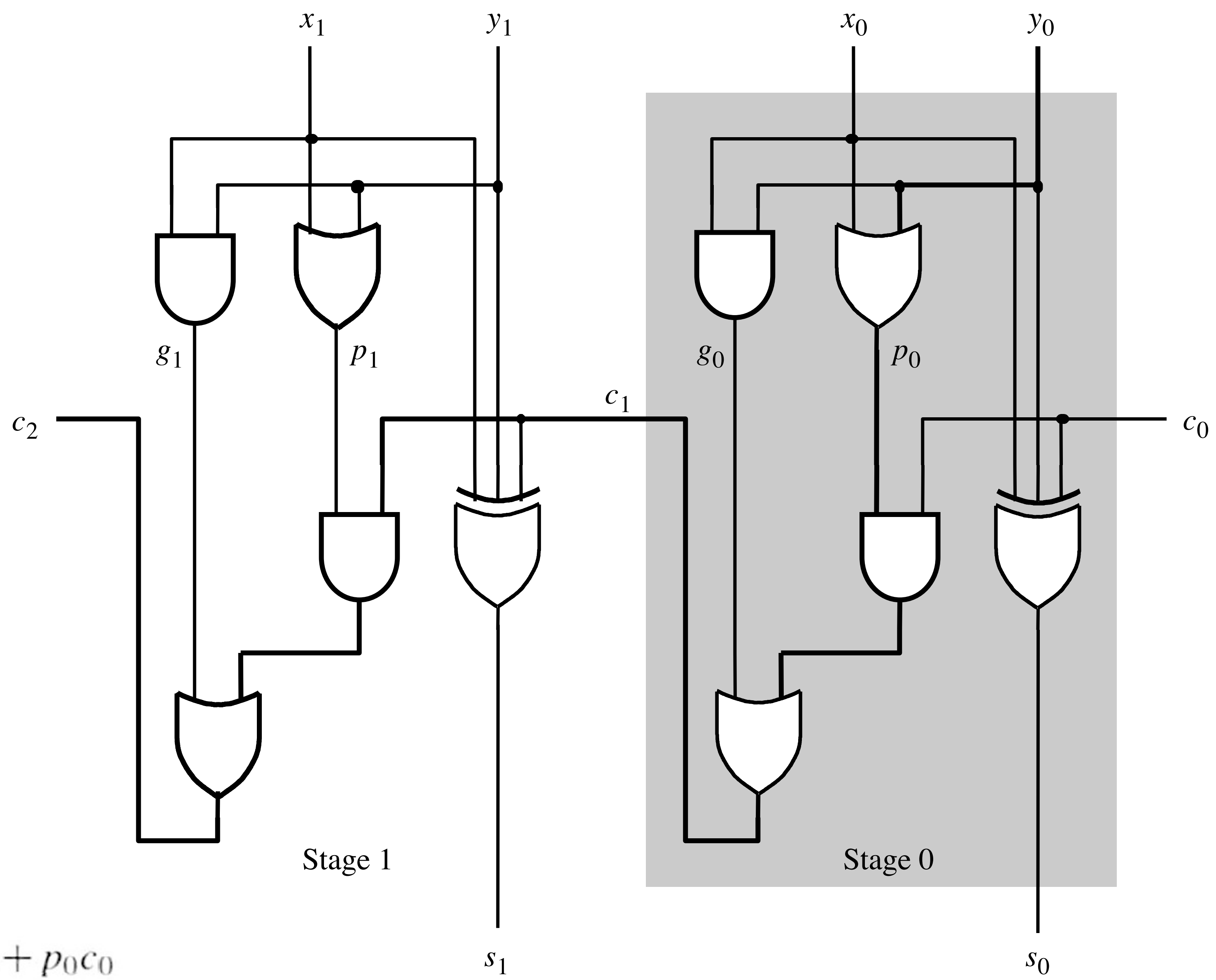
$$c_{i+1} = \underbrace{x_i\, y_i}_{g_i} + \underbrace{(x_i + y_i)}_{p_i} c_i$$



Yet Another Way to Draw It (Just Rotate It)



Now we can Build a Ripple-Carry Adder

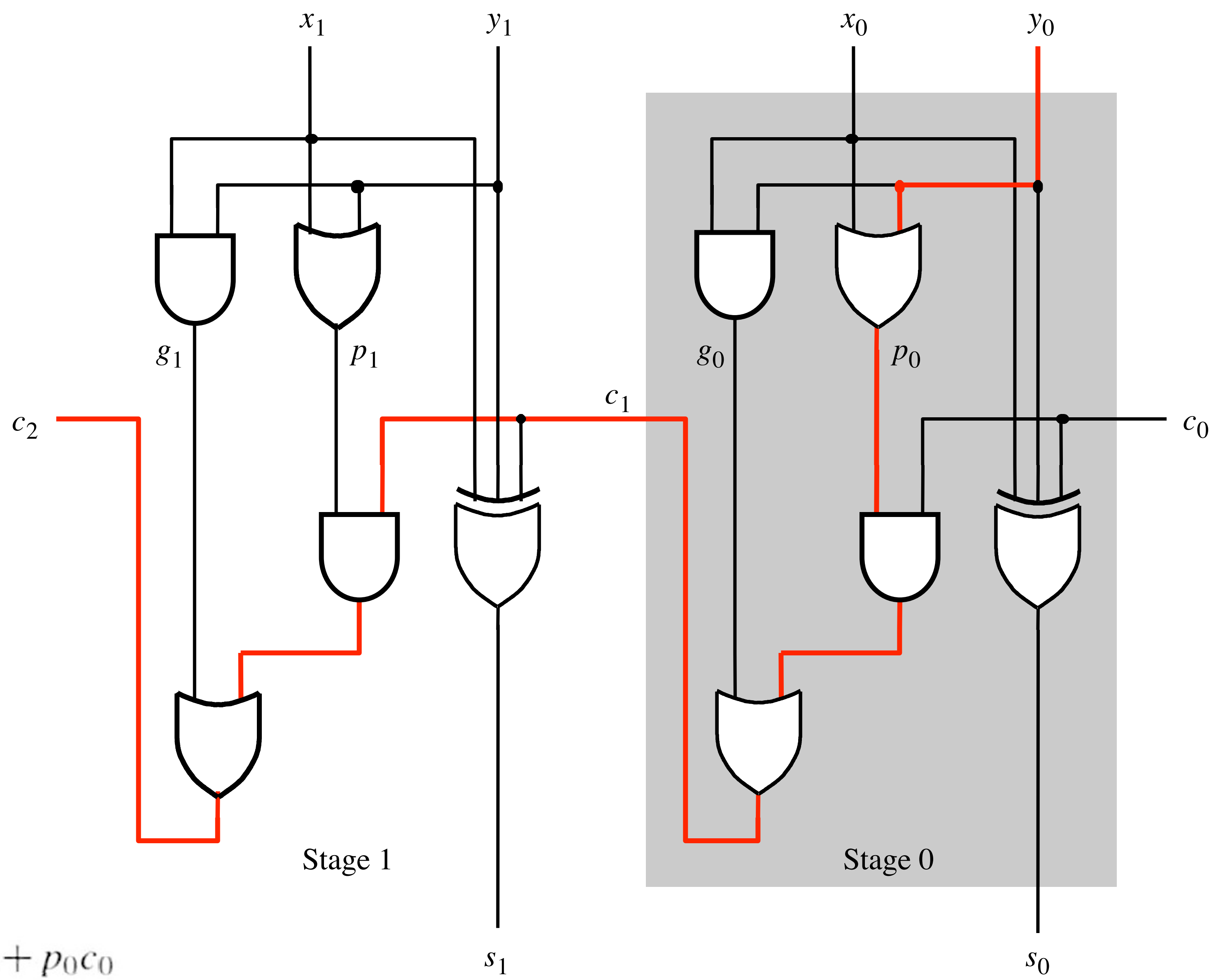


$$c_1 = g_0 + p_0 c_0$$

$$c_2 = g_1 + p_1 g_0 + p_1 p_0 c_0$$

[Figure 3.14 from the textbook]

Now we can Build a Ripple-Carry Adder

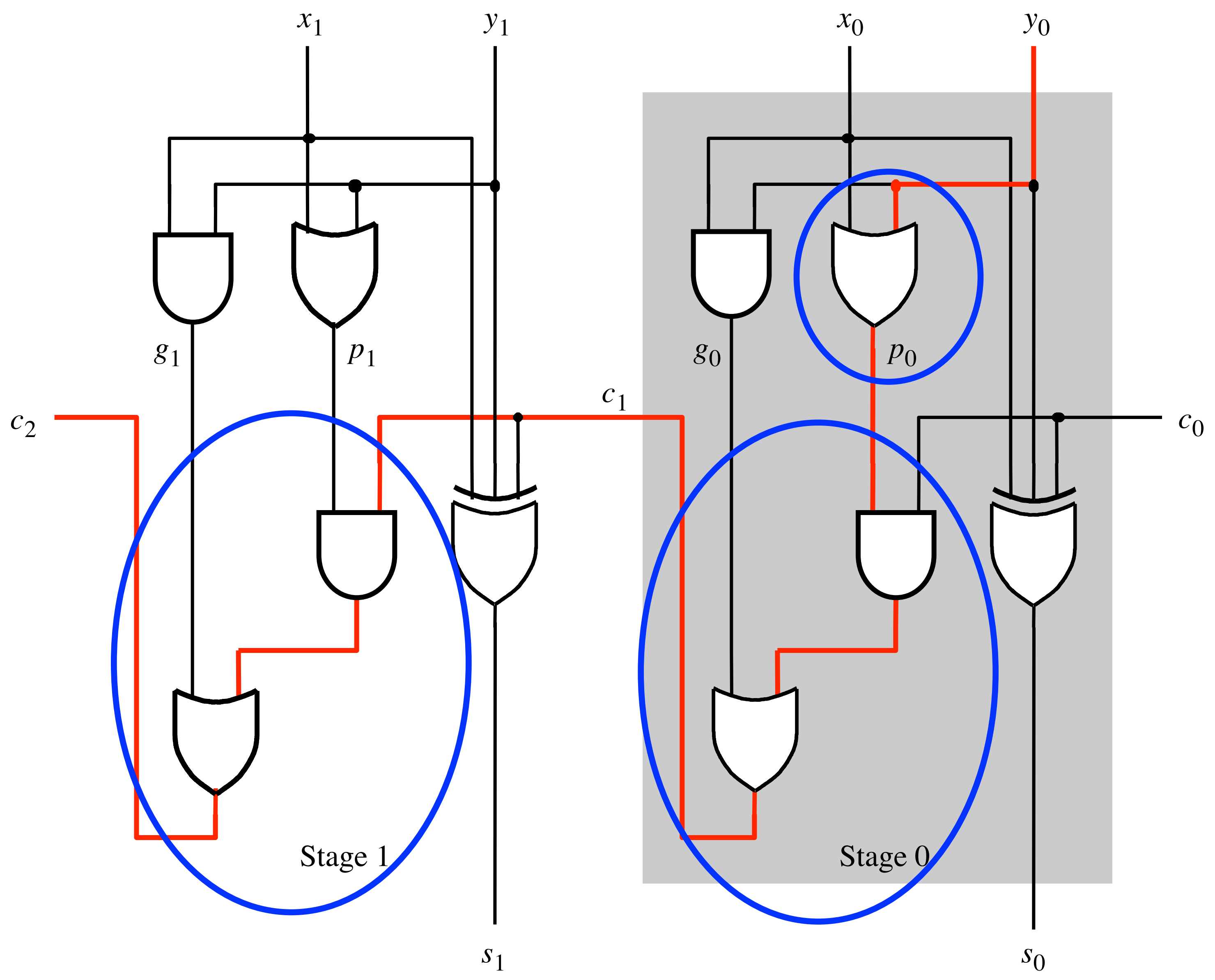


$$c_1 = g_0 + p_0 c_0$$

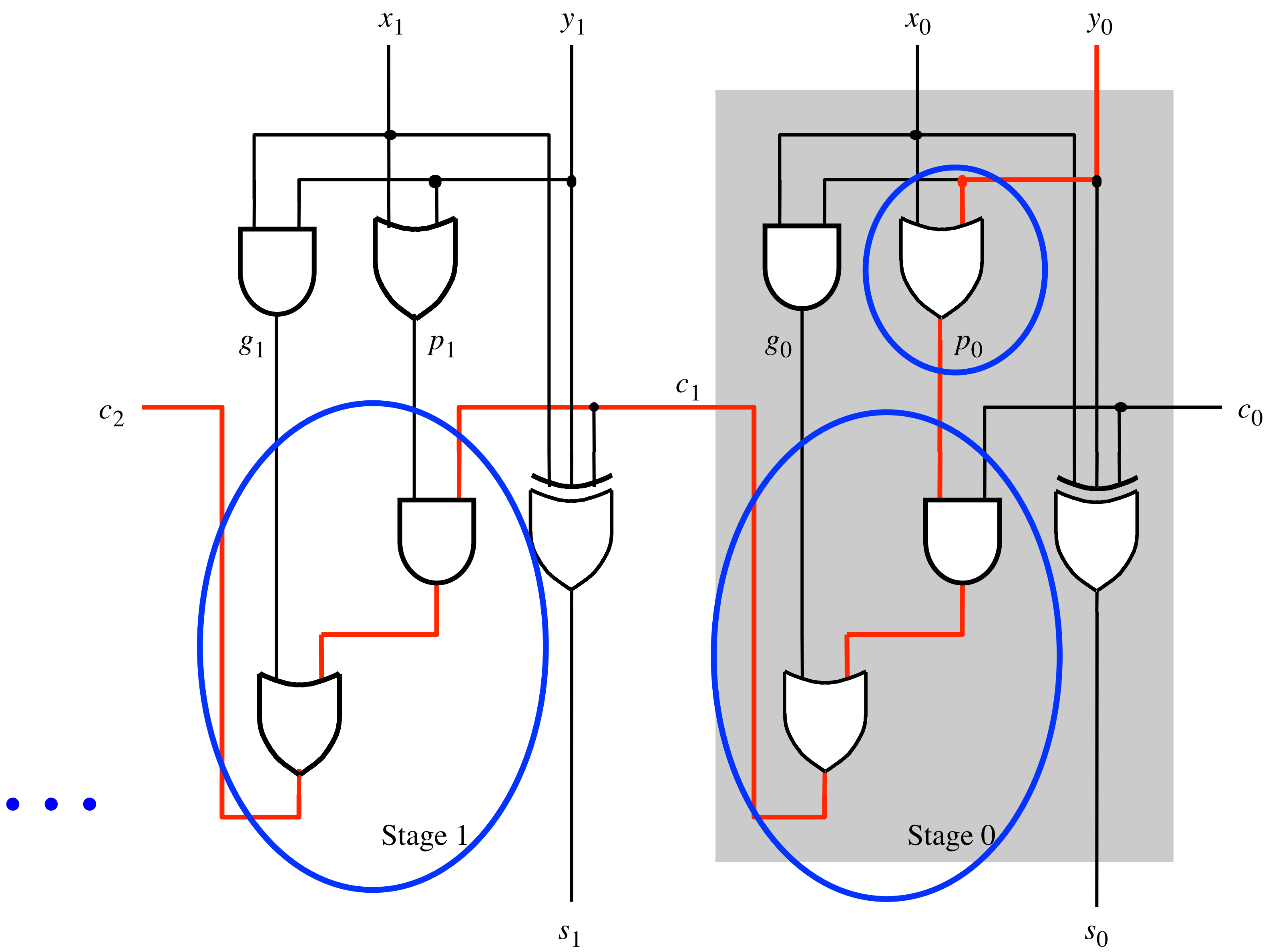
$$c_2 = g_1 + p_1 g_0 + p_1 p_0 c_0$$

[Figure 3.14 from the textbook]

The delay is 5 gates (1+2+2)



n-bit ripple-carry adder: 2n+1 gate delays



Decomposing the Carry Expression

$$c_{i+1} = x_i\, y_i + x_i\, c_i + y_i\, c_i$$

$$c_{i+1} = \underbrace{x_i\, y_i}_{g_i} + \underbrace{(x_i + y_i)}_{p_i} c_i$$

$$c_{i+1} = g_i \;+ p_i\, c_i$$

$$c_{i+1} = g_i \;+ p_i (g_{i-1} \;+ p_{i-1}\, c_{i-1}\,)$$

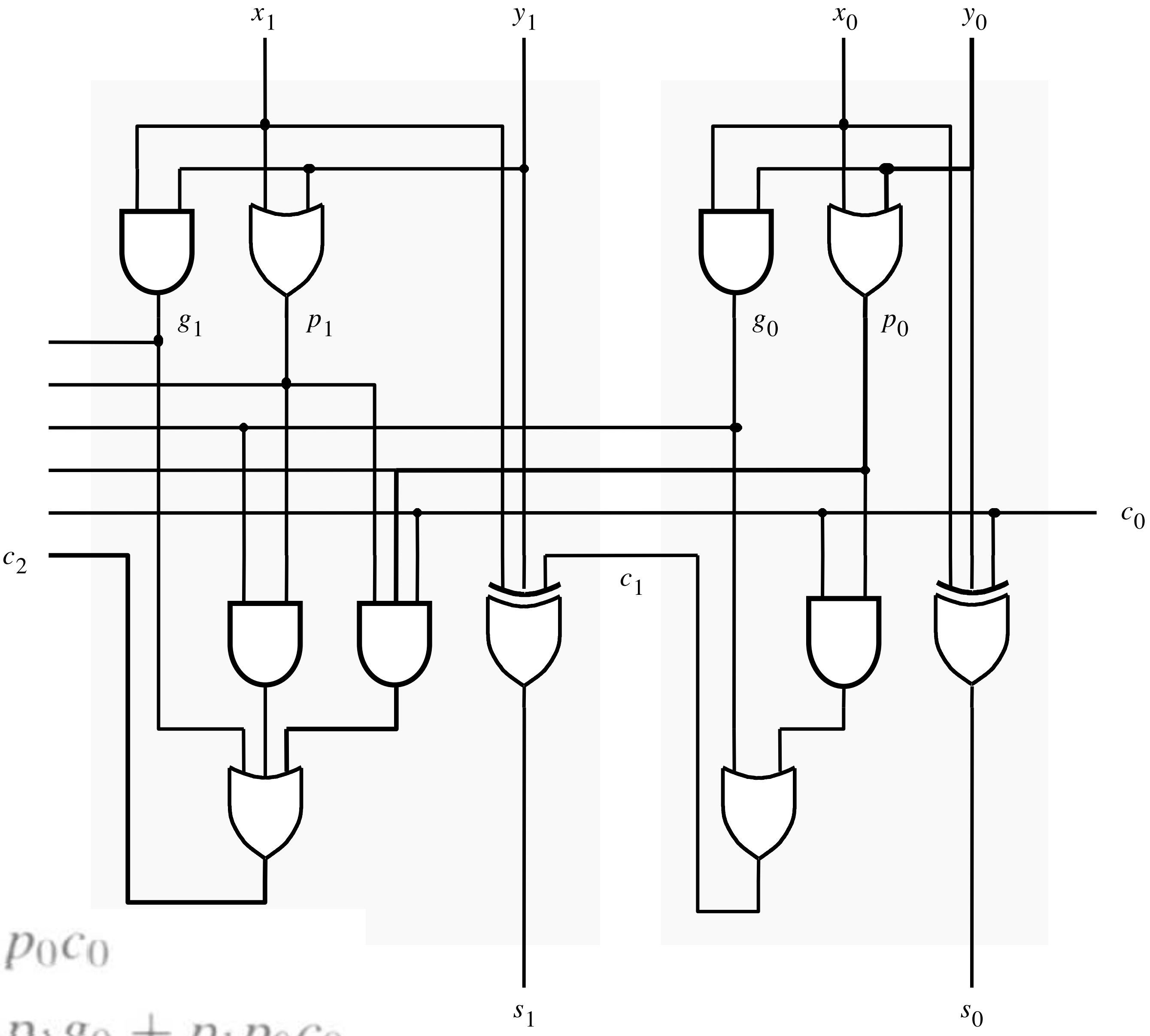
$$= g_i \;+ p_i\, g_{i-1} \;+ p_i\, p_{i-1}\, c_{i-1}$$

Carry for the first two stages

$$c_1 = g_0 + p_0 c_0$$

$$c_2 = g_1 + p_1 g_0 + p_1 p_0 c_0$$

The first two stages of a carry-lookahead adder

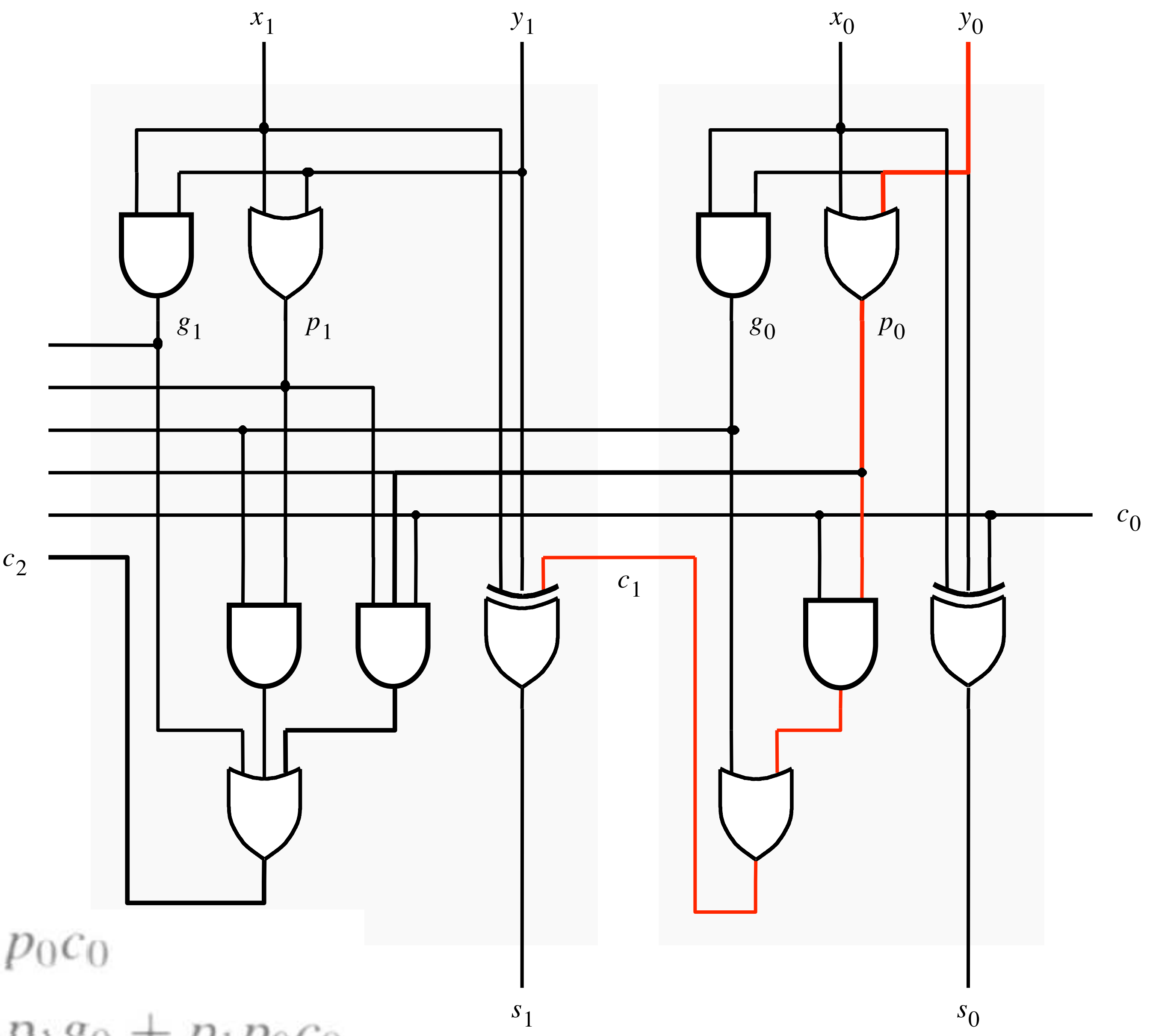


$$c_1 = g_0 + p_0c_0$$

$$c_2 = g_1 + p_1g_0 + p_1p_0c_0$$

[Figure 3.15 from the textbook]

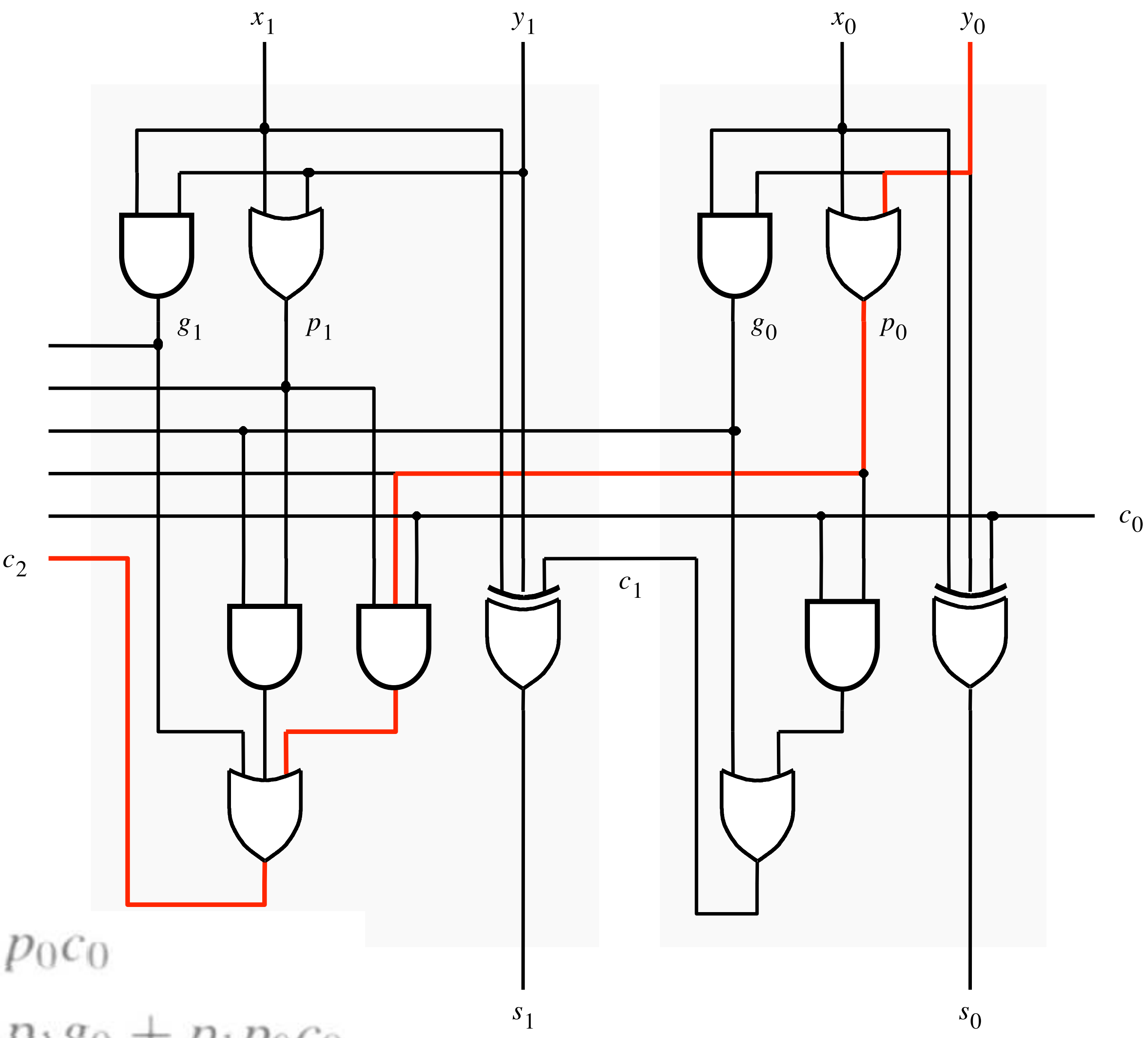
It takes 3 gate delays to generate c_1



$$c_1 = g_0 + p_0c_0$$

$$c_2 = g_1 + p_1g_0 + p_1p_0c_0$$

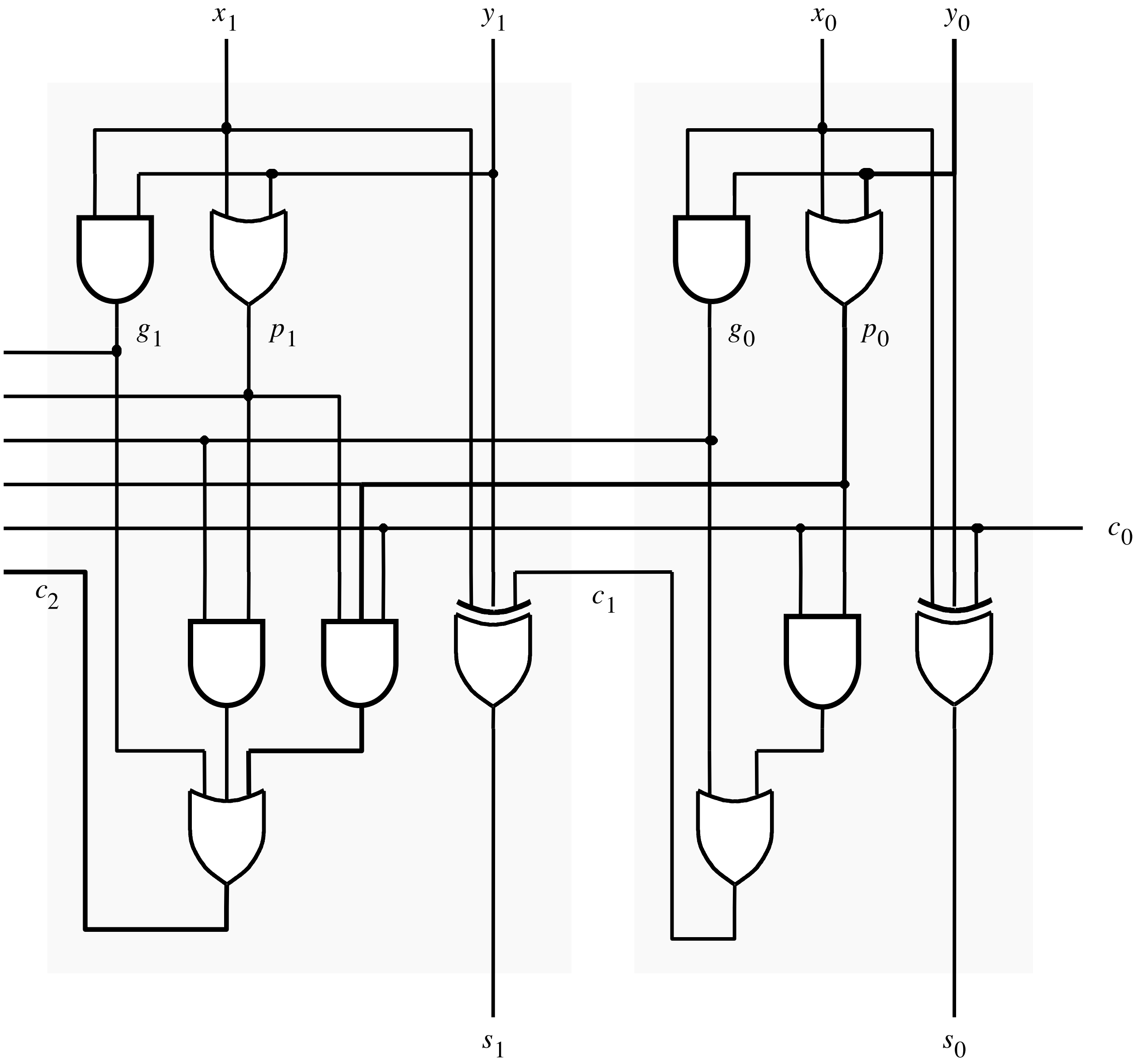
It takes 3 gate delays to generate c_2



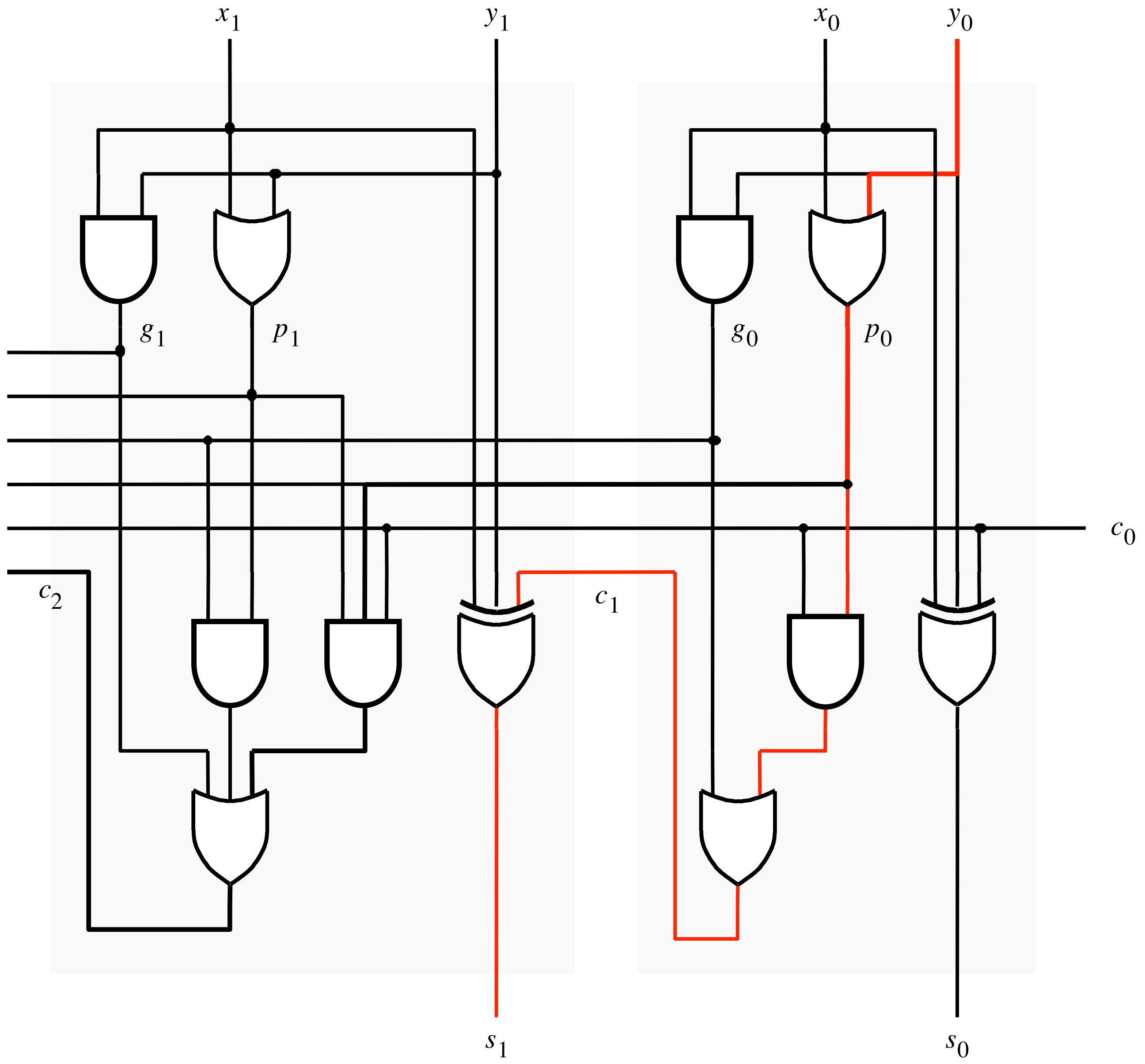
$$c_1 = g_0 + p_0c_0$$

$$c_2 = g_1 + p_1g_0 + p_1p_0c_0$$

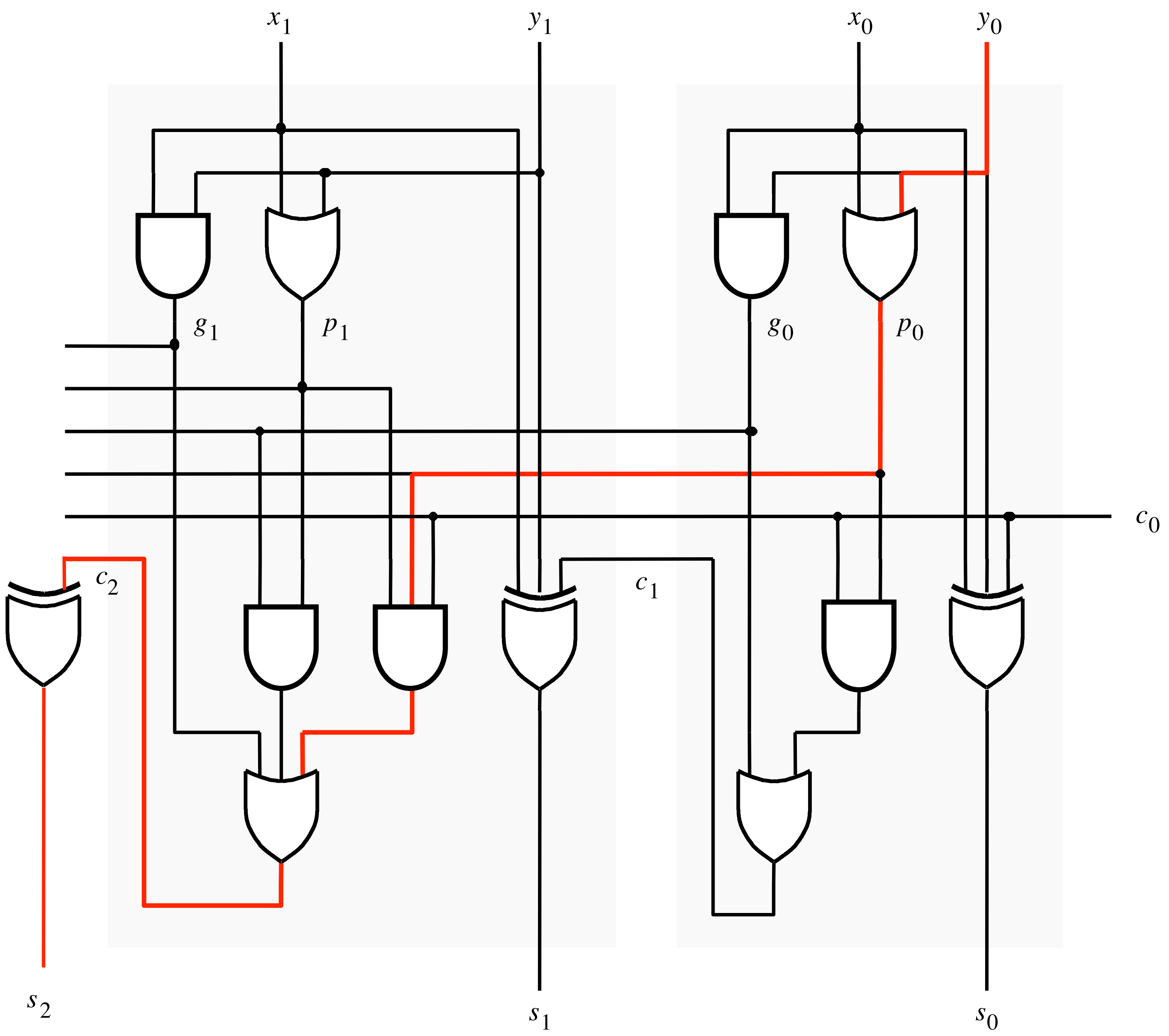
The first two stages of a carry-lookahead adder



It takes 4 gate delays to generate s_1



It takes 4 gate delays to generate s_2



N-bit Carry-Lookahead Adder

- It takes 3 gate delays to generate all carry signals
- It takes 1 more gate delay to generate all sum bits
- Thus, the total delay through an n-bit carry-lookahead adder is only 4 gate delays!

Expanding the Carry Expression

$$c_{i+1} = g_i + p_i c_i$$

$$c_1 = g_0 + p_0 c_0$$

$$c_2 = g_1 + p_1 g_0 + p_1 p_0 c_0$$

$$c_3 = g_2 + p_2 g_1 + p_2 p_1 g_0 + p_2 p_1 p_0 c_0$$

$$\cdots$$

$$\begin{aligned} c_8 = \; & g_7 + p_7 g_6 + p_7 p_6 g_5 + p_7 p_6 p_5 g_4 \\ & + p_7 p_6 p_5 p_4 g_3 + p_7 p_6 p_5 p_4 p_3 g_2 \\ & + p_7 p_6 p_5 p_4 p_3 p_2 g_1 + p_7 p_6 p_5 p_4 p_3 p_2 p_1 g_0 \\ & + p_7 p_6 p_5 p_4 p_3 p_2 p_1 p_0 c_0 \end{aligned}$$

Expanding the Carry Expression

$$c_{i+1} = g_i + p_i c_i$$

$$c_1 = g_0 + p_0 c_0$$

$$c_2 = g_1 + p_1 g_0 + p_1 p_0 c_0$$

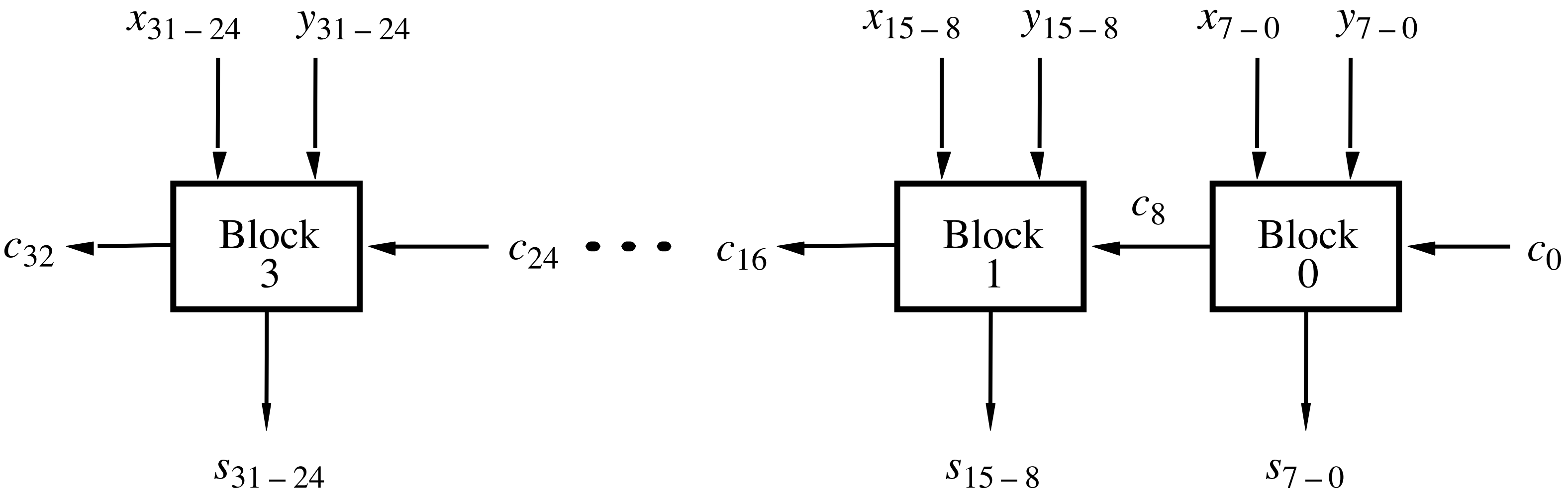
$$c_3 = g_2 + p_2 g_1 + p_2 p_1 g_0 + p_2 p_1 p_0 c_0$$

$$\cdots$$

$$\begin{aligned} c_8 = {} & g_7 + p_7 g_6 + p_7 p_6 g_5 + p_7 p_6 p_5 g_4 \\ & + p_7 p_6 p_5 p_4 g_3 + p_7 p_6 p_5 p_4 p_3 g_2 \\ & + p_7 p_6 p_5 p_4 p_3 p_2 g_1 + p_7 p_6 p_5 p_4 p_3 p_2 p_1 g_0 \\ & + p_7 p_6 p_5 p_4 p_3 p_2 p_1 p_0 c_0 \end{aligned}$$

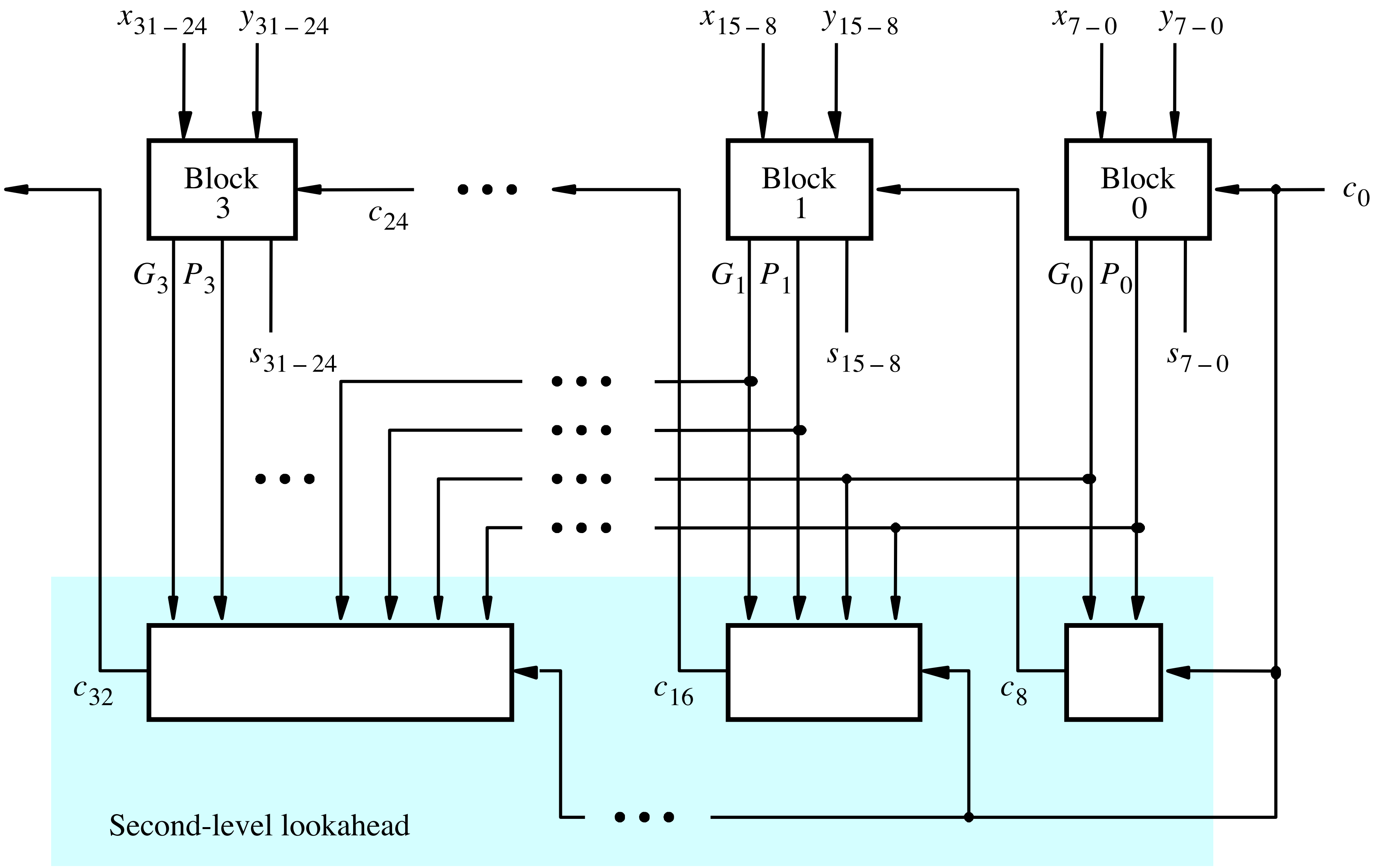
Even this takes only 3 gate delays

A hierarchical carry-lookahead adder with ripple-carry between blocks



[Figure 3.16 from the textbook]

A hierarchical carry-lookahead adder



[Figure 3.17 from the textbook]

The Hierarchical Carry Expression

$$\begin{aligned} c_8 = \; & g_7 + p_7 g_6 + p_7 p_6 g_5 + p_7 p_6 p_5 g_4 \\ & + p_7 p_6 p_5 p_4 g_3 + p_7 p_6 p_5 p_4 p_3 g_2 \\ & + p_7 p_6 p_5 p_4 p_3 p_2 g_1 + p_7 p_6 p_5 p_4 p_3 p_2 p_1 g_0 \\ & + p_7 p_6 p_5 p_4 p_3 p_2 p_1 p_0 c_0 \end{aligned}$$

The Hierarchical Carry Expression

$$\begin{aligned} c_8 = {} & \boxed{\begin{aligned} & g_7 + p_7g_6 + p_7p_6g_5 + p_7p_6p_5g_4 \\ & + p_7p_6p_5p_4g_3 + p_7p_6p_5p_4p_3g_2 \\ & + p_7p_6p_5p_4p_3p_2g_1 + p_7p_6p_5p_4p_3p_2p_1g_0 \end{aligned}} \\ & + \boxed{p_7p_6p_5p_4p_3p_2p_1p_0}c_0 \end{aligned}$$

The Hierarchical Carry Expression

$$\begin{aligned} c_8 = {} & \underbrace{\begin{aligned} & g_7 + p_7g_6 + p_7p_6g_5 + p_7p_6p_5g_4 \\ & + p_7p_6p_5p_4g_3 + p_7p_6p_5p_4p_3g_2 \\ & + p_7p_6p_5p_4p_3p_2g_1 + p_7p_6p_5p_4p_3p_2p_1g_0 \end{aligned}}_{G_0} \\ & + \underbrace{p_7p_6p_5p_4p_3p_2p_1p_0}_{P_0}c_0 \end{aligned}$$

The Hierarchical Carry Expression

$$c_8 = \underbrace{\boxed{\begin{aligned} & g_7 \;+ p_7g_6 + p_7p_6g_5 + p_7p_6p_5g_4 \\ & + p_7p_6p_5p_4g_3 + p_7p_6p_5p_4p_3g_2 \\ & + p_7p_6p_5p_4p_3p_2g_1 + p_7p_6p_5p_4p_3p_2p_1g_0 \end{aligned}}}_{\mathbf{G_0}} \\ + \underbrace{\boxed{p_7p_6p_5p_4p_3p_2p_1p_0}}_{\mathbf{P_0}} c_0$$

$$c_8 = \; G_0 \; + P_0 c_0$$

The Hierarchical Carry Expression

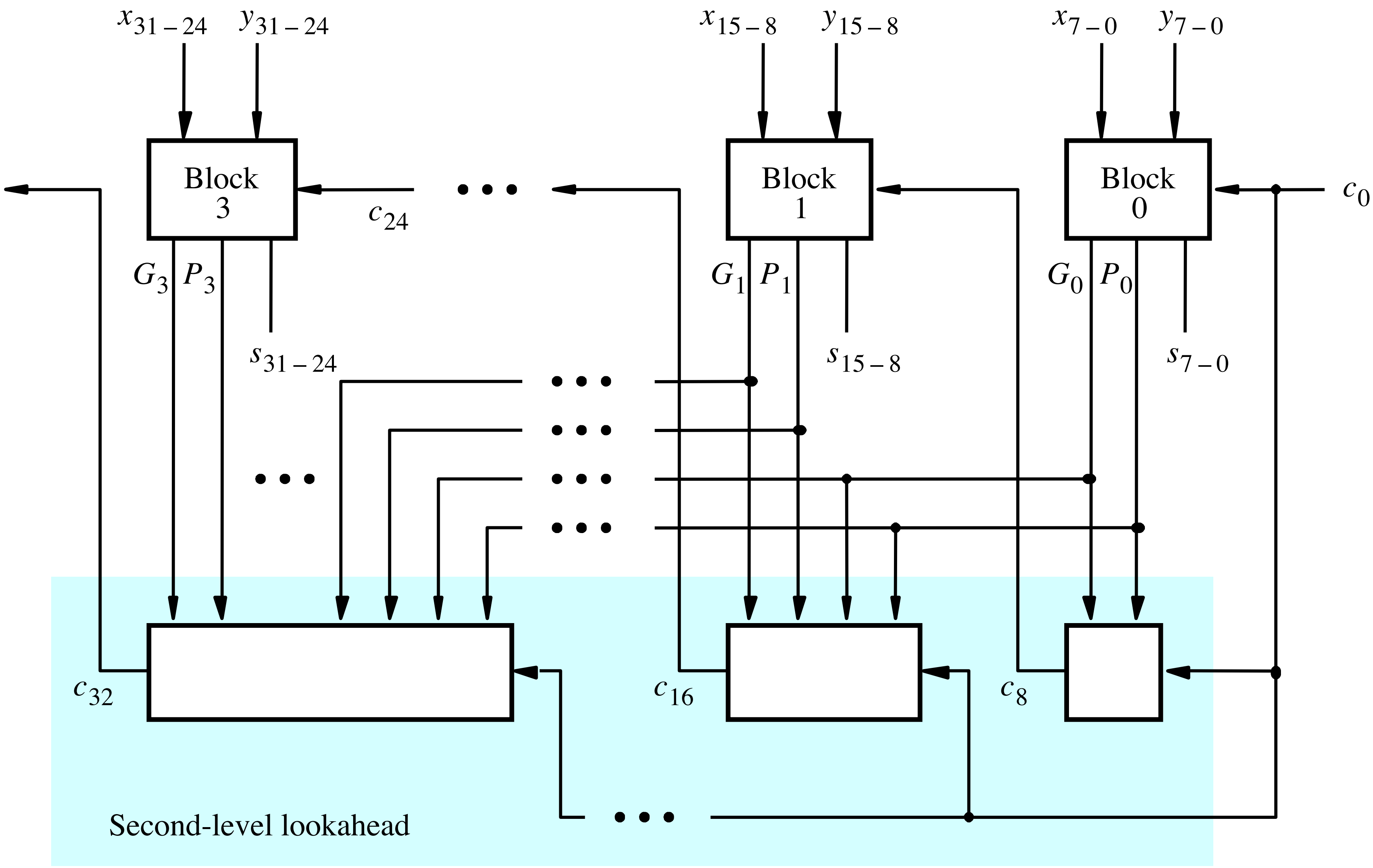
$$c_8 = G_0 + P_0 c_0$$

$$\begin{aligned} c_{16} &= G_1 + P_1 c_8 \\ &= G_1 + P_1 G_0 + P_1 P_0 c_0 \end{aligned}$$

$$c_{24} = G_2 + P_2 G_1 + P_2 P_1 G_0 + P_2 P_1 P_0 c_0$$

$$c_{32} = G_3 + P_3 G_2 + P_3 P_2 G_1 + P_3 P_2 P_1 G_0 + P_3 P_2 P_1 P_0 c_0$$

A hierarchical carry-lookahead adder



[Figure 3.17 from the textbook]

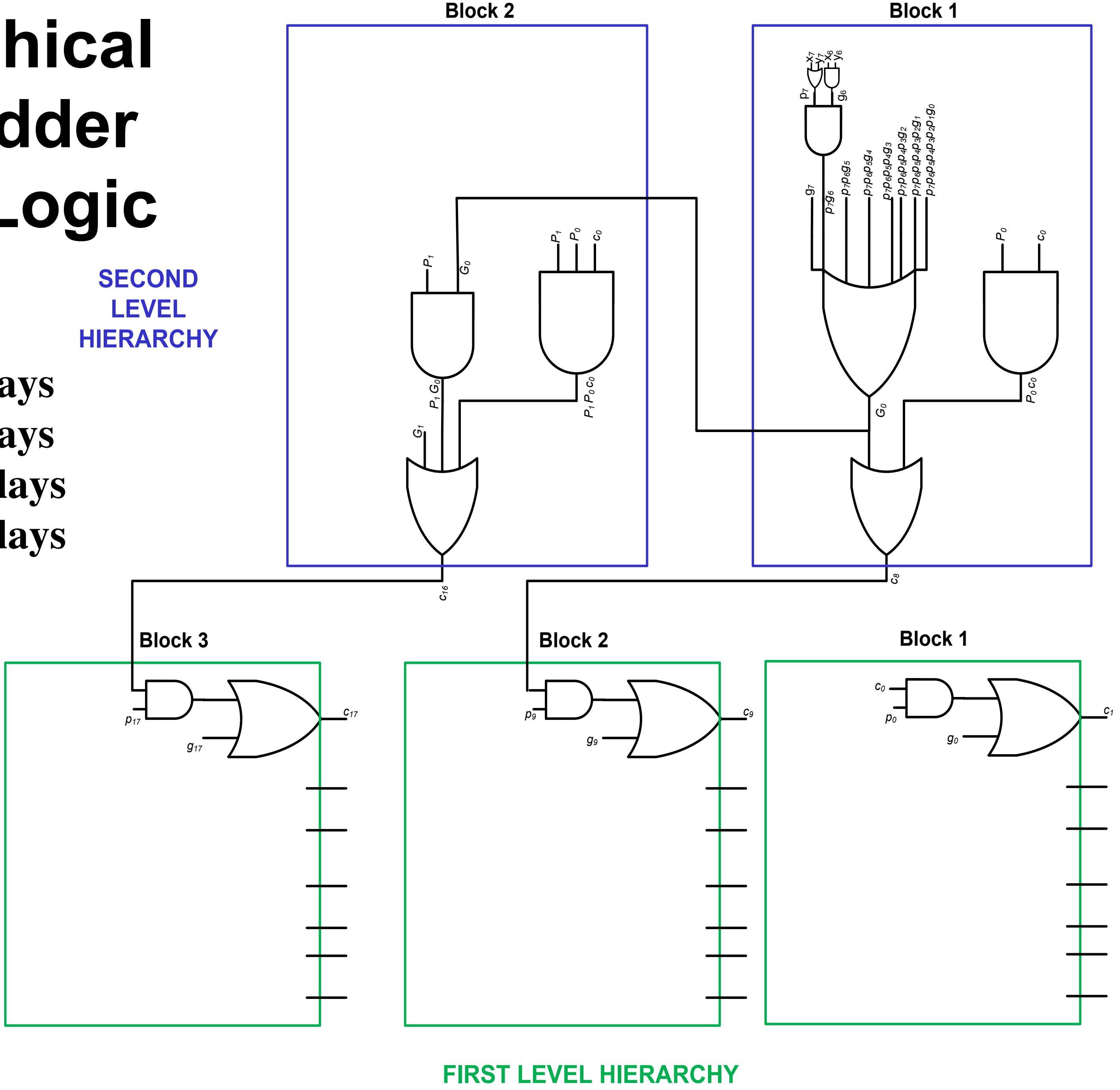
Hierarchical CLA Adder Carry Logic

C8 – 5 gate delays

C16 – 5 gate delays

C24 – 5 Gate delays

C32 – 5 Gate delays



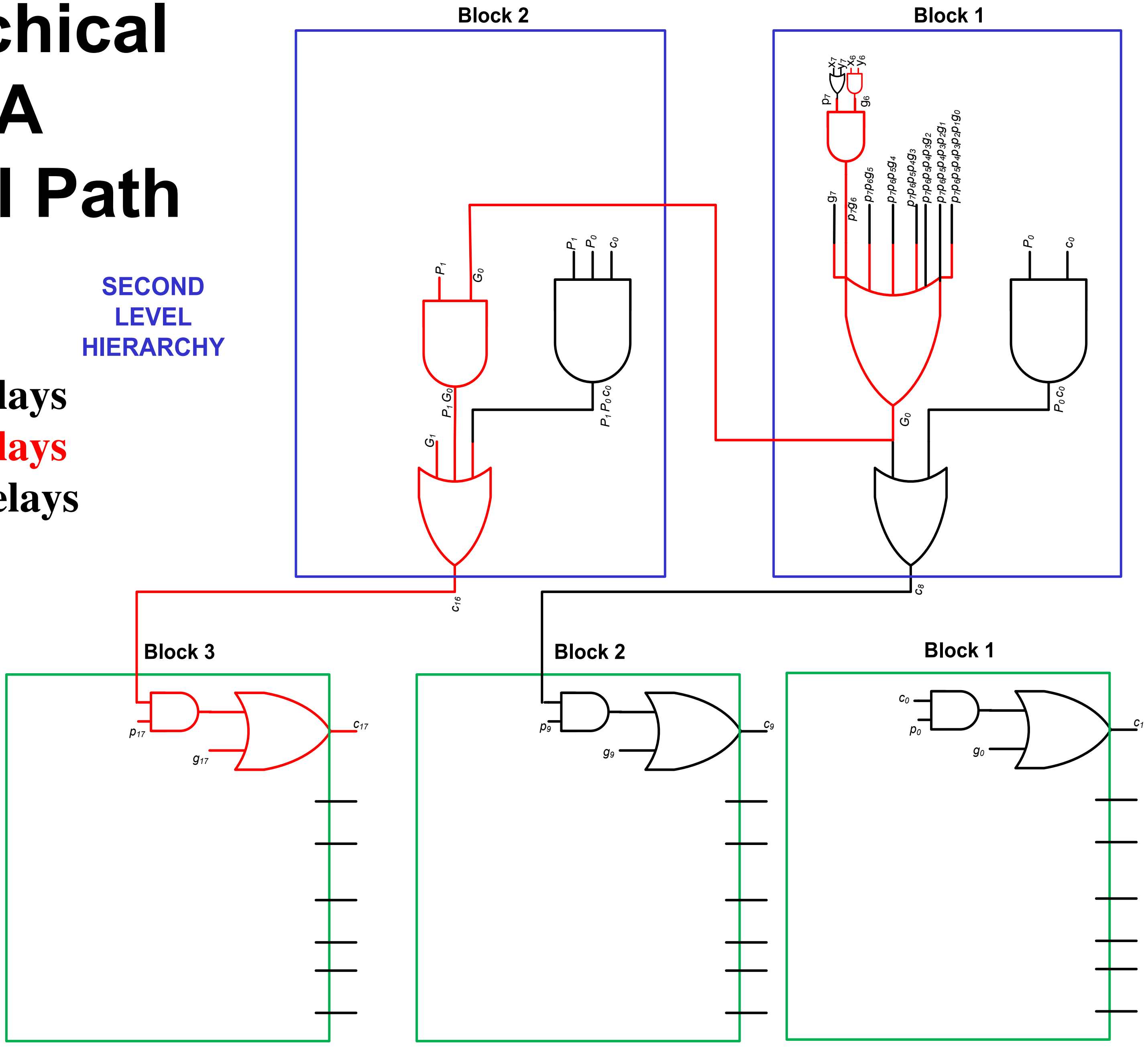
Hierarchical CLA Critical Path

SECOND LEVEL HIERARCHY

C9 – 7 gate delays

C17 – 7 gate delays

C25 – 7 Gate delays



FIRST LEVEL HIERARCHY

Total Gate Delay Through a Hierarchical Carry-Lookahead Adder

- Is 8 gates
  - 3 to generate all Gj and Pj
  - +2 to generate c8, c16, c24, and c32
  - +2 to generate internal carries in the blocks
  - +1 to generate the sum bits (one extra XOR)

Decimal Multiplication by 10

What happens when we multiply a number by 10?

4 x 10 = ?

542 x 10 = ?

1245 x 10 = ?

Decimal Multiplication by 10

What happens when we multiply a number by 10?

4 x 10 = 40

542 x 10 = 5420

1245 x 10 = 12450

Decimal Multiplication by 10

What happens when we multiply a number by 10?

4 x 10 = 40

542 x 10 = 5420

1245 x 10 = 12450

You simply add a zero as the rightmost number

Decimal Division by 10

What happens when we divide a number by 10?

14 / 10 = ?

540 / 10 = ?

1240 x 10 = ?

Decimal Division by 10

What happens when we divide a number by 10?

14 / 10 = 1 //integer division

540 / 10 = 54

1240 x 10 = 124

You simply delete the rightmost number

Binary Multiplication by 2

What happens when we multiply a number by 2?

011 times 2 = ?

101 times 2 = ?

110011 times 2 = ?

Binary Multiplication by 2

What happens when we multiply a number by 2?

011 times 2 = 0110

101 times 2 = 1010

110011 times 2 = 1100110

You simply add a zero as the rightmost number

Binary Multiplication by 4

What happens when we multiply a number by 4?

011 times 4 = ?

101 times 4 = ?

110011 times 4 = ?

Binary Multiplication by 4

What happens when we multiply a number by 4?

011 times 4 = 01100

101 times 4 = 10100

110011 times 4 = 11001100

add two zeros in the last two bits and shift everything else to the left

Binary Multiplication by 2^N

What happens when we multiply a number by 2^N?

011 times 2^N = 01100…0 // add N zeros

101 times 4 = 10100…0 // add N zeros

110011 times 4 = 11001100…0 // add N zeros

Binary Division by 2

What happens when we divide a number by 2?

0110 divided by 2 = ?

1010 divides by 2 = ?

110011 divides by 2 = ?

Binary Division by 2

What happens when we divide a number by 2?

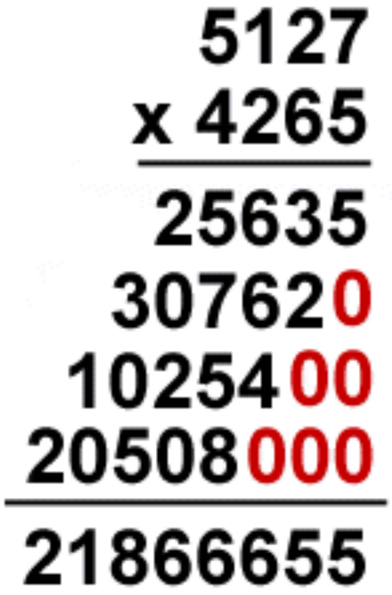
0110 divided by 2 = 011

1010 divides by 2 = 101

110011 divides by 2 = 11001

You simply delete the rightmost number

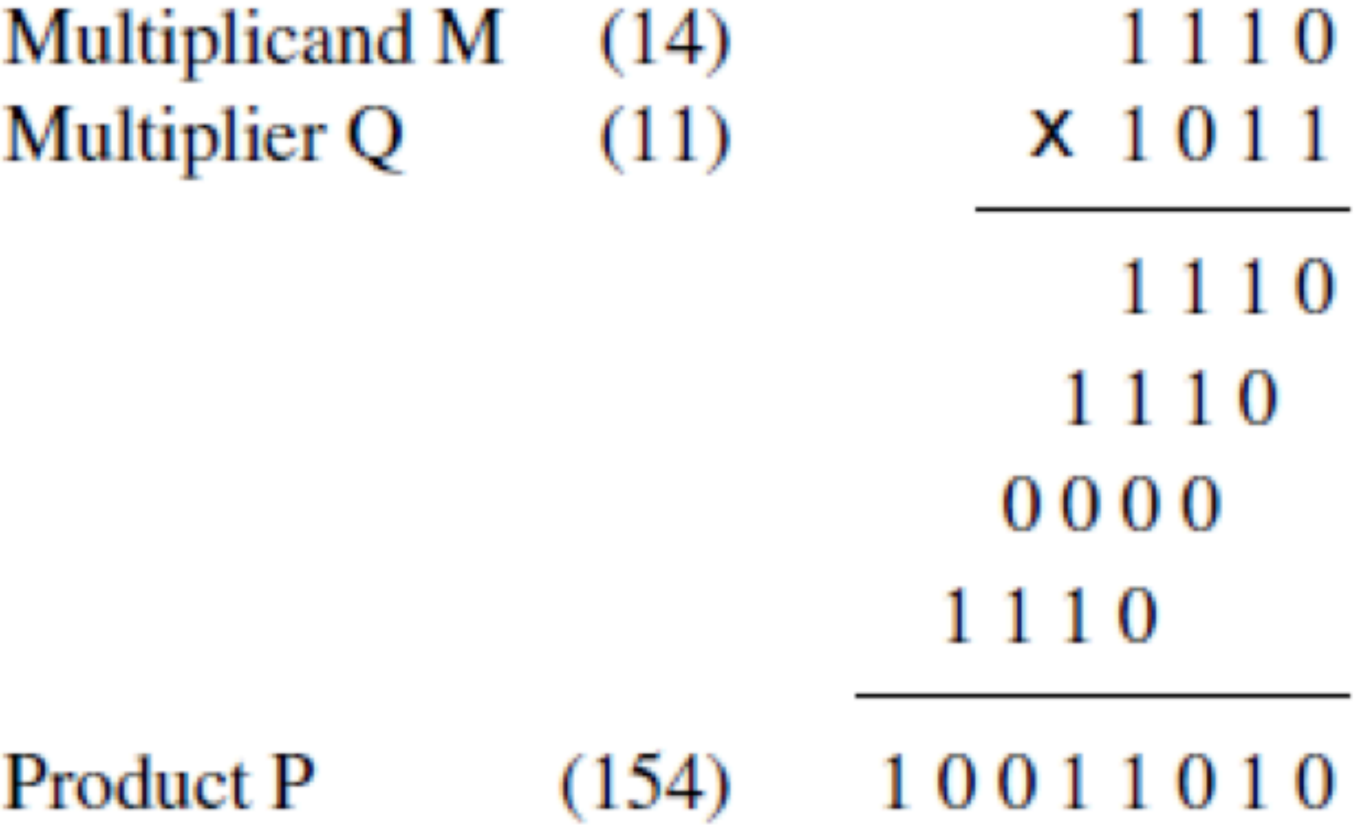
Decimal Multiplication By Hand



```
      5127
    x 4265
    ------
     25635
    307620
   1025400
  20508000
  --------
  21866655
```

[http://www.ducksters.com/kidsmath/long_multiplication.php]

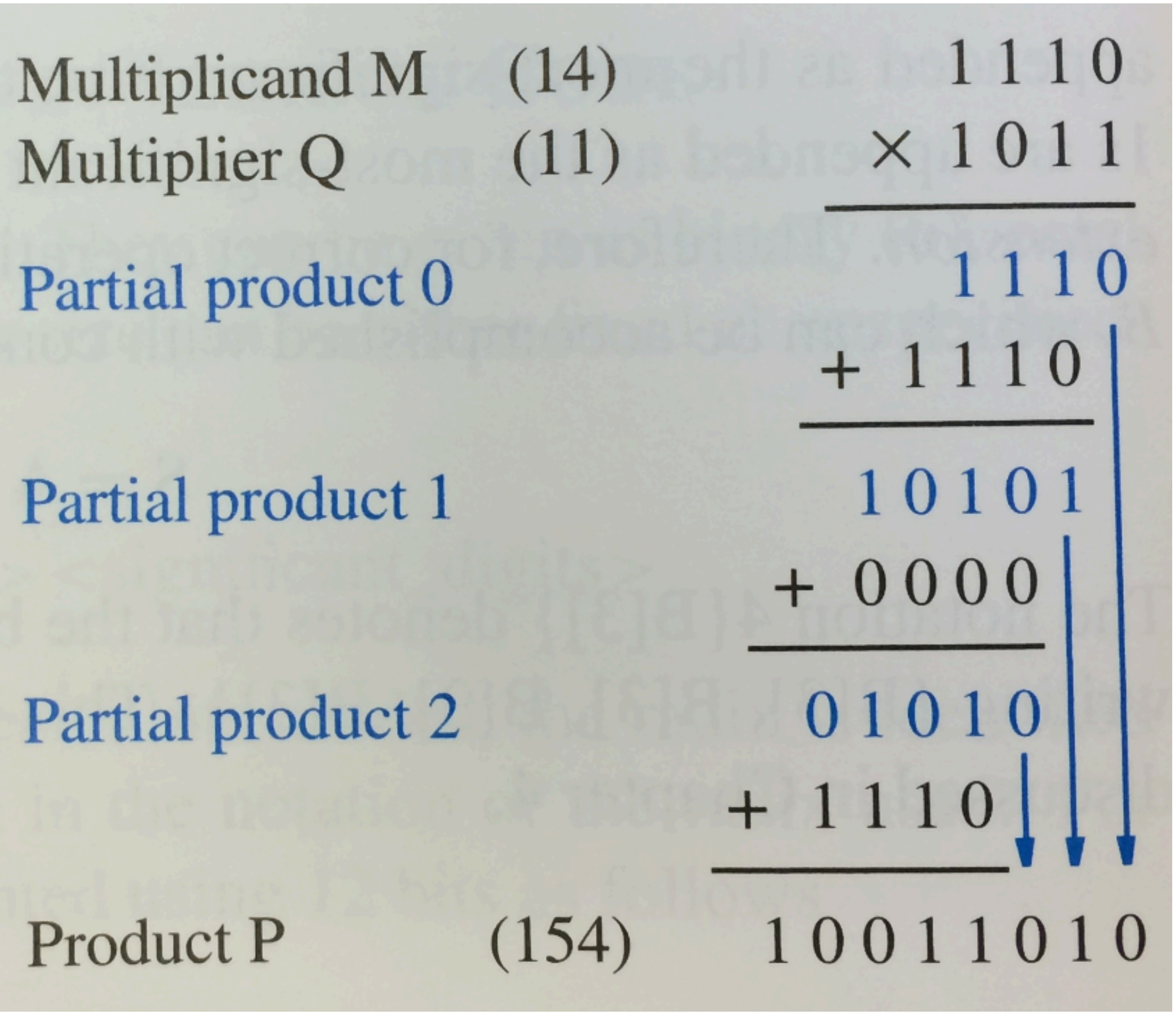
Binary Multiplication By Hand



```
Multiplicand M    (14)              1 1 1 0
Multiplier Q      (11)            x 1 0 1 1
                                  ---------
                                    1 1 1 0
                                  1 1 1 0
                                0 0 0 0
                              1 1 1 0
                            ---------------
Product P        (154)      1 0 0 1 1 0 1 0
```

[Figure 3.34a from the textbook]

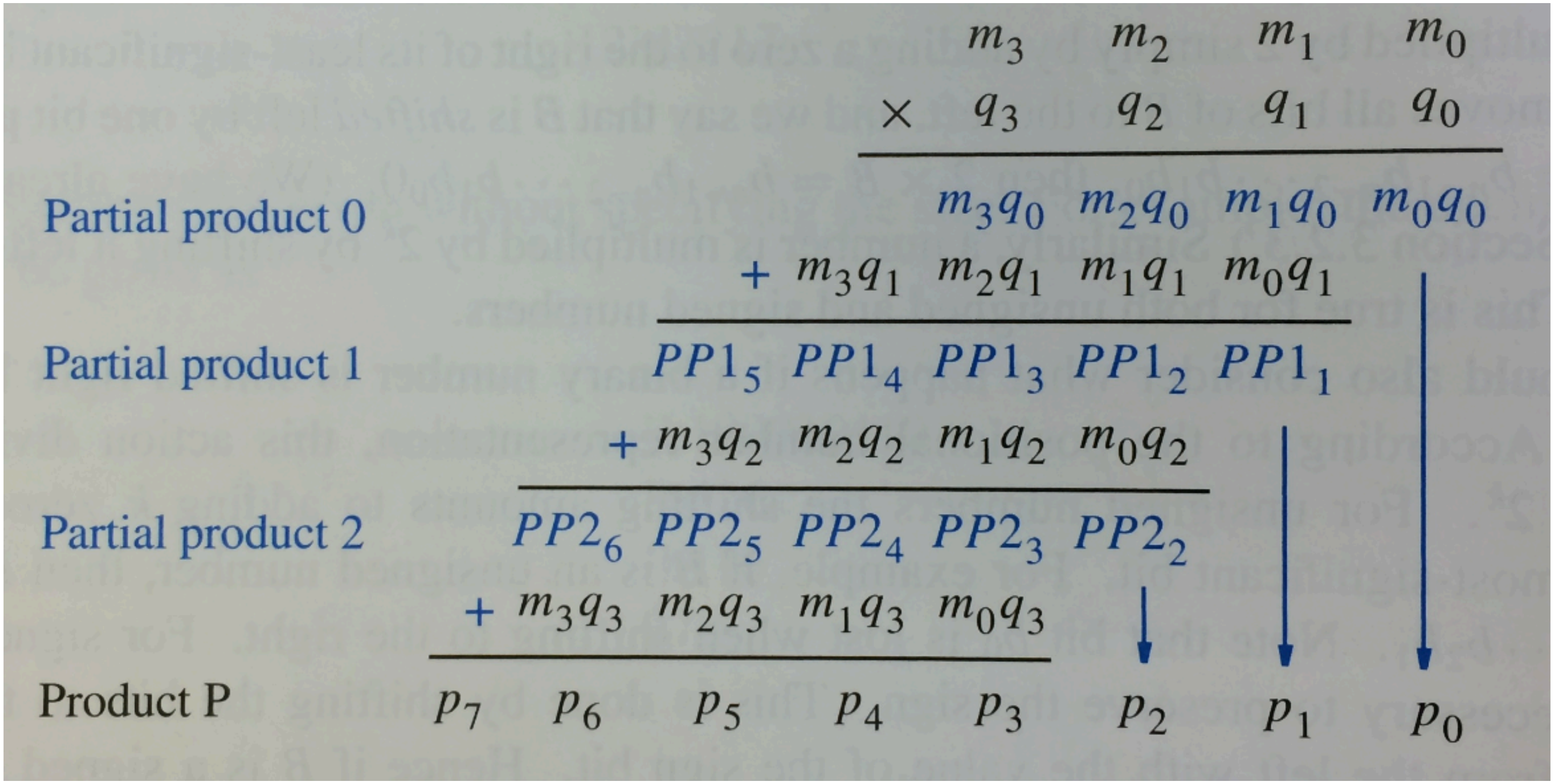
Binary Multiplication By Hand



```
Multiplicand M     (14)            1 1 1 0
Multiplier Q       (11)          × 1 0 1 1
                                 ---------
Partial product 0                  1 1 1 0
                                + 1 1 1 0
                                ---------
Partial product 1                1 0 1 0 1
                              + 0 0 0 0
                              ---------
Partial product 2              0 1 0 1 0
                            + 1 1 1 0
                            ---------
Product P          (154)   1 0 0 1 1 0 1 0
```

[Figure 3.34b from the textbook]

Binary Multiplication By Hand



$$\begin{array}{lcccccccc}
 & & & & & m_3 & m_2 & m_1 & m_0 \\
 & & & & \times & q_3 & q_2 & q_1 & q_0 \\
\cline{5-9}
\text{Partial product 0} & & & & & m_3q_0 & m_2q_0 & m_1q_0 & m_0q_0 \\
 & & & + & m_3q_1 & m_2q_1 & m_1q_1 & m_0q_1 & \downarrow \\
\cline{4-8}
\text{Partial product 1} & & & PP1_5 & PP1_4 & PP1_3 & PP1_2 & PP1_1 & \downarrow \\
 & & + & m_3q_2 & m_2q_2 & m_1q_2 & m_0q_2 & \downarrow & \downarrow \\
\cline{3-7}
\text{Partial product 2} & & PP2_6 & PP2_5 & PP2_4 & PP2_3 & PP2_2 & \downarrow & \downarrow \\
 & + & m_3q_3 & m_2q_3 & m_1q_3 & m_0q_3 & \downarrow & \downarrow & \downarrow \\
\cline{2-6}
\text{Product P} & p_7 & p_6 & p_5 & p_4 & p_3 & p_2 & p_1 & p_0
\end{array}$$

[Figure 3.34c from the textbook]

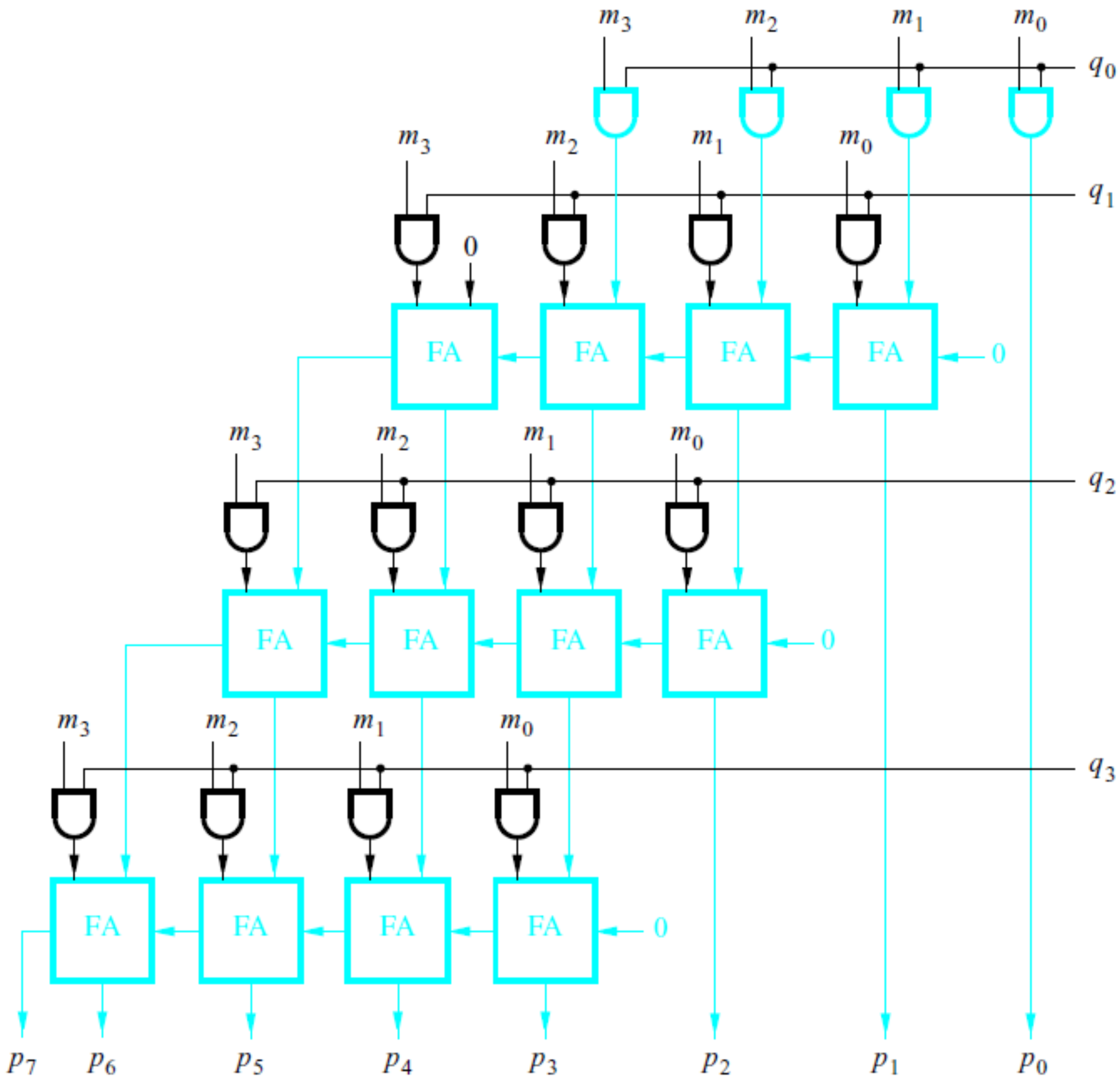


Figure 3.35. A 4x4 multiplier circuit.

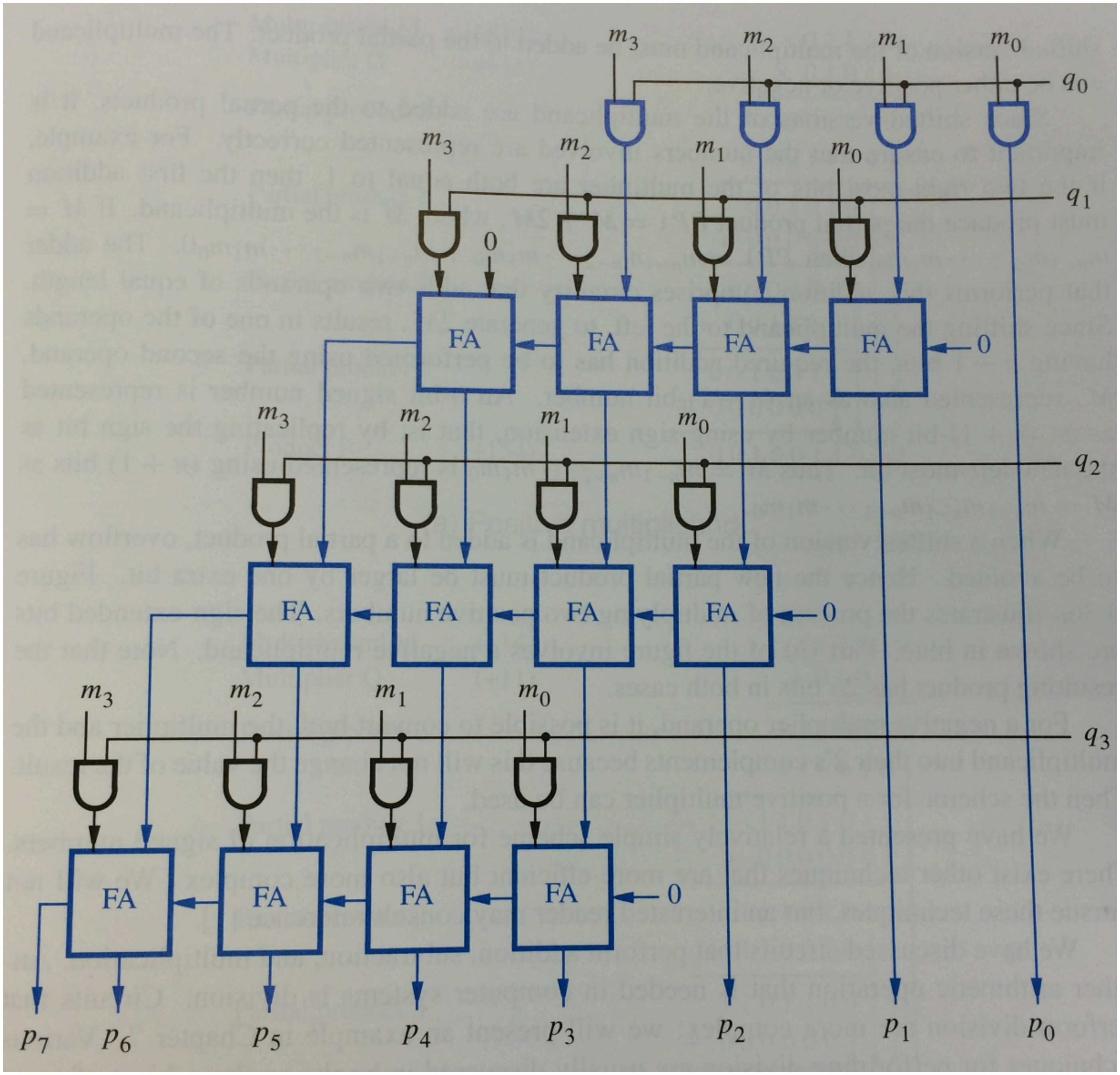
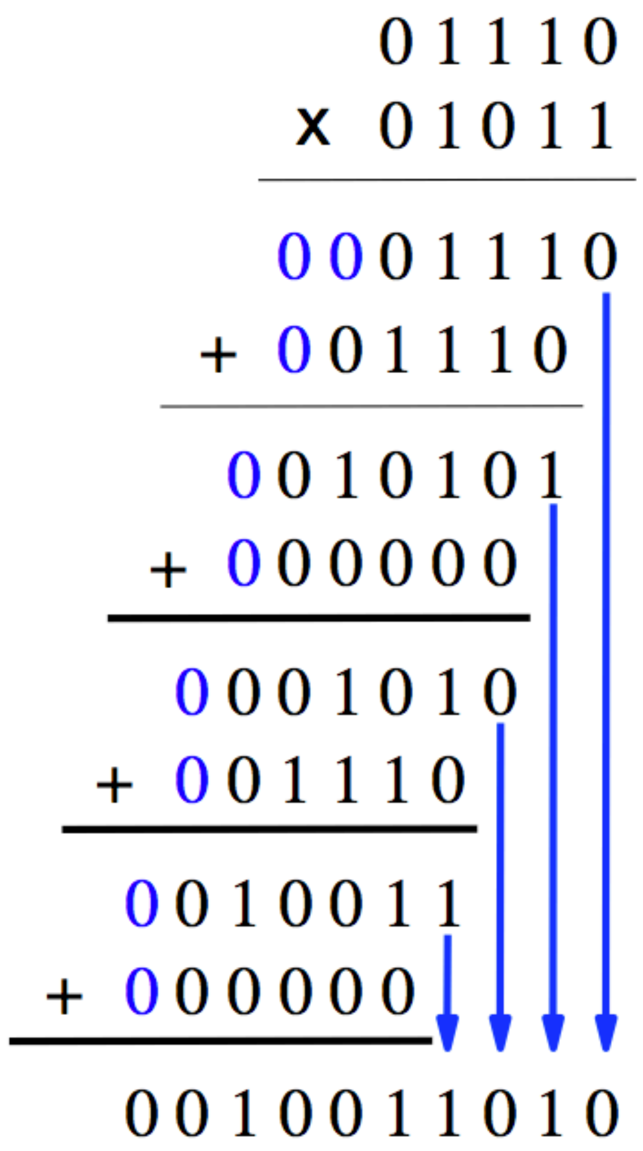


Figure 3.35. A 4x4 multiplier circuit.

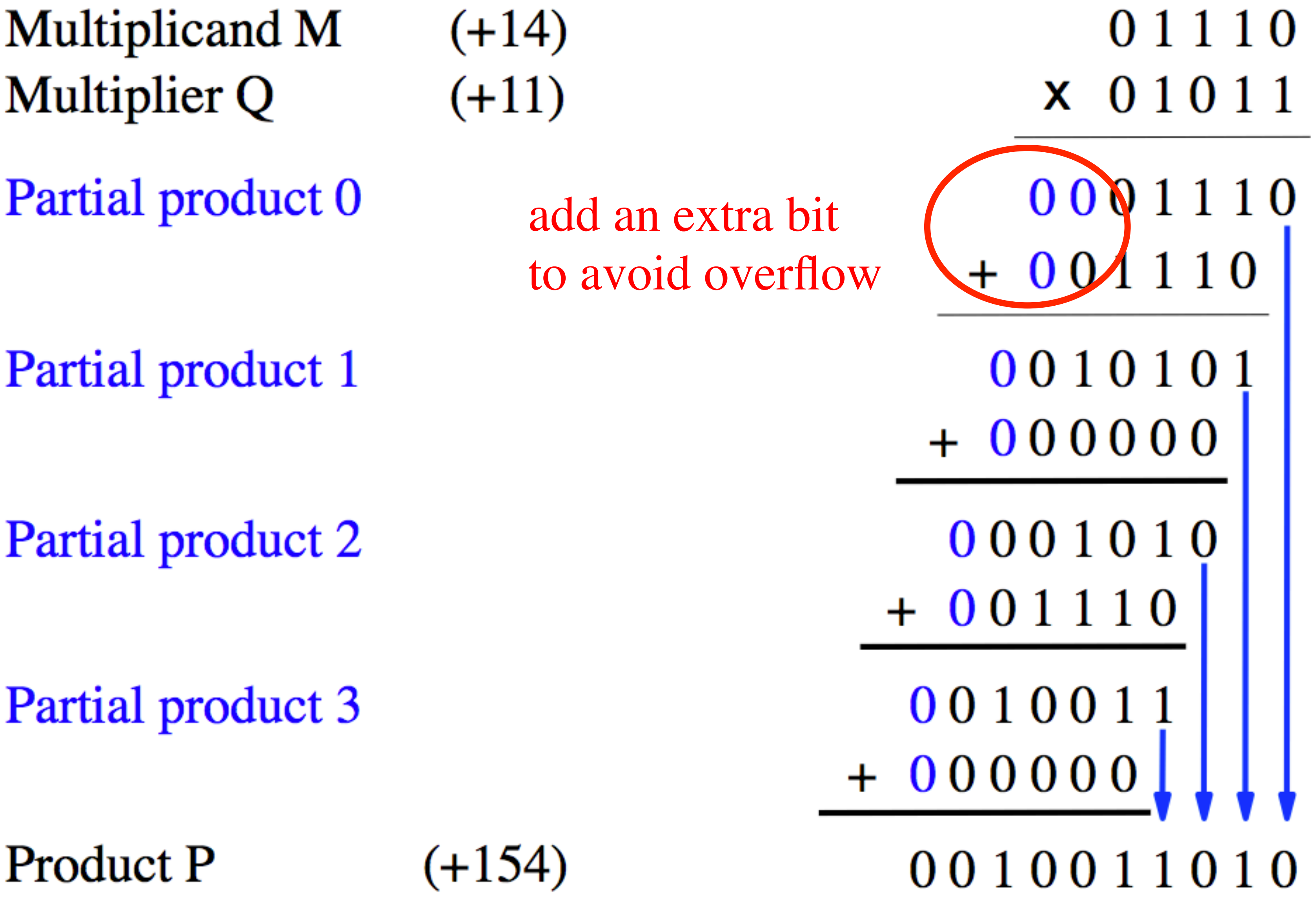
Positive Multiplicand Example



Multiplicand M	(+14)	0 1 1 1 0
Multiplier Q	(+11)	x 0 1 0 1 1
Partial product 0		0 0 0 1 1 1 0
		+ 0 0 1 1 1 0
Partial product 1		0 0 1 0 1 0 1
		+ 0 0 0 0 0 0
Partial product 2		0 0 0 1 0 1 0
		+ 0 0 1 1 1 0
Partial product 3		0 0 1 0 0 1 1
		+ 0 0 0 0 0 0
Product P	(+154)	0 0 1 0 0 1 1 0 1 0

[Figure 3.36a in the textbook]

Positive Multiplicand Example

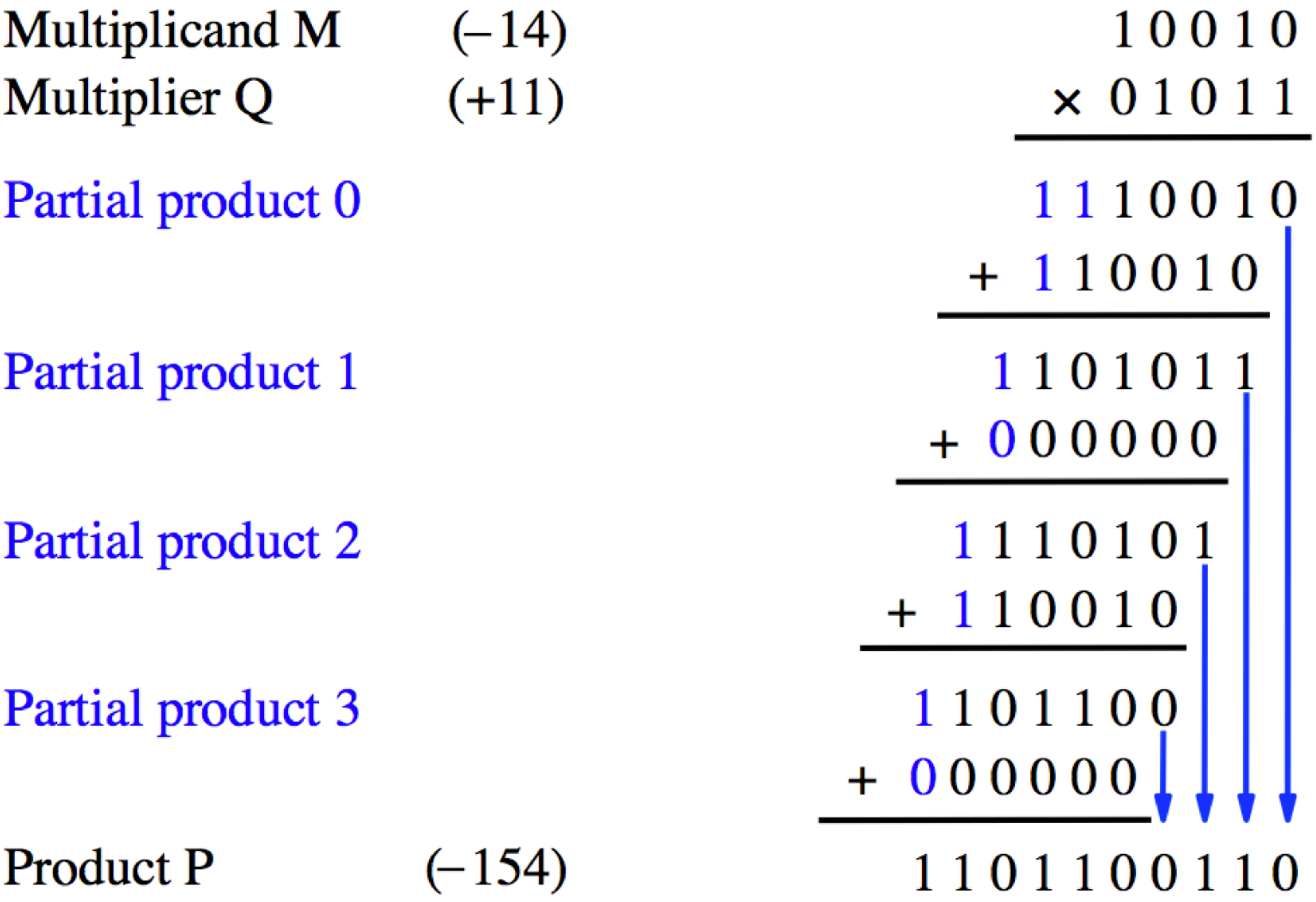


```
Multiplicand M      (+14)              0 1 1 1 0
Multiplier Q        (+11)            x 0 1 0 1 1
                                    -------------
Partial product 0                  0 0 0 1 1 1 0
                                 + 0 0 1 1 1 0
                                 ---------------
Partial product 1                0 0 1 0 1 0 1
                               + 0 0 0 0 0 0
                               ---------------
Partial product 2              0 0 0 1 0 1 0
                             + 0 0 1 1 1 0
                             ---------------
Partial product 3            0 0 1 0 0 1 1
                           + 0 0 0 0 0 0
                           ---------------
Product P          (+154)    0 0 1 0 0 1 1 0 1 0
```

add an extra bit
to avoid overflow

[Figure 3.36a in the textbook]

Negative Multiplicand Example



Multiplicand M (–14) 1 0 0 1 0

Multiplier Q (+11) × 0 1 0 1 1

Partial product 0 1 1 1 0 0 1 0

+ 1 1 0 0 1 0

Partial product 1 1 1 0 1 0 1 1

+ 0 0 0 0 0 0

Partial product 2 1 1 1 0 1 0 1

+ 1 1 0 0 1 0

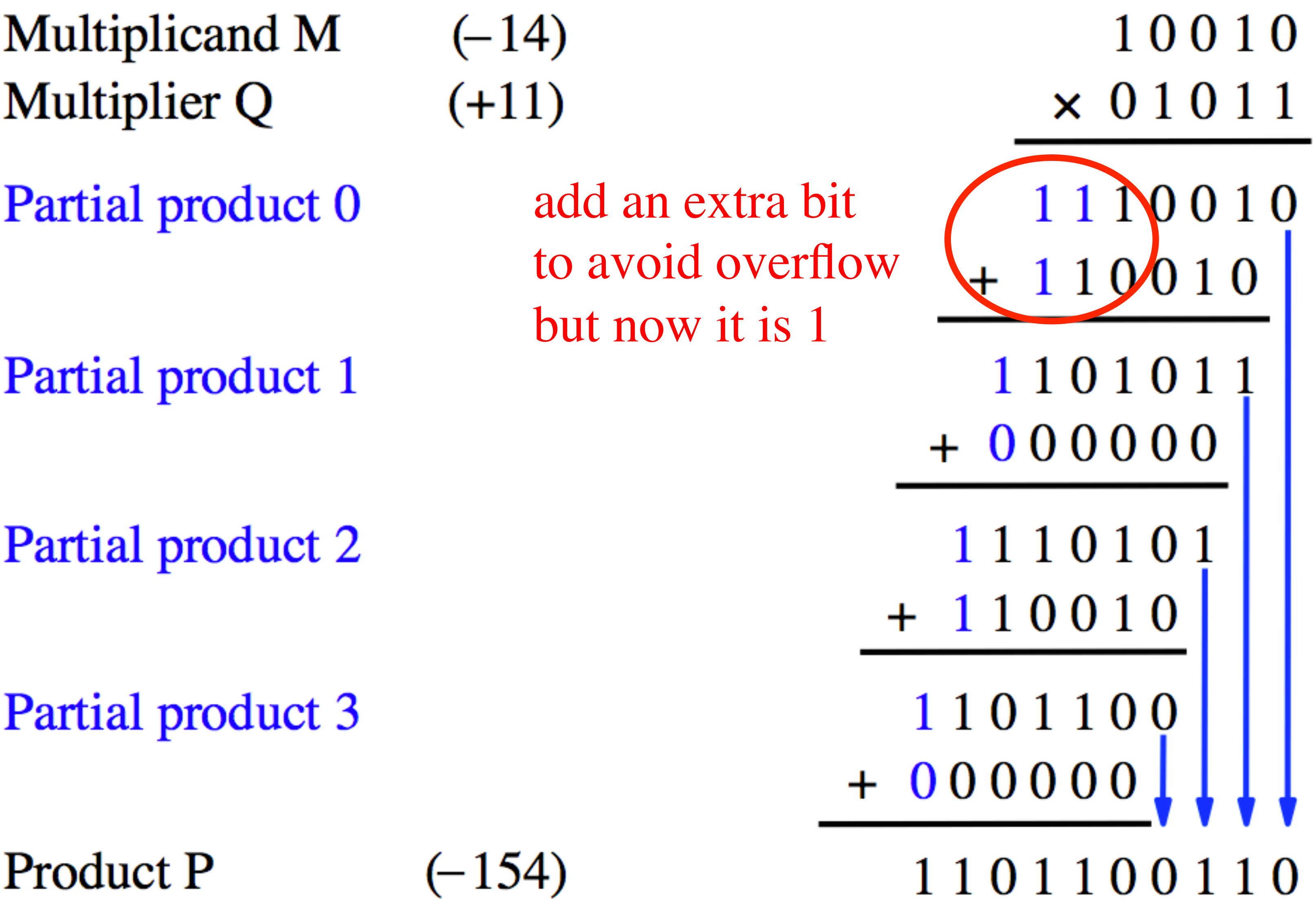
Partial product 3 1 1 0 1 1 0 0

+ 0 0 0 0 0 0

Product P (–154) 1 1 0 1 1 0 0 1 1 0

[Figure 3.36b in the textbook]

Negative Multiplicand Example



```
Multiplicand M      (–14)              1 0 0 1 0
Multiplier Q        (+11)            × 0 1 0 1 1
                                    -------------
Partial product 0                  1 1 1 0 0 1 0
                                 + 1 1 0 0 1 0
                                 -------------
Partial product 1                1 1 0 1 0 1 1
                               + 0 0 0 0 0 0
                               -------------
Partial product 2              1 1 1 0 1 0 1
                             + 1 1 0 0 1 0
                             -------------
Partial product 3            1 1 0 1 1 0 0
                           + 0 0 0 0 0 0
                           -------------
Product P          (–154)    1 1 0 1 1 0 0 1 1 0
```

add an extra bit
to avoid overflow
but now it is 1

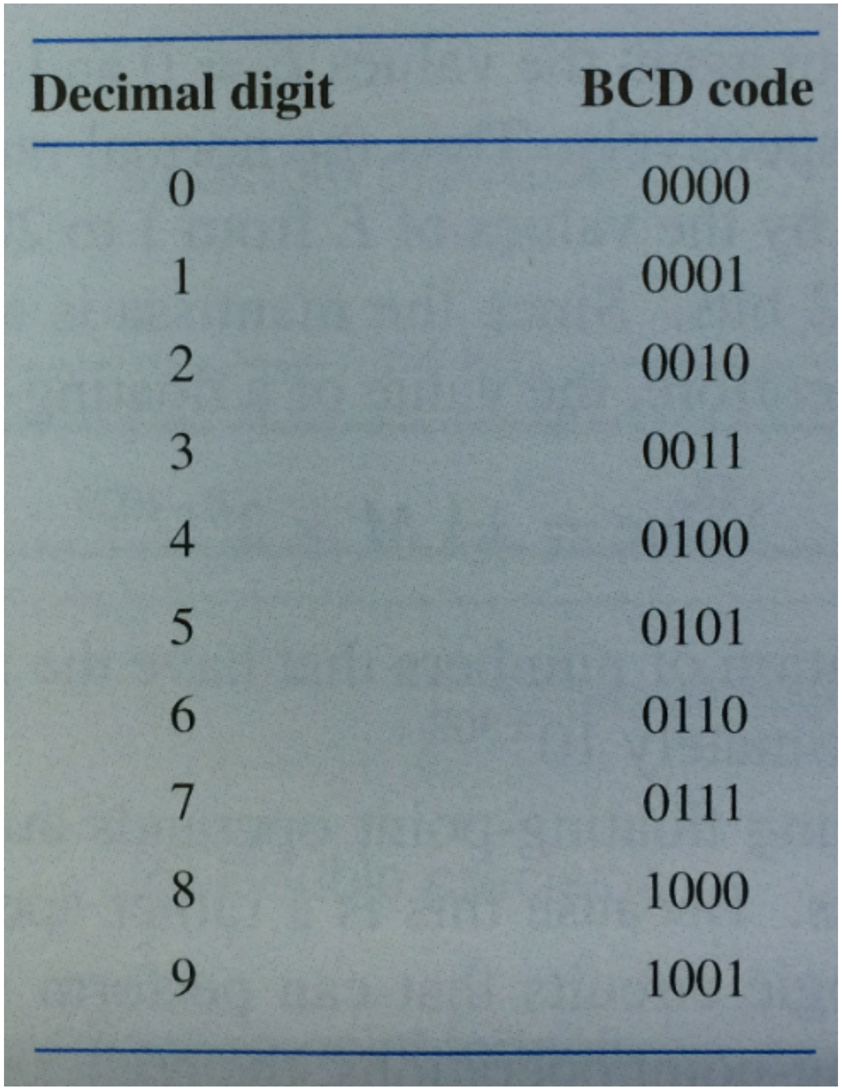
[Figure 3.36b in the textbook]

What if the Multiplier is Negative?

- Convert both to their 2's complement version
- This will make the multiplier positive
- Then Proceed as normal
- This will not affect the result
- Example: 5*(-4) = (-5)*(4)= -20

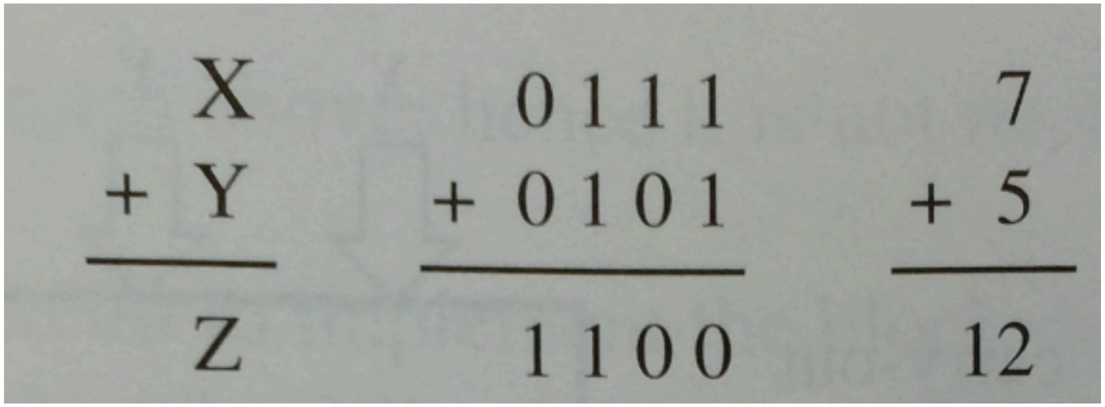
Binary Coded Decimal

Table of Binary-Coded Decimal Digits



Decimal digit	BCD code
0	0000
1	0001
2	0010
3	0011
4	0100
5	0101
6	0110
7	0111
8	1000
9	1001

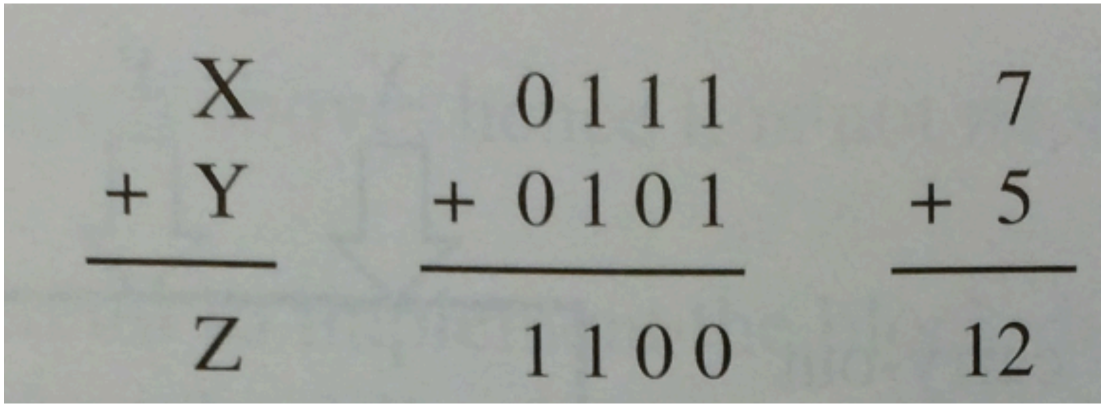
Addition of BCD digits



$$\begin{array}{r} X \\ +\ Y \\ \hline Z \end{array} \qquad \begin{array}{r} 0\,1\,1\,1 \\ +\ 0\,1\,0\,1 \\ \hline 1\,1\,0\,0 \end{array} \qquad \begin{array}{r} 7 \\ +\ 5 \\ \hline 12 \end{array}$$

[Figure 3.38a in the textbook]

Addition of BCD digits

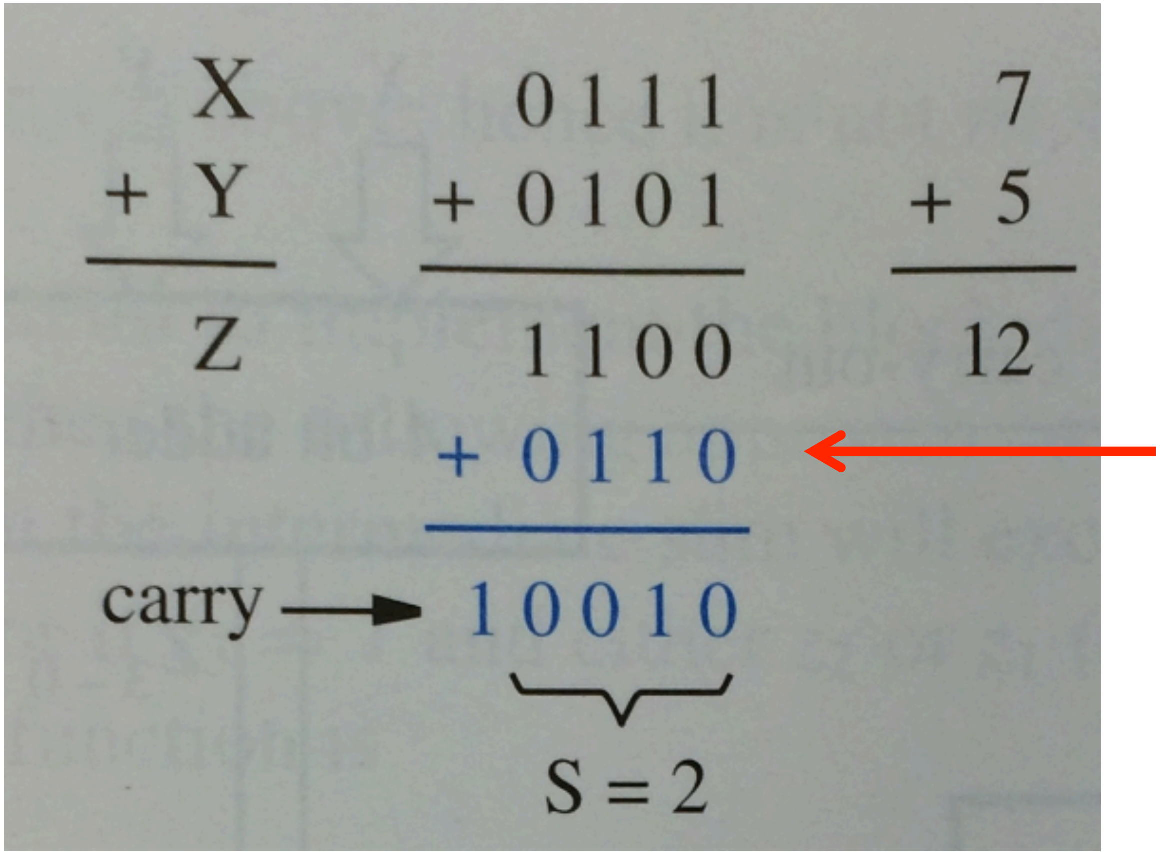


$$\begin{array}{r} X \\ +\ Y \\ \hline Z \end{array} \qquad \begin{array}{r} 0111 \\ +\ 0101 \\ \hline 1100 \end{array} \qquad \begin{array}{r} 7 \\ +\ 5 \\ \hline 12 \end{array}$$

The result is greater than 9, which is not a valid BCD number

[Figure 3.38a in the textbook]

Addition of BCD digits

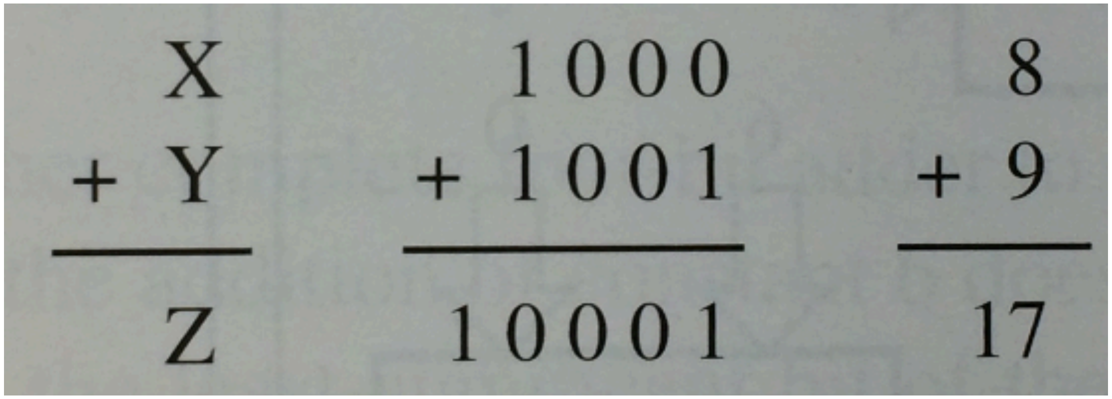


$$\begin{array}{rrr} X & 0111 & 7 \\ +\;Y & +\;0101 & +\;5 \\ \hline Z & 1100 & 12 \\ & +\;0110 & \\ \cline{2-2} \text{carry} \longrightarrow & 1\underbrace{0010}_{S\,=\,2} & \end{array}$$

add 6

[Figure 3.38a in the textbook]

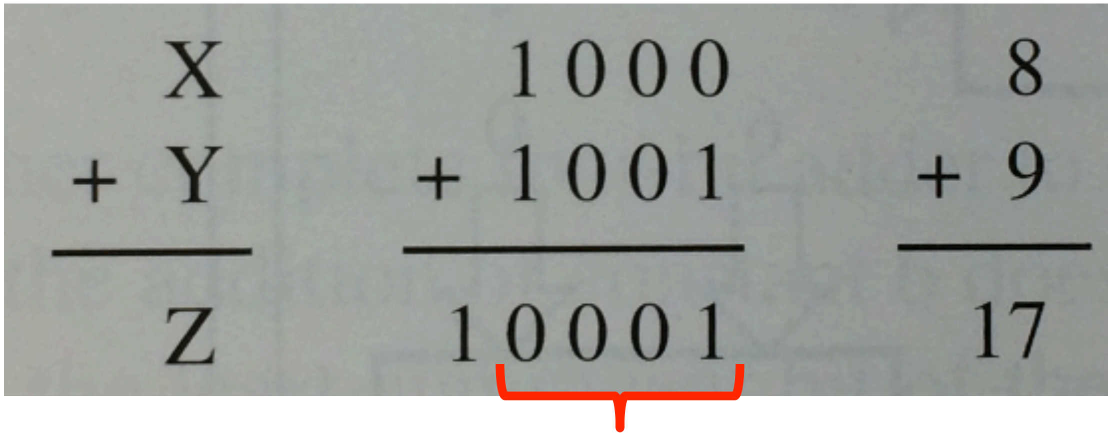
Addition of BCD digits



$$\begin{array}{r} X \\ +\ Y \\ \hline Z \end{array} \qquad \begin{array}{r} 1000 \\ +\ 1001 \\ \hline 10001 \end{array} \qquad \begin{array}{r} 8 \\ +\ 9 \\ \hline 17 \end{array}$$

[Figure 3.38b in the textbook]

Addition of BCD digits

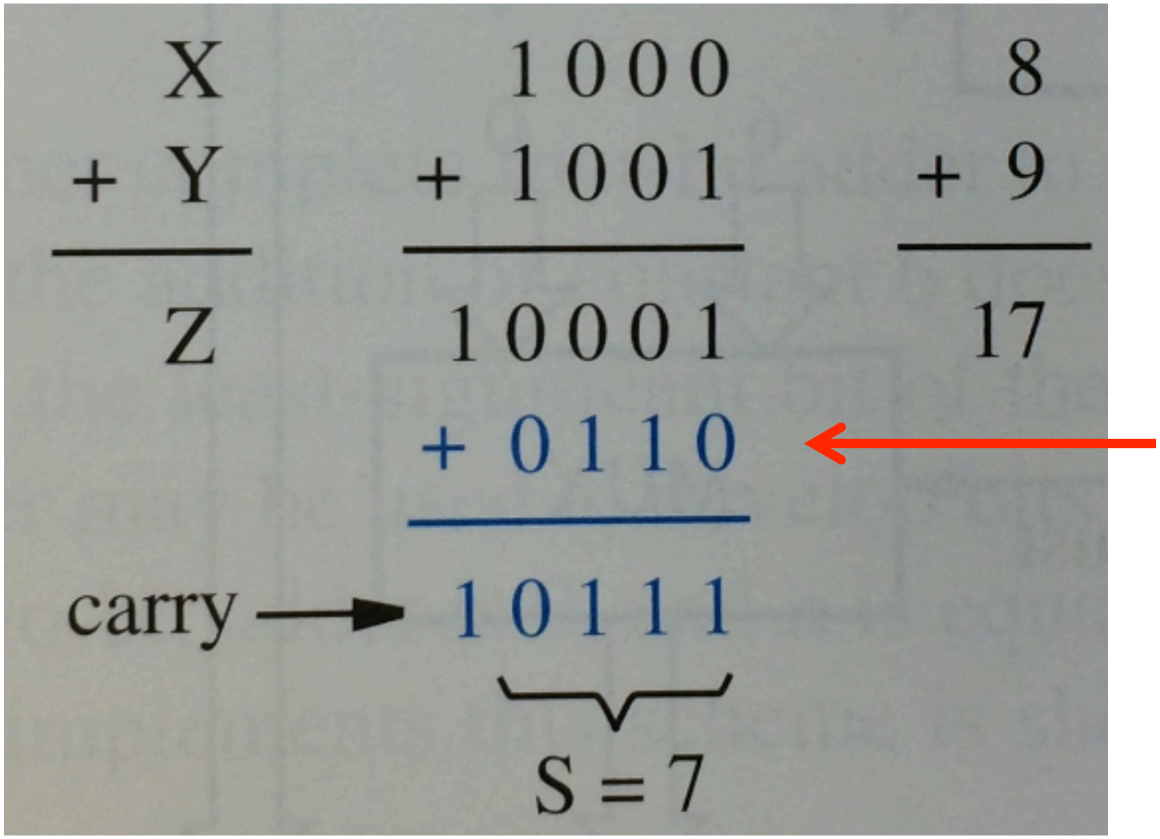


$$\begin{array}{r} X \\ +\ Y \\ \hline Z \end{array} \qquad \begin{array}{r} 1000 \\ +\ 1001 \\ \hline 1\underbrace{0001} \end{array} \qquad \begin{array}{r} 8 \\ +\ 9 \\ \hline 17 \end{array}$$

The result is 1, but it should be 7

[Figure 3.38b in the textbook]

Addition of BCD digits



$$\begin{array}{rrr} X & 1\,0\,0\,0 & 8 \\ +\ Y & +\ 1\,0\,0\,1 & +\ 9 \\ \hline Z & 1\,0\,0\,0\,1 & 17 \\ & +\ 0\,1\,1\,0 & \\ & \text{carry} \longrightarrow 1\,\underbrace{0\,1\,1\,1}_{S\,=\,7} & \end{array}$$

add 6

[Figure 3.38b in the textbook]

Why add 6?

- Think of BCD addition as a mod 16 operation

- Decimal addition is mod 10 operation

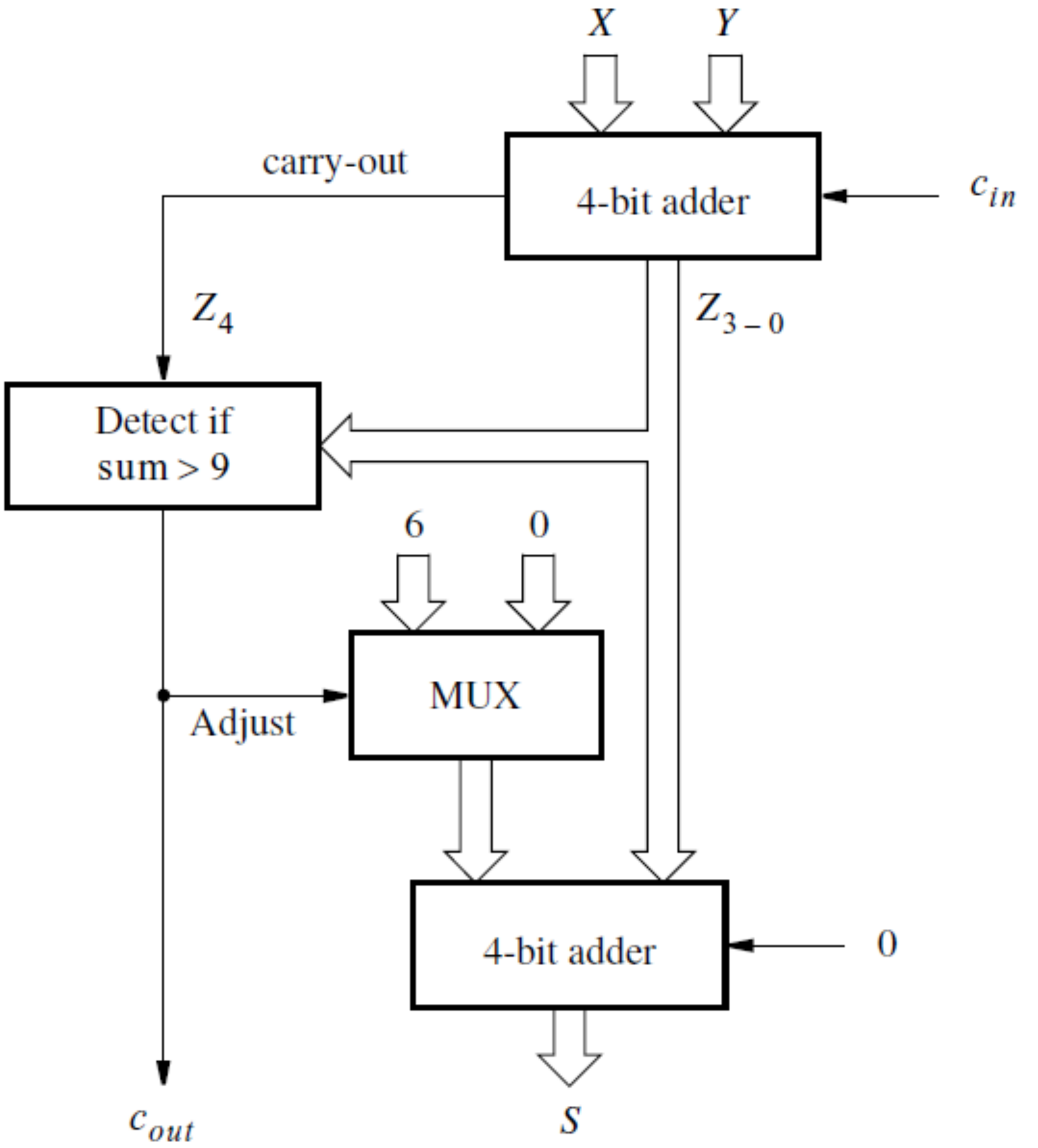
BCD Arithmetic Rules

Z = X + Y

If Z <= 9, then S=Z and carry-out = 0

If Z > 9, then S=Z+6 and carry-out =1

Block diagram for a one-digit BCD adder



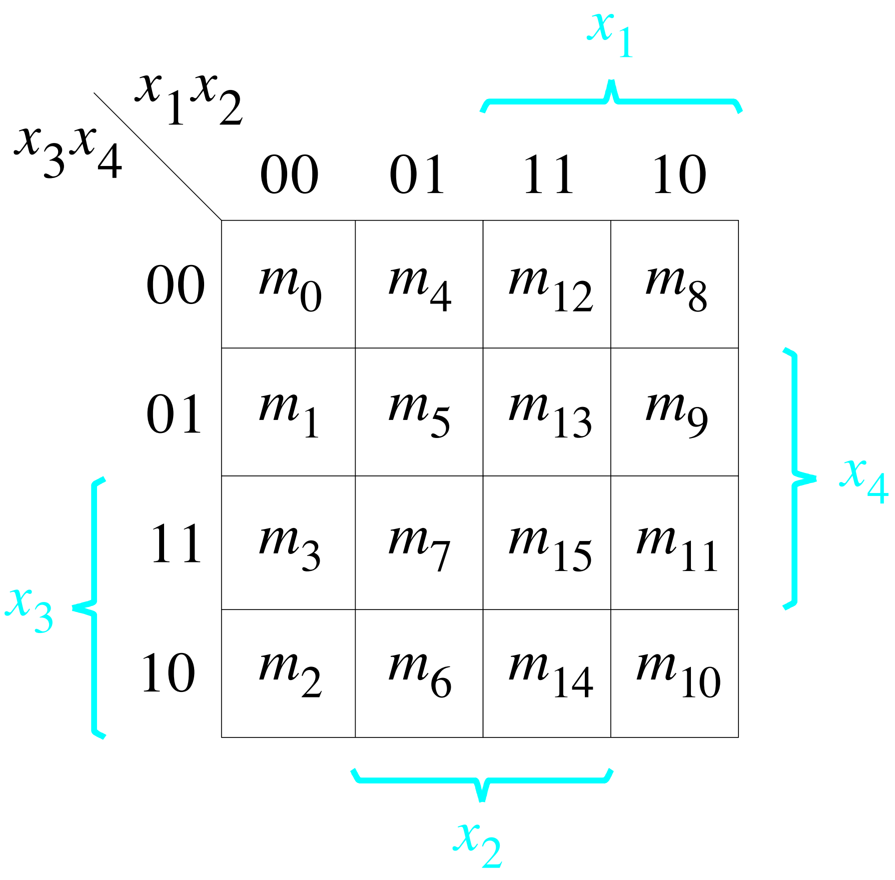
[Figure 3.39 in the textbook]

How to check if the number is > 9?

7	-	0111
8	-	1000
9	-	1001
10	-	1010
11	-	1011
12	-	1100
13	-	1101
14	-	1110
15	-	1111

A four-variable Karnaugh map

x1	x2	x3	x4	
0	0	0	0	m0
0	0	0	1	m1
0	0	1	0	m2
0	0	1	1	m3
0	1	0	0	m4
0	1	0	1	m5
0	1	1	0	m6
0	1	1	1	m7
1	0	0	0	m8
1	0	0	1	m9
1	0	1	0	m10
1	0	1	1	m11
1	1	0	0	m12
1	1	0	1	m13
1	1	1	0	m14
1	1	1	1	m15



x_3x_4 \ x_1x_2	00	01	11	10
00	m_0	m_4	m_{12}	m_8
01	m_1	m_5	m_{13}	m_9
11	m_3	m_7	m_{15}	m_{11}
10	m_2	m_6	m_{14}	m_{10}

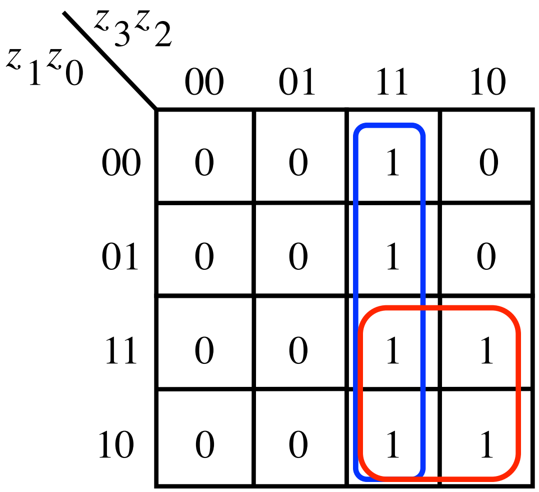
How to check if the number is > 9?

z3	z2	z1	z0	
0	0	0	0	m0
0	0	0	1	m1
0	0	1	0	m2
0	0	1	1	m3
0	1	0	0	m4
0	1	0	1	m5
0	1	1	0	m6
0	1	1	1	m7
1	0	0	0	m8
1	0	0	1	m9
1	0	1	0	m10
1	0	1	1	m11
1	1	0	0	m12
1	1	0	1	m13
1	1	1	0	m14
1	1	1	1	m15

z_1z_0 \ z_3z_2	00	01	11	10
00	0	0	1	0
01	0	0	1	0
11	0	0	1	1
10	0	0	1	1

How to check if the number is > 9?

z3	z2	z1	z0	
0	0	0	0	m0
0	0	0	1	m1
0	0	1	0	m2
0	0	1	1	m3
0	1	0	0	m4
0	1	0	1	m5
0	1	1	0	m6
0	1	1	1	m7
1	0	0	0	m8
1	0	0	1	m9
1	0	1	0	m10
1	0	1	1	m11
1	1	0	0	m12
1	1	0	1	m13
1	1	1	0	m14
1	1	1	1	m15

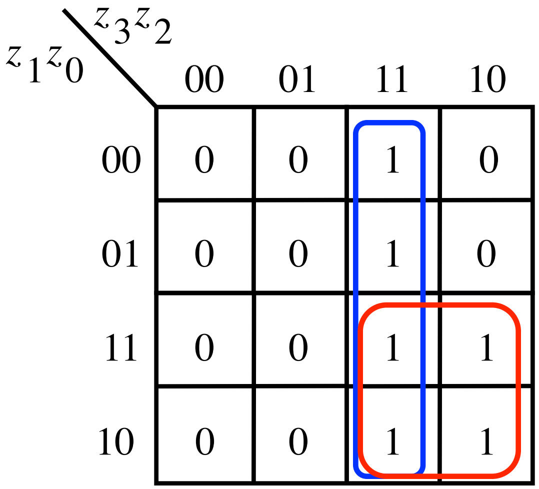


z_1z_0 z_3z_2	00	01	11	10
00	0	0	1	0
01	0	0	1	0
11	0	0	1	1
10	0	0	1	1

$$f = z_3z_2 + z_3z_1$$

How to check if the number is > 9?

z3	z2	z1	z0	
0	0	0	0	m0
0	0	0	1	m1
0	0	1	0	m2
0	0	1	1	m3
0	1	0	0	m4
0	1	0	1	m5
0	1	1	0	m6
0	1	1	1	m7
1	0	0	0	m8
1	0	0	1	m9
1	0	1	0	m10
1	0	1	1	m11
1	1	0	0	m12
1	1	0	1	m13
1	1	1	0	m14
1	1	1	1	m15



z_1z_0 \ z_3z_2	00	01	11	10
00	0	0	1	0
01	0	0	1	0
11	0	0	1	1
10	0	0	1	1

$$f = z_3z_2 + z_3z_1$$

In addition, also check if there was a carry

$$f = \text{carry-out} + z_3z_2 + z_3z_1$$

Verilog code for a one-digit BCD adder

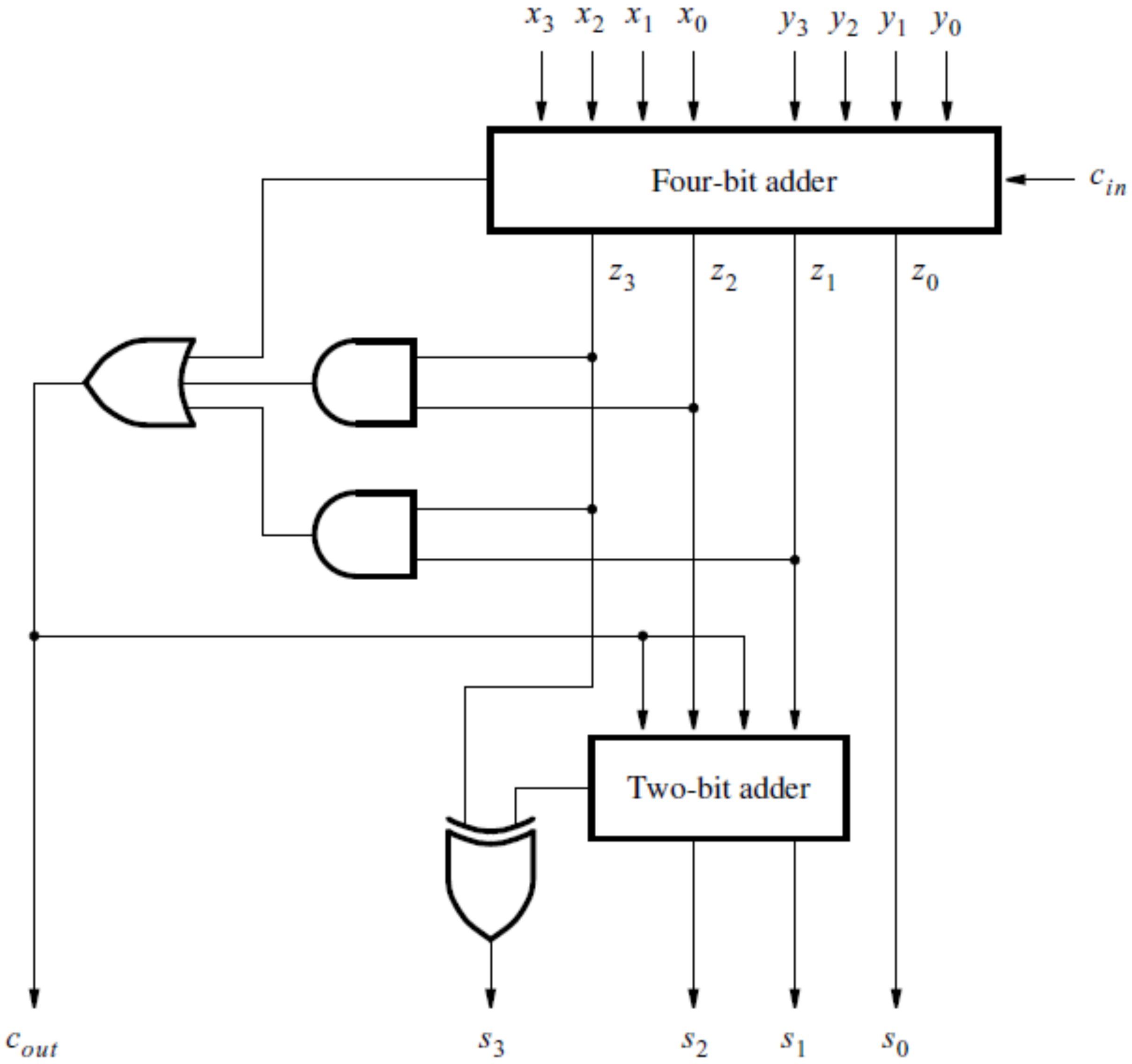
```
module bcdadd(Cin, X, Y, S, Cout);
    input Cin;
    input [3:0] X, Y;
    output reg [3:0] S;
    output reg Cout;
    reg [4:0] Z;

    always @ (X, Y, Cin)
    begin
        Z = X + Y + Cin;
        if (Z < 10)
            {Cout, S} = Z;
        else
            {Cout, S} = Z + 6;
    end

endmodule
```

[Figure 3.40 in the textbook]

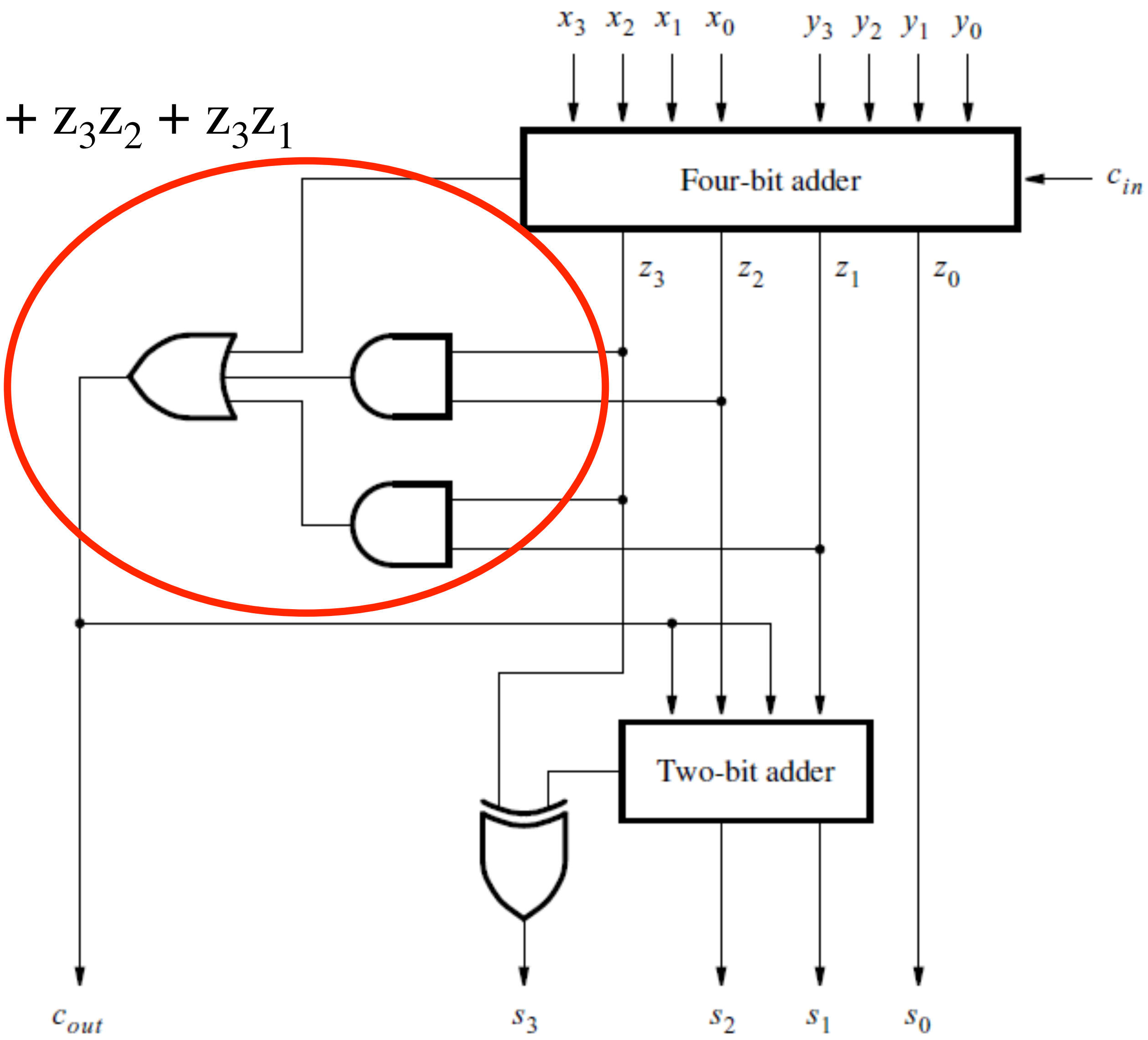
Circuit for a one-digit BCD adder



[Figure 3.41 in the textbook]

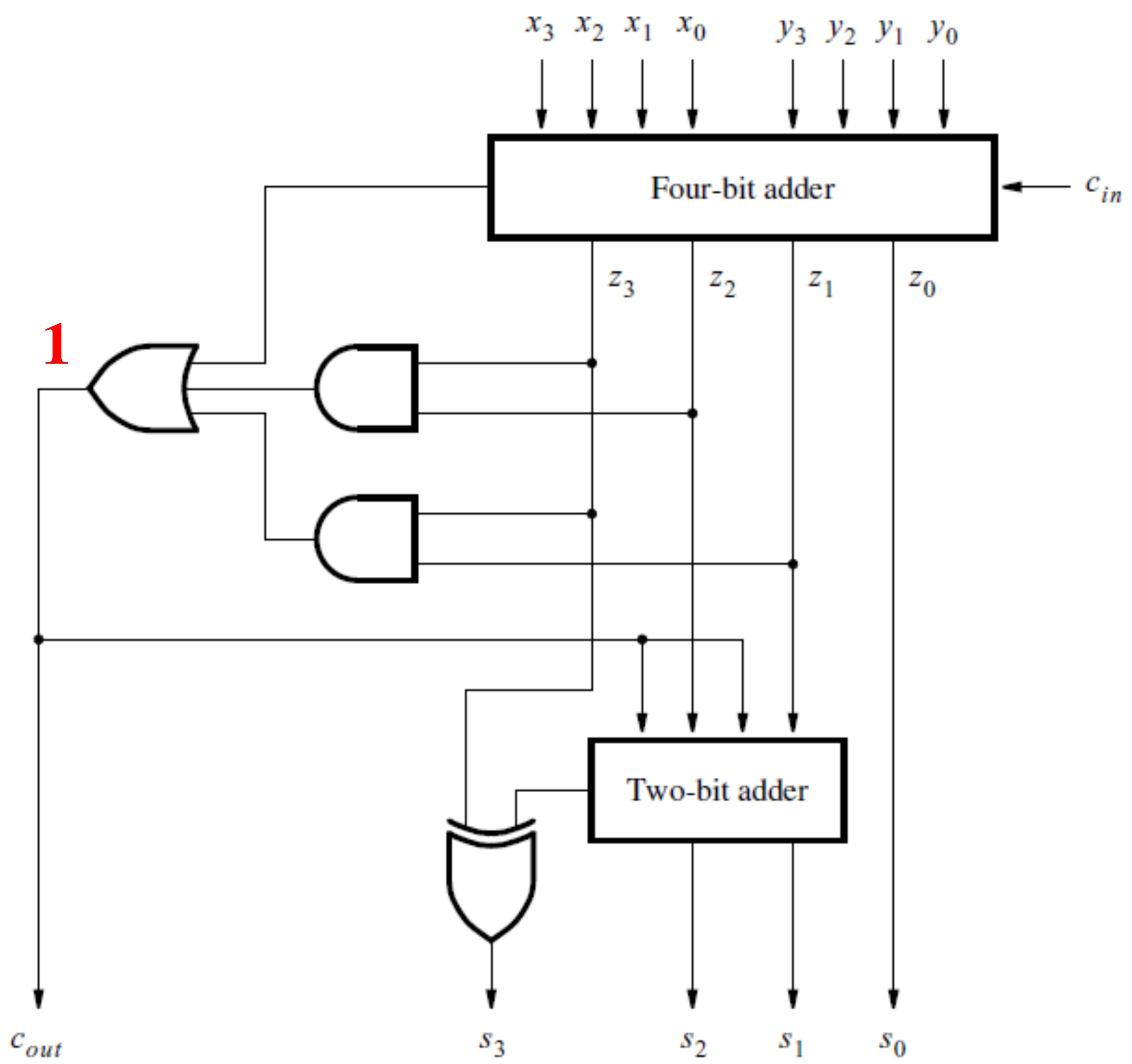
Circuit for a one-digit BCD adder

carry-out + z_3z_2 + z_3z_1



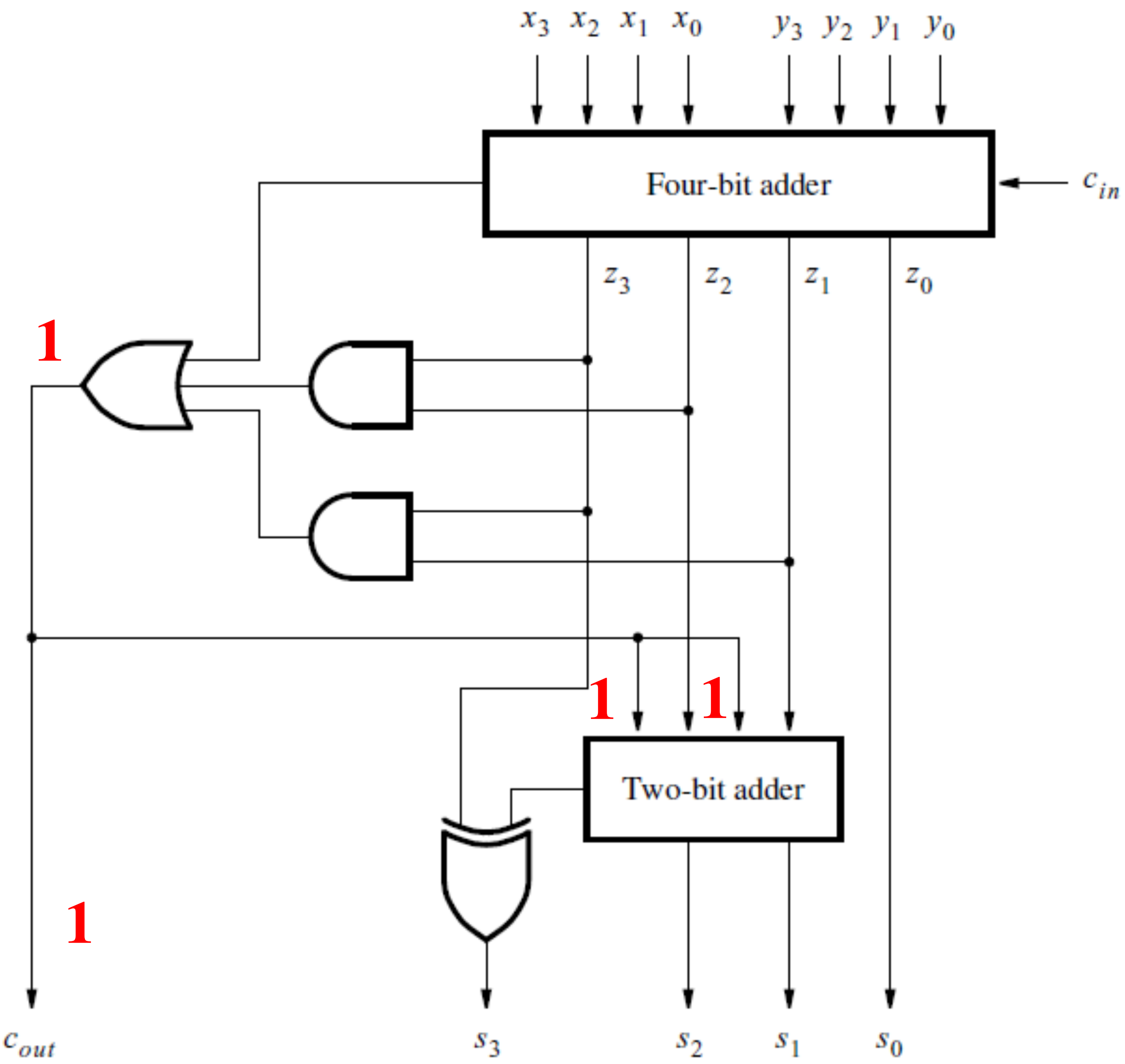
[Figure 3.41 in the textbook]

Circuit for a one-digit BCD adder



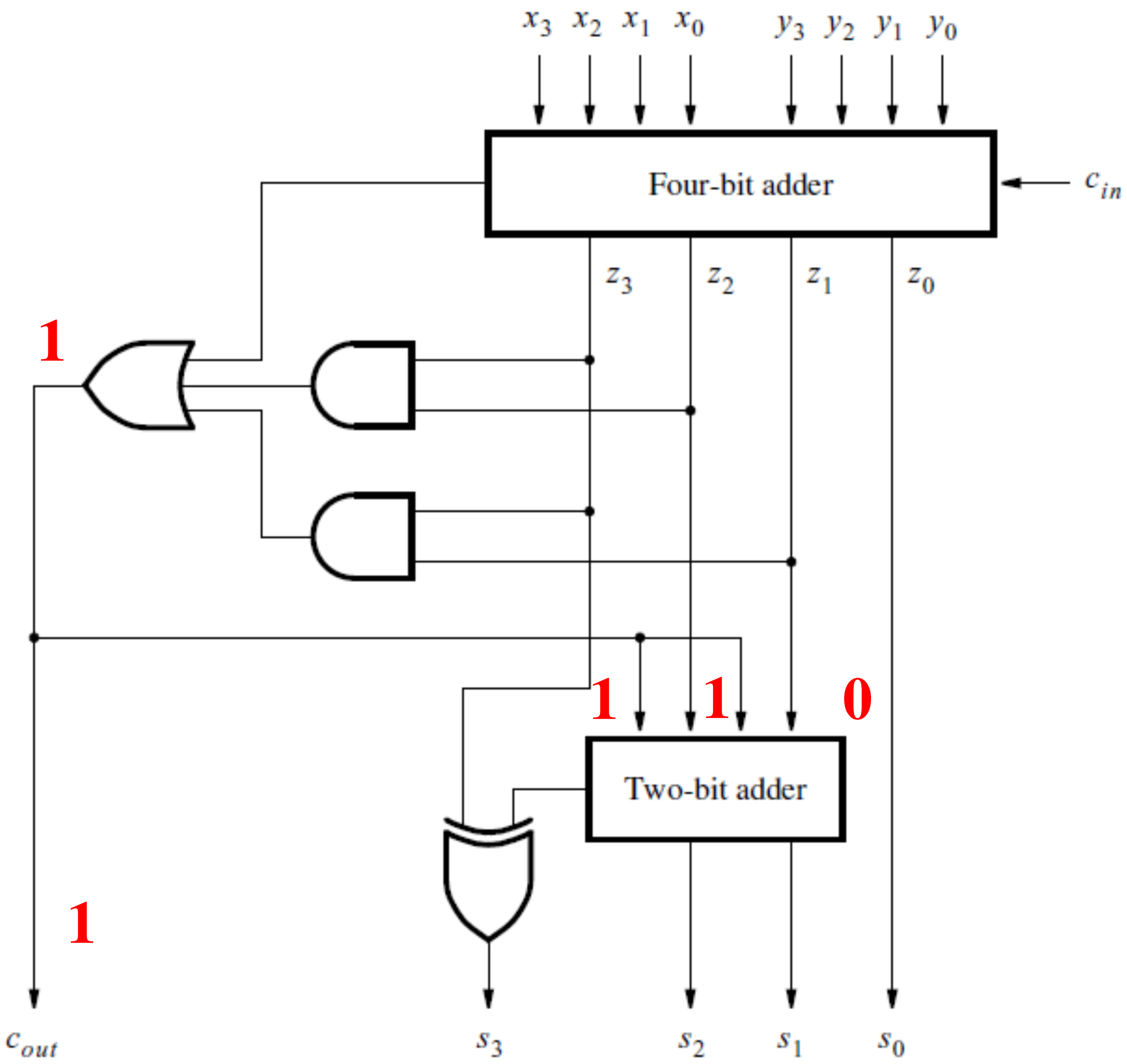
[Figure 3.41 in the textbook]

Circuit for a one-digit BCD adder



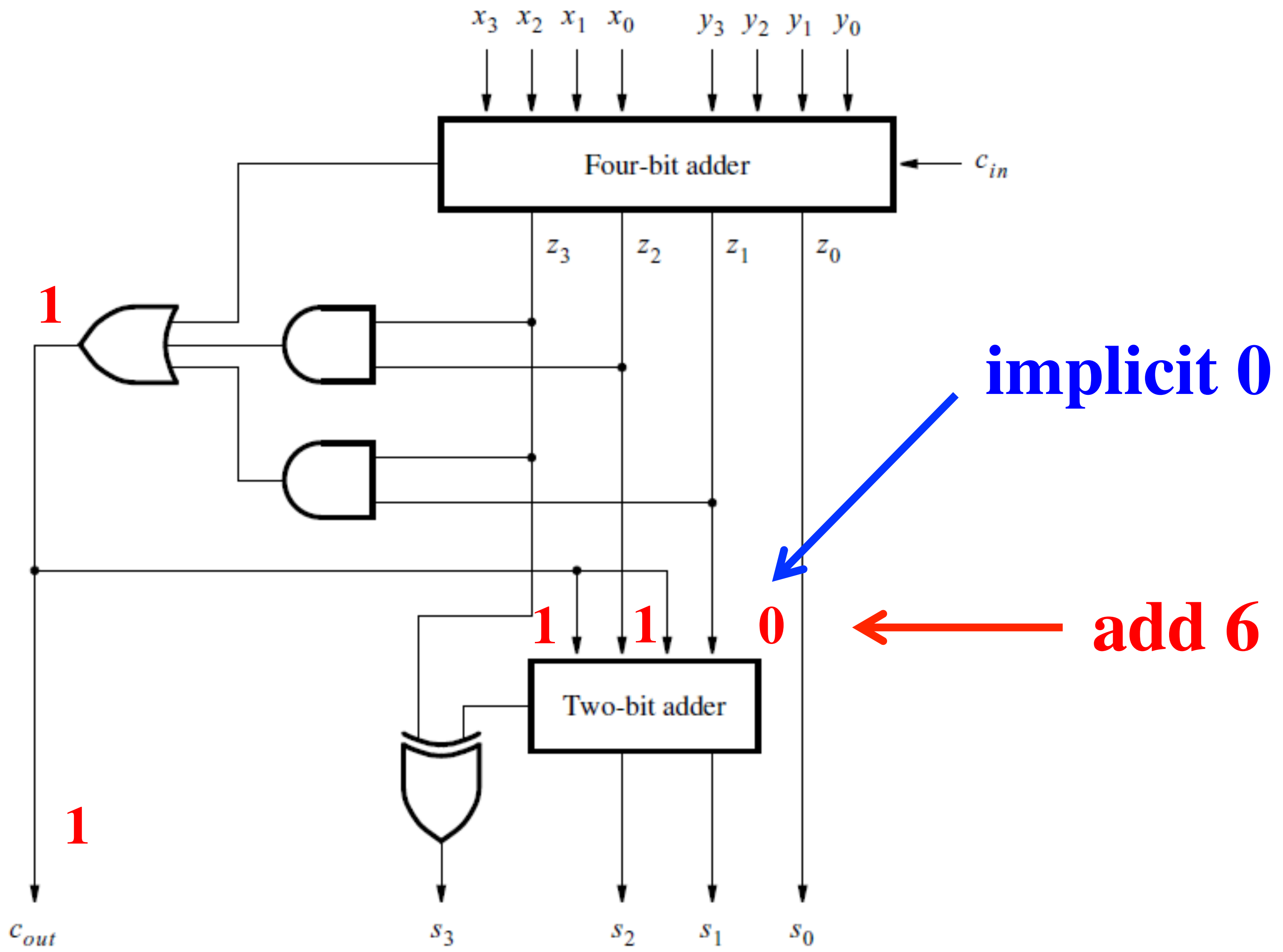
[Figure 3.41 in the textbook]

Circuit for a one-digit BCD adder



[Figure 3.41 in the textbook]

Circuit for a one-digit BCD adder



[Figure 3.41 in the textbook]

Questions?

THE END