EECS150 - Digital Design

Lecture 22 - Arithmetic Blocks, Part 1

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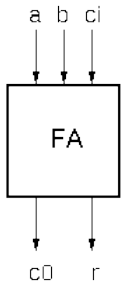
Carry-ripple Adder Revisited

- Each cell:

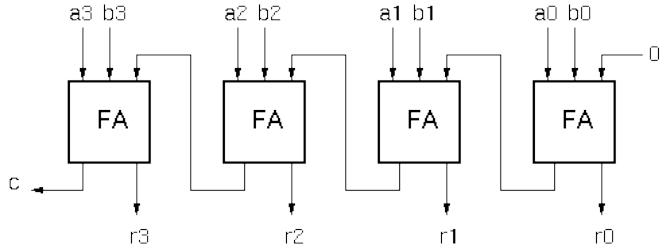
  $r_i = a_i$ XOR b_i XOR c_{in}

  $c_{out} = a_i c_{in} + a_i b_i + b_i c_{in} = c_{in}(a_i + b_i) + a_i b_i$



"Full adder cell"

- 4-bit adder:



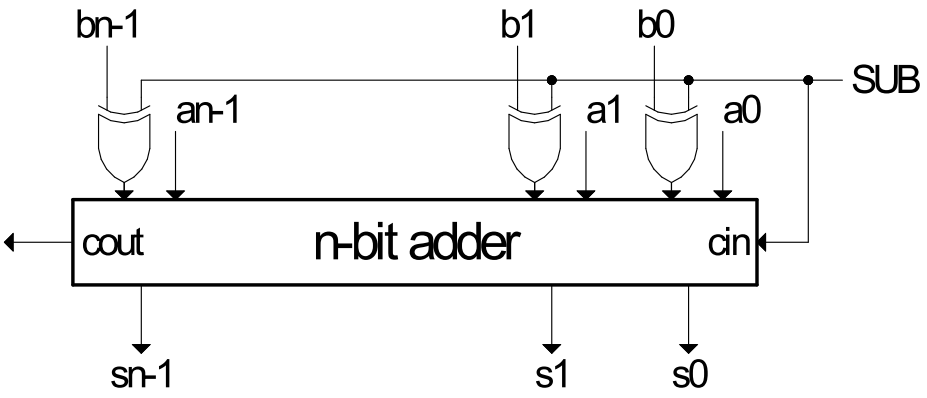
- What about subtraction?

Subtractor

A - B = A + (-B)

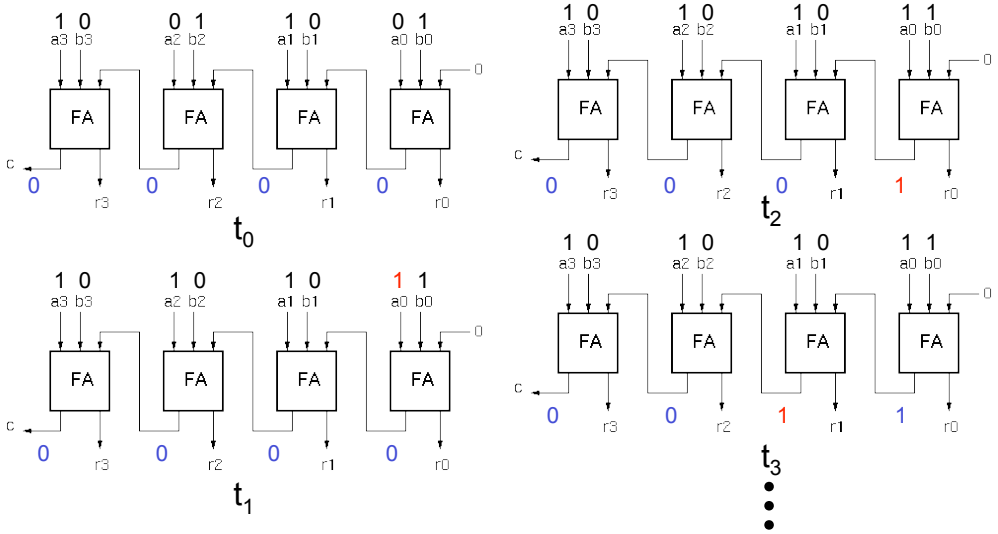
How do we form -B?

1. complement B
2. add 1



Delay in Ripple Adders

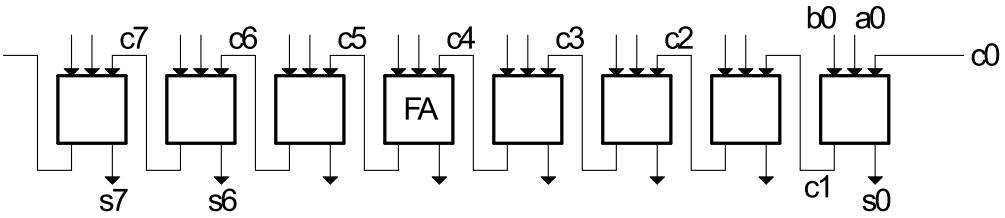
- Ripple delay amount is a function of the data inputs:



- However, we usually only consider the worst case delay on the critical path. There is usually at least one set of input data that exposes the worst case delay.

Adders (cont.)

Ripple Adder

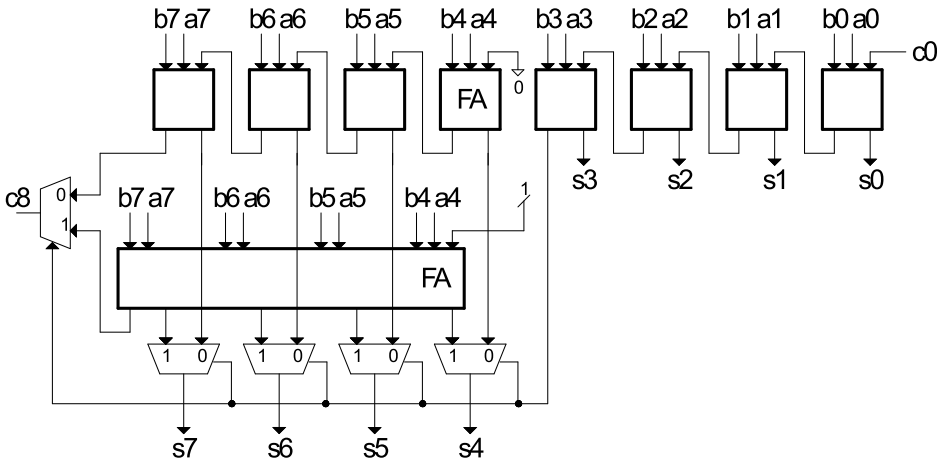


Ripple adder is inherently slow because, in general s7 must wait for c7 which must wait for c6 …

$$\boldsymbol{T} \propto n, \quad \boldsymbol{Cost} \propto n$$

How do we make it faster, perhaps with more cost?

Carry Select Adder

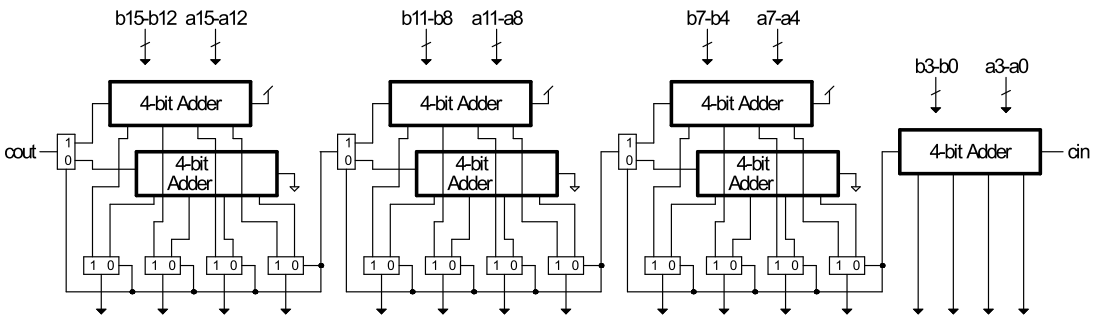


$T = T_{ripple\_adder} / 2 + T_{MUX}$

$COST = 1.5 * COST_{ripple\_adder} + (n/2 + 1) * COST_{MUX}$

Carry Select Adder

- Extending Carry-select to multiple blocks

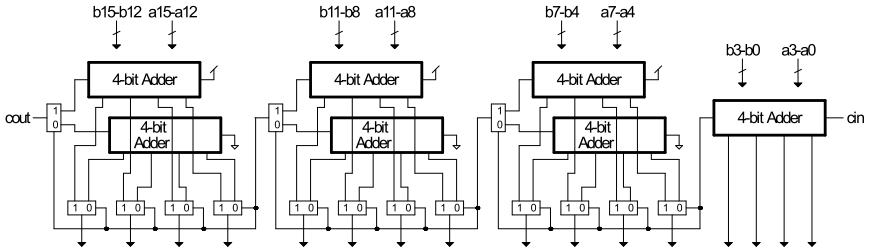


- What is the optimal # of blocks and # of bits/block?
  - If # blocks too large delay dominated by total mux delay
  - If # blocks too small delay dominated by adder delay

$\sqrt{N}$ stages of $\sqrt{N}$ bits

T α sqrt(N),
Cost ≈2*ripple + muxes

Carry Select Adder



- Compare to ripple adder delay:

  T_{total} = 2 sqrt(N) T_{FA} – T_{FA}, assuming T_{FA} = T_{MUX}

  For ripple adder T_{total} = N T_{FA}

  "cross-over" at N=3, Carry select faster for any value of N>3.
- Is sqrt(N) really the optimum?
  - From right to left increase size of each block to better match delays
  - Ex: 64-bit adder, use block sizes [12 11 10 9 8 7 7]
- How about recursively defined carry select?

Carry Look-ahead Adders

- In general, for n-bit addition best we can achieve is
  delay α log(n)
- How do we arrange this? (think trees)
- First, reformulate basic adder stage:

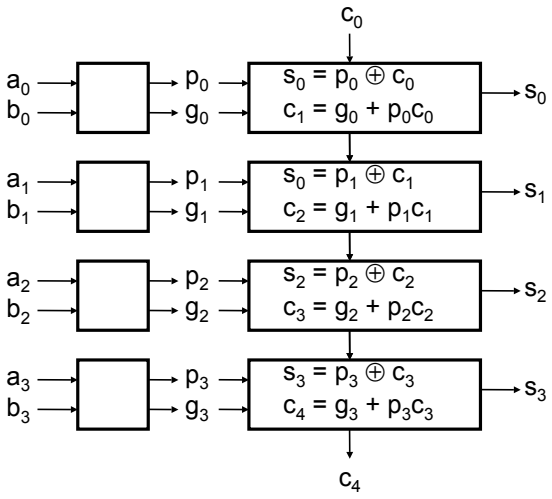
a b c_i	c_{i+1}	s	
0 0 0	0	0	carry "kill"
0 0 1	0	1	$k_i = a_i' b_i'$
0 1 0	0	1	
0 1 1	1	0	carry "propagate"
1 0 0	0	1	$p_i = a_i \oplus b_i$
1 0 1	1	0	
1 1 0	1	0	carry "generate"
1 1 1	1	1	$g_i = a_i b_i$

$c_{i+1} = g_i + p_i c_i$
$s_i = p_i \oplus c_i$

Carry Look-ahead Adders

- Ripple adder using p and g signals:

$p_i = a_i \oplus b_i$
$g_i = a_i b_i$



- So far, no advantage over ripple adder: T α N

Carry Look-ahead Adders

- Expand carries:

c_0

$c_1 = g_0 + p_0 c_0$

$c_2 = g_1 + p_1c_1 = g_1 + p_1g_0 + p_1p_0c_0$

$c_3 = g_2 + p_2c_2 = g_2 + p_2g_1 + p_1p_2g_0 + p_2p_1p_0c_0$

$c_4 = g_3 + p_3c_3 = g_3 + p_3g_2 + p_3p_2g_1 + \ldots$

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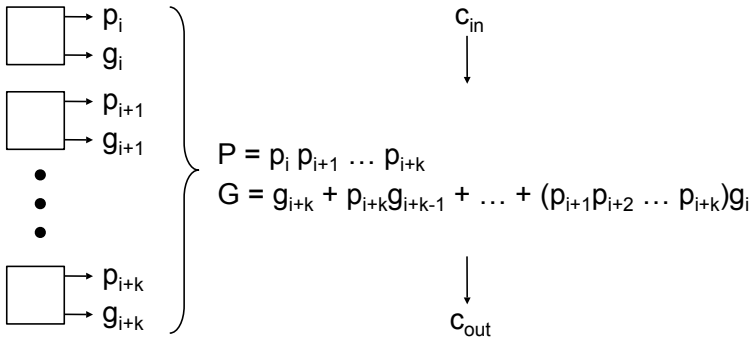
- Why not implement these equations directly to avoid ripple delay?
  - Lots of gates. Redundancies (full tree for each).
  - Gate with high # of inputs.
- Let's reorganize the equations.

Carry Look-ahead Adders

- "Group" propagate and generate signals:

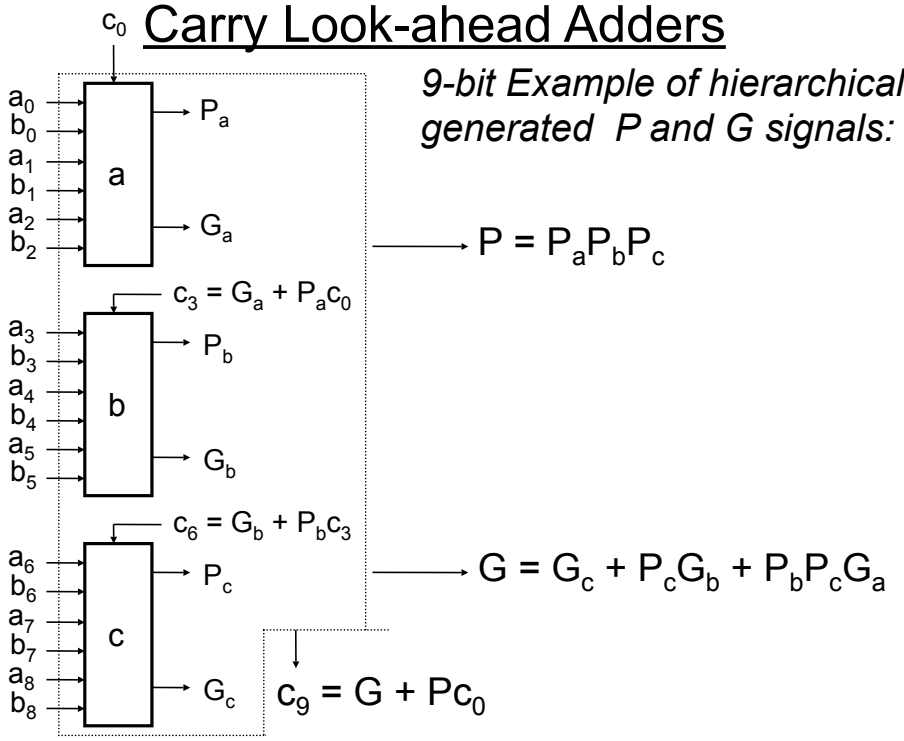


- P true if the group as a whole propagates a carry to c_{out}
- G true if the group as a whole generates a carry

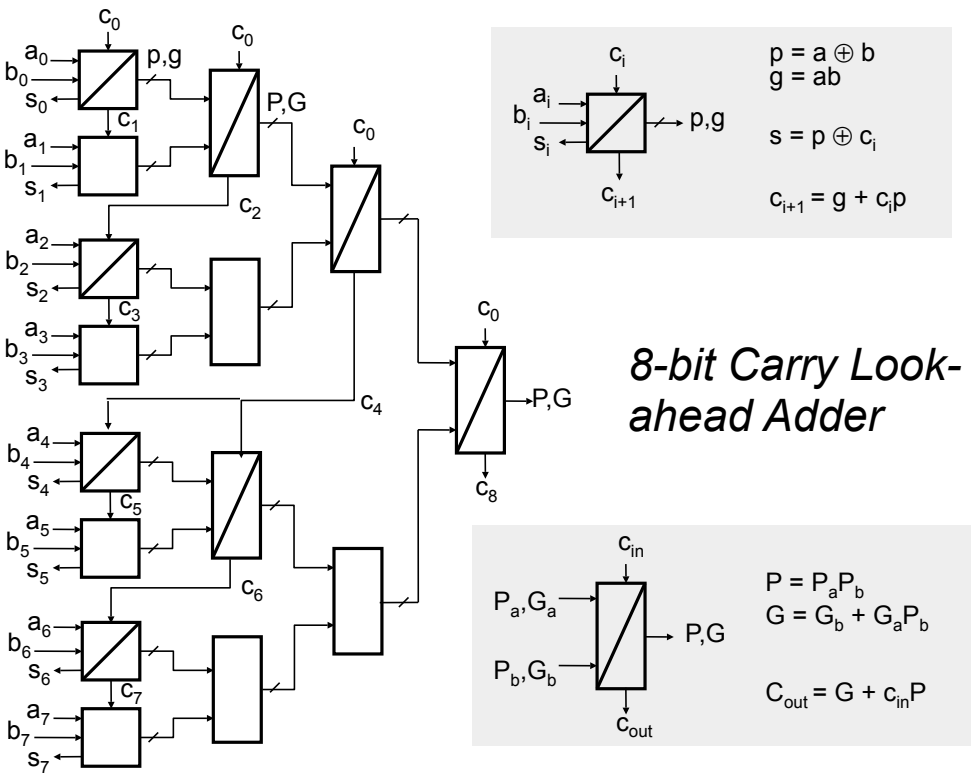
$$\boxed{c_{out} = G + Pc_{in}}$$

- Group P and G can be generated hierarchically.

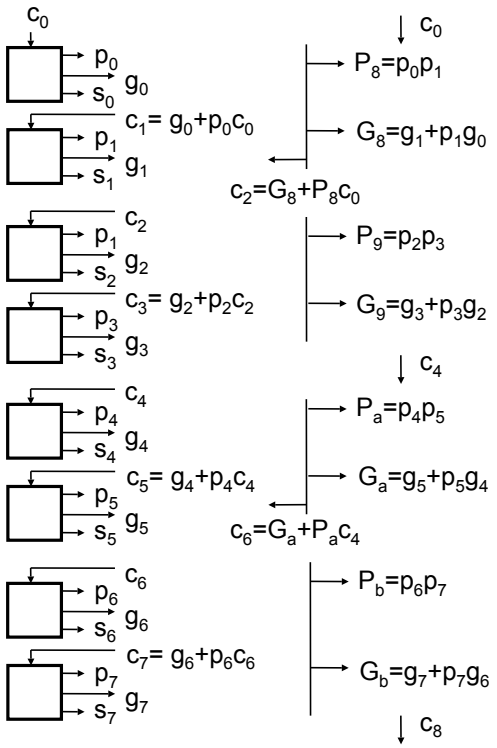
Carry Look-ahead Adders



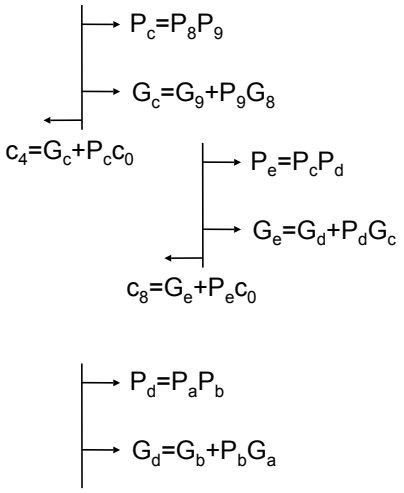
9-bit Example of hierarchically generated P and G signals:



8-bit Carry Look-ahead Adder



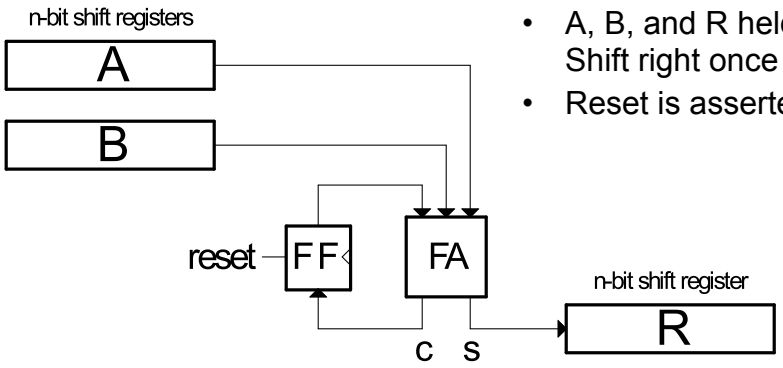
8-bit Carry Look-ahead Adder with 2-input gates.



Carry look-ahead Wrap-up

- Adder delay O(logN) (up then down the tree).
- Cost? Energy per add?
- Can be applied with other techniques. Group P & G signals can be generated for sub-adders, but another carry propagation technique (for instance ripple) used within the group.
  - For instance on FPGA. Ripple carry up to 32 bits is fast (1.25ns), CLA used to extend to large adders. CLA tree quickly generates carry-in for upper blocks.
- Other more complex techniques exist that can bring the delay down below O(logN), but are only efficient for very wide adders.

Bit-serial Adder

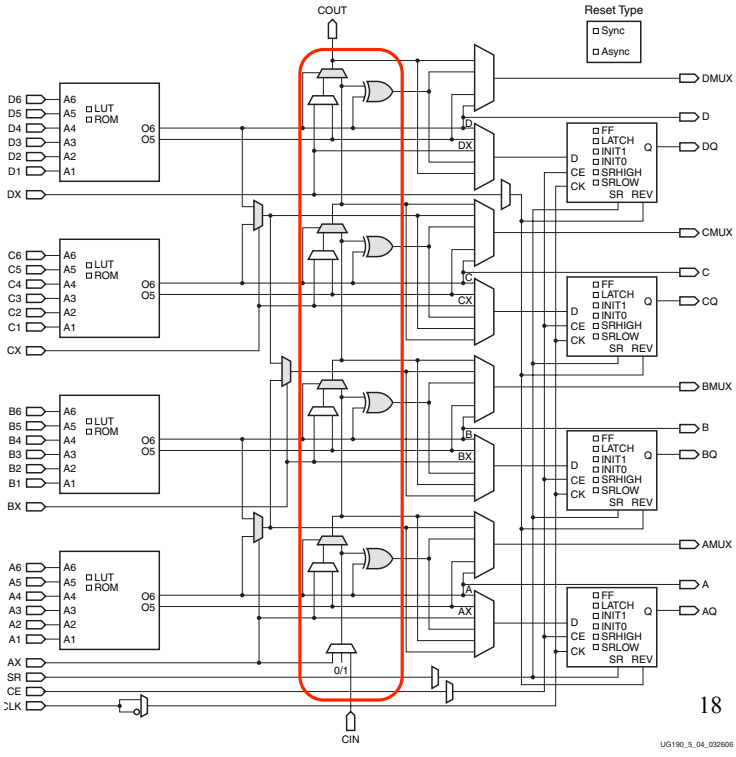


- A, B, and R held in shift-registers. Shift right once per clock cycle.
- Reset is asserted by controller.

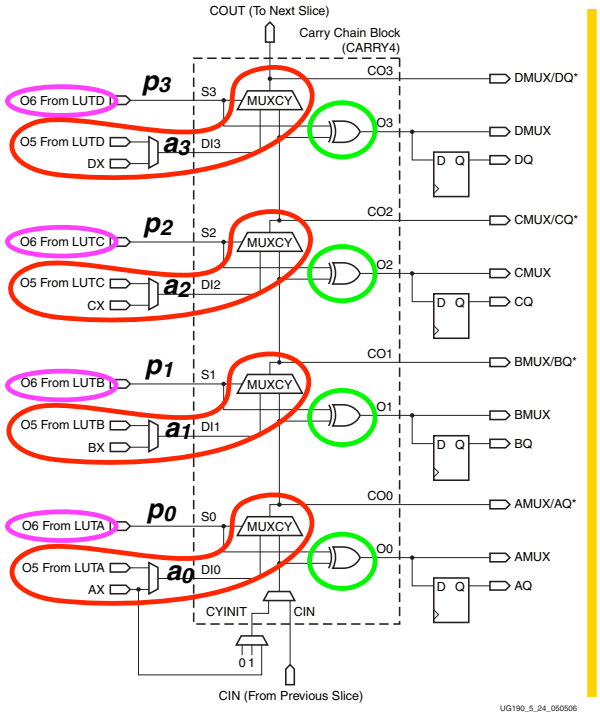
- Addition of 2 n-bit numbers:
  - takes n clock cycles,
  - uses 1 FF, 1 FA cell, plus registers
  - the bit streams may come from or go to other circuits, therefore the registers might not be needed.

Adders on the Xilinx Virtex-5

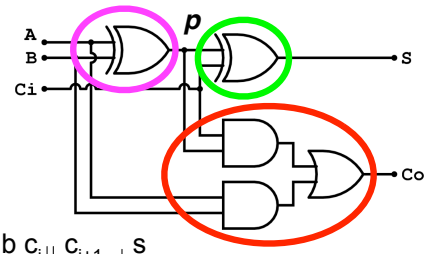
- Dedicated carry logic provides fast arithmetic carry capability for high-speed arithmetic functions.
- Cin to Cout (per bit) delay = 40ps, versus 900ns for F to X delay.
- 64-bit add delay = 2.5ns.



Virtex 5 Vertical Logic



We can map ripple-carry addition onto carry-chain block.



a	b	c_i	c_{i+1}	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

$c_{out} = p_i\, c_{in} + a_i\, b_i$

$c_{out} = p_i \; ? \; c_{in} : a_i$

$p_i = a_i \text{ xor } b_i$

The carry-chain block also useful for speeding up other adder structures and counters.

Adder Final Words

Type	Cost	Delay
Ripple	O(N)	O(N)
Carry-select	O(N)	O(sqrt(N))
Carry-lookahead	O(N)	O(log(N))

- Dynamic energy per addition for all of these is O(n).
- "O" notation hides the constants. Watch out for this!
- The cost of the carry-select is at least 2X the cost of the ripple. Cost of the CLA is probably at least 2X the cost of the carry-select.
- The actual multiplicative constants depend on the implementation details and technology.
- FPGA and ASIC synthesis tools will try to choose the best adder architecture automatically
  - assuming you specify addition using the "+" operator, as in "assign A = B + C"