FPGA Carry Chain Adder (1A)

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Please send corrections (or suggestions) to youngwlim@hotmail.com.

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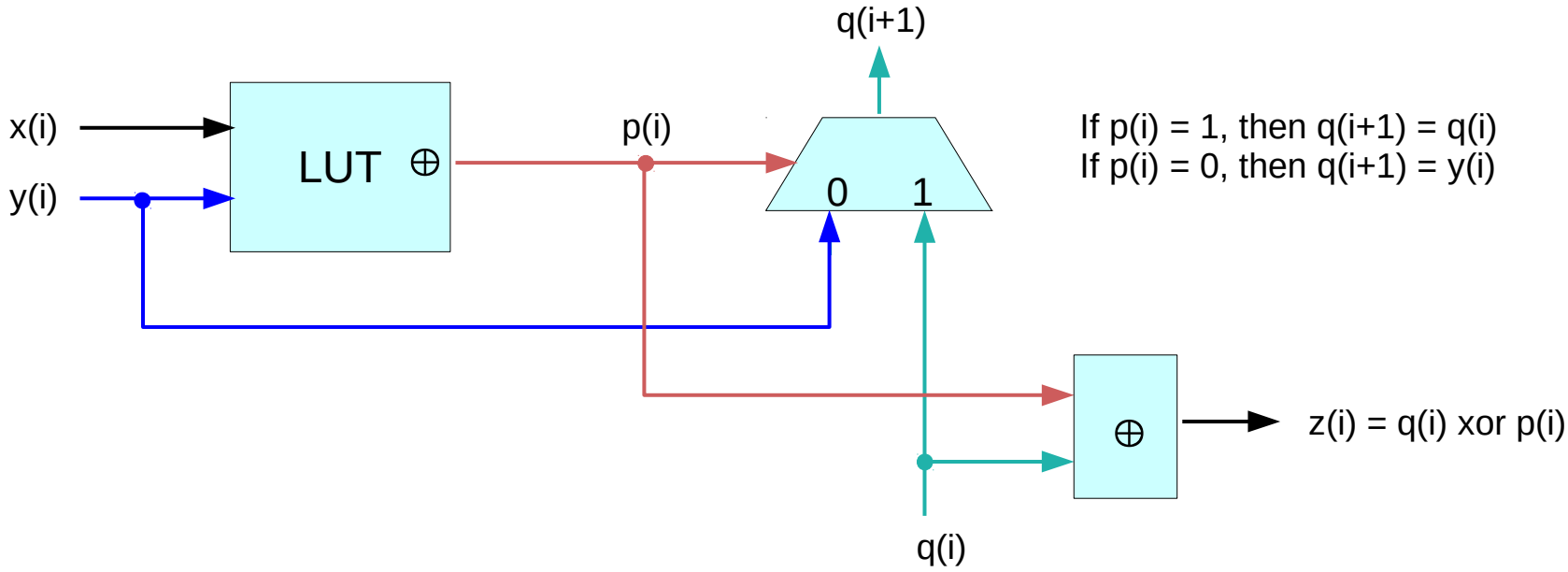
FPGA Carry Chain Cell



$$s_i = (a_i \oplus b_i) \oplus c_i = p_i \oplus c_i$$

$$c_{i+1} = (a_i \cdot b_i) + (a_i \oplus b_i) c_i = \overline{p_i} \cdot g_i + p_i \cdot c_i = \overline{p_i} \cdot a_i + p_i \cdot c_i = \overline{p_i} \cdot b_i + p_i \cdot c_i$$

when $\overline{p_i} = 1$, *then* $a_i = b_i$

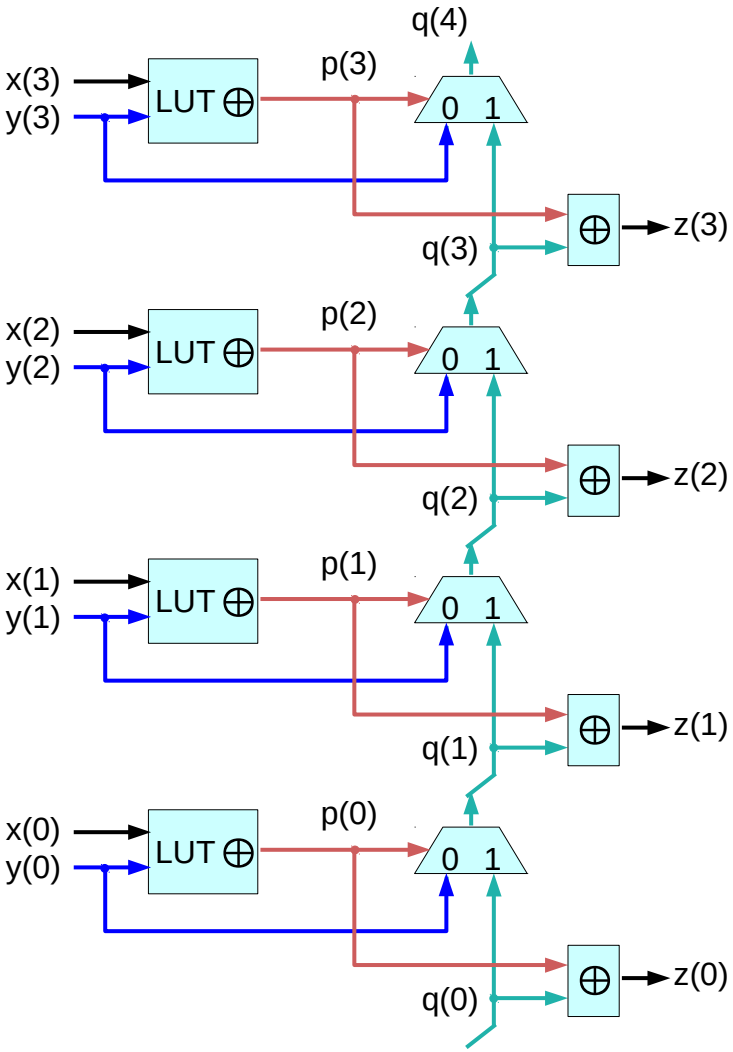
when $g_i = 1$, *then* $a_i = b_i = 1$

p(i)	0	1
0	0	1
1	1	0

g(i)	0	1
0	0	0
1	0	1

Synthesis of Arithmetic Circuits: FPGA, ASIC and Ebedded Systems, J-P Deschamps et al

FPGA Carry Chain Cell



Synthesis of Arithmetic Circuits: FPGA, ASIC and Ebedded Systems, J-P Deschamps et al

FPGA Carry Chain

FPGAs generally contain dedicated computation resources
for generating fast adders

The Virtex family programmable arrays include
logic gates (**XOR**) and **multiplexers** that along with the
general purpose **lookup tables** allow one to build effective carry-chain adders

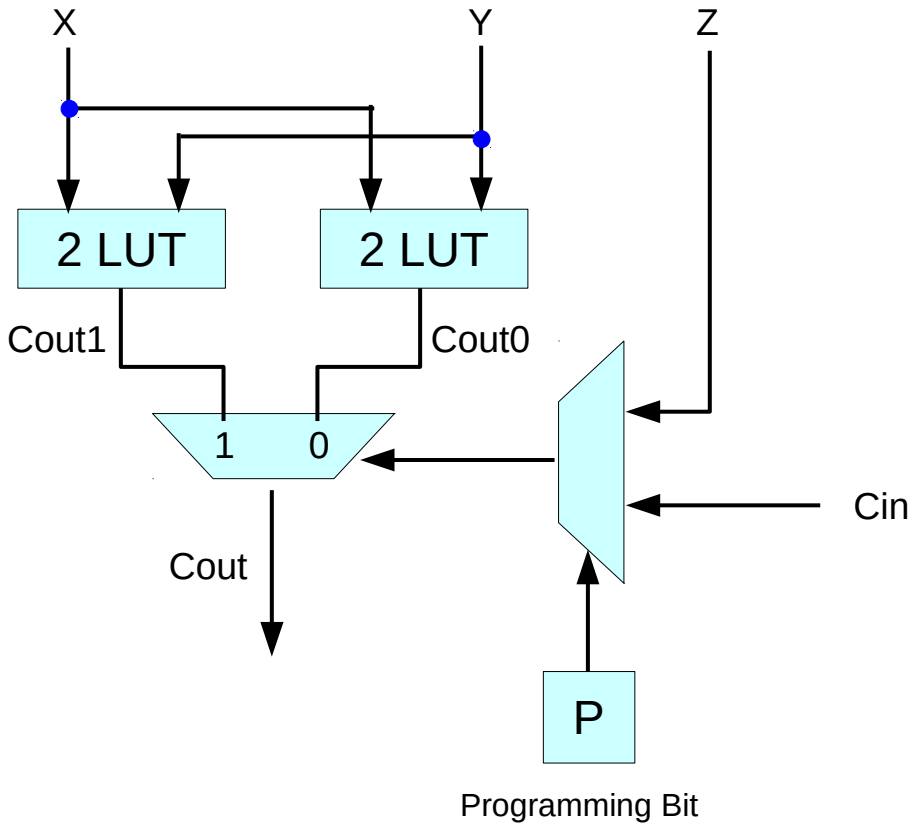
The carry chain is made up of multiplexers
belonging to adjacent configurable blocks

the lookup table is used for implementing the exclusive or function

p(i) = x(i) xor y(i)

https://en.wikipedia.org/wiki/Carry-lookahead_adder

FPGA Carry Chain Cell



Cout1, Cout2 : functions of X, Y, Cin

Cout1 = X+Y when Cin=1
Cout0 = X Y when Cin=0

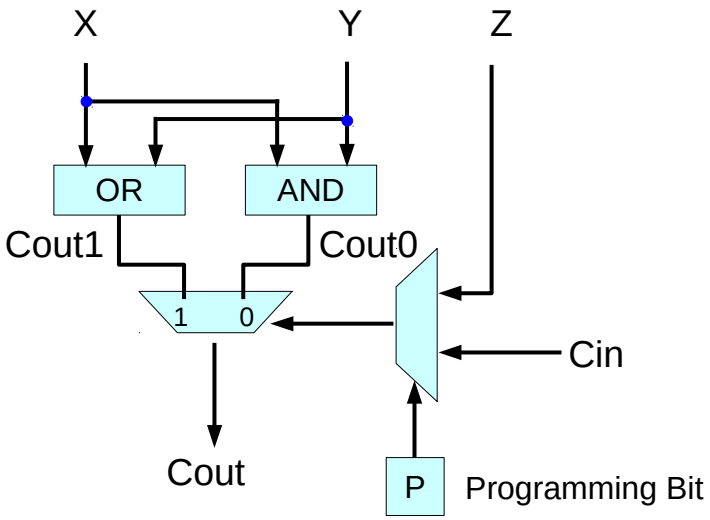
Cout = (X + Y) Cin + X Y $\overline{Cin}$

Cout = P' Cin + G $\overline{Cin}$ … P' = relaxed P

Cout1	Cout0	Cout	Name
0	0	0	Kill
0	1	$\overline{Cin}$	Inverse Propagate
1	0	Cin	Propagate
1	1	1	Generate

High Performance Carry Chains for FPGAs, S. Hauck, M. M. Hosler, T. W. Fry

FPGA Carry Chain Cell



		Cin	$\overline{Cin}$	
X	Y	Cout1	Cout0	
0	0	0	0	$\overline{X}\ \overline{Y}$
0	1	1	0	$\overline{X}$ Y
1	0	1	0	X $\overline{Y}$
1	1	1	1	X Y

Cout : functions of X, Y, Cin

Cout(X, Y, 1) = Cout1 = X + Y
Cout(X, Y, 0) = Cout0 = X Y

Cout1 = X + Y when Cin=1
Cout0 = XY when Cin=0

Cout1 = P' Cin … P' = relaxed P
Cout0 = G $\overline{Cin}$

If Cin, then Cout = ($\overline{X}$ Y + X $\overline{Y}$ + X Y)
If $\overline{Cin}$, then Cout = X Y

Cin (X + Y) + $\overline{Cin}$ X Y
Cin ($\overline{X}$ Y + X $\overline{Y}$ + X Y) + $\overline{Cin}$ X Y
Cin ($\overline{X}$ Y + X $\overline{Y}$) + (Cin + $\overline{Cin}$) X Y
P Cin + G

Cin (X + Y) + $\overline{Cin}$ X Y
Cin P' + $\overline{Cin}$ G … P' : relaxed P

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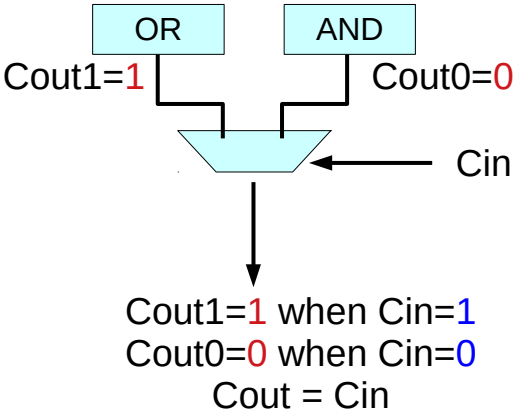
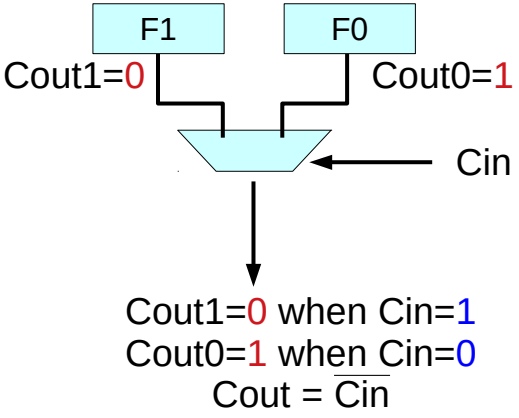
FPGA Carry Chain Cell



Cout0	Cout1	Cout	Name
0	0	0	Kill
0	1	Cin	Propagate
1	0	$\overline{Cin}$	Inverse Propagate
1	1	1	Generate



Cout1	Cout0	Cout	Name
0	0	$\overline{0}$	Kill
0	1	$\overline{Cin}$	Inverse Propagate
1	0	Cin	Propagate
1	1	1	Generate

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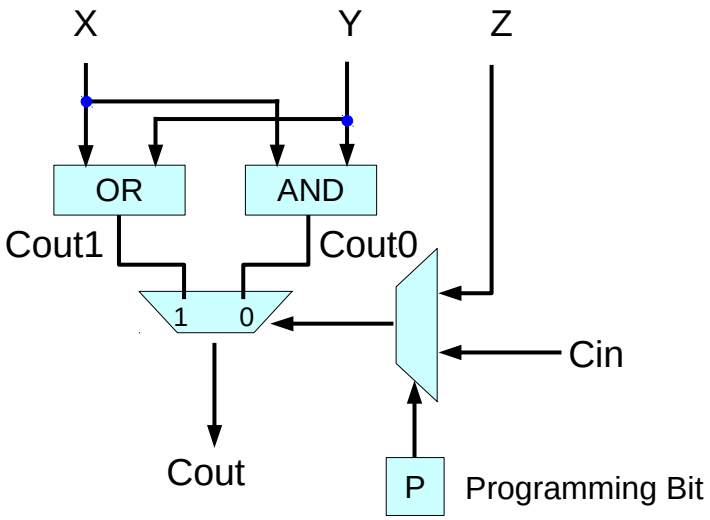
Carry Chain



		Cin	$\overline{Cin}$	
X	Y	Cout1	Cout0	
0	0	0	0	$\overline{X}\ \overline{Y}$
0	1	1	0	$\overline{X}\ Y$
1	0	1	0	$X\ \overline{Y}$
1	1	1	1	$X\ Y$

Cout1	Cout0	Cout	Name
0	0	0	Kill
0	1	$\overline{Cin}$	Inverse Propagate
1	0	Cin	Propagate
1	1	1	Generate

Carry Out

X	Y	Cin	
0	0	Cin	Cin
0	1	Cin	$\overline{Cin}$
1	0	Cin	$\overline{Cin}$
1	1	Cin	Cin

Cout1=1 when Cin=1
Cout0=0 when Cin=0
Cout = Cin propage

Cout1=0 when Cin=1
Cout0=1 when Cin=0
Cout = $\overline{Cin}$ inverse propagate

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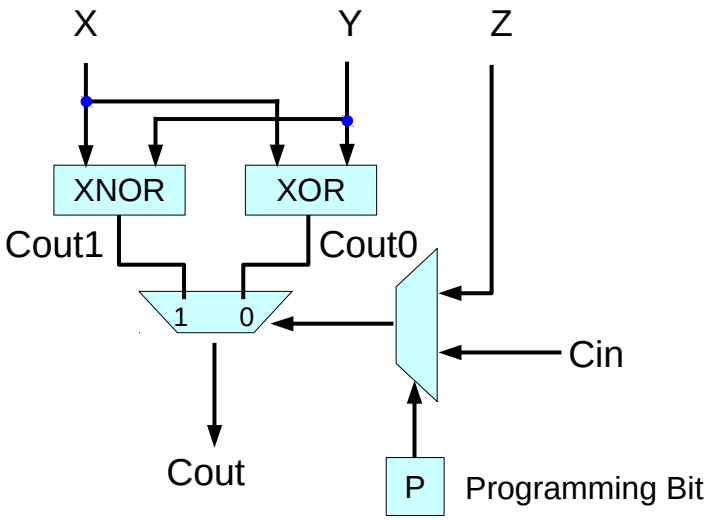
Parity Checker



		Cin	$\overline{Cin}$	
X	Y	Cout1	Cout0	
0	0	1	0	$\overline{X}\ \overline{Y}$
0	1	0	1	$\overline{X}\ Y$
1	0	0	1	$X\ \overline{Y}$
1	1	1	0	$X\ Y$

Cout1	Cout0	Cout	Name
0	0	0	Kill
0	1	$\overline{Cin}$	Inverse Propagate
1	0	Cin	Propagate
1	1	1	Generate

Computing Parity	
X ⊕ Y ⊕ Cin	
0 ⊕ 0 ⊕ Cin	Cin
0 ⊕ 1 ⊕ Cin	$\overline{Cin}$
1 ⊕ 0 ⊕ Cin	$\overline{Cin}$
1 ⊕ 1 ⊕ Cin	Cin

Cout1=1 when Cin=1
Cout0=0 when Cin=0
Cout = Cin propagate

Cout1=0 when Cin=1
Cout0=1 when Cin=0
Cout = $\overline{Cin}$ inverse propagate

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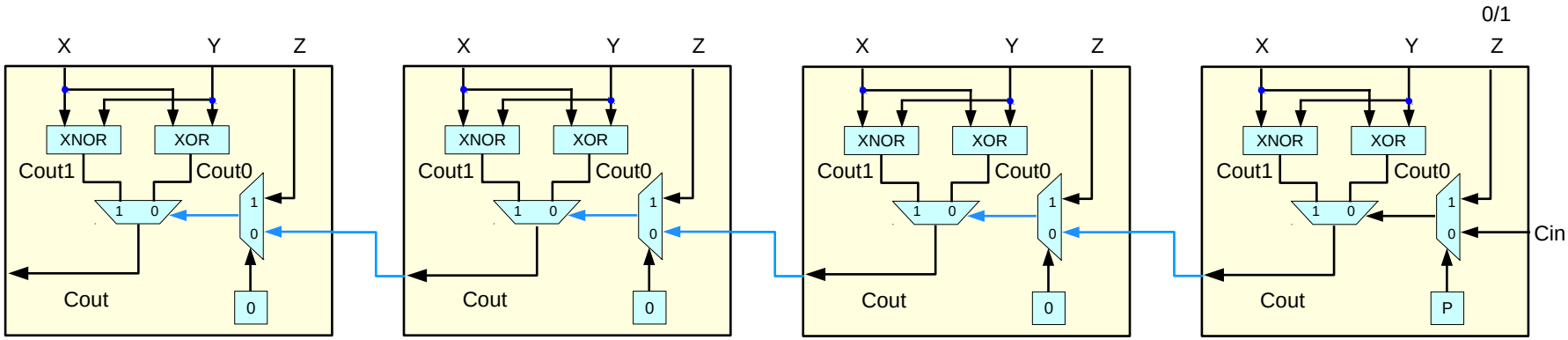
Ripple Carry Chain



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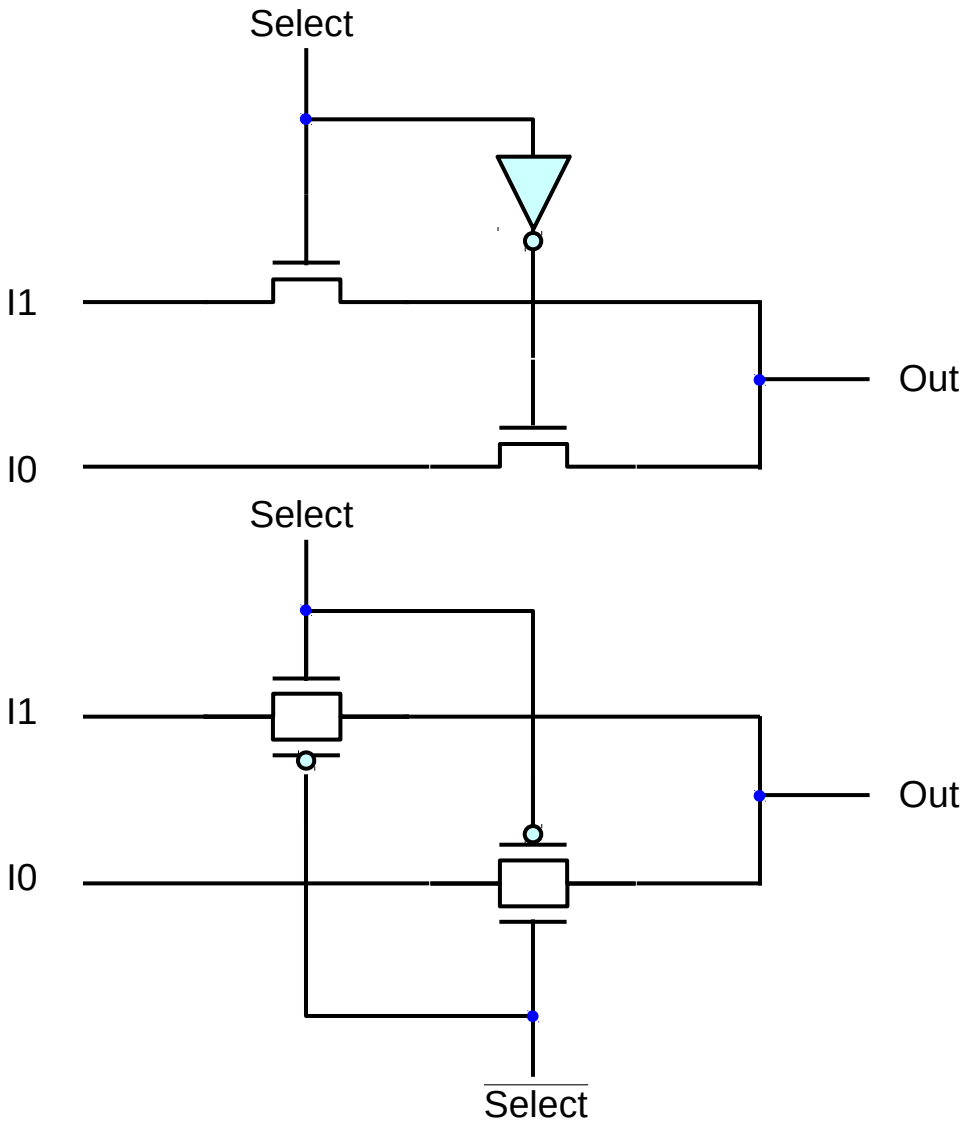
Ripple Carry Chain



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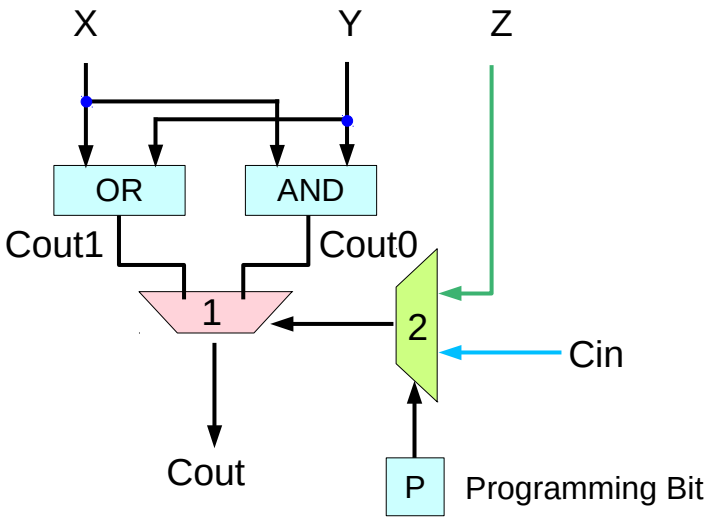
FPGA Carry Chain Cell



Significantly slower
Two muxes on the carry chain in each cell
Delay 1 for first cell
Delay 3 for each additional cell in the carry chain
1 delay for mux 2 and 2 delays for mux 1
Overall 2n-2 for an n-cell carry chain

The critical path comes from th 2-LUTs and not input Z
Since the delay through the 2-LUTs will be larger than
Through mux 2 in the first cell

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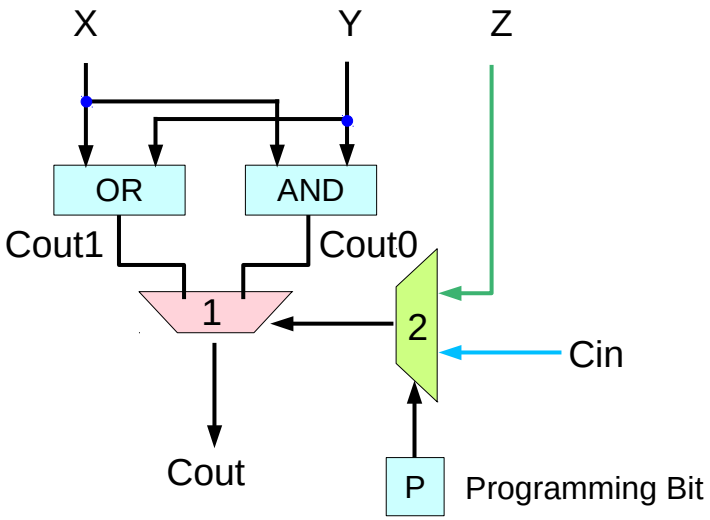
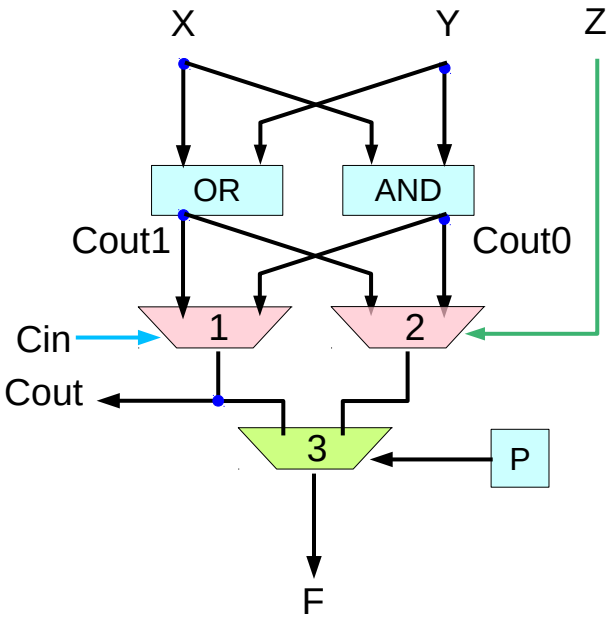
FPGA Carry Chain Cell





- not logically equivalent
- no longer use the Z input in the first cell
  since Z is only attached to mux2
  and mux 2 does not lead to the carry cells

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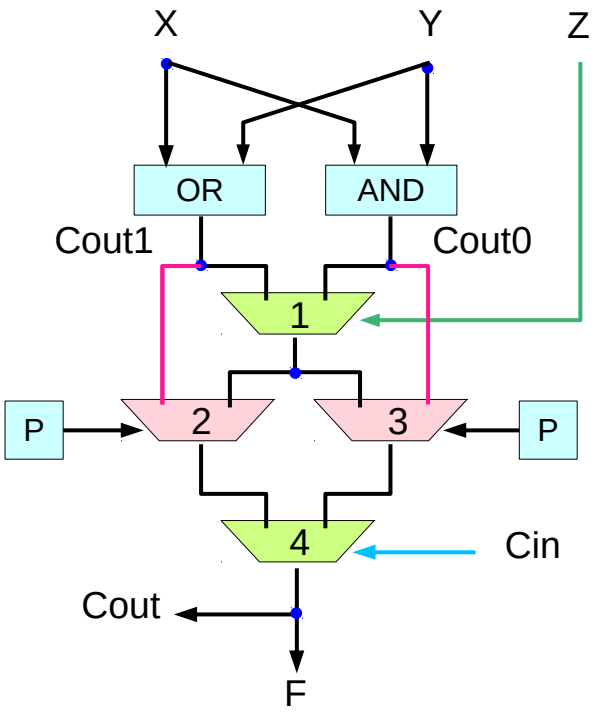
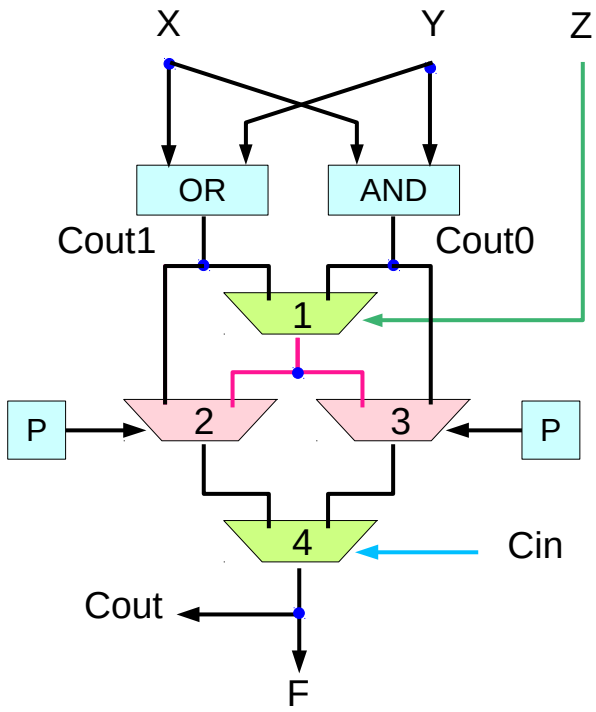
FPGA Carry Chain Cell





for cells in the middle of a carry chain
mux2 passes Cout1
mux3 passes Cout0
mux4 receives Cout1 and Cout0
provides a standard ripple carry path.

For the first cell in a carry chain
with a carry input (provided by input Z),
mux2 and mux3 both pass the value from mux1

the two main inputs to mux4 are identical
the output of mux4 (Cout) will be the same
as the output of mux1 (ignoring Cin)

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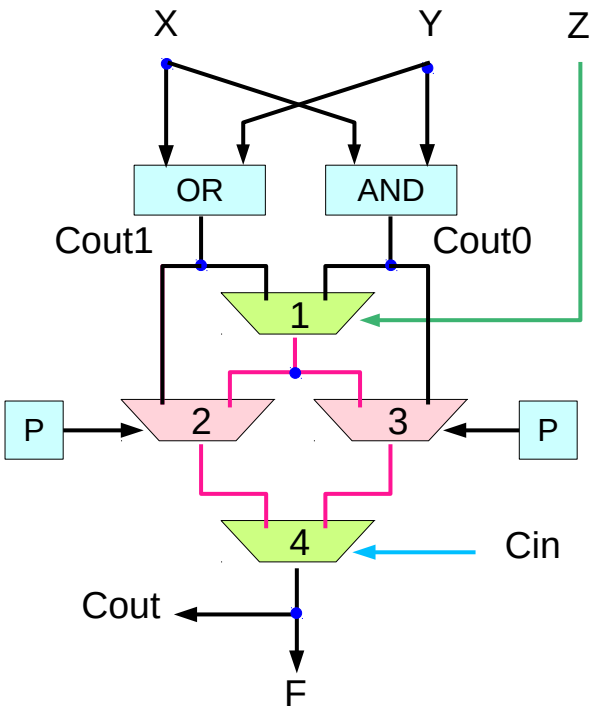
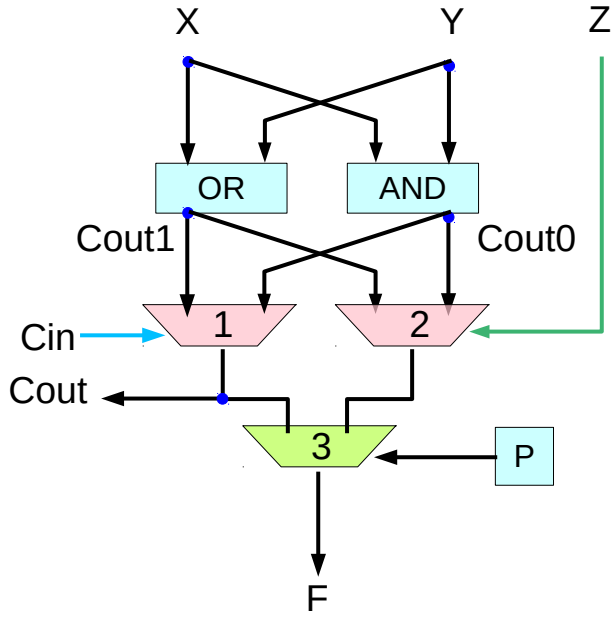
FPGA Carry Chain Cell



mux1's main inputs are driven
by two 2-LUTs (OR, AND) controlled by X and Y
mux1 forms a 3-LUT with the other 2-LUTs

When mux2 and mux3 pass the value from mux1
(Cout1 and Cout2 respectively)
the circuit is configured to continue the carry chain

Functionally equivalent



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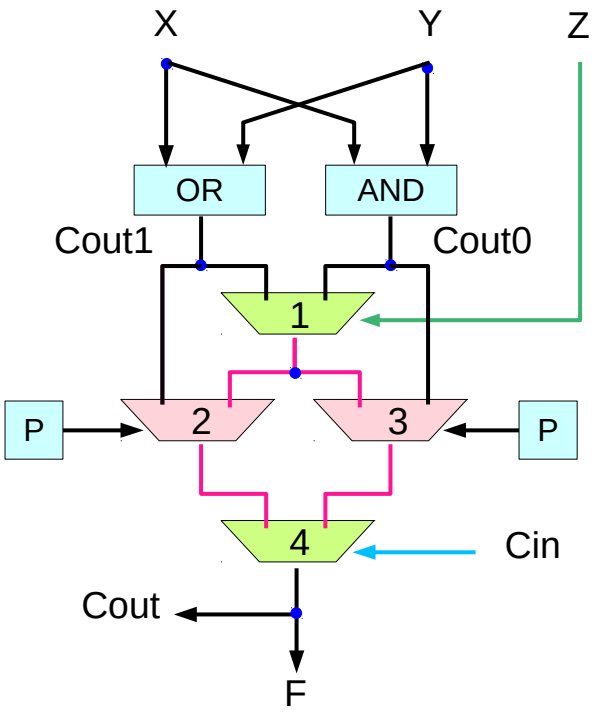
FPGA Carry Chain Cell



a delay of 3 in the first cell
(1 in mux1, 1 in mux2, 1 in mux4)
2 in all other cells in the carry chain
an total delay of 2n+1 for an n-bit carry chain

t1 gate delay slower than that of fig 2a,
a carry input to the first cell is enabled

Also, for carry computations that do not need this feature,
the first cell in a carry chain built from fig 2b
can be configured to bypass mux1,
reducing the overall delay to 2n,
which is identical to that of fig2a.

in order to implement a n-bit carry chain with a carry input,
the design of fig 2a requires an additional cell
at the beginning of the chain to bring in this input,
resulting in a delay of 2(n+1)=2n+2,
which is lower than that of the design in fig2b

thus, the design of fig 2b is the preferrred
ripple carry design among those presented so far

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FPGA Carry Chain Cell

However, carry chains built from this design have a delay of 3 in the first cell
(1 in mux1, 1 in mux2, 1 in mux4) and 2 in all other cells in the carry chain,
yielding an overall delay of 2n+1 for an n-bit carry chain.
thus, although this design is 1 gate delay slower than that of fig 2a,
it provides the ability to have a carry input to the first cell in a carry chain,
something that is important in many computations.
Also, for carry computations that do not need this feature, the first cell in a carry
chain built from fig 2b can be configured to bypass mux1, reducing the overall delay to 2n,
which is identical to that of fig2a.
on the other hand, in order to implment a n-bit carry chain with a carry input,
the designof fig 2a requires an additional cell at the beginning of the chain to bring in this input,
resulting in a delay of 2(n+1)=2n+2, which is lower than that of the design in fig2b
thus, the design of fig 2b is the preferrred ripple carry design among those presented so far

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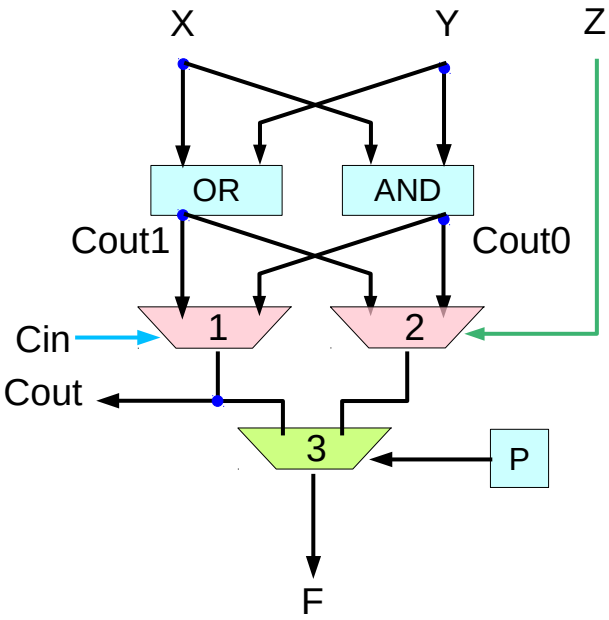
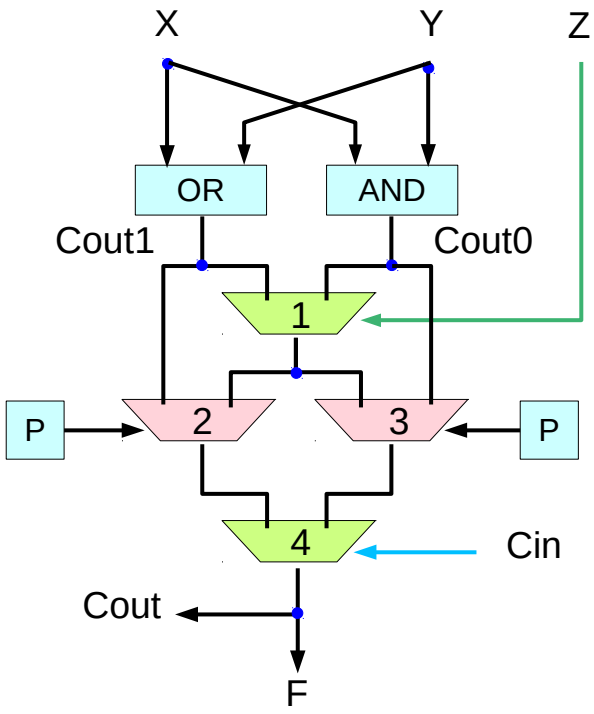
FPGA Carry Chain Cell





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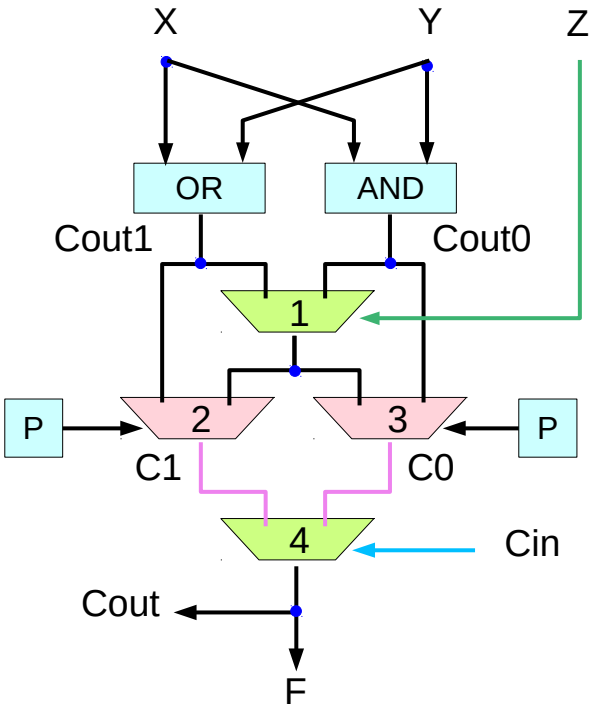
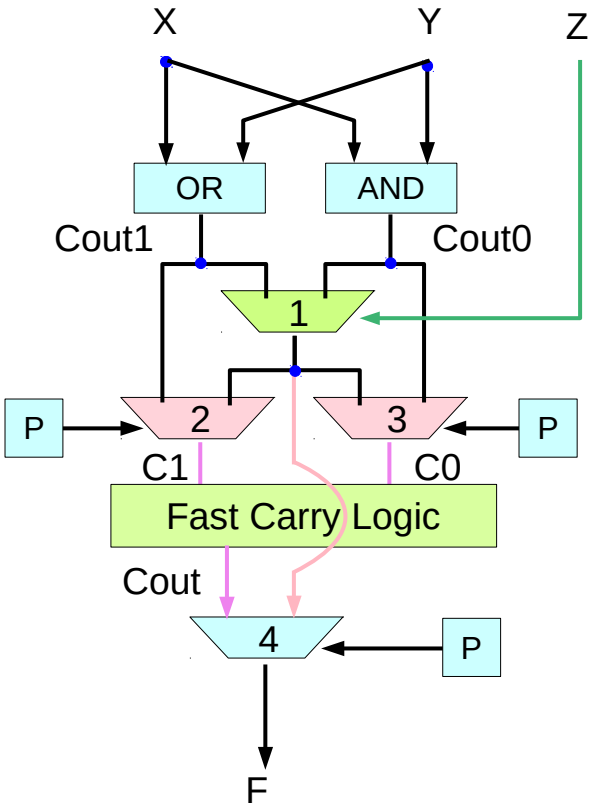
FPGA Carry Chain Cell





$$Cout_i = (Cout_{i-1} \cdot C1_i) + (\overline{Cout_{i-1}} \cdot C0_i)$$

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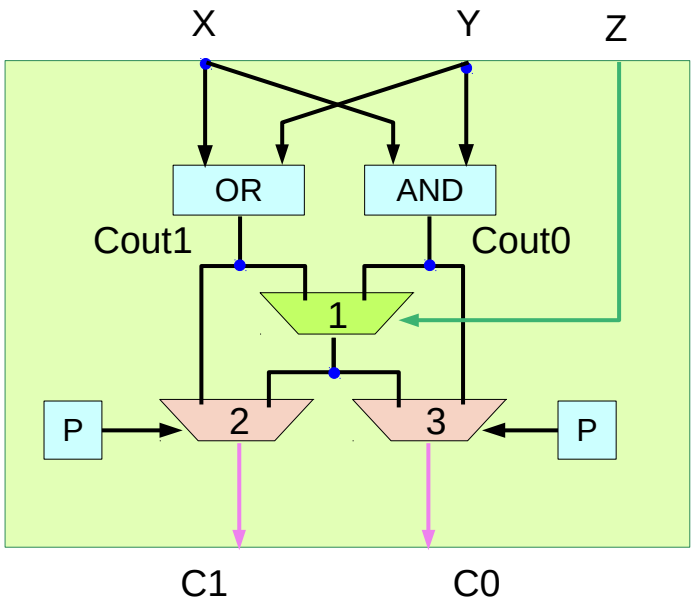
FPGA Carry Chain Cell



$$Cout_i = (Cout_{i-1} \cdot C1_i) + (\overline{Cout_{i-1}} \cdot C0_i)$$

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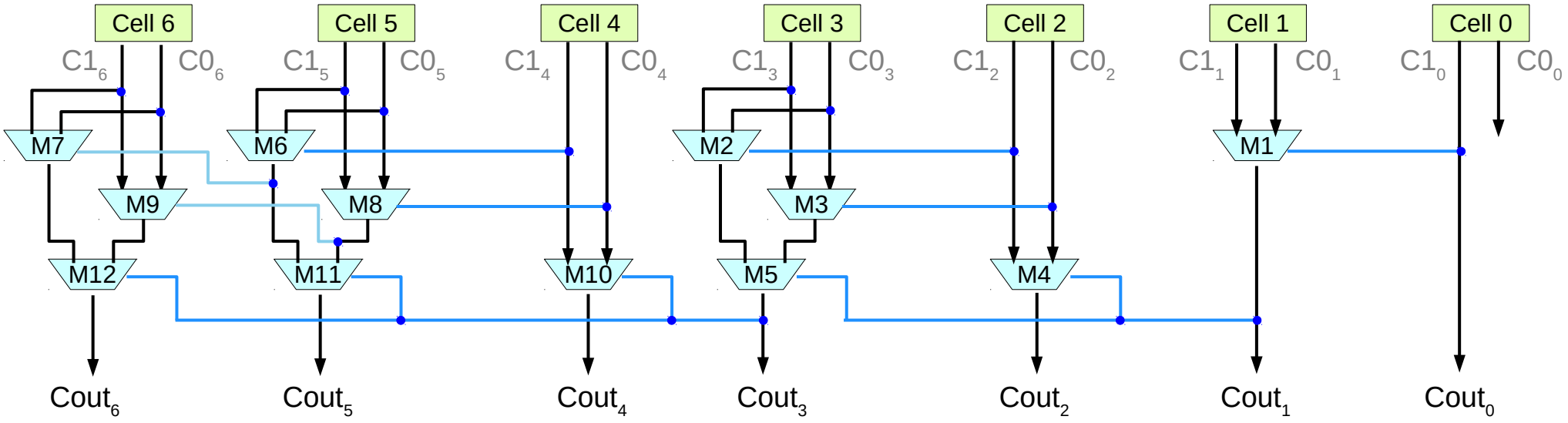
Fast Carry Logc

Carry Select Adder
Carry Lookahead Adder
    Brent-Kung
Variable Block
Ripple Carry Adder

https://en.wikipedia.org/wiki/Carry-lookahead_adder

FPGA Carry Chain Cell



$$Cout_i = (Cout_{i-1} \cdot C1_i) + (\overline{Cout_{i-1}} \cdot C0_i)$$

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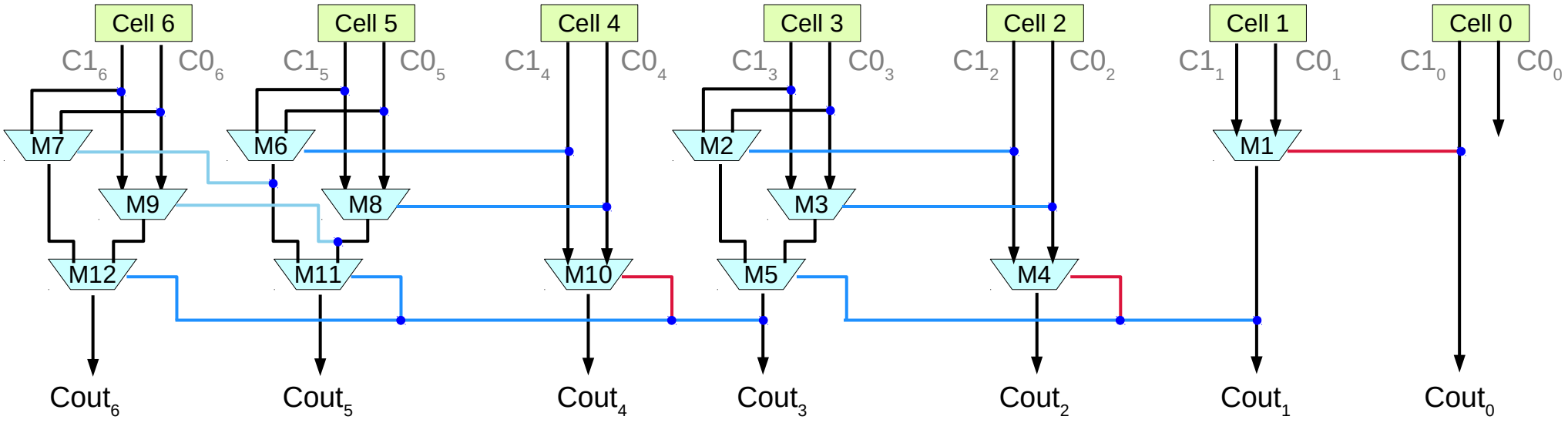
FPGA Carry Chain Cell



$$Cout_i = (Cout_{i-1} \cdot C1_i) + (\overline{Cout_{i-1}} \cdot C0_i)$$

$$Cout_1 = (Cout_0 \cdot C1_1) + (\overline{Cout_0} \cdot C0_1)$$

$$Cout_1 = (C1_0 \cdot C1_1) + (\overline{C1_0} \cdot C0_1)$$

$$Cout_{i+1} = (Cout_i \cdot C1_{i+1}) + (\overline{Cout_i} \cdot C0_{i+1})$$

$$Cout_{i+1} = ([(Cout_{i-1} \cdot C1_i) + (\overline{Cout_{i-1}} \cdot C0_i)] \cdot C1_{i+1}) + (\overline{[(Cout_{i-1} \cdot C1_i) + (\overline{Cout_{i-1}} \cdot C0_i)]} \cdot C0_{i+1})$$

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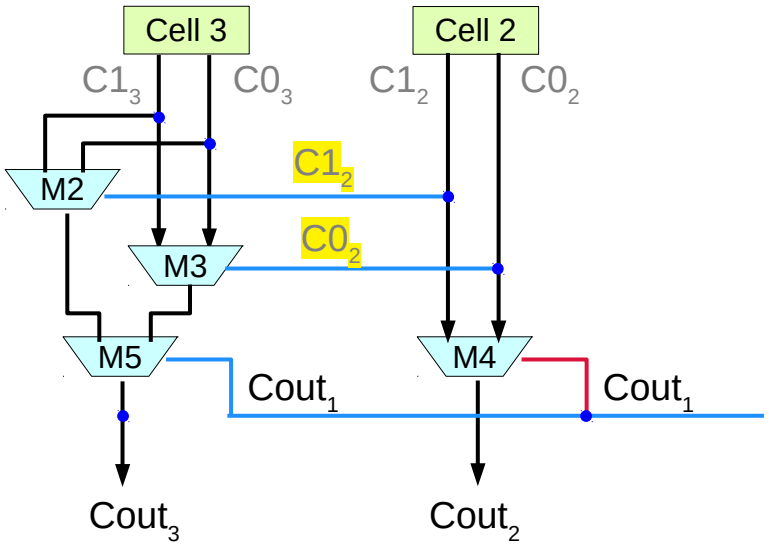
FPGA Carry Chain Cell



$$(C1_3\,C1_2 + C0_3\overline{C1_2})Cout_1 + (C1_3\,C0_2 + C0_3\overline{C0_2})\overline{Cout_1}$$

$$Cout_i = (Cout_{i-1} \cdot C1_i) + (\overline{Cout_{i-1}} \cdot C0_i)$$

$$Cout_{i+1} = (Cout_i \cdot C1_{i+1}) + (\overline{Cout_i} \cdot C0_{i+1})$$

$$Cout_2 = (Cout_1 \cdot C1_2) + (\overline{Cout_1} \cdot C0_2)$$

$$Cout_3 = (Cout_2 \cdot C1_3) + (\overline{Cout_2} \cdot C0_3)$$

$$= (((Cout_1 \cdot C1_2) + (\overline{Cout_1} \cdot C0_2)) \cdot C1_3)$$

$$+ (\overline{((Cout_1 \cdot C1_2) + (\overline{Cout_1} \cdot C0_2))} \cdot C0_3)$$

$$(((Cout_1 \cdot C1_2) + (\overline{Cout_1} \cdot C0_2)) \cdot C1_3)$$

$$= (C1_3\,C1_2\,Cout_1 + C1_3\,C0_2\,\overline{Cout_1})$$

$$(\overline{((Cout_1 \cdot C1_2)} \cdot \overline{(\overline{Cout_1} \cdot C0_2)}) \cdot C0_3)$$

$$= (((\overline{Cout_1} + \overline{C1_2}) \cdot (Cout_1 + \overline{C0_2})) \cdot C0_3)$$

$$= (\overline{Cout_1}\,Cout_1 + \overline{C1_2}\,Cout_1 + \overline{Cout_1}\,\overline{C0_2} + \overline{C1_2}\,\overline{C0_2}) \cdot C0_3$$

$$= (\overline{C1_2}\,Cout_1 + \overline{C0_2}\,\overline{Cout_1}) \cdot C0_3$$

$$= (C0_3\,\overline{C1_2}\,Cout_1 + C0_3\,\overline{C0_2}\,\overline{Cout_1})$$

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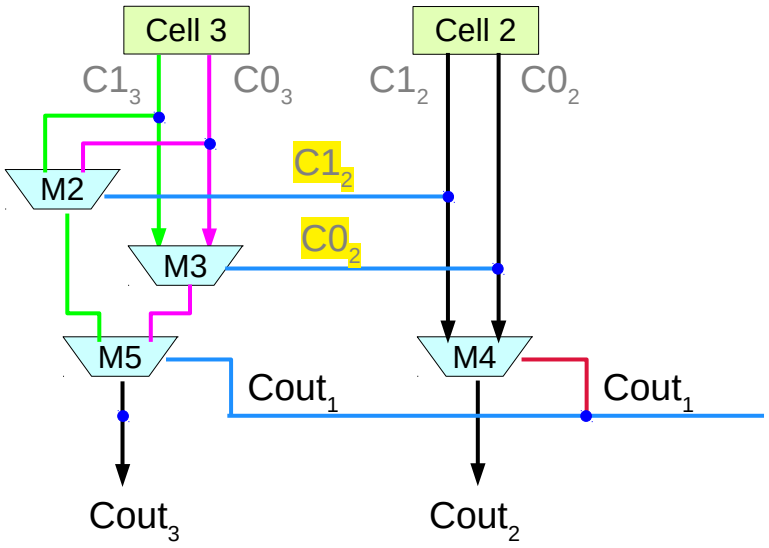

$$(C1_3\,C1_2 + C0_3\overline{C1_2})Cout_1 + (C1_3\,C0_2 + C0_3\overline{C0_2})\overline{Cout_1}$$

$$= (\overline{Cout_1}Cout_1 + \overline{C1_2}Cout_1 + \overline{Cout_1}\,\overline{C0_2} + \overline{C1_2}\,\overline{C0_2}) \cdot C0_3$$

$$= (\overline{C1_2}Cout_1 + \overline{C0_2}\,\overline{Cout_1}) \cdot C0_3$$

$$= (C0_3\,\overline{C1_2}Cout_1 + C0_3\,\overline{C0_2}\,\overline{Cout_1})$$

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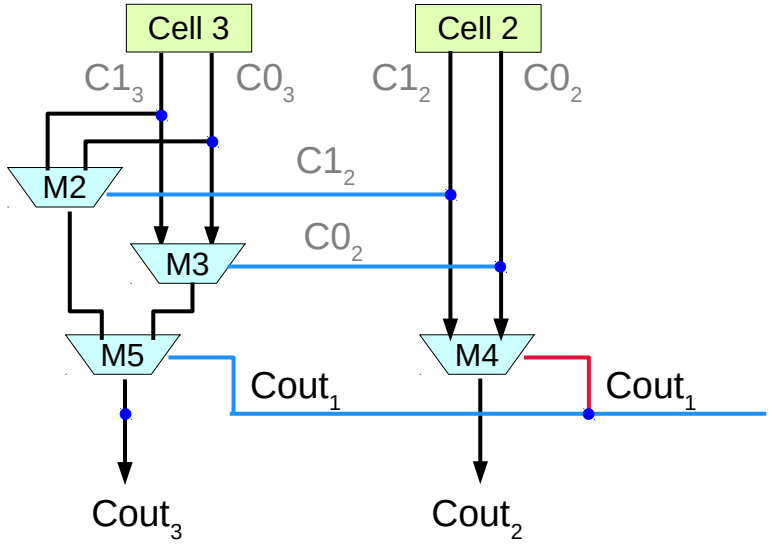
FPGA Carry Chain Cell

$C1_3\,C1_2 + C0_3\overline{C1_2}$

$C1_3\,C0_2 + C0_3\overline{C0_2}$



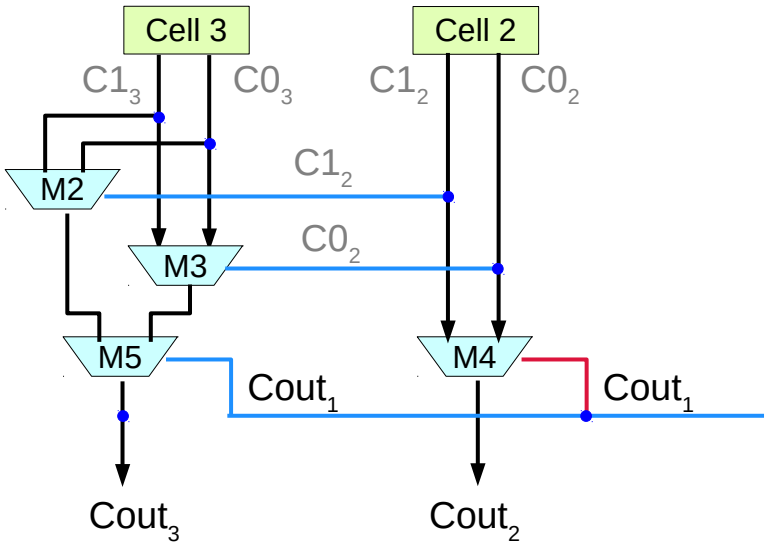
$(C1_3\,C1_2 + C0_3\overline{C1_2})Cout_1 + (C1_3\,C0_2 + C0_3\overline{C0_2})\overline{Cout_1}$

$$= C1_3 \cdot (C1_2\,Cout_1 + C0_2\overline{Cout_1})$$

$$+ C0_3 \cdot (\overline{C1_2}\,Cout_1 + \overline{C0_2}\,\overline{Cout_1})$$

High Performance Carry Chains for FPGAs, S. Hauck, M. M. Hosler, T. W. Fry

FPGA Carry Chain Cell



$$Cout_i = (Cout_{i-1} \cdot C1_i) + (\overline{Cout_{i-1}} \cdot C0_i)$$

$$Cout_{i+1} = (Cout_i \cdot C1_{i+1}) + (\overline{Cout_i} \cdot C0_{i+1})$$

$$Cout_{i+1} = ([(Cout_{i-1} \cdot C1_i) + (\overline{Cout_{i-1}} \cdot C0_i)] \cdot C1_{i+1})$$

$$+ (\overline{[(Cout_{i-1} \cdot C1_i) + (\overline{Cout_{i-1}} \cdot C0_i)]} \cdot C0_{i+1})$$

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References

[1] http://en.wikipedia.org/
[2] J-P Deschamps,et. al., “Sunthesis of Arithmetic Circuits”, 2006