ELECTRICAL ENGINEERING
UNIVERSITY *of* WASHINGTON

Lecture 15: Multipliers

Based on material prepared by prof. Visvesh S. Sathe

ELECTRICAL & COMPUTER ENGINEERING

Acknowledgements

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UW (2013-2022)
GaTech (2022-present)

Roadmap for today

- Unsigned multiplication
- Signed multiplication (Baugh-Wooley)
- Booth encoding to improve performance
- Prefix computation…. **again?!!**

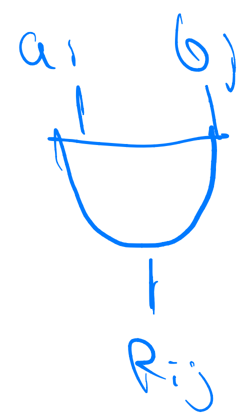
Multipliers

- How do you multiply binary numbers?

```
      1 0 1 1
        1 0 1
    ---------
      1 0 1 1
    0 0 0 0
  1 0 1 1
-------------
  1 1 0 1 1 1
```

```
  11
x  5
----

----
  55
```



1	1	1
1	0	0
0	1	0
0	0	0

- Multiplication
  - Generate partial products
  - Sum partial products together
  - M X N multiplication → M+N bit result

Multiplication

- Given multiplicand Y = $y_{n-1}\ y_{n-2}\ y_{n-3}\ \ldots\ y_1\ y_0$
- Given multiplicand X = $x_{m-1}\ x_{n-2}\ x_{n-3}\ \ldots\ x_1\ x_0$
- $X \times Y = \left(\sum_{i=0}^{m-1} x_i 2^i\right)\left(\sum_{j=0}^{n-1} y_j 2^j\right) = \sum_{i=0}^{m-1}\sum_{j=0}^{n-1} x_i y_j 2^{i+j}$
- In the case m=5, n=5

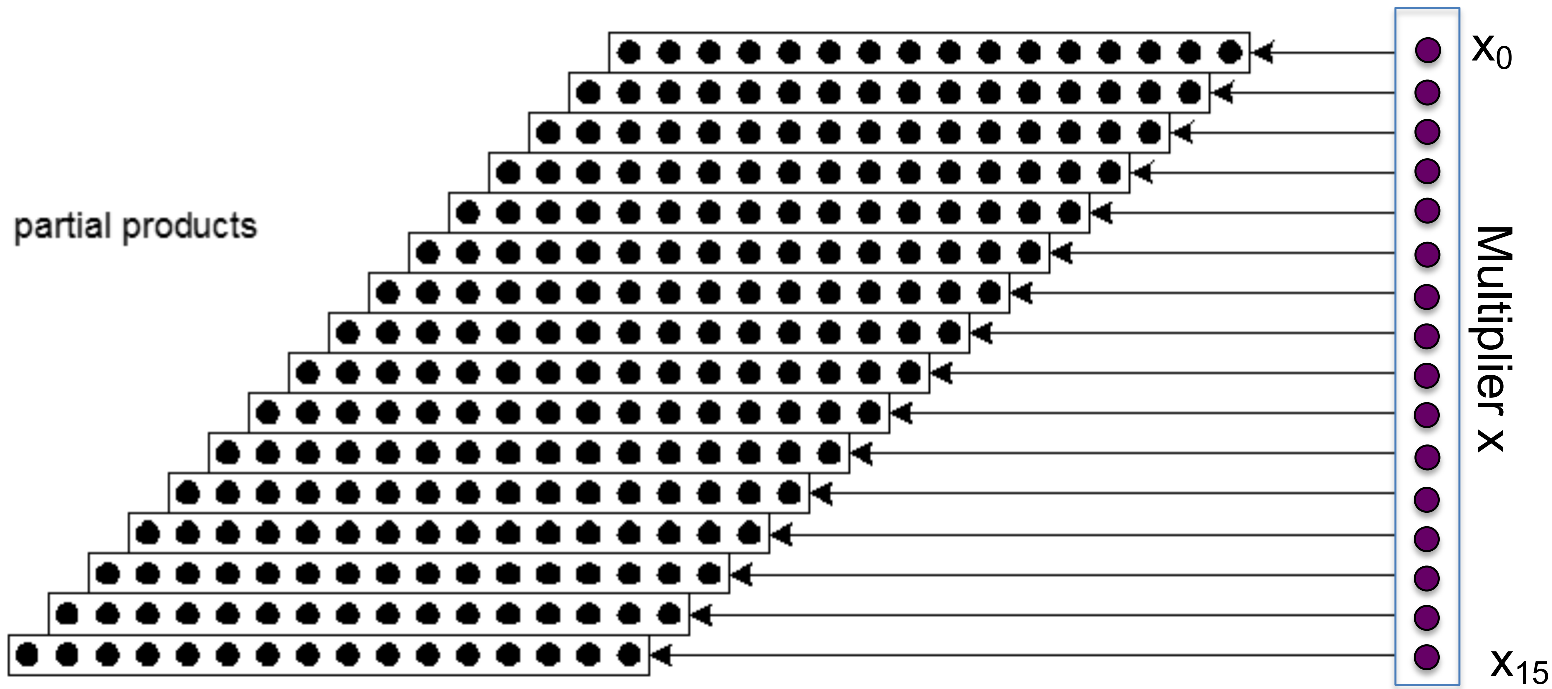
						y_5	y_4	y_3	y_2	y_1	y_0	Multiplicand
						x_5	x_4	x_3	x_2	x_1	x_0	Multiplier
						x_0y_5	x_0y_4	x_0y_3	x_0y_2	x_0y_1	x_0y_0	Partial Products
					x_1y_5	x_1y_4	x_1y_3	x_1y_2	x_1y_1	x_1y_0		
				x_2y_5	x_2y_4	x_2y_3	x_2y_2	x_2y_1	x_2y_0			
			x_3y_5	x_3y_4	x_3y_3	x_3y_2	x_3y_1	x_3y_0				
		x_4y_5	x_4y_4	x_4y_3	x_4y_2	x_4y_1	x_4y_0					
	x_5y_5	x_5y_4	x_5y_3	x_5y_2	x_5y_1	x_5y_0						
p_{11}	p_{10}	p_9	p_8	p_7	p_6	p_5	p_4	p_3	p_2	p_1	p_0	Products

Source: Weste-Harris

Dot Diagram

y $y_2 y_1 y_0$

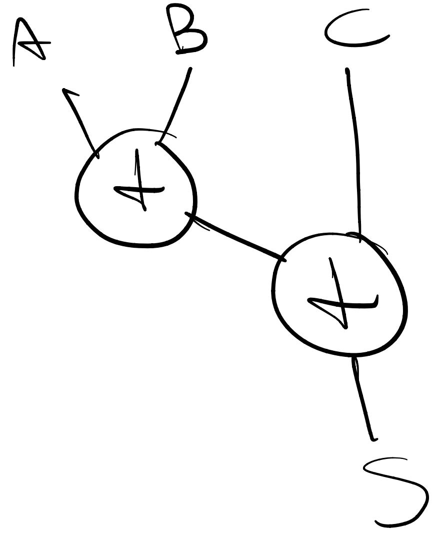
× x $x_2 x_1 x_0$

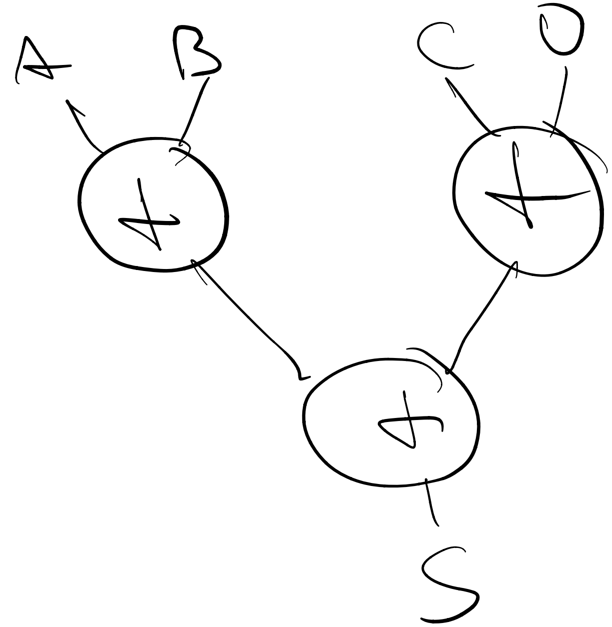


Source: Weste-Harris

- Each "●" represents a bit-product

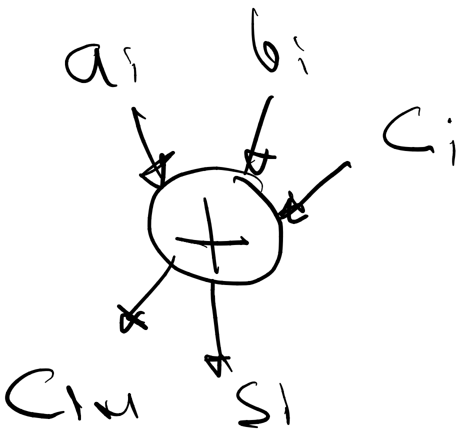
How to sum more than 2 numbers?



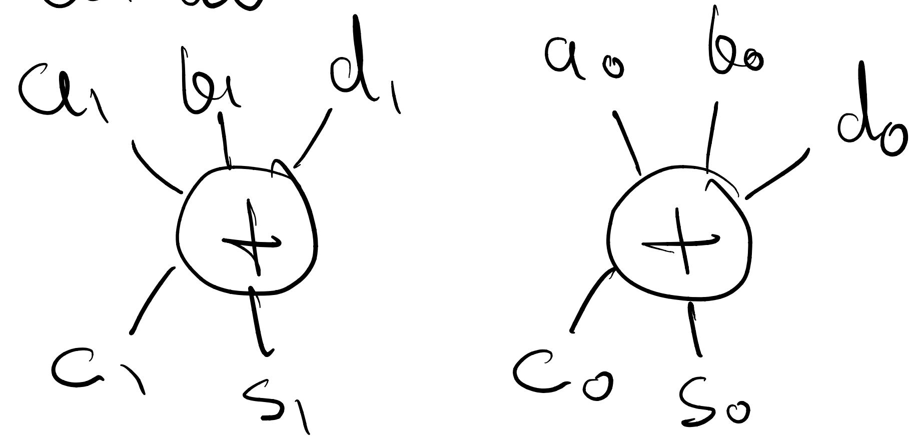


How to sum more than 2 numbers?

- Remember full-adders?



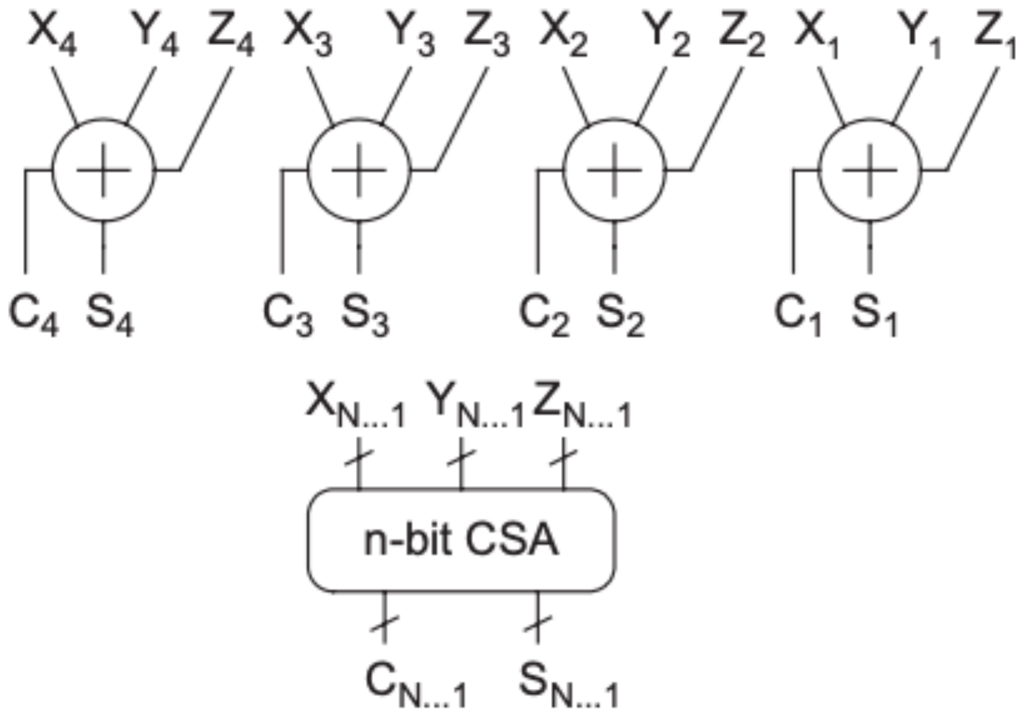
$$
\begin{array}{rcc}
 & a_1 & a_0 \\
+ & b_1 & b_0 \\
+ & d_1 & d_0
\end{array}
$$



$$A + B + C = S_1 S_0 + 2 \cdot C_1 C_0$$

$$
\begin{array}{rccc}
= & & S_1 & S_0 \\
+ & C_1 & C_0 & 0 \\
\hline
\end{array}
$$

Carry Save Adder (CSA)

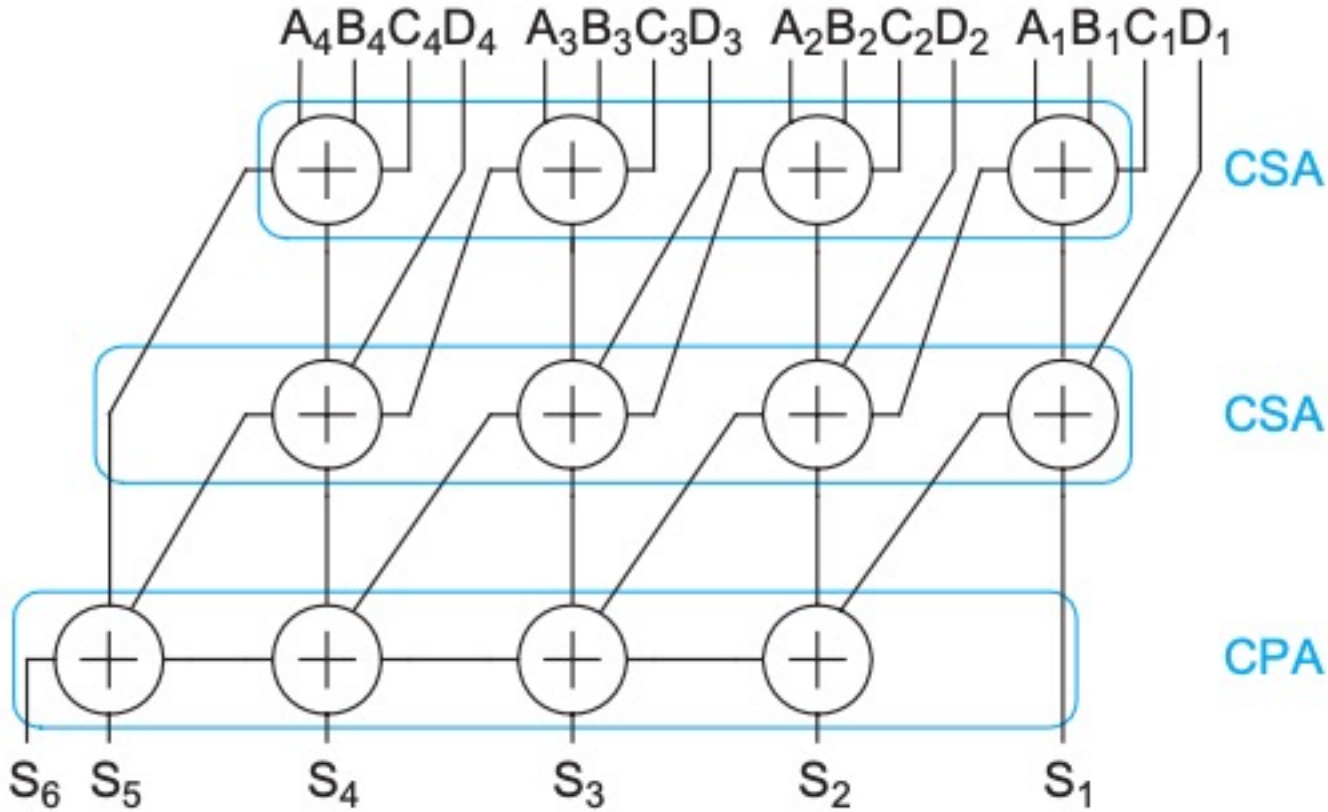


$$X + Y + Z = S + 2C$$

Source: Weste-Harris

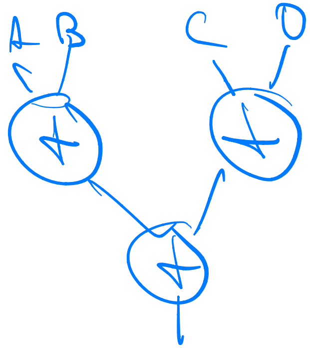
CSAs to add four numbers

$A_4 A_3 A_2 A_1$
$B_4 B_3 B_2 B_1$
$C_4 C_3 C_2 C_1$
$D_4 D_3 D_2 D_1$



Source: Weste-Harris

Array Multiplier



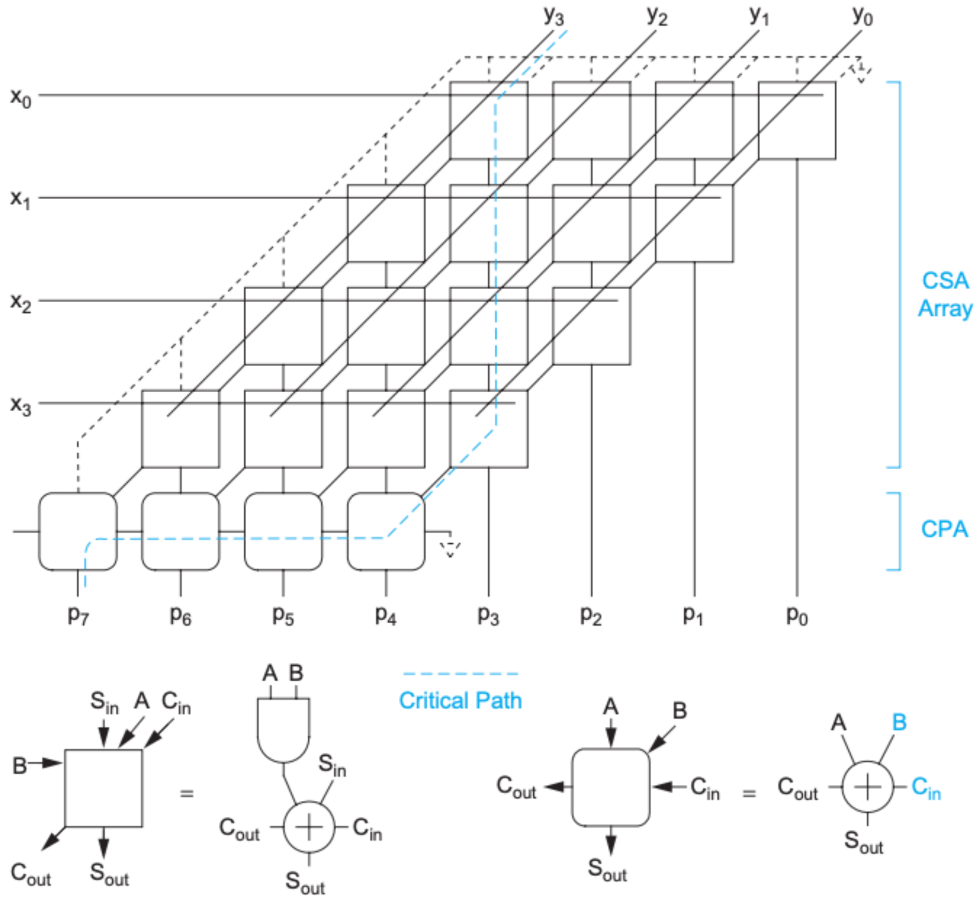


FIGURE 11.74 Array multiplier

Source: Weste-Harris

- Sequential addition of partial products (Analogous to Ripple-Carry Addition)
- Final addition of partial products is an Adder operation
  - All inputs do not arrive at the same time

Array Multiplier

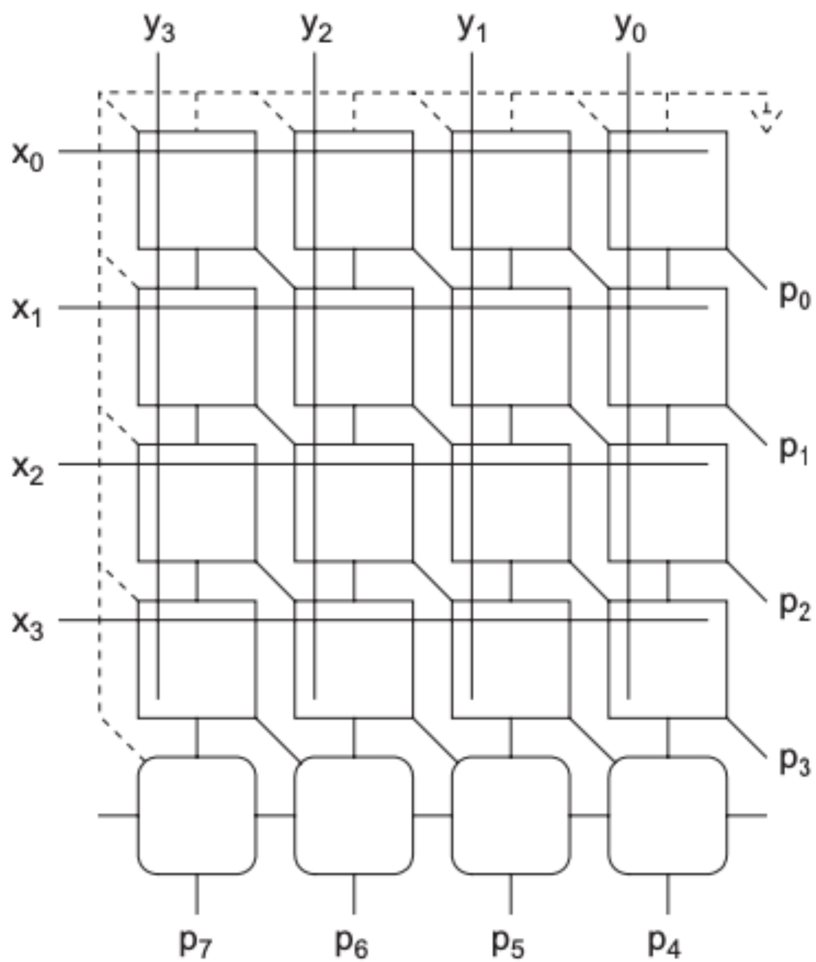


FIGURE 11.75 Rectangular array multiplier

Source: Weste-Harris

- "Straightening it" to be rectangular

Do you remember how to compute -x?

Two's complement

x . How do you compute $-x$?

$$-x = \overline{x} + 1$$

Signed Multiplication (Baugh-Wooley)

- Multiplier topology thus far has been signed multiplication

un

- $P_{signed} = X \times Y$

$$\left(-x_{m-1}2^{m-1} + \sum_{i=0}^{m-2} x_i 2^i\right)\left(-y_{n-1}2^{n-1} + \sum_{j=0}^{n-2} y_j 2^j\right)$$

$$= y_{n-1}\, x_{m-1} 2^{m+n-2}$$

$$- 2^{n-1} \sum_{i=0}^{m-2} y_{n-1} x_i 2^i \; - \; 2^{m-1} \sum_{j=0}^{n-1} x_{m-1} y_i 2^i$$

$$+ \sum_{i=0}^{m-2} \sum_{j=0}^{n-2} x_i y_j 2^{i+j}$$

$X = X_{m-1} X_{m-2} \cdots X_1 X_0$

$Y = Y_{n-1} Y_{n-2} - Y_1 Y_0$

Signed Array Multiplier (Baugh-Wooley)

$$\sum_{i=0}^{m-2} \sum_{j=0}^{n-2} x_i y_j 2^{i+j}$$

				x_0y_4	x_0y_3	x_0y_2	x_0y_1	x_0y_0
			x_1y_4	x_1y_3	x_1y_2	x_1y_1	x_1y_0	
		x_2y_4	x_2y_3	x_2y_2	x_2y_1	x_2y_0		
	x_3y_4	x_3y_3	x_3y_2	x_3y_1	x_3y_0			
x_4y_4	x_4y_3	x_4y_2	x_4y_1	x_4y_0				

Signed Array Multiplier (Baugh-Wooley)

							x_0y_4	x_0y_3	x_0y_2	x_0y_1	x_0y_0
						x_1y_4	x_1y_3	x_1y_2	x_1y_1	x_1y_0	
$\sum_{i=0}^{m-2} \sum_{j=0}^{n-2} x_i y_j 2^{i+j}$					x_2y_4	x_2y_3	x_2y_2	x_2y_1	x_2y_0		
				x_3y_4	x_3y_3	x_3y_2	x_3y_1	x_3y_0			
			x_4y_4	x_4y_3	x_4y_2	x_4y_1	x_4y_0				
$+\, y_{n-1}\, x_{m-1} 2^{m+n-2}$	x_5y_5										

Signed Array Multiplier (Baugh-Wooley)

								x_0y_4	x_0y_3	x_0y_2	x_0y_1	x_0y_0
							x_1y_4	x_1y_3	x_1y_2	x_1y_1	x_1y_0	
$\sum_{i=0}^{m-2}\sum_{j=0}^{n-2} x_i y_j 2^{i+j}$						x_2y_4	x_2y_3	x_2y_2	x_2y_1	x_2y_0		
					x_3y_4	x_3y_3	x_3y_2	x_3y_1	x_3y_0			
				x_4y_4	x_4y_3	x_4y_2	x_4y_1	x_4y_0				
$+\, y_{n-1}\, x_{m-1} 2^{m+n-2}$		x_5y_5										
												1
$-\, 2^{m-1}\sum_{j=0}^{n-1} x_{m-1} y_i 2^i$	$\overline{0}$	$\overline{0}$	$\overline{x_5y_4}$	$\overline{x_5y_3}$	$\overline{x_5y_2}$	$\overline{x_5y_1}$	$\overline{x_5y_0}$	$\overline{0}$	$\overline{0}$	$\overline{0}$	$\overline{0}$	$\overline{0}$

Signed Array Multiplier (Baugh-Wooley)

								x_0y_4	x_0y_3	x_0y_2	x_0y_1	x_0y_0
							x_1y_4	x_1y_3	x_1y_2	x_1y_1	x_1y_0	
$\sum_{i=0}^{m-2}\sum_{j=0}^{n-2} x_i y_j 2^{i+j}$						x_2y_4	x_2y_3	x_2y_2	x_2y_1	x_2y_0		
					x_3y_4	x_3y_3	x_3y_2	x_3y_1	x_3y_0			
				x_4y_4	x_4y_3	x_4y_2	x_4y_1	x_4y_0				
$+\, y_{n-1}\, x_{m-1} 2^{m+n-2}$		x_5y_5										
												1
$-\, 2^{m-1} \sum_{j=0}^{n-1} x_{m-1} y_i 2^i$	$\overline{0}$	$\overline{0}$	$\overline{x_5y_4}$	$\overline{x_5y_3}$	$\overline{x_5y_2}$	$\overline{x_5y_1}$	$\overline{x_5y_0}$	$\overline{0}$	$\overline{0}$	$\overline{0}$	$\overline{0}$	$\overline{0}$
$-\, 2^{n-1} \sum_{i=0}^{m-2} y_{n-1} x_i 2^i$	$\overline{0}$	$\overline{0}$	$\overline{x_4y_5}$	$\overline{x_3y_5}$	$\overline{x_2y_5}$	$\overline{x_1y_5}$	$\overline{x_0y_5}$	$\overline{0}$	$\overline{0}$	$\overline{0}$	$\overline{0}$	$\overline{0}$
												1

Signed Array Multiplier (Baugh-Wooley)

								x_0y_4	x_0y_3	x_0y_2	x_0y_1	x_0y_0
							x_1y_4	x_1y_3	x_1y_2	x_1y_1	x_1y_0	
$\sum_{i=0}^{m-2}\sum_{j=0}^{n-2} x_i y_j 2^{i+j}$						x_2y_4	x_2y_3	x_2y_2	x_2y_1	x_2y_0		
					x_3y_4	x_3y_3	x_3y_2	x_3y_1	x_3y_0			
				x_4y_4	x_4y_3	x_4y_2	x_4y_1	x_4y_0				
$+\, y_{n-1}\, x_{m-1} 2^{m+n-2}$		x_5y_5										1
$-\, 2^{m-1}\sum_{j=0}^{n-1} x_{m-1} y_i 2^i$	1	1	$\overline{x_5y_4}$	$\overline{x_5y_3}$	$\overline{x_5y_2}$	$\overline{x_5y_1}$	$\overline{x_5y_0}$	1	1	1	1	1
$-\, 2^{n-1}\sum_{i=0}^{m-2} y_{n-1} x_i 2^i$	1	1	$\overline{x_4y_5}$	$\overline{x_3y_5}$	$\overline{x_2y_5}$	$\overline{x_1y_5}$	$\overline{x_0y_5}$	1	1	1	1	1
												1

Signed Array Multiplier (Baugh-Wooley)

$\sum_{i=0}^{m-2}\sum_{j=0}^{n-2} x_i y_j 2^{i+j}$

$+\, y_{n-1}\, x_{m-1} 2^{m+n-2}$

$-\, 2^{m-1}\sum_{j=0}^{n-1} x_{m-1} y_i 2^i$

$-\, 2^{n-1}\sum_{i=0}^{m-2} y_{n-1} x_i 2^i$

							x_0y_4	x_0y_3	x_0y_2	x_0y_1	x_0y_0
						x_1y_4	x_1y_3	x_1y_2	x_1y_1	x_1y_0	
					x_2y_4	x_2y_3	x_2y_2	x_2y_1	x_2y_0		
				x_3y_4	x_3y_3	x_3y_2	x_3y_1	x_3y_0			
			x_4y_4	x_4y_3	x_4y_2	x_4y_1	x_4y_0				
	x_5y_5										1
1	1	$\overline{x_5y_4}$	$\overline{x_5y_3}$	$\overline{x_5y_2}$	$\overline{x_5y_1}$	$\overline{x_5y_0}$	1	1	1	1	1
1	1	$\overline{x_4y_5}$	$\overline{x_3y_5}$	$\overline{x_2y_5}$	$\overline{x_1y_5}$	$\overline{x_0y_5}$	1	1	1	1	1
											1

						1	$\overline{x_0y_5}$	x_0y_4	x_0y_3	x_0y_2	x_0y_1	x_0y_0
						$\overline{x_1y_5}$	x_1y_4	x_1y_3	x_1y_2	x_1y_1	x_1y_0	
					$\overline{x_2y_5}$	x_2y_4	x_2y_3	x_2y_2	x_2y_1	x_2y_0		
				$\overline{x_3y_5}$	x_3y_4	x_3y_3	x_3y_2	x_3y_1	x_3y_0			
			$\overline{x_4y_5}$	x_4y_4	x_4y_3	x_4y_2	x_4y_1	x_4y_0				
1	1	x_5y_5	$\overline{x_5y_4}$	$\overline{x_5y_3}$	$\overline{x_5y_2}$	$\overline{x_5y_1}$	$\overline{x_5y_0}$					

Removing leading 1's from signed numbers?

5 bit number

2's (5 bits) 1 1 0 1 0 $= -16 + 8 + 2 = -6$

2's (4 bits) 1 0 1 0 $= -8 + 2 = -6$

$1\ 1\ a_2\ a_1\ a_0$

$$= -2^4 + 2^3 + a_2 2^2 + a_1 2^1 + a_0$$

$$= -2^3 + a_2 2^2 + a_1 2^1 + a_0$$

$$\boxed{\begin{array}{l} 2^3 + 2^3 = 2 \cdot 2^3 = 2^4 \\ -2^4 + 2^3 = -2^3 \end{array}}$$

$1\ a_2\ a_1\ a_0$

Signed Array Multiplier (Baugh-Wooley)

$\sum_{i=0}^{m-2} \sum_{j=0}^{n-2} x_i y_j 2^{i+j}$

$+ y_{n-1}\, x_{m-1} 2^{m+n-2}$

$- 2^{m-1} \sum_{j=0}^{n-1} x_{m-1} y_i 2^i$

$- 2^{n-1} \sum_{i=0}^{m-2} y_{n-1} x_i 2^i$

					1	$\overline{x_0y_5}$	x_0y_4	x_0y_3	x_0y_2	x_0y_1	x_0y_0
					$\overline{x_1y_5}$	x_1y_4	x_1y_3	x_1y_2	x_1y_1	x_1y_0	
				$\overline{x_2y_5}$	x_2y_4	x_2y_3	x_2y_2	x_2y_1	x_2y_0		
			$\overline{x_3y_5}$	x_3y_4	x_3y_3	x_3y_2	x_3y_1	x_3y_0			
		$\overline{x_4y_5}$	x_4y_4	x_4y_3	x_4y_2	x_4y_1	x_4y_0				
1	x_5y_5	$\overline{x_5y_4}$	$\overline{x_5y_3}$	$\overline{x_5y_2}$	$\overline{x_5y_1}$	$\overline{x_5y_0}$					

unsigned

0	0	0	•	•	•	•
0	0	•	•	•	•	0
0	•	•	•	•	0	0
•	•	•	•	0	0	0

signed ?

$S = 2^{-k}$

S	S	S	S	•	•	•
S	S	S	•	•	•	0
S	S	•	•	•	0	0
S	•	•	•	0	0	0

Signed Array Multiplier (Baugh-Wooley)

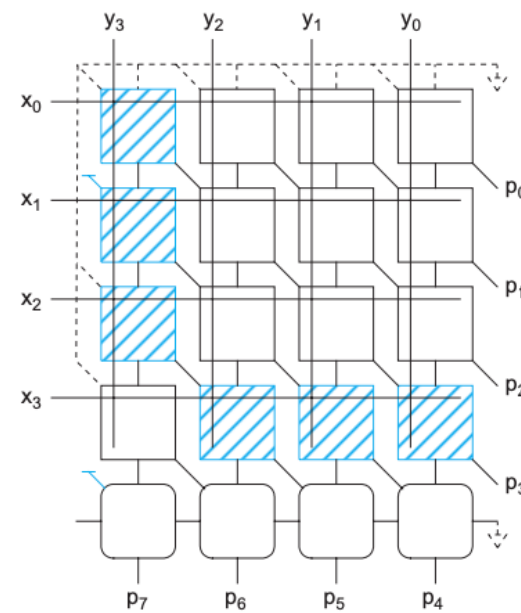
$$\sum_{i=0}^{m-2}\sum_{j=0}^{n-2} x_i y_j 2^{i+j}$$

$$+\, y_{n-1}\, x_{m-1} 2^{m+n-2}$$

$$-\, 2^{m-1}\sum_{j=0}^{n-1} x_{m-1} y_i 2^i$$

$$-\, 2^{n-1}\sum_{i=0}^{m-2} y_{n-1} x_i 2^i$$

					1	$\overline{x_0y_5}$	x_0y_4	x_0y_3	x_0y_2	x_0y_1	x_0y_0
					$\overline{x_1y_5}$	x_1y_4	x_1y_3	x_1y_2	x_1y_1	x_1y_0	
				$\overline{x_2y_5}$	x_2y_4	x_2y_3	x_2y_2	x_2y_1	x_2y_0		
			$\overline{x_3y_5}$	x_3y_4	x_3y_3	x_3y_2	x_3y_1	x_3y_0			
		$\overline{x_4y_5}$	x_4y_4	x_4y_3	x_4y_2	x_4y_1	x_4y_0				
1	x_5y_5	$\overline{x_5y_4}$	$\overline{x_5y_3}$	$\overline{x_5y_2}$	$\overline{x_5y_1}$	$\overline{x_5y_0}$					



Source: Weste-Harris

FIGURE 11.78 Modified Baugh-Wooley two's complement multiplier

Reducing the Number of Partial Products

- Array multipliers require merging M partial products
  - We're adding too many partial products!

- Choose r for "radix-2^r" Booth Encoding
- → reduction to $\lfloor M/r \rfloor$ partial products

r = 2

1 0 1 1 0 0
0 1 1 0 0 1

1 0 1 1 0 0
1 0 1 1 0 0 0
1 0 1 1 0 0

M = 5

3

5/2 = 2.5

Reducing the Number of Partial Products

- Array multipliers require merging M partial products
  - We're adding too many partial products!

Traditional: r = 1

r = 2

00 0
01 1
10 2
11 3

- Choose r for "radix-2^r" Booth Encoding
- → reduction to M/r partial products
  - Groups of r multiplier bits looked at to generate a single partial product (PP)
  - Referred to as radix-2^r encoding
  - Traditional radix-2 encoding: PP is selected as either 0 or Y (AND Array)
  - Radix-4 encoding: PP is selected as either 0, Y, 2Y or 3Y (Selection logic)

Similar ideas are relatively common in Digital VLSI. See for example:

Jeong, J., Collins, N., & Flynn, M. P. (2016). *A 260 MHz IF Sampling Bit-Stream Processing Digital Beamformer With an Integrated Array of Continuous-Time Band-Pass ΔΣ Modulators.* IEEE Journal of Solid-State Circuits, 51(5), 1168-1176.

Reducing the Number of Partial Products

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$r=2$ $r=3$

- Radix-4 and radix-8 encoding used more often
  - Increased complexity in generating partial products with ↑r
  - Use of even higher radix justified in rare cases

Booth Encoding (Radix-4)

- Idea: Scale partial product by 0, 1, 2 or 3
  - 2Y generated from a shift <<1
  - 3Y is a problem.

0	easy
1	easy
2	easy
3	hard
4	easy

4 − 1 = 3 !!

3Y = 4Y − Y

```
  101110
11 10 01 00
--------------
      000000
    101110
   1011100
1001010
```

```
 101110
     11
--------
 101110
101110
--------
1001010
```

Booth Encoding (Radix-4)

- Idea: Scale partial product by 0, 1, 2 or 3
  - 2Y generated from a shift <<1
  - 3Y is a problem.

0	easy
1	easy
2	easy
3	hard
4	easy

4 - 1 = 3 :)

$3Y = 4Y - Y$

1 0 1 1 1 0

$\underbrace{1\ 1}\ \underbrace{0\ 0}_{+1}\ \underbrace{1\ 1}\ \underbrace{0\ 0}$

-Y

easy

Booth Encoding (Radix-4)

- Idea: Scale partial product by 0, 1, 2 or 3
  - 2Y generated from a shift <<1
  - 3Y is a problem. Try 4-1 instead of 2+1

Booth Encoding (Radix-4)

- Idea: Scale partial product by 0, 1, 2 or 3
  - 2Y generated from a shift <<1
  - 3Y is a problem. Try 4-1 instead of 2+1
- Let's try this: Detect a 3X case in the previous group and +1 to current group

01 00 11

+1 +1 -1

01 10 11

+1 +3 -1

+2 -1 -1

01 10 10

+1 +2 +2

Booth Encoding (Radix-4)

- Idea: Scale partial product by 0, 1, 2 or 3
  - 2Y generated from a shift <<1
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01 10 10 11

X +1 +2 +3 -1

X +1 +3 -1 -1

+2 -1 -1 -1

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$$\boxed{\mathbf{2 = 4 - 2}}$$

x0 x1 x2 x3 → x0 x1 x2 x(4-1)

x0 x1 x2 x3 → x0 x1 x2 or x(4-2) x(4-1)

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$$\boxed{\mathbf{2 = 4 - 2}}$$

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  - 2Y implemented as
    - sometimes 2Y
    - sometimes 4Y-2Y

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+1 +1 +1 +1

$\underbrace{00}_{+1}\ \underbrace{10}_{-2}\ \underbrace{01}_{+2}\ \underbrace{10}_{-1}\ \underbrace{10}_{-1}\ \underbrace{11}_{-1}$

$\underbrace{01}_{+1}\ \underbrace{0}$

$\underbrace{01}_{+2}\ \underbrace{1}$

$\underbrace{10}_{-2}\ \underbrace{0}$

$\underbrace{10}_{-1}\ \underbrace{1}$

- Why is this a good idea?
  - We only need to look at the MSB bit of the previous 2-bit group! (No prefix ☺)

Booth-Encoding: rules and how it works

- Add extra group with leading 0s if needed
- Form partial products according to the following rules:
  - Add 4Y to next group based on MSB of current group

Inputs (numbers to multiply)			Outputs
Current Group		MSB from previous group	Partial product
x_{2i+1}	x_{2i}	x_{2i-1}	PP_i
0	0	0	0
0	1	0	Y
1	0	0	-2Y
1	1	0	-Y
0	0	1	Y
0	1	1	2Y
1	0	1	-Y
1	1	1	0

$$PP = \begin{cases} 0 \\ y \\ 2y \\ -2y \\ -y \end{cases}$$

Tree Multipliers

- Array multipliers inherently process PPs serially
- This addition can also be performed in parallel

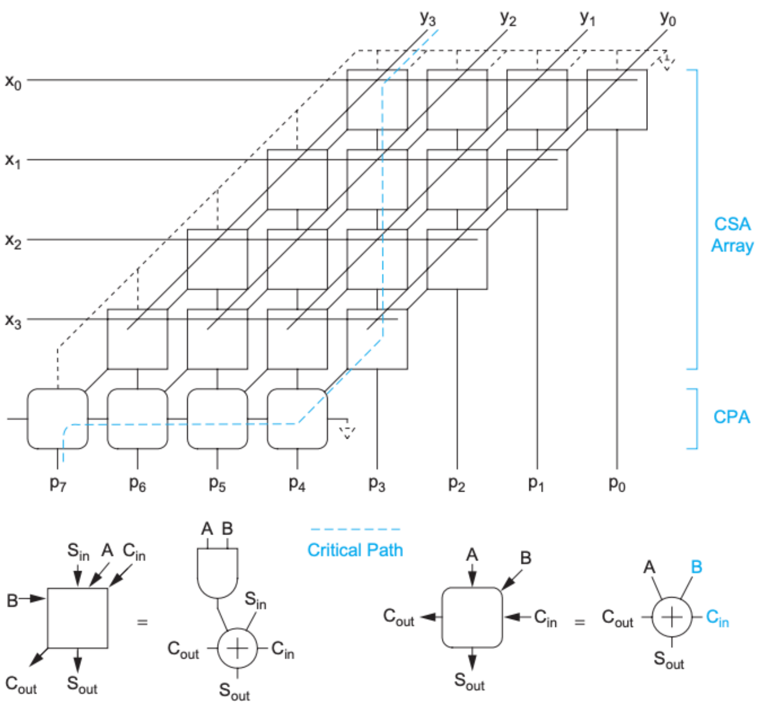

FIGURE 11.74 Array multiplier

Source: Weste-Harris

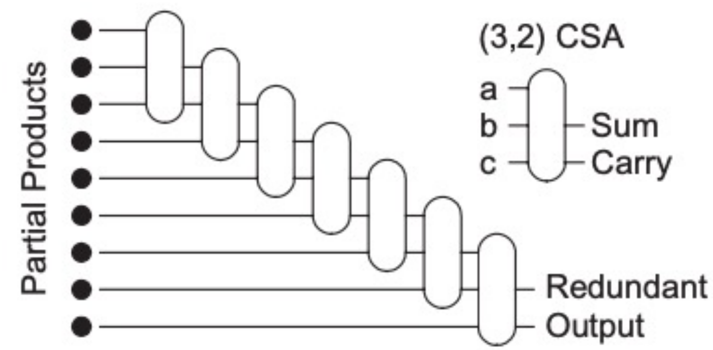

FIGURE 11.84 Dot diagram for array multiplier

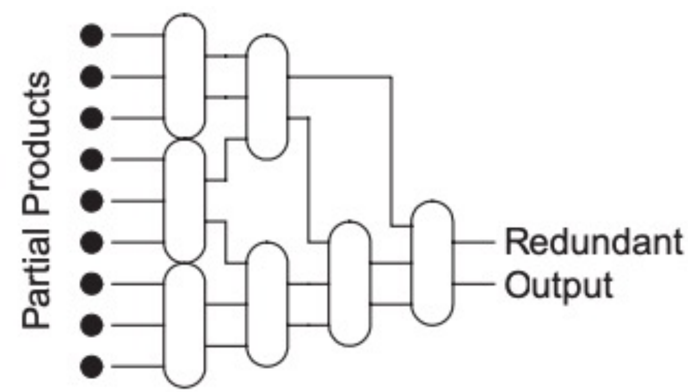

FIGURE 11.85 Dot diagram for Wallace tree multiplier

Tree Multipliers

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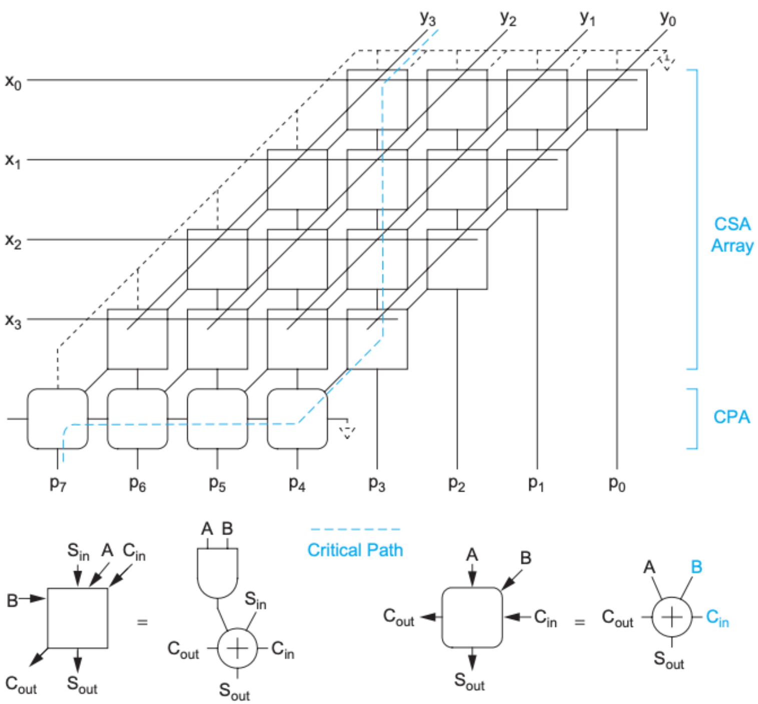

FIGURE 11.74 Array multiplier

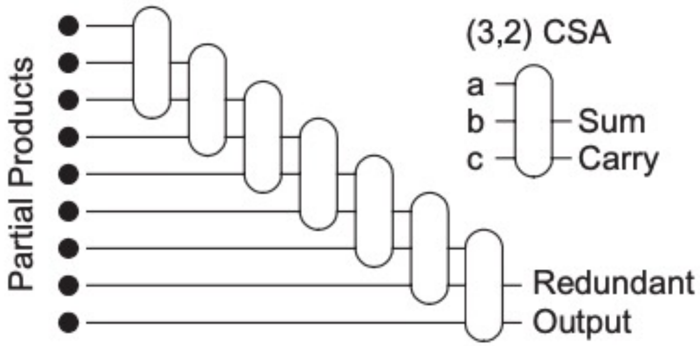

FIGURE 11.84 Dot diagram for array multiplier

Source: Weste-Harris

Questions/Assignments

- Signed booth multiplier?
- Non-equal width of the carry-save segment