



EECS151/251A

Spring 2023

**Digital Design and
Integrated Circuits**

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**Lecture 24:
Multiplier Circuits and
Shifters**

Announcements

Warmup

- Recall long multiplication of base-10 by hand:

$$\begin{array}{r} 12 \\ \times 56 \\ \hline \end{array}$$

- In base-2 (binary), we do the same thing:

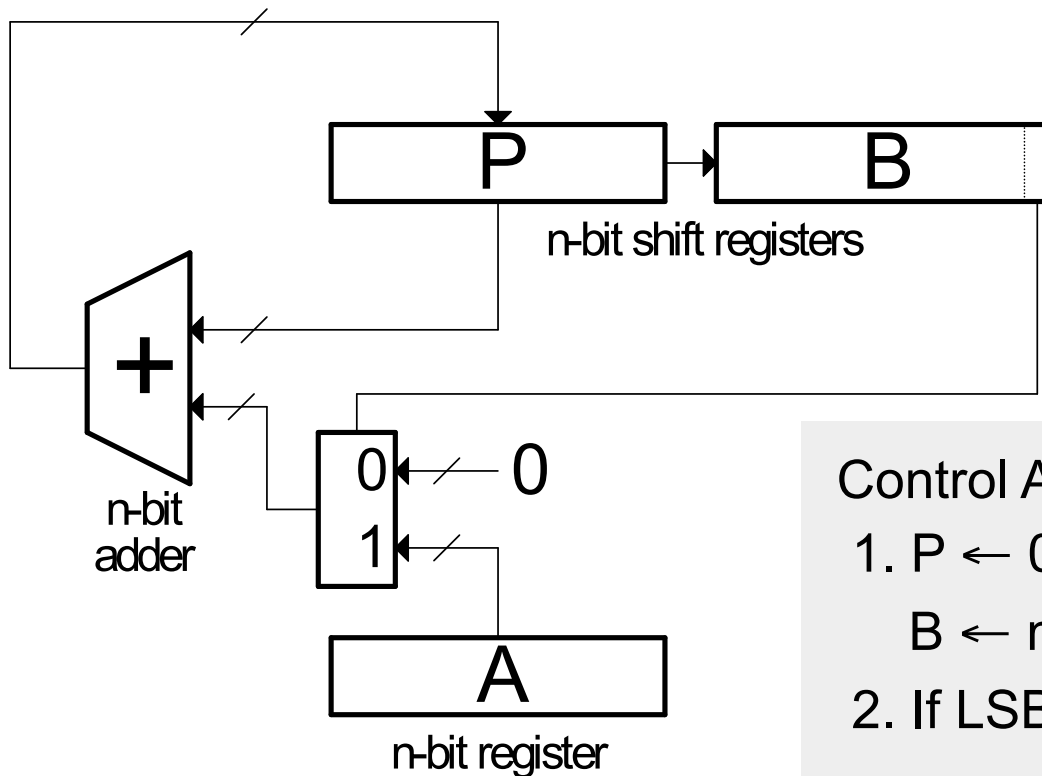
$$\begin{array}{r} 011 \\ \times 101 \\ \hline \end{array}$$

Multiplication

			a_3	a_2	a_1	a_0	← <i>Multiplicand</i>	
			b_3	b_2	b_1	b_0	← <i>Multiplier</i>	
		X	a_3b_0	a_2b_0	a_1b_0	a_0b_0	}	
			a_3b_1	a_2b_1	a_1b_1	a_0b_1		<i>Partial products</i>
			a_3b_2	a_2b_2	a_1b_2	a_0b_2		
			a_3b_3	a_2b_3	a_1b_3	a_0b_3		
			...		$a_1b_0 + a_0b_1$	a_0b_0	← <i>Product</i>	

Many different circuits exist for multiplication. Each one has a different balance between speed (performance) and amount of logic (cost).

“Shift and Add” Multiplier



- Sums each partial product, one at a time.
- In binary, each partial product is shifted versions of A or 0.

Control Algorithm:

1. $P \leftarrow 0$, $A \leftarrow$ multiplicand,
 $B \leftarrow$ multiplier
2. If LSB of $B == 1$ then add A to P
else add 0
3. Shift $[P][B]$ right 1
4. Repeat steps 2 and 3 $n-1$ more times.
5. $[P][B]$ has product.

- Cost $\propto n$, $T = n$ clock cycles.
- What is the critical path for determining the min clock period?

“Shift and Add” Multiplier

Signed Multiplication:

Remember for 2's complement numbers MSB has negative weight:

$$X = \sum_{i=0}^{n-2} x_i \cdot 2^i - x_{n-1} \cdot 2^{n-1}$$

$$\begin{aligned} \text{ex: } -6 &= 11010_2 = 0 \cdot 2^0 + 1 \cdot 2^1 + 0 \cdot 2^2 + 1 \cdot 2^3 - 1 \cdot 2^4 \\ &= 0 + 2 + 0 + 8 - 16 = -6 \end{aligned}$$

- Therefore for multiplication:
 - a) subtract final partial product
 - b) sign-extend partial products
- Modifications to shift & add circuit:
 - a) adder/subtractor
 - b) sign-extender on P shifter register

Convince yourself

- What's -3×5 ?

$$\begin{array}{r} 1101 \\ \times 0101 \\ \hline \end{array}$$

Outline for Multipliers



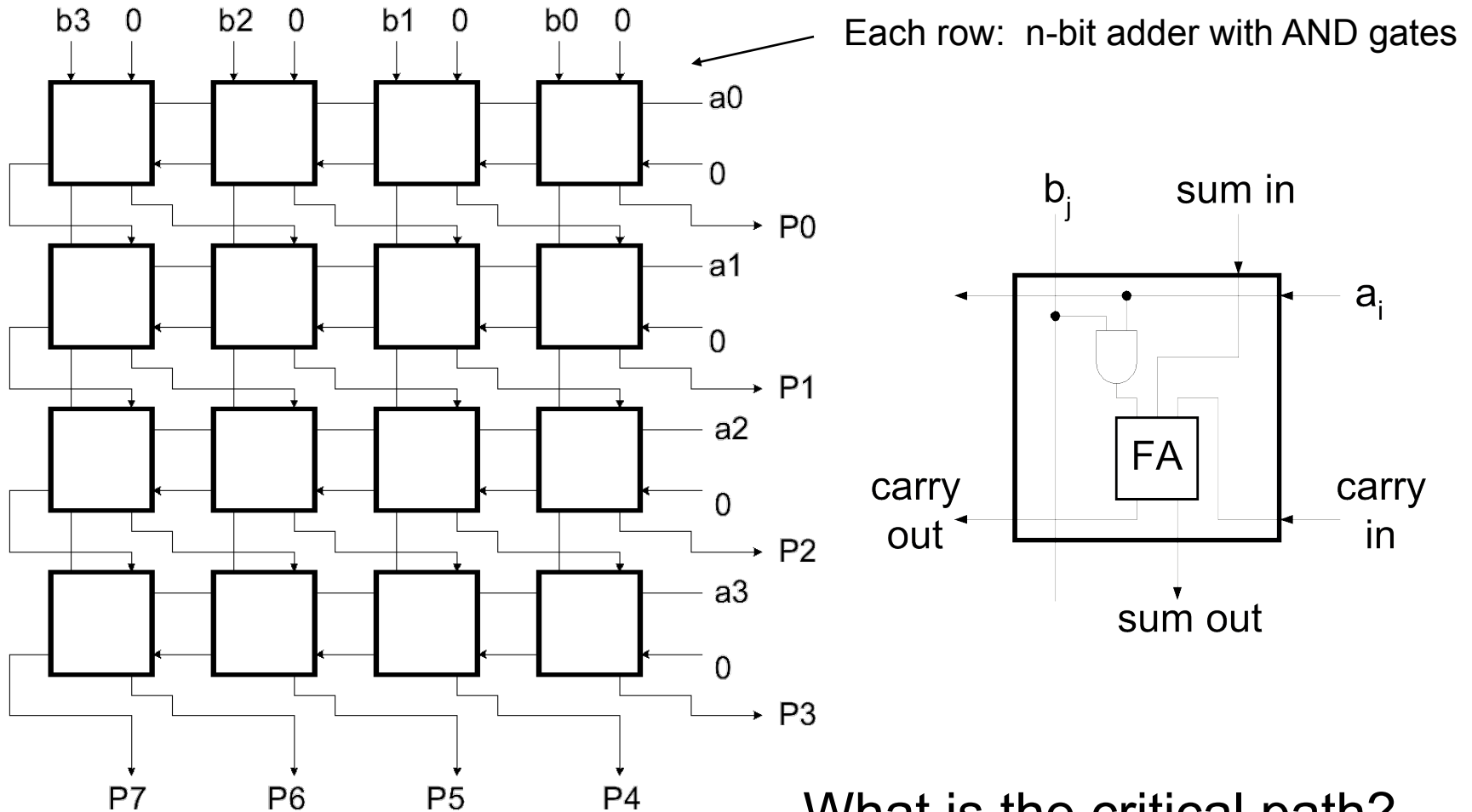
- ❑ Combinational multiplier
- ❑ Latency & Throughput
 - Wallace Tree
 - Pipelining to increase throughput
- ❑ Smaller multipliers
 - Booth encoding
 - Serial, bit-serial
- ❑ Two's complement multiplier



Unsigned Combinational Multiplier

Array Multiplier

Single cycle multiply: Generates all n partial products simultaneously.



What is the critical path?

Carry-Save Addition

- Speeding up multiplication is a matter of speeding up the summing of the partial products.
- “Carry-save” addition can help.
- Carry-save addition passes (saves) the carries to the output, rather than propagating them.

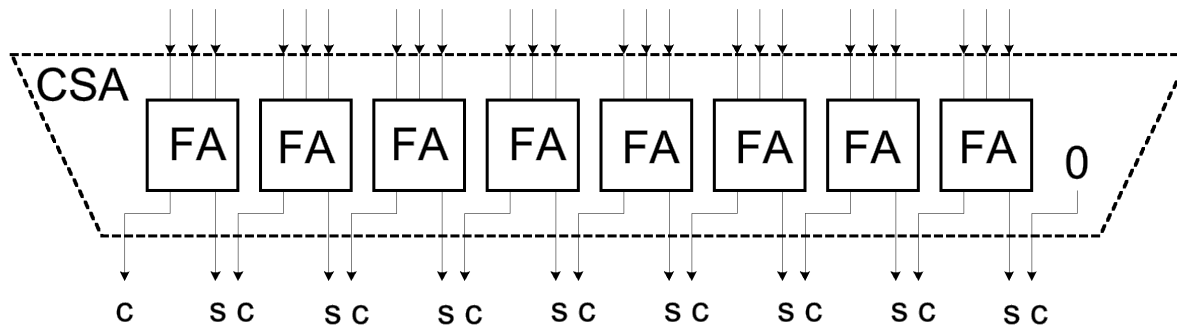
- Example: sum three numbers, $3_{10} = 0011$, $2_{10} = 0010$, $3_{10} = 0011$

$$\begin{array}{r}
 3_{10} \quad 0011 \\
 + 2_{10} \quad 0010 \\
 \hline
 c \quad 0100 = 4_{10} \\
 s \quad 0001 = 1_{10} \\
 \hline
 3_{10} \quad 0011 \\
 c \quad 0010 = 2_{10} \\
 s \quad 0110 = 6_{10} \\
 \hline
 1000 = 8_{10}
 \end{array}$$

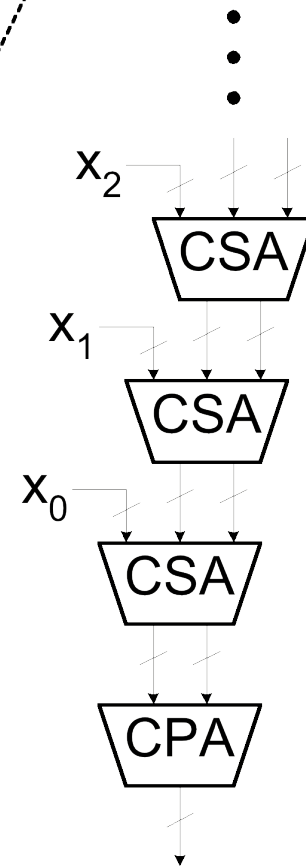
carry-save add (bracketed around the first two rows)
 carry-propagate add (bracketed around the last two rows)

- In general, *carry-save* addition takes in 3 numbers and produces 2.
 - Sometimes called a “3:2 compressor”: 3 input signals into 2
- Whereas, *carry-propagate* takes 2 and produces 1.
- With this technique, we can avoid carry propagation until final addition

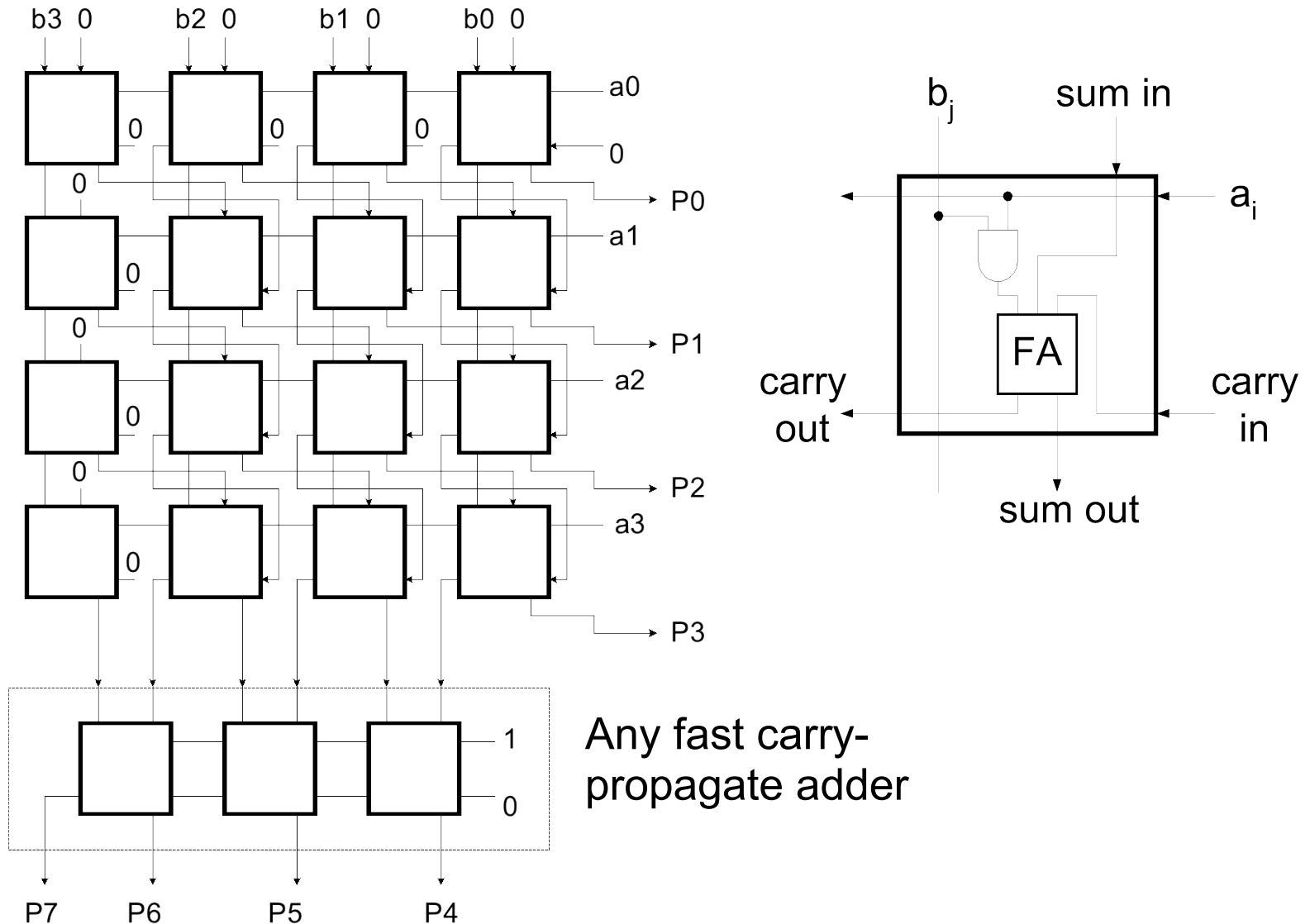
Carry-save Circuits



- When adding sets of numbers, carry-save can be used on all but the final sum.
- Standard adder (carry propagate) is used for final sum.
- Carry-save is fast (no carry propagation) and cheap (same cost as ripple adder)



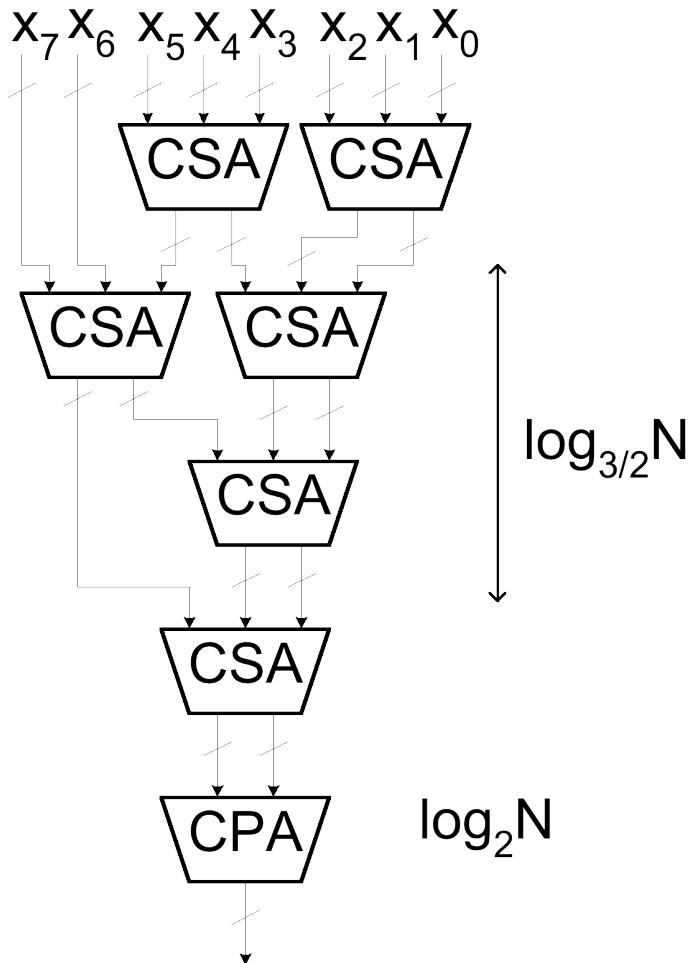
Array Multiplier using Carry-save Addition



Carry-save Addition

CSA is associative and commutative. For example:

$$(((X_0 + X_1) + X_2) + X_3) = ((X_0 + X_1) + (X_2 + X_3))$$

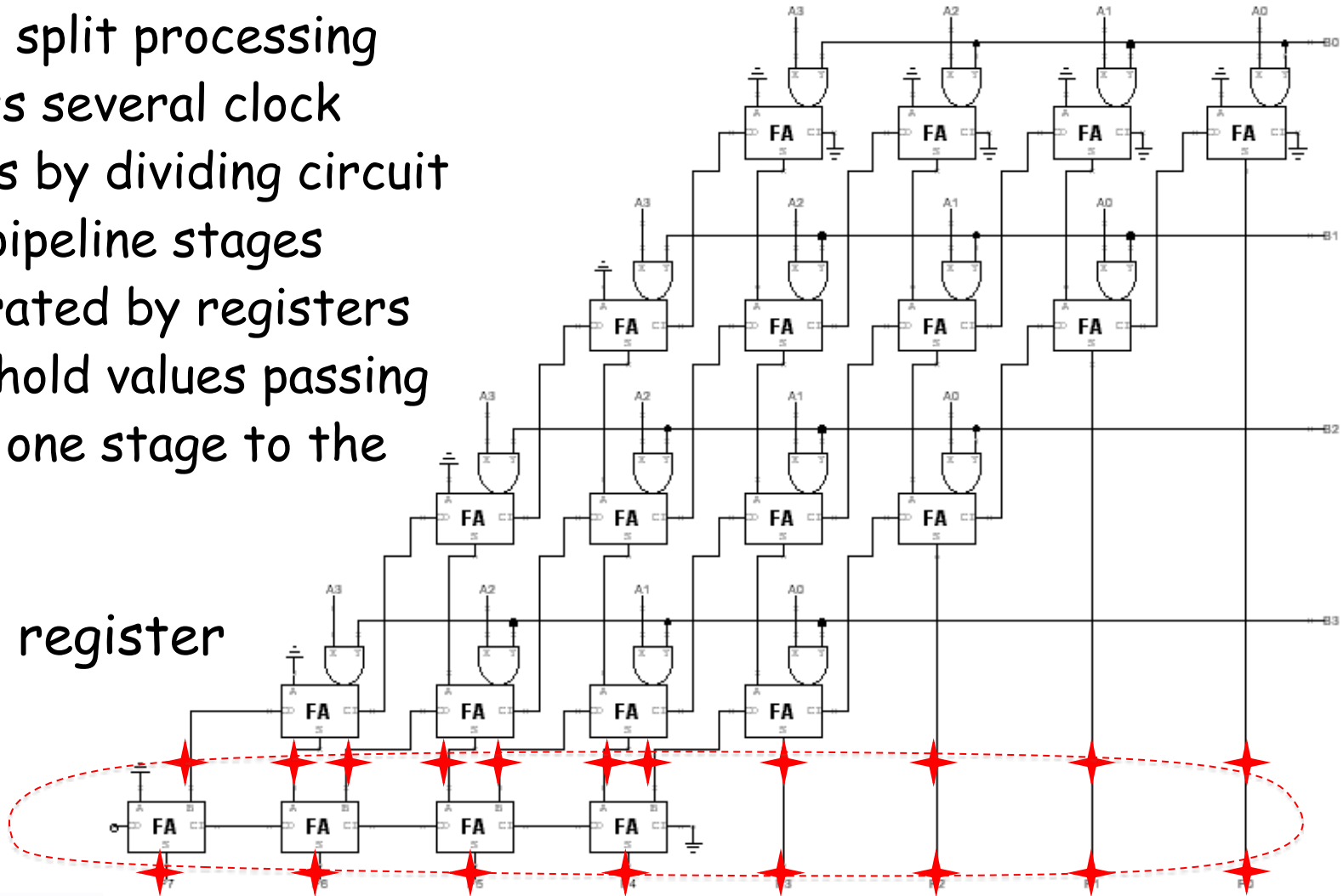


- A balanced tree can be used to reduce the logic delay.
- It doesn't matter where you add the carries and sums, as long as you eventually do add them.
- This structure is the basis of the **Wallace Tree Multiplier**.
- Partial products are summed with the CSA tree. Fast CPA (ex: CLA) is used for final sum.
- Multiplier delay $\propto \log_{3/2} N + \log_2 N$

Increasing Throughput: Pipelining

Idea: split processing across several clock cycles by dividing circuit into pipeline stages separated by registers that hold values passing from one stage to the next.

★ = register

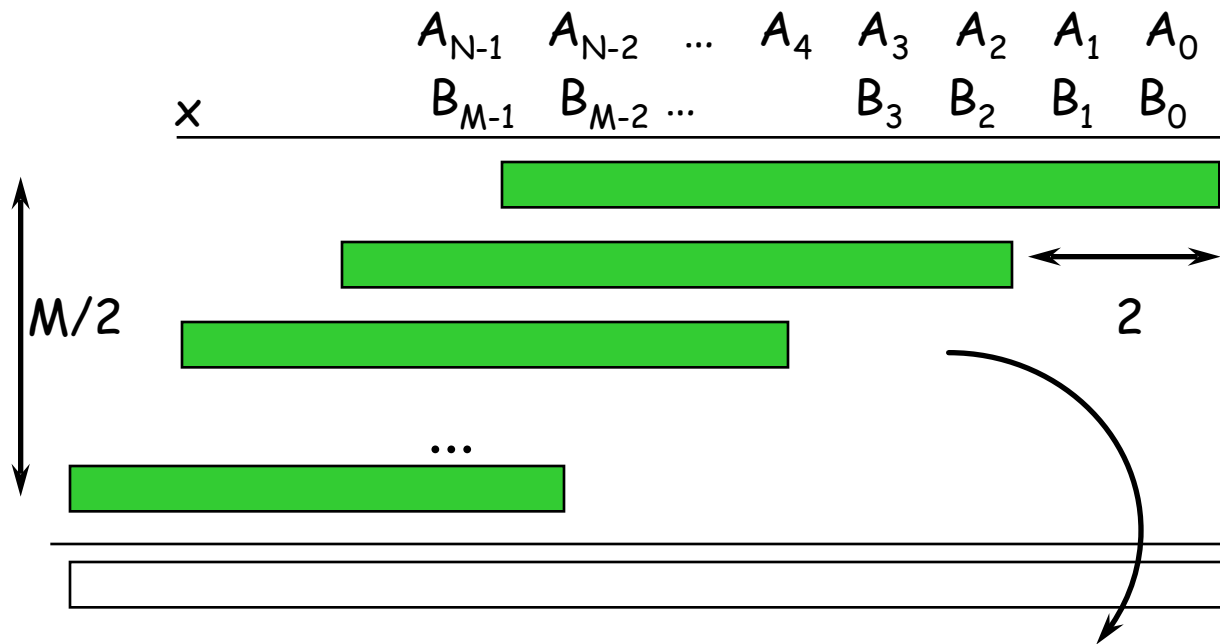




Smaller Combinational Multipliers

Booth Recoding: Higher-radix mult.

Idea: If we could use, say, 2 bits of the multiplier in generating each partial product we would **halve the number of rows and halve the latency of the multiplier!**



Booth's insight: rewrite $2*A$ and $3*A$ cases, leave $4A$ for next partial product to do!

$$\begin{aligned}
 B_{K+1,K} * A &= 0 * A \rightarrow 0 \\
 &= 1 * A \rightarrow A \\
 &= 2 * A \rightarrow 4A - 2A \\
 &= 3 * A \rightarrow 4A - A
 \end{aligned}$$

Booth recoding

current bit pair

from previous bit pair

B_{K+1}	B_K	B_{K-1}	action
0	0	0	add 0
0	0	1	add A
0	1	0	add A
0	1	1	add 2^*A
1	0	0	sub 2^*A
1	0	1	sub A
1	1	0	sub A
1	1	1	add 0

$$\begin{aligned}
 B_{K+1,K}^*A &= 0^*A \rightarrow 0 \\
 &= 1^*A \rightarrow A \\
 &= 2^*A \rightarrow 4A - 2A \\
 &= 3^*A \rightarrow 4A - A
 \end{aligned}$$

$$\leftarrow -2^*A + A$$

$$\leftarrow -A + A$$

A "1" in this bit means the previous stage needed to add 4^*A . Since this stage is shifted by 2 bits with respect to the previous stage, adding 4^*A in the previous stage is like adding A in this stage!

Example

Shifted left

(A) 0111 7_{10}

(B) x 1010 10_{10}

(10[0] sub 2A) -01110

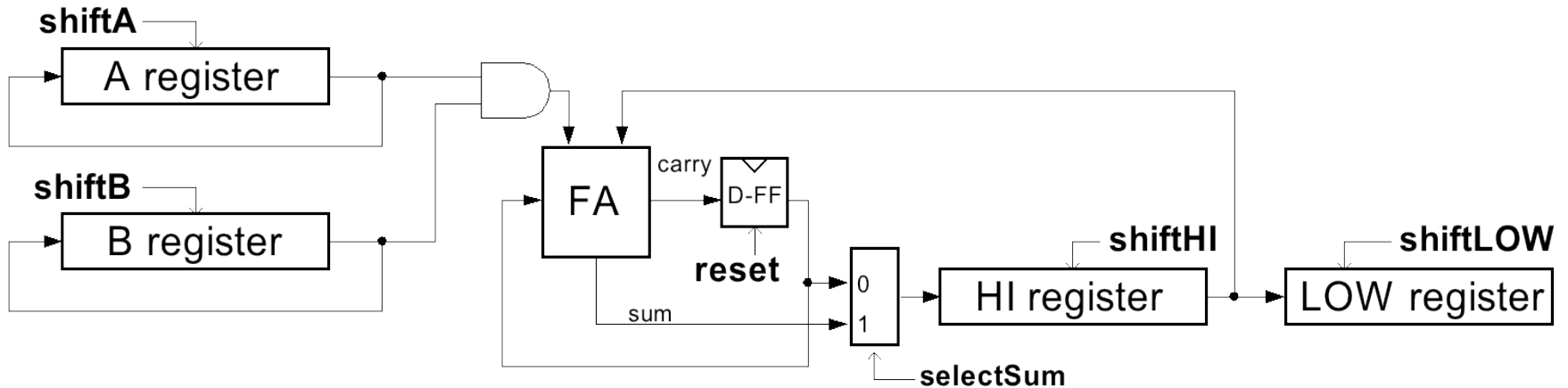
(101 sub A) -0111

(001 add A) +0111

01000110 70_{10}

Bit-serial Multiplier

- Bit-serial multiplier (n^2 cycles, one bit of result per n cycles):



- Control Algorithm:

```

repeat n cycles { // outer (i) loop
  repeat n cycles{ // inner (j) loop
    shiftA, selectSum, shiftHI
  }
  shiftB, shiftHI, shiftLOW, reset
}

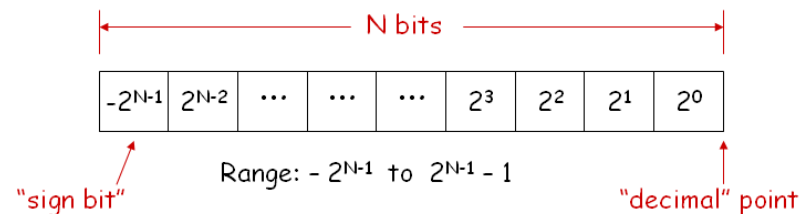
```

Note: The occurrence of a control signal x means $x=1$. The absence of x means $x=0$.



Signed Multipliers

Combinational Multiplier (signed!)



$$X * Y = (-3) * (-2)$$

(-3)

(-2)

	1	0	1	(X)
*	1	1	0	(Y)

0 0 0 0 0 0

$Y_0 * X = 0$

+ **1 1 1 0 1**

$2Y_1 * X = -6$

- **1 1 0 1**

$4Y_2 * X = -12$

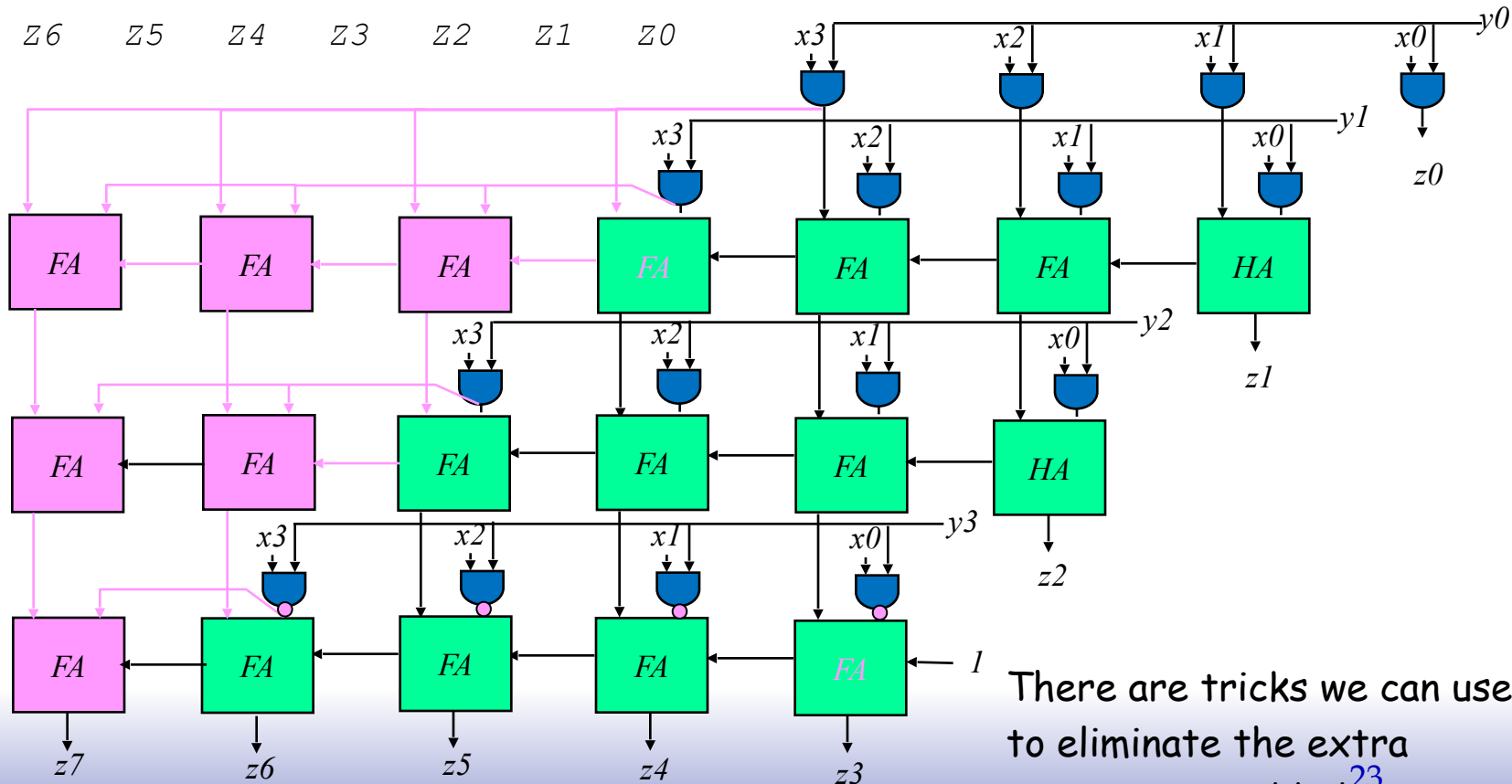
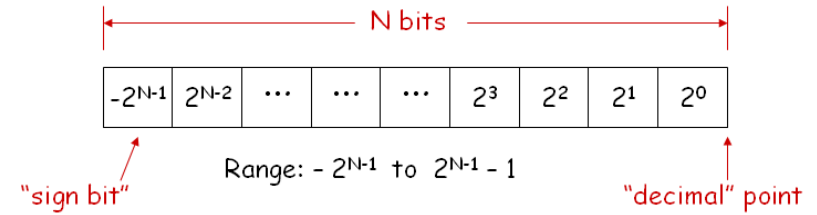
(+6)

0 0 0 1 1 0

Combinational Multiplier (signed)

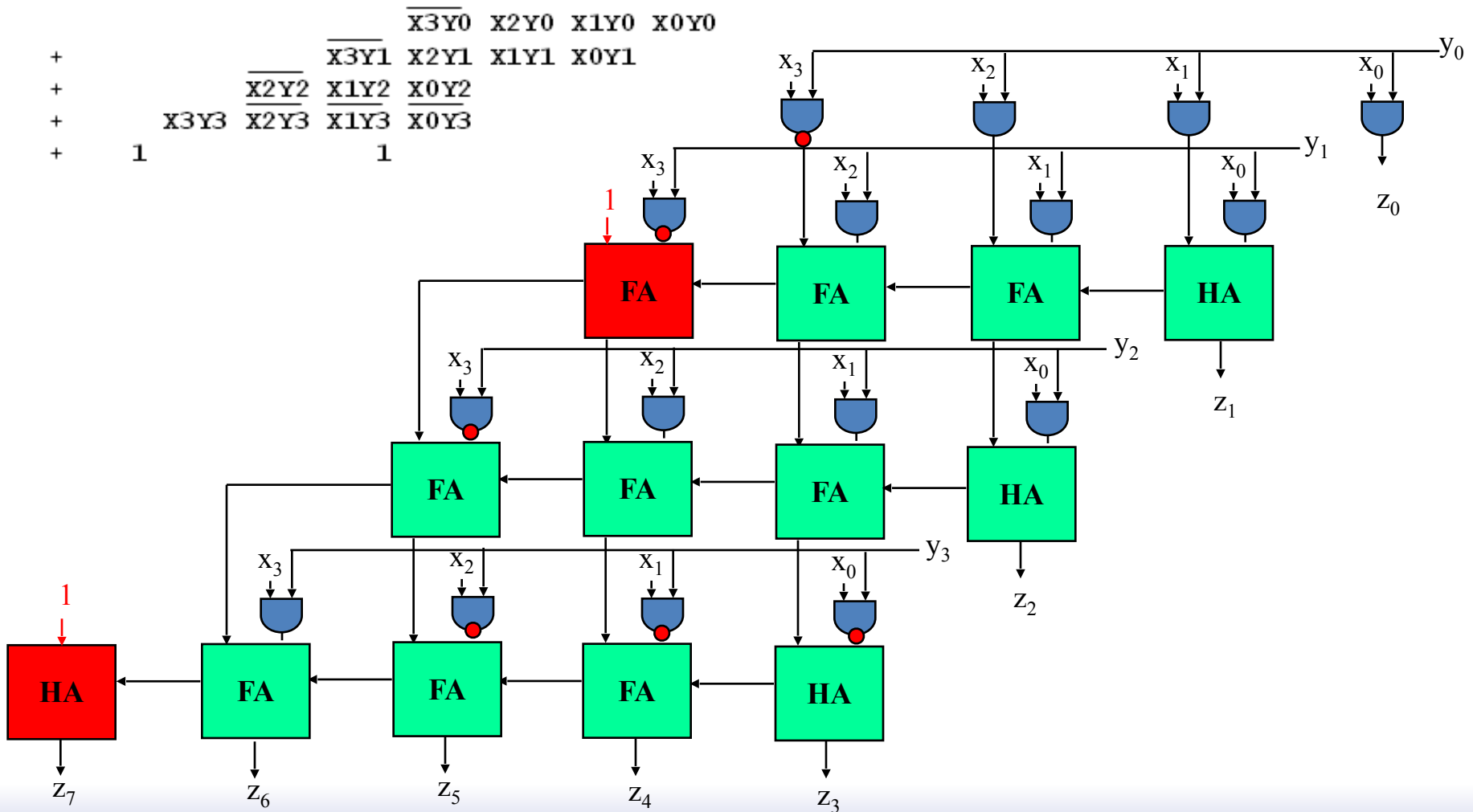
$$\begin{array}{r}
 X3 \quad X2 \quad X1 \quad X0 \\
 * \quad Y3 \quad Y2 \quad Y1 \quad Y0 \\
 \hline
 \end{array}$$

$$\begin{array}{r}
 X3Y0 \quad X3Y0 \quad X3Y0 \quad X3Y0 \quad X3Y0 \quad X2Y0 \quad X1Y0 \quad X0Y0 \\
 + \quad X3Y1 \quad X3Y1 \quad X3Y1 \quad X3Y1 \quad X2Y1 \quad X1Y1 \quad X0Y1 \\
 + \quad X3Y2 \quad X3Y2 \quad X3Y2 \quad X2Y2 \quad X1Y2 \quad X0Y2 \\
 - \quad X3Y3 \quad X3Y3 \quad X2Y3 \quad X1Y3 \quad X0Y3 \\
 \hline
 z7 \quad z6 \quad z5 \quad z4 \quad z3 \quad z2 \quad z1 \quad z0
 \end{array}$$



There are tricks we can use to eliminate the extra circuitry we added...²³

2's Complement Multiplication



Example

- What's -3×-5 ?

$$\begin{array}{r} 1101 \\ \times 1011 \\ \hline \end{array}$$

Multiplication in Verilog

You can use the “*” operator to multiply two numbers:

```
wire [9:0] a,b;  
wire [19:0] result = a*b; // unsigned multiplication!
```

If you want Verilog to treat your operands as signed two’s complement numbers, add the keyword `signed` to your `wire` or `reg` declaration:

```
wire signed [9:0] a,b;  
wire signed [19:0] result = a*b; // signed multiplication!
```

Remember: unlike addition and subtraction, you need different circuitry if your multiplication operands are signed vs. unsigned. Same is true of the `>>>` (arithmetic right shift) operator. To get signed operations all operands must be signed.

```
wire signed [9:0] a;  
wire [9:0] b;  
wire signed [19:0] result = a*$signed(b);
```

To make a signed constant: `10’sh37C`

Outline



- ❑ *Constant Coefficient Multiplication*
- ❑ *Shifters*
- ❑ *Counters*

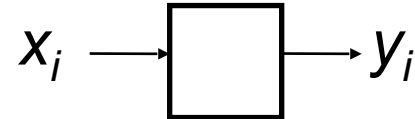
Constant Multiplication

- ❑ Our multiplier circuits so far has assumed both the multiplicand (A) and the multiplier (B) can vary at runtime.
- ❑ What if one of the two is a constant?

$$Y = C * X$$

- ❑ “Constant Coefficient” multiplication comes up often in signal processing and other hardware. Ex:

$$y_i = \alpha y_{i-1} + x_i$$

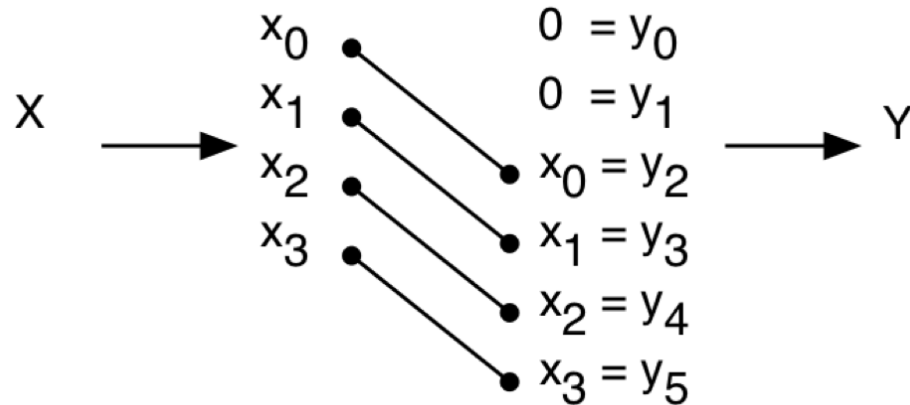


where α is an application dependent constant that is hard-wired into the circuit.

- ❑ How do we build an array style (combinational) multiplier that takes advantage of the constancy of one of the operands?

Multiplication by a Constant

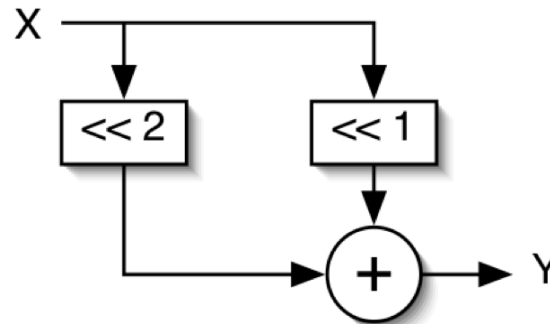
- If the constant C in $C \cdot X$ is a power of 2, then the multiplication is simply a shift of X .
- Ex: $4 \cdot X$



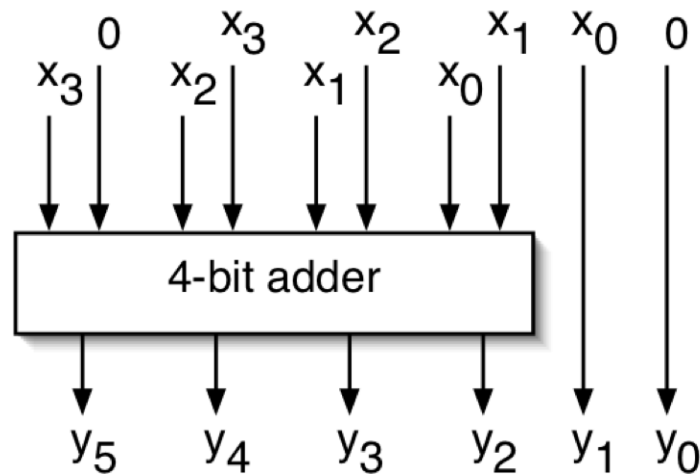
- What about division?
- What about multiplication by non-powers of 2?

Multiplication by a Constant

- In general, a combination of fixed shifts and addition:
 - Ex: $6 * X = 0110 * X = (2^2 + 2^1) * X = 2^2 X + 2^1 X$

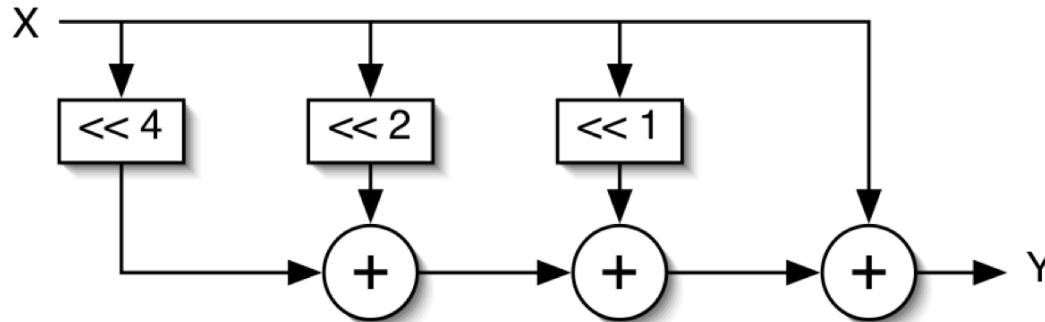


- Details:



Multiplication by a Constant

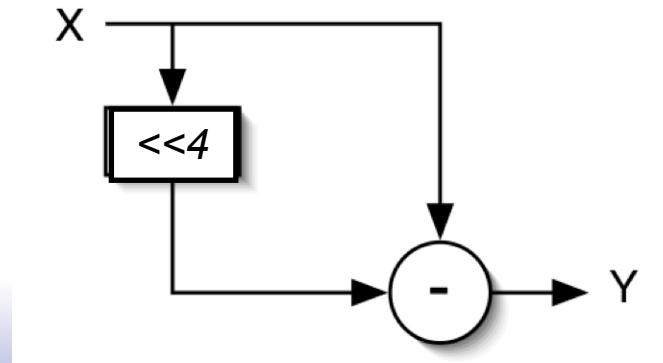
- Another example: $C = 23_{10} = 010111$



- *In general, the number of additions equals one less than the number of 1's in the constant.*
- Using carry-save adders (for all but one of these) helps reduce the delay and cost, and using balanced trees helps with delay, but the number of adders is still the number of 1's in C minus 2.
- Is there a way to further reduce the number of adders (and thus the cost and delay)?

Multiplication using Subtraction

- ❑ *Subtraction is approximately the same cost and delay as addition.*
- ❑ Consider $C \cdot X$ where C is the constant value $15_{10} = 01111_2$.
 $C \cdot X$ requires 3 additions.
- ❑ We can “recode” 15
 - from $01111 = (2^3 + 2^2 + 2^1 + 2^0)$
 - to $1000\bar{1} = (2^4 - 2^0)$
 - where $\bar{1}$ means negative weight.
- ❑ Therefore, $15 \cdot X$ can be implemented with only one subtractor.



Canonic Signed Digit Representation

- CSD represents numbers using 1, $\bar{1}$, & 0 with the least possible number of non-zero digits.
 - Strings of 2 or more non-zero digits are replaced.
 - Leads to a unique representation.

- To form CSD representation might take 2 passes:

- First pass: replace all occurrences of 2 or more 1's:

$$01..10 \text{ by } 10..\bar{1}0$$

- Second pass: same as above, plus replace $01\bar{1}0$ by 0010 and $0\bar{1}10$ by $00\bar{1}0$

- Examples:

$$011101 = 29$$

$$100\bar{1}01 = 32 - 4 + 1$$

$$0010111 = 23$$

$$001100\bar{1}$$

$$010\bar{1}00\bar{1} = 32 - 8 - 1$$

$$0110110 = 54$$

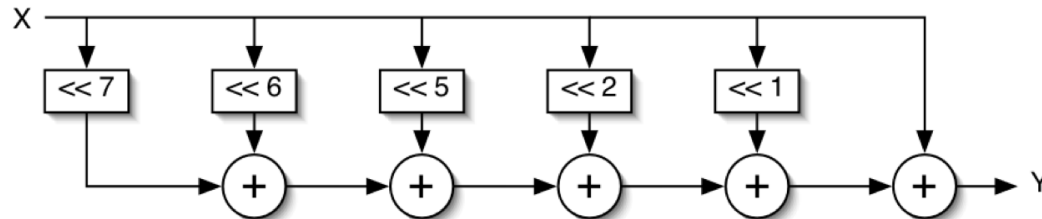
$$10\bar{1}10\bar{1}0$$

$$100\bar{1}0\bar{1}0 = 64 - 8 - 2$$

- Can we further simplify the multiplier circuits?

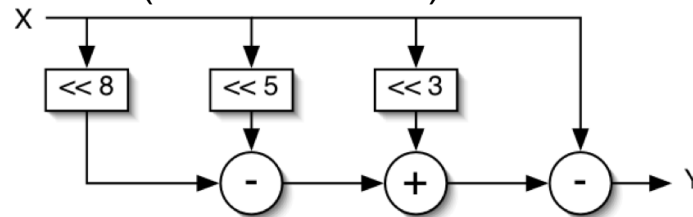
“Constant Coefficient Multiplication” (KCM)

Binary multiplier: $Y = 231 * X = (2^7 + 2^6 + 2^5 + 2^2 + 2^1 + 2^0) * X$



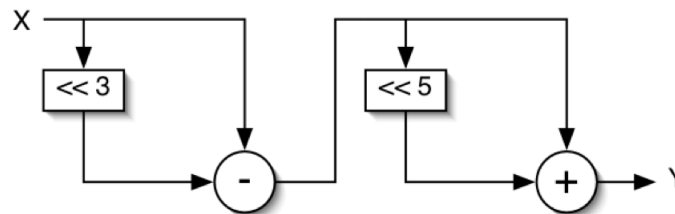
- CSD helps, but the multipliers are limited to shifts followed by adds.

- CSD multiplier: $Y = 231 * X = (2^8 - 2^5 + 2^3 - 2^0) * X$



- How about shift/add/shift/add ...?

- KCM multiplier: $Y = 231 * X = 7 * 33 * X = (2^3 - 2^0) * (2^5 + 2^0) * X$

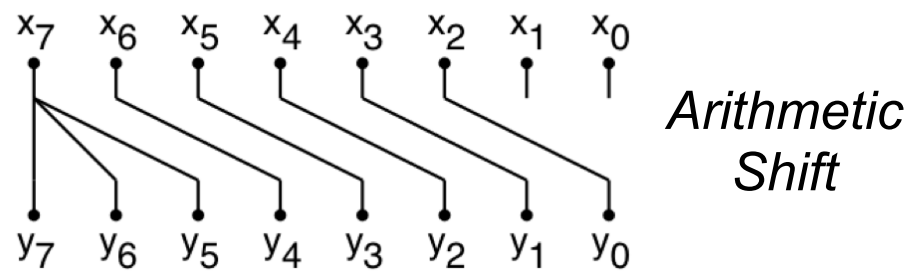
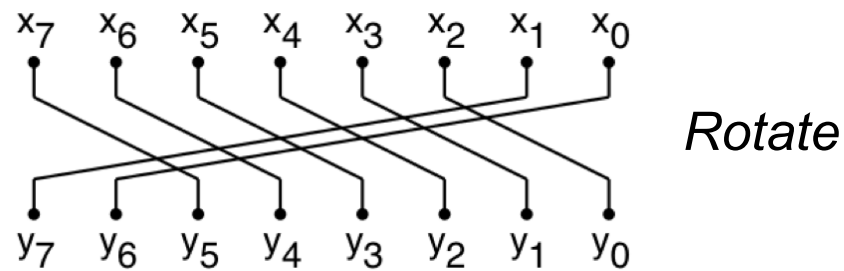
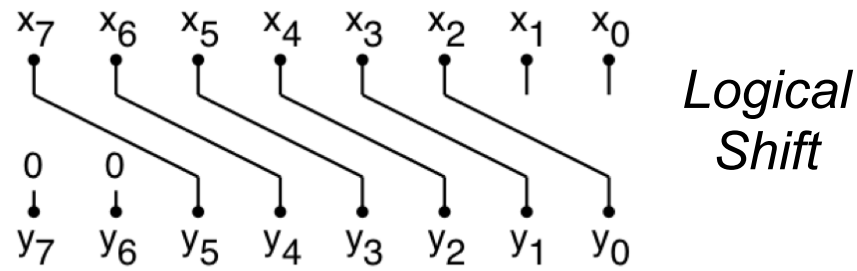


- No simple algorithm exists to determine the optimal KCM representation.
- Most use exhaustive search method.



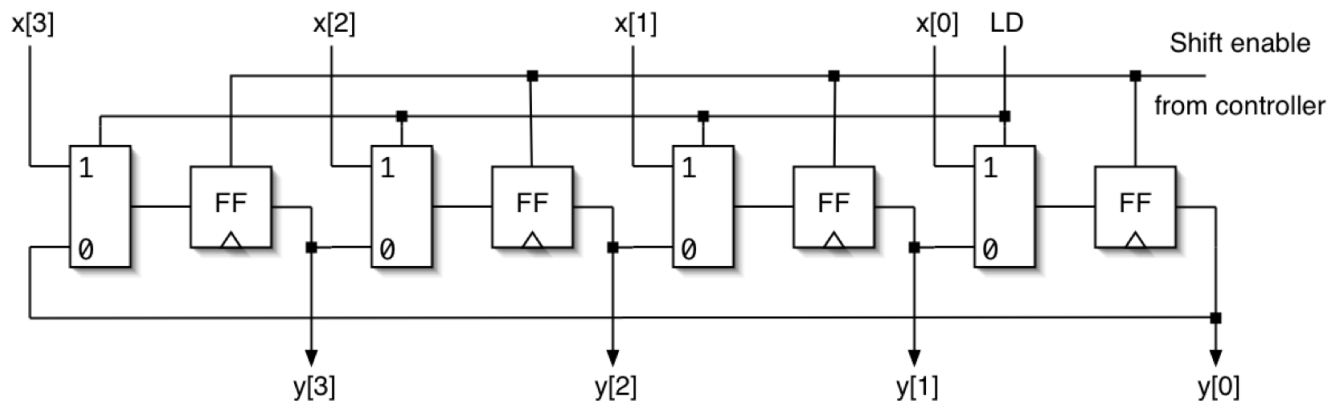
Shifters

Fixed Shifters / Rotators Defined



Variable Shifters / Rotators

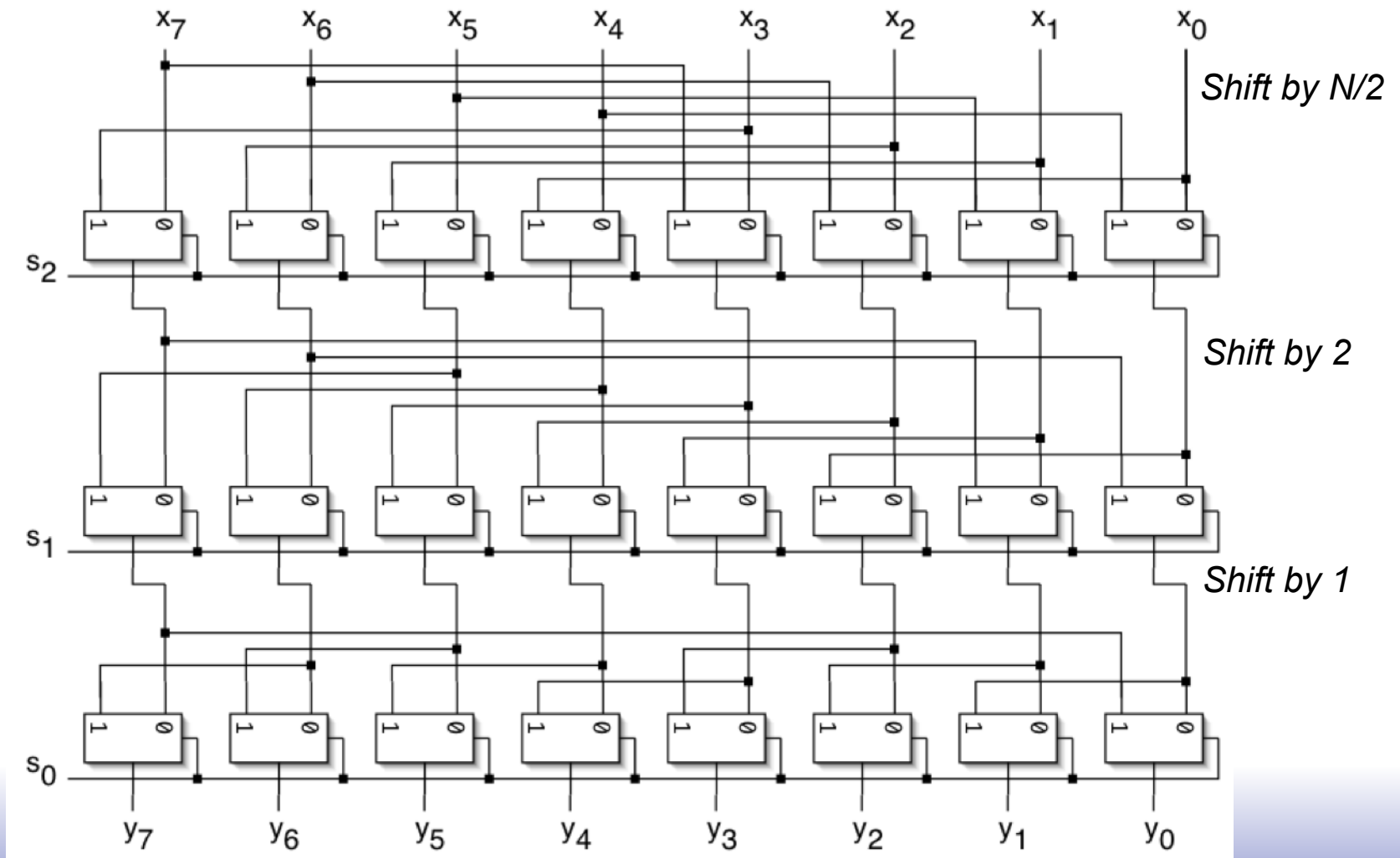
- Example: $X \gg S$, where S is unknown when we synthesize the circuit.
- Uses: shift instruction in processors (ARM includes a shift on every instruction), floating-point arithmetic, division/multiplication by powers of 2, etc.
- One way to build this is a simple shift-register:
 - a) Load word,
 - b) shift enable for S cycles,
 - c) read word.



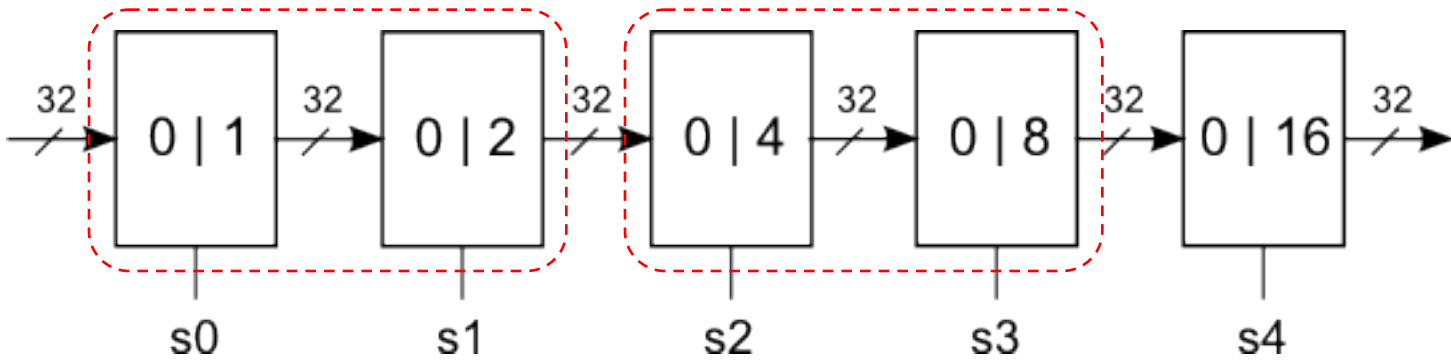
- Worst case delay $O(N)$, not good for processor design.
- Can we do it in $O(\log N)$ time and fit it in one cycle?

Log Shifter / Rotator

- Log(N) stages, each shifts (or not) by a power of 2 places, $S=[s_2;s_1;s_0]$:

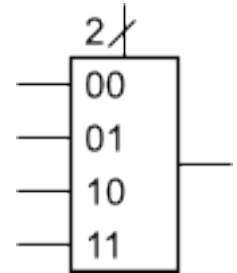


LUT Mapping of Log shifter

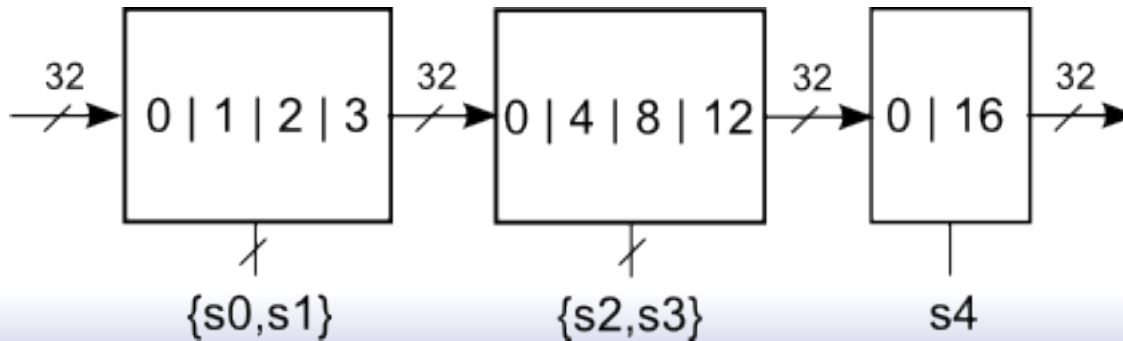


Efficient with 2to1 multiplexors, for instance, 3LUTs.

Virtex6 has 6LUTs. Naturally makes 4to1 muxes:



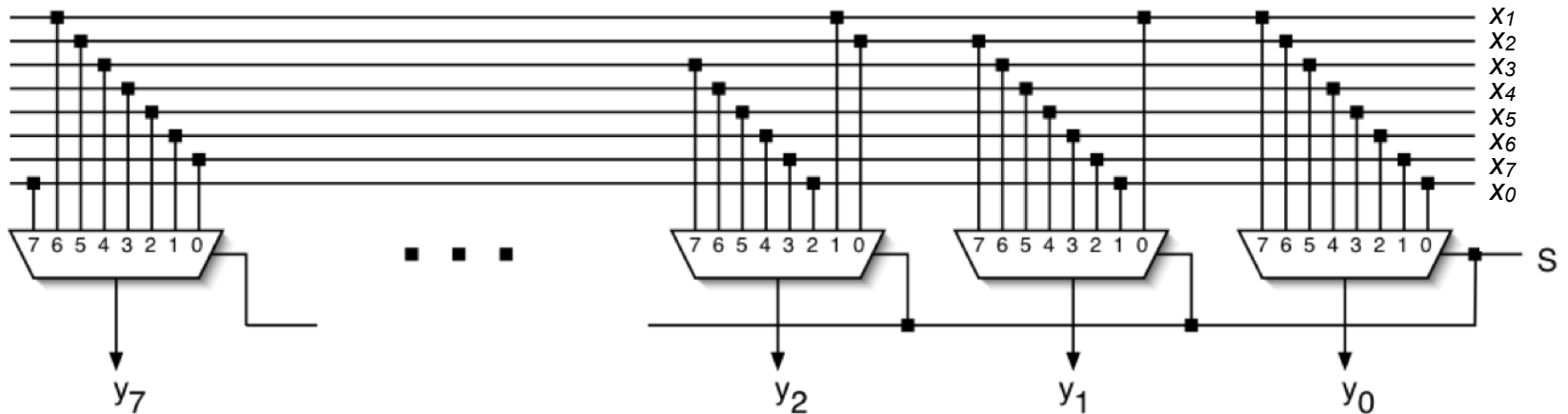
Reorganize shifter to use 4to1 muxes.



Final stage uses F7 mux

“Improved” Shifter / Rotator

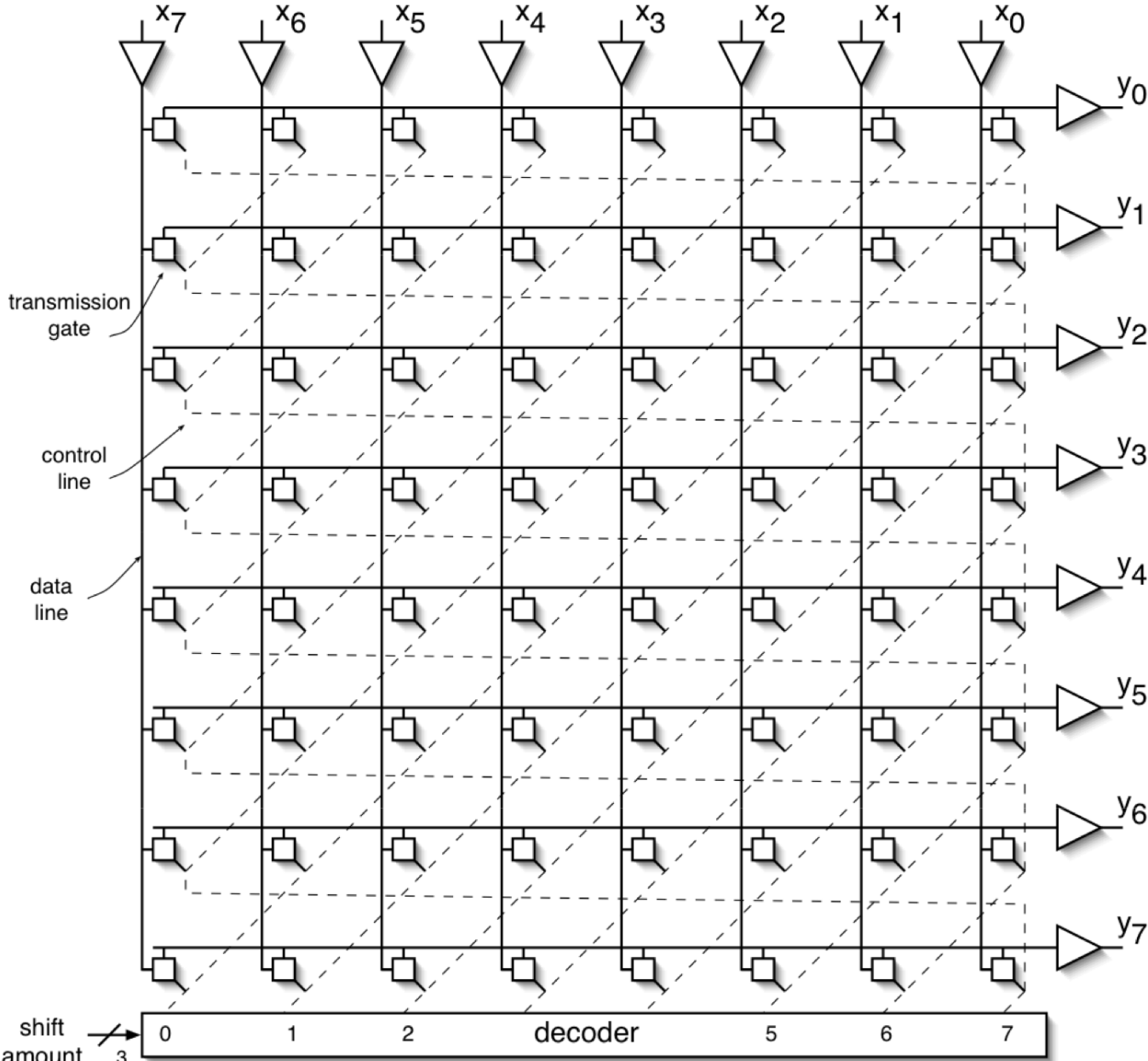
- How about this approach? Could it lead to even less delay?



Left-shift with rotate

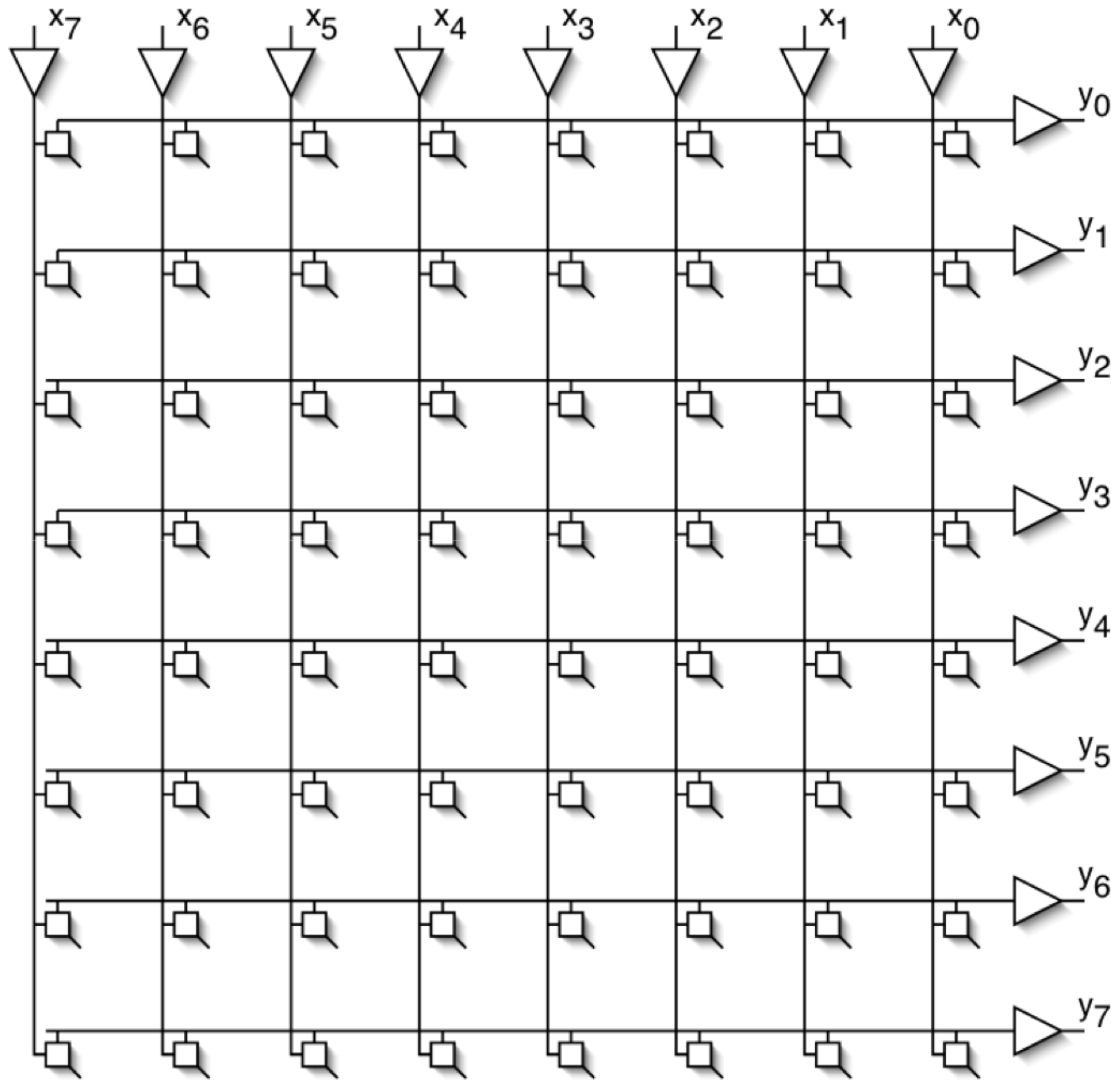
- What is the delay of these big muxes?
- Look a transistor-level implementation?

Barrel Shifter



Cost/delay?

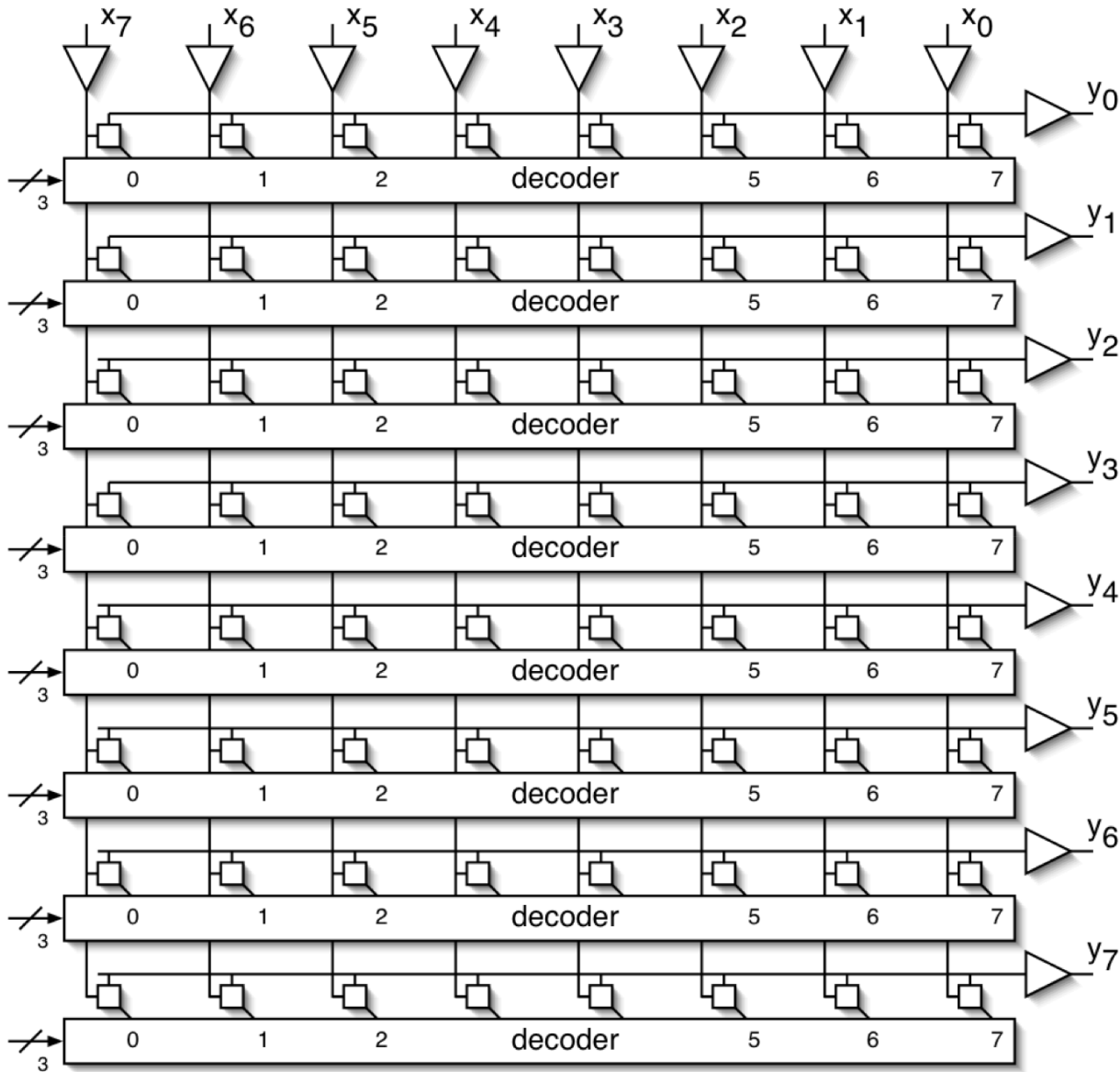
Connection Matrix



□ Generally useful structure:

- N^2 control points.
- What other interesting functions can it do?

Cross-bar Switch



$N \log(N)$ control signals.

Supports all interesting permutations

- All one-to-one and one-to-many connections.

Commonly used in communication hardware (switches, routers).