

Introduction to Digital Logic

Prof. Nizamettin AYDIN

naydin@yildiz.edu.tr

naydin@ieee.org

1

Course Outline

1. Digital Computers, Number Systems, Arithmetic Operations, Decimal, Alphanumeric, and Gray Codes
2. Binary Logic, Gates, Boolean Algebra, Standard Forms
3. Circuit Optimization, Two-Level Optimization, Map Manipulation, Multi-Level Circuit Optimization
4. Additional Gates and Circuits, Other Gate Types, Exclusive-OR Operator and Gates, High-Impedance Outputs
5. Implementation Technology and Logic Design, Design Concepts and Automation, The Design Space, Design Procedure, The major design steps
6. Programmable Implementation Technologies: Read-Only Memories, Programmable Logic Arrays, Programmable Array Logic, Technology mapping to programmable logic devices
7. Combinational Functions and Circuits
8. **Arithmetic Functions and Circuits**
9. Sequential Circuits Storage Elements and Sequential Circuit Analysis
10. Sequential Circuits, Sequential Circuit Design State Diagrams, State Tables
11. Counters, register cells, buses, & serial operations
12. Sequencing and Control, Datapath and Control, Algorithmic State Machines (ASM)
13. Memory Basics

2

Introduction to Digital Logic

Lecture 8

Arithmetic Functions and Circuits

3

Overview

- Iterative combinational circuits
- Binary adders
 - Half and full adders
 - Ripple carry and carry lookahead adders
- Binary subtraction
- Binary adder-subtractors
 - Signed binary numbers
 - Signed binary addition and subtraction
 - Overflow
- Binary multiplication
- Other arithmetic functions
 - Design by contraction

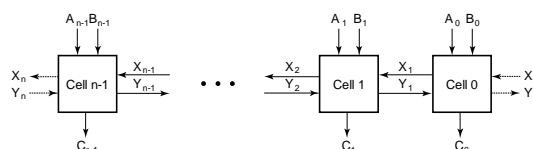
4

Iterative Combinational Circuits

- Arithmetic functions
 - Operate on binary vectors
 - Use the same subfunction in each bit position
- Can design functional block for subfunction and repeat to obtain functional block for overall function
- *Cell* - subfunction block
- *Iterative array* - an array of interconnected cells
- An iterative array can be in a single dimension (1D) or multiple dimensions

5

Block Diagram of a 1D Iterative Array



- Example: $n = 32$
 - Number of inputs = ?
 - Truth table rows = ?
 - Equations with up to ? input variables
 - Equations with huge number of terms
 - Design impractical!
- Iterative array takes advantage of the regularity to make design feasible

6

Functional Blocks: Addition

- Binary addition used frequently
- Addition Development:
 - *Half-Adder (HA)*, a 2-input bit-wise addition functional block,
 - *Full-Adder (FA)*, a 3-input bit-wise addition functional block,
 - *Ripple Carry Adder*, an iterative array to perform binary addition, and
 - *Carry-Look-Ahead Adder (CLA)*, a hierarchical structure to improve performance.

7

Functional Block: Half-Adder

- A 2-input, 1-bit width binary adder that performs the following computations:

	X	0	0	1	1
	+Y	+0	+1	+0	+1
	CS	00	01	01	10

- A half adder adds two bits to produce a two-bit sum

- The sum is expressed as a sum bit, S and a carry bit, C

- The half adder can be specified as a truth table for S and C \Rightarrow

X	Y	C	S
0	0	0	0
0	1	0	1
1	0	0	1
1	1	1	0

8

Logic Simplification: Half-Adder

- The K-Map for S, C is:

- This is a pretty trivial map!
By inspection:

$$S = X \cdot \bar{Y} + \bar{X} \cdot Y = X \oplus Y$$

$$C = (X + Y) \cdot (\bar{X} + \bar{Y})$$

and

$$C = X \cdot Y$$

$$C = \overline{(\bar{X} \cdot \bar{Y})}$$

- These equations lead to several implementations.

S	Y	
	0	1
X	1	0
	2	3

C	Y	
	0	1
X	0	1
	2	3

9

Five Implementations: Half-Adder

- We can derive following sets of equations for a half-adder:

$$(a) S = X \cdot \bar{Y} + \bar{X} \cdot Y \quad (d) S = (X + Y) \cdot \bar{C}$$

$$C = X \cdot Y \quad C = \overline{(\bar{X} + \bar{Y})}$$

$$(b) S = (X + Y) \cdot (\bar{X} + \bar{Y}) \quad (e) S = X \oplus Y$$

$$C = \overline{X \cdot Y} \quad C = X \cdot Y$$

$$(c) S = (C + \bar{X} \cdot \bar{Y})$$

$$C = X \cdot Y$$

- (a), (b), and (e) are SOP, POS, and XOR implementations for S.

- In (c), the C function is used as a term in the AND-NOR implementation of S, and in (d), the \bar{C} function is used in a POS term for S.

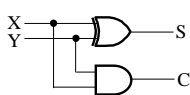
10

Implementations: Half-Adder

- The most common half adder implementation is (e)

$$S = X \oplus Y$$

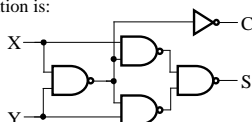
$$C = X \cdot Y$$



- A NAND only implementation is:

$$S = (X + Y) \cdot \bar{C}$$

$$C = \overline{(\bar{X} \cdot \bar{Y})}$$



11

Functional Block: Full-Adder

- A full adder is similar to a half adder, but includes a carry-in bit from lower stages. Like the half-adder, it computes a sum bit, S and a carry bit, C.

- For a carry-in (Z) of 0, it is the same as the half-adder:

Z	0	0	0	0
X	0	0	1	1
+Y	+0	+1	+0	+1
CS	00	01	01	10

- For a carry-in (Z) of 1:

Z	1	1	1	1
X	0	0	1	1
+Y	+0	+1	+0	+1
CS	01	10	10	11

12

Logic Optimization: Full-Adder

- Full-Adder Truth Table:

X	Y	Z	C	S
0	0	0	0	0
0	0	1	0	1
0	1	0	0	1
0	1	1	1	0
1	0	0	0	1
1	0	1	1	0
1	1	0	1	0
1	1	1	1	1

- Full-Adder K-Map:

13

Equations: Full-Adder

- From the K-Map, we get:

$$S = X\bar{Y}\bar{Z} + \bar{X}Y\bar{Z} + \bar{X}\bar{Y}Z + XYZ$$

$$C = XY + XZ + YZ$$

- The S function is the three-bit XOR function (Odd Function):

$$S = X \oplus Y \oplus Z$$

- The Carry bit C is 1 if both X and Y are 1 (the sum is 2), or if the sum is 1 and a carry-in (Z) occurs. Thus C can be re-written as:

$$C = XY + (X \oplus Y)Z$$

- The term $X \cdot Y$ is *carry generate*.
- The term $X \oplus Y$ is *carry propagate*.

14

Implementation: Full Adder

- Full Adder Schematic

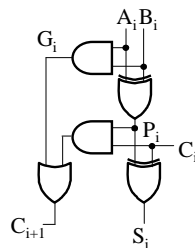
- Here X, Y, and Z, and C (from the previous pages) are A, B, C_i and C_o respectively. Also,

G = generate and
P = propagate.

- Note: This is really a combination of a 3-bit odd function (for S) and Carry logic (for C_o):

(G = Generate) OR (P = Propagate AND C_i = Carry In)

$$C_o = G + P \cdot C_i$$



15

Binary Adders

- To add multiple operands, we "bundle" logical signals together into vectors and use functional blocks that operate on the vectors

- Example: 4-bit ripple carry adder: Adds input vectors A(3:0) and B(3:0) to get a sum vector S(3:0)

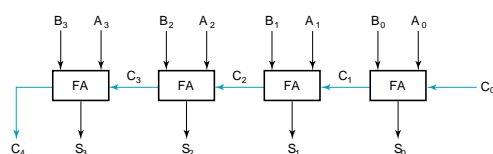
- Note: carry out of cell i becomes carry in of cell i + 1

Description	Subscript	Name
Carry In	3 2 1 0	C_i
Augend	1 0 1 1	A_i
Addend	0 0 1 1	B_i
Sum	1 1 1 0	S_i
Carry out	0 0 1 1	C_{i+1}

16

4-bit Ripple-Carry Binary Adder

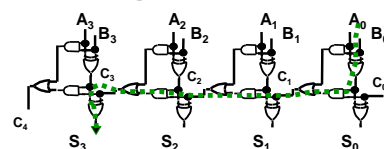
- A four-bit Ripple Carry Adder made from four 1-bit Full Adders:



17

Carry Propagation & Delay

- One problem with the addition of binary numbers is the length of time to propagate the ripple carry from the least significant bit to the most significant bit.
- The gate-level propagation path for a 4-bit ripple carry adder of the last example:

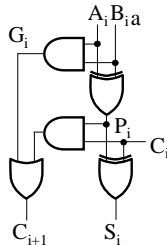


- Note: The "long path" is from A_0 or B_0 through the circuit to S_3 .

18

Carry Lookahead

- Given Stage i from a Full Adder, we know that there will be a carry generated when $A_i = B_i = "1"$, whether or not there is a carry-in.
- Alternately, there will be carry propagated if the "half-sum" is "1" and a carry-in, C_i occurs.
- These two signal conditions are called *generate*, denoted as G_i , and *propagate*, denoted as P_i respectively and are identified in the circuit:



19

Carry Lookahead (continued)

- In the ripple carry adder:
 - G_i , P_i , and S_i are local to each cell of the adder
 - C_i is also local each cell
- In the carry lookahead adder, in order to reduce the length of the carry chain, C_i is changed to a more global function spanning multiple cells
- Defining the equations for the Full Adder in term of the P_i and G_i :

$$P_i = A_i \oplus B_i$$

$$G_i = A_i B_i$$

$$S_i = P_i \oplus C_i$$

$$C_{i+1} = G_i + P_i C_i$$

20

Carry Lookahead Development

- C_{i+1} can be removed from the cells and used to derive a set of carry equations spanning multiple cells.
- Beginning at the cell 0 with carry in C_0 :

$$C_1 = G_0 + P_0 C_0$$

$$C_2 = G_1 + P_1 C_1 = G_1 + P_1(G_0 + P_0 C_0) = G_1 + P_1 G_0 + P_1 P_0 C_0$$

$$C_3 = G_2 + P_2 C_2 = G_2 + P_2(G_1 + P_1 G_0 + P_1 P_0 C_0) = G_2 + P_2 G_1 + P_2 P_1 G_0 + P_2 P_1 P_0 C_0$$

$$C_4 = G_3 + P_3 C_3 = G_3 + P_3 G_2 + P_3 P_2 G_1 + P_3 P_2 P_1 G_0 + P_3 P_2 P_1 P_0 C_0$$

21

Group Carry Lookahead Logic

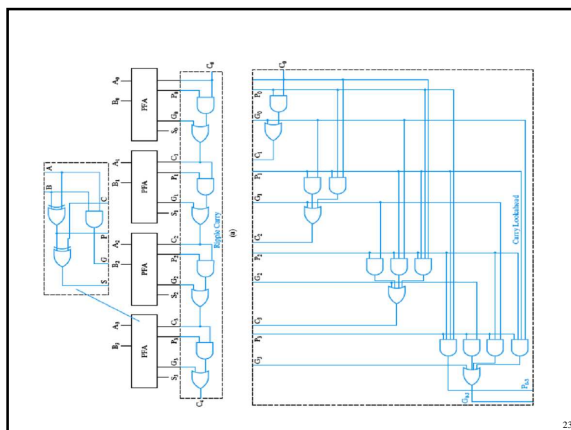
- Figure 5-6 in the text shows the implementation of these equations for four bits. This could be extended to more than four bits; in practice, due to limited gate fan-in, such extension is not feasible.
- Instead, the concept is extended another level by considering *group generate* (G_{0-3}) and *group propagate* (P_{0-3}) functions:

$$G_{0-3} = G_3 + P_3 G_2 + P_3 P_2 G_1 + P_3 P_2 P_1 G_0$$

$$P_{0-3} = P_3 P_2 P_1 P_0$$
- Using these two equations:

$$C_4 = G_{0-3} + P_{0-3} C_0$$
- Thus, it is possible to have four 4-bit adders use one of the same carry lookahead circuit to speed up 16-bit addition

22



23

Unsigned Subtraction

- Algorithm:
 - Subtract the subtrahend N from the minuend M
 - If no end borrow occurs, then $M \geq N$, and the result is a non-negative number and correct.
 - If an end borrow occurs, the $N > M$ and the difference $M - N + 2^n$ is subtracted from 2^n , and a minus sign is appended to the result.

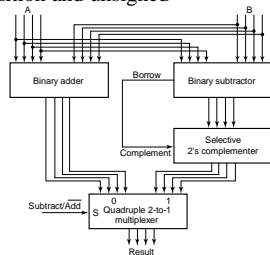
- Examples:

0	1
1001	0100
- 0111	- 0111
0010	1101
	10000
	- 1101
	(-) 0011

24

Unsigned Subtraction (continued)

- The subtraction, $2^n - N$, is taking the 2's complement of N
- To do both unsigned addition and unsigned subtraction requires:
- Quite complex!
- Goal: Shared simpler logic for both addition and subtraction
- Introduce complements as an approach



25

Complements

- Two complements:
 - **Diminished Radix Complement of N**
 - $(r - 1)$'s complement for radix r
 - 1's complement for radix 2
 - Defined as $(r^n - 1) - N$
 - **Radix Complement**
 - r 's complement for radix r
 - 2's complement in binary
 - Defined as $r^n - N$
- Subtraction is done by adding the complement of the subtrahend
- If the result is negative, takes its 2's complement

26

Binary 1's Complement

- For $r = 2$, $N = 01110011_2$, $n = 8$ (8 digits):
 $(r^n - 1) = 256 - 1 = 255_{10}$ or 11111111_2
- The 1's complement of 01110011_2 is then:

$$\begin{array}{r} 11111111 \\ - 01110011 \\ \hline 10001100 \end{array}$$
- Since the $2^n - 1$ factor consists of all 1's and since $1 - 0 = 1$ and $1 - 1 = 0$, the one's complement is obtained by complementing each individual bit (bitwise NOT).

27

Binary 2's Complement

- For $r = 2$, $N = 01110011_2$, $n = 8$ (8 digits), we have:
 $(r^n) = 256_{10}$ or 100000000_2
- The 2's complement of 01110011 is then:

$$\begin{array}{r} 100000000 \\ - 01110011 \\ \hline 10001101 \end{array}$$
- Note the result is the 1's complement plus 1, a fact that can be used in designing hardware

28

Alternate 2's Complement Method

- Given: an n -bit binary number, beginning at the least significant bit and proceeding upward:
 - Copy all least significant 0's
 - Copy the first 1
 - Complement all bits thereafter.
- 2's Complement Example:

$$\begin{array}{r} 10010100 \\ \hline 100 \\ \hline 01101100 \end{array}$$
 - Copy underlined bits:
 - and complement bits to the left:

29

Subtraction with 2's Complement

- For n -digit, unsigned numbers M and N , find $M - N$ in base 2:
 - Add the 2's complement of the subtrahend N to the minuend M :
 $M + (2^n - N) = M - N + 2^n$
 - If $M \geq N$, the sum produces end carry 2^n which is discarded; from above, $M - N$ remains.
 - If $M < N$, the sum does not produce an end carry and, from above, is equal to $2^n - (N - M)$, the 2's complement of $(N - M)$.
 - To obtain the result $-(N - M)$, take the 2's complement of the sum and place a $-$ to its left.

30

Unsigned 2's Complement Subtraction Example 1

- Find $01010100_2 - 01000011_2$

$$\begin{array}{r} 01010100 \\ - 01000011 \\ \hline \end{array} \xrightarrow{\text{2's comp}} \begin{array}{r} 1010100 \\ + 10111101 \\ \hline \end{array}$$

00010001

- The carry of **1** indicates that no correction of the result is required.

31

Unsigned 2's Complement Subtraction Example 2

- Find $01000011_2 - 01010100_2$

$$\begin{array}{r} 01000011 \\ - 01010100 \\ \hline \end{array} \xrightarrow{\text{2's comp}} \begin{array}{r} 01000011 \\ + 10101100 \\ \hline \end{array}$$

11101111 $\xrightarrow{\text{2's comp}}$
00010001

- The carry of **0** indicates that a correction of the result is required.
- Result = $-(00010001)$

32

Subtraction with Diminished Radix Complement

- For n-digit, unsigned numbers M and N, find $M - N$ in base 2:
 - Add the 1's complement of the subtrahend N to the minuend M:
 $M + (2^n - 1 - N) = M - N + 2^n - 1$
 - If $M \geq N$, the result is excess by $2^n - 1$. The end carry 2^n when discarded removes 2^n , leaving a result short by 1. To fix this shortage, whenever an end carry occurs, add 1 in the LSB position. This is called the *end-around carry*.
 - If $M < N$, the sum does not produce an end carry and, from above, is equal to $2^n - 1 - (N - M)$, the 1's complement of $(N - M)$.
 - To obtain the result $-(N - M)$, take the 1's complement of the sum and place a $-$ to its left.

33

Unsigned 1's Complement Subtraction - Example 1

- Find $01010100_2 - 01000011_2$

$$\begin{array}{r} 01010100 \\ - 01000011 \\ \hline \end{array} \xrightarrow{\text{1's comp}} \begin{array}{r} 01010100 \\ + 10111100 \\ \hline \end{array}$$

00010000
+1

00010001

- The end-around carry occurs.

34

Unsigned 1's Complement Subtraction Example 2

- Find $01000011_2 - 01010100_2$

$$\begin{array}{r} 01000011 \\ - 01010100 \\ \hline \end{array} \xrightarrow{\text{1's comp}} \begin{array}{r} 01000011 \\ + 10101011 \\ \hline \end{array}$$

11101110 $\xrightarrow{\text{1's comp}}$
00010001

- The carry of 0 indicates that a correction of the result is required.
- Result = $-(00010001)$

35

Signed Integers

- Positive numbers and zero can be represented by unsigned n-digit, radix r numbers. We need a representation for negative numbers.
- To represent a sign (+ or -) we need exactly one more bit of information (1 binary digit gives $2^1 = 2$ elements which is exactly what is needed).
- Since computers use binary numbers, by convention, the most significant bit is interpreted as a sign bit:

$$s \ a_{n-2} \dots a_2 a_1 a_0$$

where:

- $s = 0$ for Positive numbers
- $s = 1$ for Negative numbers
- and $a_i = 0$ or 1 represent the magnitude in some form.

36

Signed Integer Representations

- *Signed-Magnitude* – here the $n - 1$ digits are interpreted as a positive magnitude.
- *Signed-Complement* – here the digits are interpreted as the rest of the complement of the number. There are two possibilities here:
 - *Signed 1's Complement*
 - Uses 1's Complement Arithmetic
 - *Signed 2's Complement*
 - Uses 2's Complement Arithmetic

37

Signed Integer Representation Example

- $r=2, n=3$

Number	Sign -Mag.	1's Comp.	2's Comp.
+3	011	011	011
+2	010	010	010
+1	001	001	001
+0	000	000	000
-0	100	111	—
-1	101	110	111
-2	110	101	110
-3	111	100	101
-4	—	—	100

38

Signed-Magnitude Arithmetic

- If the parity of the three signs is 0:
 1. Add the magnitudes.
 2. Check for overflow (a carry out of the MSB)
 3. The sign of the result is the same as the sign of the first operand.
- If the parity of the three signs is 1:
 1. Subtract the second magnitude from the first.
 2. If a borrow occurs:
 - take the two's complement of result
 - and make the result sign the complement of the sign of the first operand.
 3. Overflow will never occur.

39

Sign-Magnitude Arithmetic Examples

- Example 1: $0010 (+2)$
 $+0101 (+5)$
 $0111 (7)$
 $1(\text{borrow})$
- Example 2: $0010 (+2)$
 $+1101 (-5)$
 $1101 \Rightarrow 2s \text{ comp} \Rightarrow 1011 (-3)$
- Example 3: $1010 (-2)$
 $-0101 (-5)$
 $1111 (-7)$

40

Signed-Complement Arithmetic

- Addition:
 1. Add the numbers including the sign bits, discarding a carry out of the sign bits (2's Complement), or using an end-around carry (1's Complement).
 2. If the sign bits were the same for both numbers and the sign of the result is different, an overflow has occurred.
 3. The sign of the result is computed in step 1.
- Subtraction:
 - Form the complement of the number you are subtracting and follow the rules for addition.

41

Signed 2's Complement Examples

- Example 1: $1101 (-3)$
 $+0011 (+3)$
 $10000 (0)$
- Example 2: $1101 (-3)$ $1101 (-3)$
 $-0011 (-+3)$ $1101 (-3)$
 $1010 (-6)$ $11010 (-6)$

42

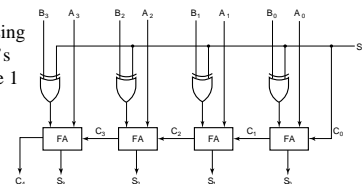
Signed 1's Complement Examples

- Example 1: 1101 (-2)
 $+0011$ (+3)
 $10000 \Rightarrow 0000+1 \Rightarrow 0001$
- Example 2: 1101 (-2)
 -0011 -(+3)
 1010 (-5)

43

2's Complement Adder/Subtractor

- Subtraction can be done by addition of the 2's Complement.
 1. Complement each bit (1's Complement.)
 2. Add 1 to the result.
- The circuit shown computes $A + B$ and $A - B$:
- For $S = 1$, subtract, the 2's complement of B is formed by using XORs to form the 1's comp and adding the 1 applied to C_0 .
- For $S = 0$, add, B is passed through unchanged



44

Overflow Detection

- Overflow occurs if $n + 1$ bits are required to contain the result from an n -bit addition or subtraction
- Overflow can occur for:
 - Addition of two operands with the same sign
 - Subtraction of operands with different signs
- Signed number overflow cases with correct result sign

0	0	1	1
+0	-1	-0	+1
0	0	1	1
- Detection can be performed by examining the result signs which should match the signs of the top operand

45

Overflow Detection

- Signed number cases with carries C_n and C_{n-1} shown for correct result signs:

00	00	11	11
0	0	1	1
+0	-1	-0	+1
0	0	1	1
- Signed number cases with carries shown for erroneous result signs (indicating overflow):

01	01	10	10
0	0	1	1
+0	-1	-0	+1
1	1	0	0
- Simplest way to implement overflow $V = C_n \oplus C_{n-1}$
- This works correctly only if 1's complement and the addition of the carry in of 1 is used to implement the complementation! Otherwise fails for $-10 \dots 0$

46

Binary Multiplication

- The binary digit multiplication table is trivial:

$(a \times b)$	$b = 0$	$b = 1$
$a = 0$	0	0
$a = 1$	0	1
- This is simply the Boolean AND function.
- Form larger products the same way we form larger products in base 10.

47

Review - Decimal Example: $(237 \times 149)_{10}$

- Partial products are: 237×9 , 237×4 , and 237×1
- Note that the partial product summation for n digit, base 10 numbers requires adding up to n digits (with carries).

		2	3	7
\times	1	4	9	
	2	1	3	3
	9	4	8	-
	+	2	3	7
	3	5	3	1
- Note also $n \times m$ digit multiply generates up to an $m + n$ digit result.

48

Binary Multiplication Algorithm

- We execute radix 2 multiplication by:
 - Computing partial products, and
 - Justifying and summing the partial products. (same as decimal)
- To compute partial products:
 - Multiply the row of multiplicand digits by each multiplier digit, one at a time.
 - With binary numbers, partial products are very simple! They are either:
 - all zero (if the multiplier digit is zero), or
 - the same as the multiplicand (if the multiplier digit is one).
- Note: No carries are added in partial product formation!

49

Example: (101 x 011) Base 2

- Partial products are: 101×1 , 101×1 , and 101×0
- Note that the partial product summation for n digit, base 2 numbers requires adding up to n digits (with carries) in a column.
- Note also $n \times m$ digit multiply generates up to an $m + n$ digit result (same as decimal).

$$\begin{array}{r}
 101 \\
 \times 011 \\
 \hline
 101 \\
 000 \\
 101 \\
 \hline
 00111
 \end{array}$$

50

Multiplier Boolean Equations

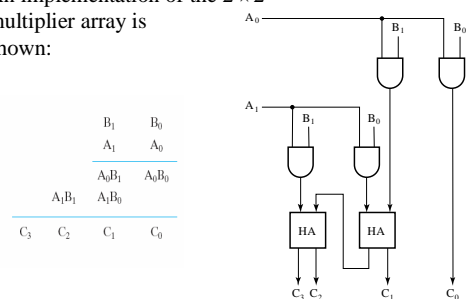
- We can also make an $n \times m$ "block" multiplier and use that to form partial products.
- Example: 2×2 – The logic equations for each partial-product binary digit are shown below:
- We need to "add" the columns to get the product bits P0, P1, P2, and P3.
- Note that some columns may generate carries.

$$\begin{array}{r}
 b_1 b_0 \\
 \times a_1 a_0 \\
 \hline
 (a_0 \cdot b_1) (a_0 \cdot b_0) \\
 + (a_1 \cdot b_1) (a_1 \cdot b_0) \\
 \hline
 P_3 P_2 P_1 P_0
 \end{array}$$

51

Multiplier Arrays Using Adders

- An implementation of the 2×2 multiplier array is shown:

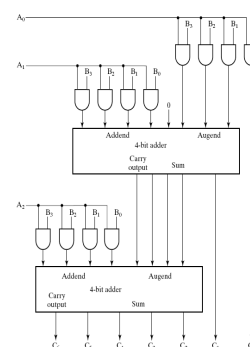


52

Multiplier Using Wide Adders

- A more "structured" way to develop an $n \times m$ multiplier is to sum partial products using adder trees
- The partial products are formed using an $n \times m$ array of AND gates
- Partial products are summed using $m - 1$ adders of width n bits
- Example: 4-bit by 3-bit adder
- Following figure shows a $4 \times 3 = 12$ element array of AND gates and two 4-bit adders

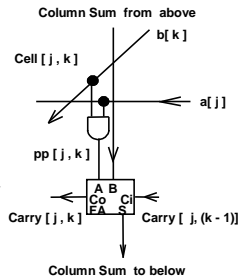
53



54

Cellular Multiplier Array

- Another way to implement multipliers is to use an $n \times m$ cellular array structure of uniform elements as shown:
- Each element computes a single bit product equal to $a_i \cdot b_j$, and implements a single bit full adder



55

Other Arithmetic Functions

- Convenient to design the functional blocks by *contraction* - removal of redundancy from circuit to which input fixing has been applied
- Functions
 - Incrementing
 - Decrementing
 - Multiplication by Constant
 - Division by Constant
 - Zero Fill and Extension

56

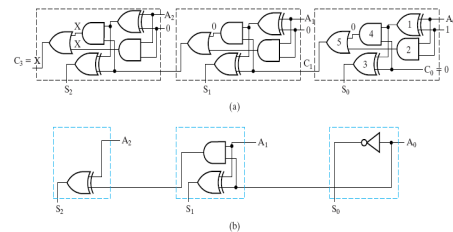
Design by Contraction

- Contraction is a technique for simplifying the logic in a functional block to implement a different function
 - The new function must be realizable from the original function by applying rudimentary functions to its inputs
 - Contraction is treated here only for application of 0s and 1s (not for X and \bar{X})
 - After application of 0s and 1s, equations or the logic diagram are simplified by using rules given on pages 224 - 225 of the text.

57

Design by Contraction Example

- Contraction of a ripple carry adder to incrementer for $n = 3$
 - Set $B = 001$



- The middle cell can be repeated to make an incrementer with $n > 3$.

58

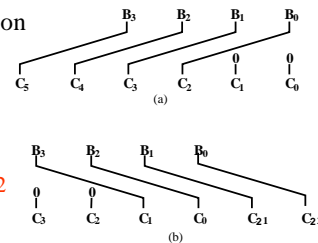
Incrementing & Decrementing

- Incrementing**
 - Adding a fixed value to an arithmetic variable
 - Fixed value is often 1, called *counting (up)*
 - Examples: $A + 1$, $B + 4$
 - Functional block is called *incrementer*
- Decrementing**
 - Subtracting a fixed value from an arithmetic variable
 - Fixed value is often 1, called *counting (down)*
 - Examples: $A - 1$, $B - 4$
 - Functional block is called *decrementer*

59

Multiplication/Division by 2^n

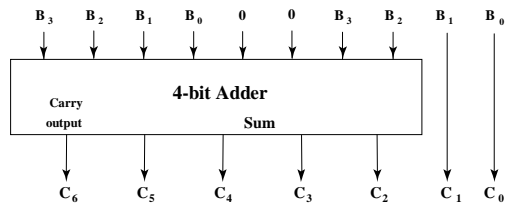
- (a) Multiplication by 100
 - Shift left by 2
- (b) Division by 100
 - Shift right by 2
 - Remainder preserved



60

Multiplication by a Constant

- Multiplication of B(3:0) by 101
- See text Figure 5-13 (a) for contraction



61

Zero Fill

- *Zero fill* - filling an m -bit operand with 0s to become an n -bit operand with $n > m$
- Filling usually is applied to the MSB end of the operand, but can also be done on the LSB end
- Example: 11110101 filled to 16 bits

– MSB end: 0000000011110101

– LSB end: 1111010100000000

62

Extension

- *Extension* - increase in the number of bits at the MSB end of an operand by using a complement representation
 - Copies the MSB of the operand into the new positions
 - Positive operand example - 01110101 extended to 16 bits:

0000000001110101
 - Negative operand example - 11110101 extended to 16 bits:

1111111111110101

63