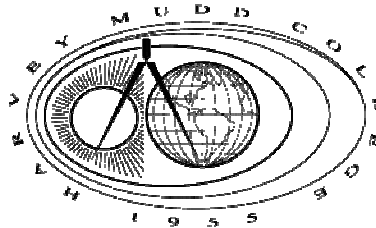


# Introduction to CMOS VLSI Design

## Lecture 11: Adders

David Harris



Harvey Mudd College  
Spring 2004

# Outline

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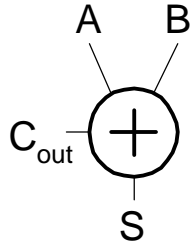
- Single-bit Addition
- Carry-Ripple Adder
- Carry-Skip Adder
- Carry-Lookahead Adder
- Carry-Select Adder
- Carry-Increment Adder
- Prefix Adder

# Single-Bit Addition

Half Adder

$$S =$$

$$C_{out} =$$

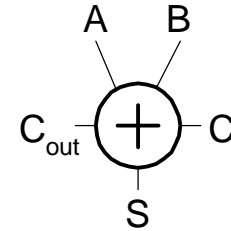


A	B	$C_{out}$	S
0	0		
0	1		
1	0		
1	1		

Full Adder

$$S =$$

$$C_{out} =$$



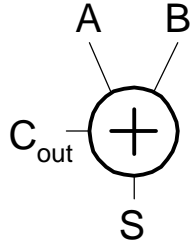
A	B	C	$C_{out}$	S
0	0	0		
0	0	1		
0	1	0		
0	1	1		
1	0	0		
1	0	1		
1	1	0		
1	1	1		

# Single-Bit Addition

Half Adder

$$S = A \oplus B$$

$$C_{out} = A \cdot B$$

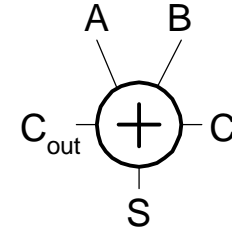


A	B	$C_{out}$	S
0	0	0	0
0	1	0	1
1	0	0	1
1	1	1	0

Full Adder

$$S = A \oplus B \oplus C$$

$$C_{out} = MAJ(A, B, C)$$



A	B	C	$C_{out}$	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

# PGK

- For a full adder, define what happens to carries
  - Generate:  $C_{out} = 1$  independent of C
    - G =
  - Propagate:  $C_{out} = C$ 
    - P =
  - Kill:  $C_{out} = 0$  independent of C
    - K =

# PGK

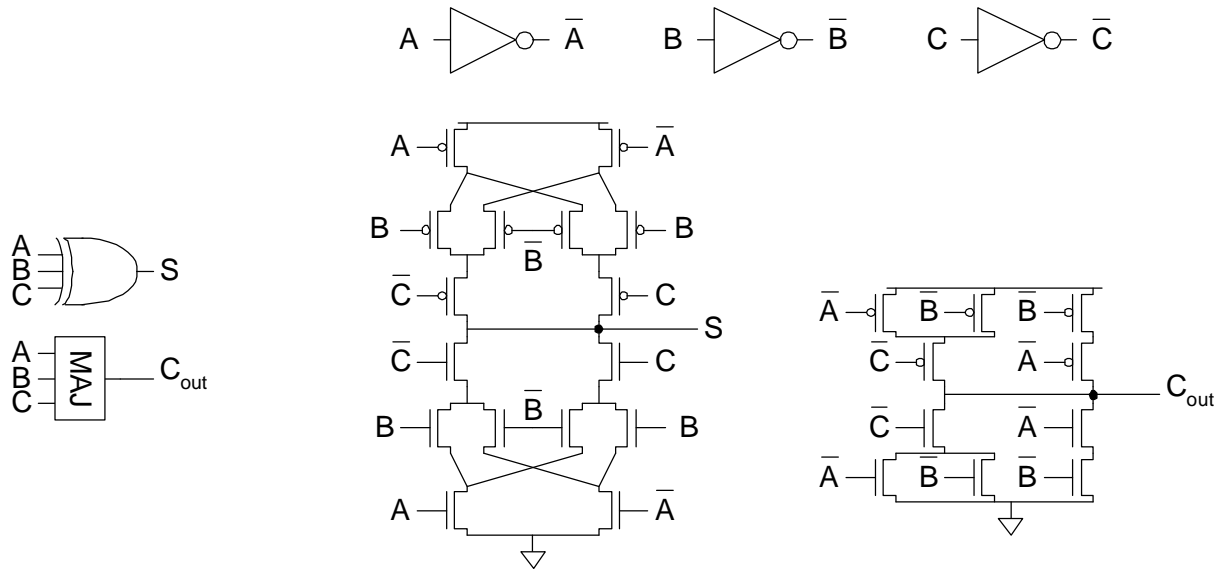
- For a full adder, define what happens to carries
  - Generate:  $C_{out} = 1$  independent of C
    - $G = A \cdot B$
  - Propagate:  $C_{out} = C$ 
    - $P = A \oplus B$
  - Kill:  $C_{out} = 0$  independent of C
    - $K = \sim A \cdot \sim B$

# Full Adder Design I

- Brute force implementation from eqns

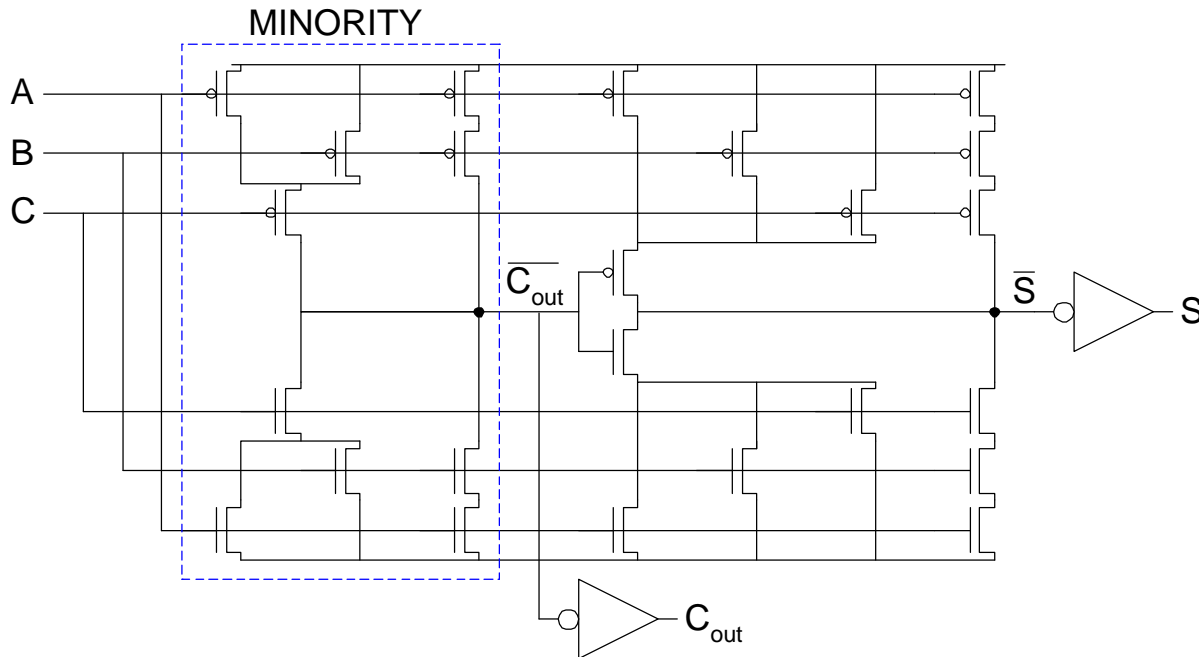
$$S = A \oplus B \oplus C$$

$$C_{out} = MAJ(A, B, C)$$



# Full Adder Design II

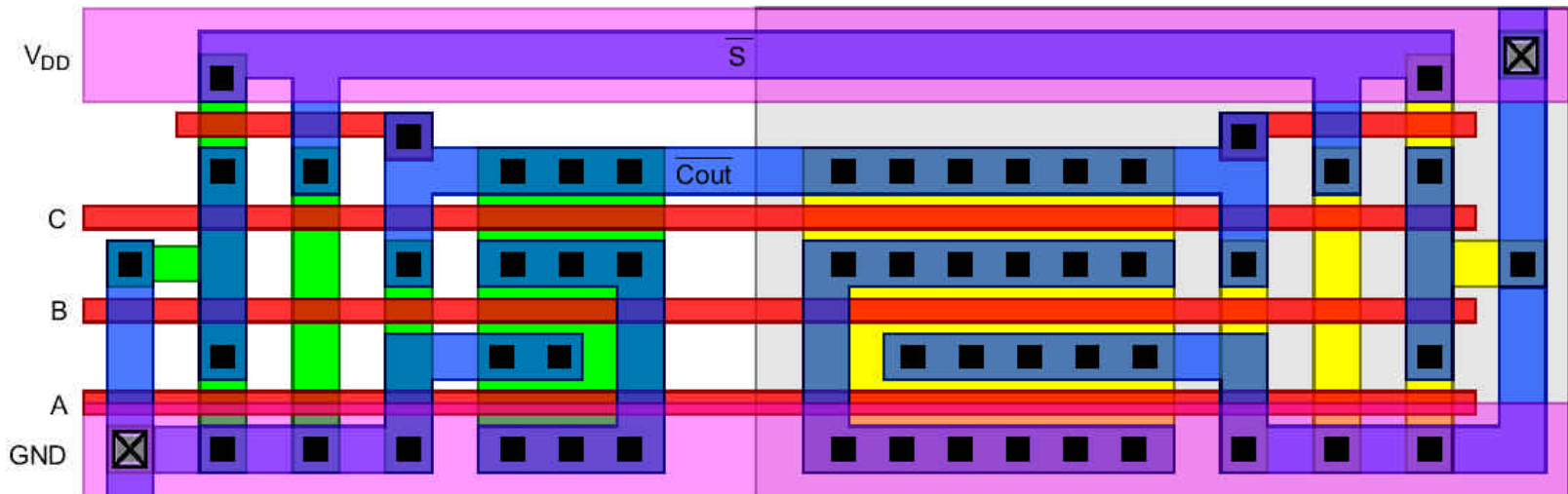
- ❑ Factor S in terms of  $C_{out}$   
$$S = ABC + (A + B + C)(\sim C_{out})$$
- ❑ Critical path is usually C to  $C_{out}$  in ripple adder





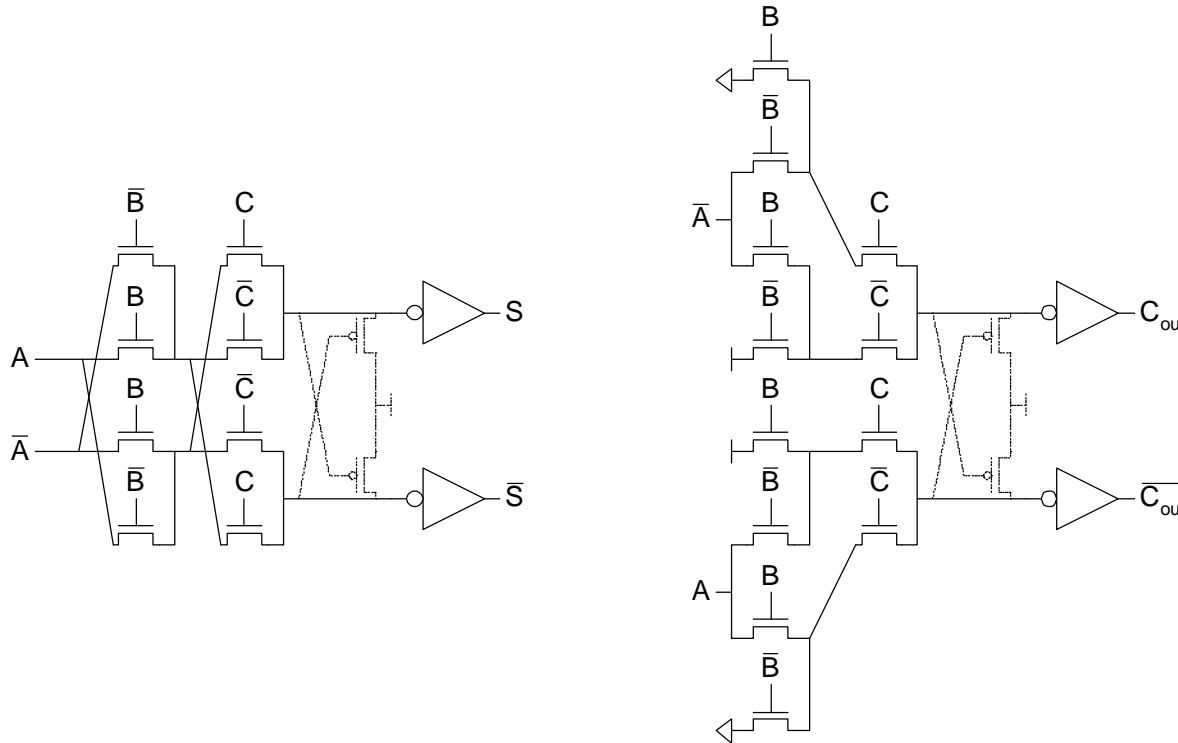
# Layout

- ❑ Clever layout circumvents usual line of diffusion
  - Use wide transistors on critical path
  - Eliminate output inverters



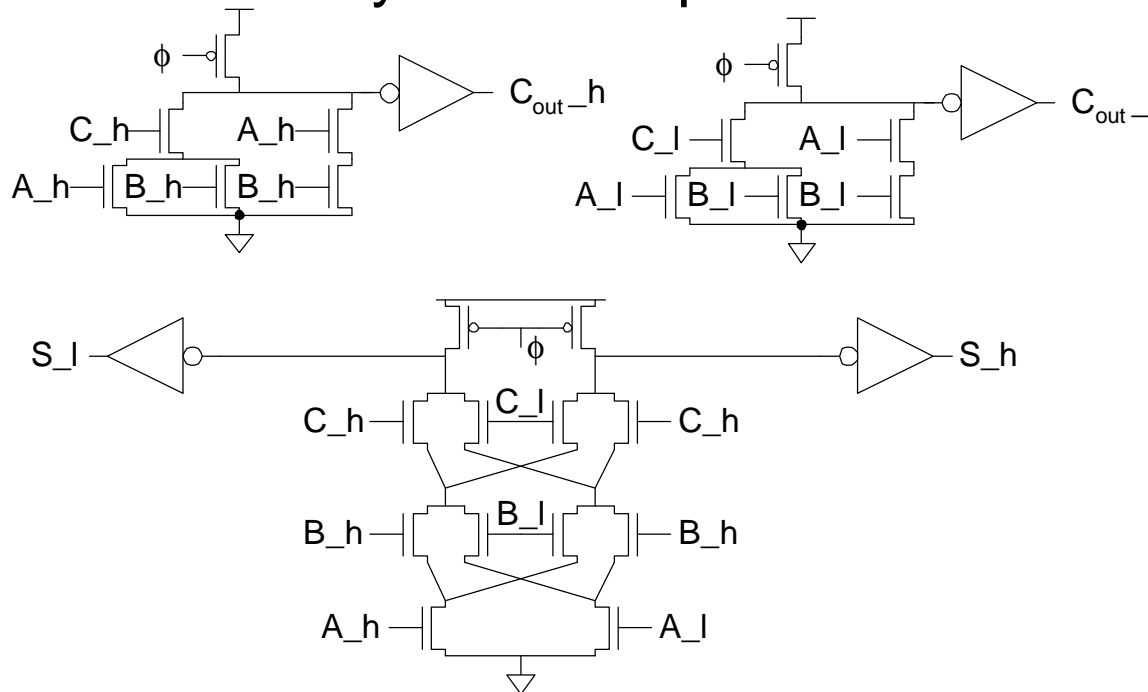
# Full Adder Design III

- ❑ Complementary Pass Transistor Logic (CPL)
  - Slightly faster, but more area



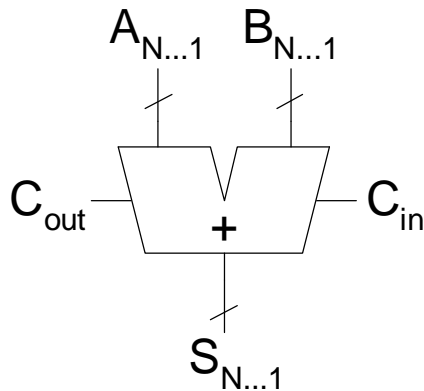
# Full Adder Design IV

- ❑ Dual-rail domino
  - Very fast, but large and power hungry
  - Used in very fast multipliers



# Carry Propagate Adders

- N-bit adder called CPA
  - Each sum bit depends on all previous carries
  - How do we compute all these carries quickly?

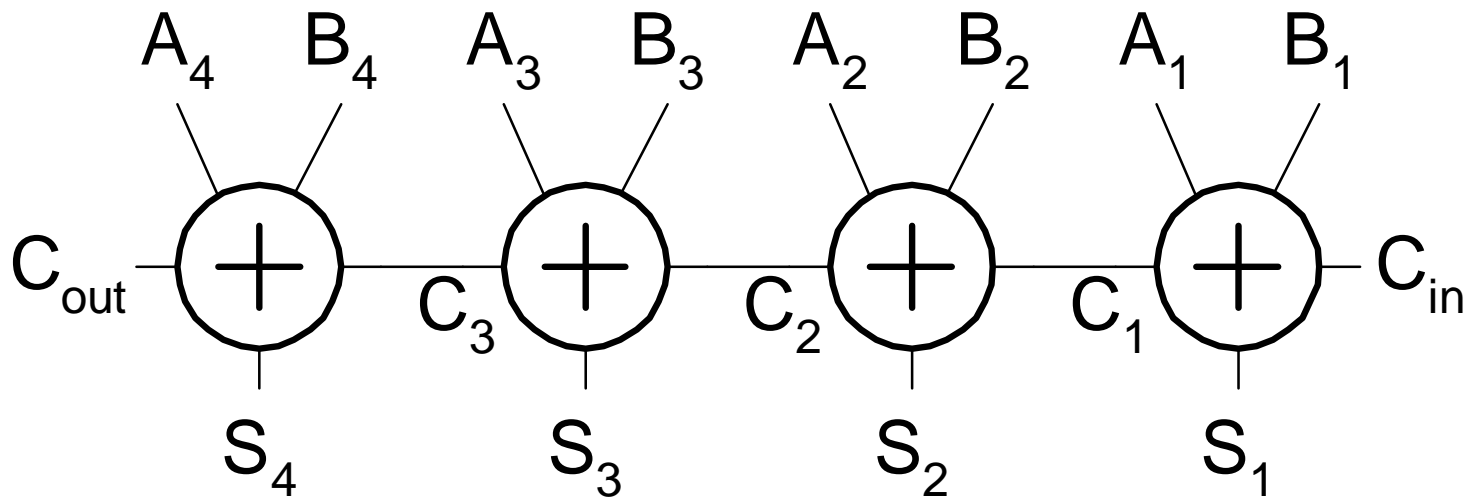


$$\begin{array}{r} \text{C}_{out} \swarrow \quad \nwarrow \text{C}_{in} \\ \textcircled{0}0000\textcircled{0} \\ 1111 \\ +0000 \\ \hline 1111 \end{array}$$

$$\begin{array}{r} \text{C}_{out} \swarrow \quad \nwarrow \text{C}_{in} \\ \textcircled{1}1111\textcircled{1} \quad \text{carries} \\ 1111 \quad A_{4...1} \\ +0000 \quad B_{4...1} \\ \hline 0000 \quad S_{4...1} \end{array}$$

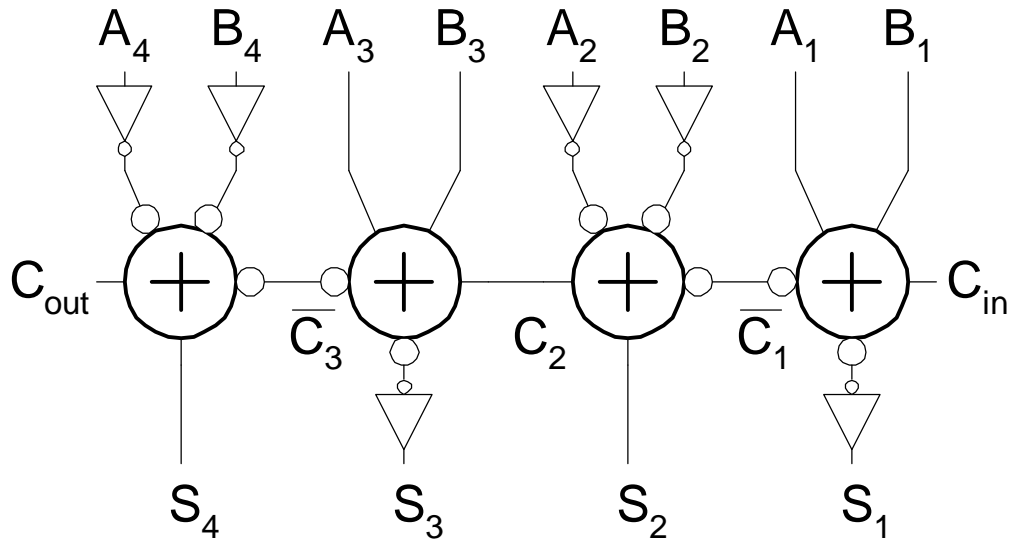
# Carry-Ripple Adder

- Simplest design: cascade full adders
  - Critical path goes from  $C_{in}$  to  $C_{out}$
  - Design full adder to have fast carry delay



# Inversions

- ❑ Critical path passes through majority gate
  - Built from minority + inverter
  - Eliminate inverter and use inverting full adder



# Generate / Propagate

- Equations often factored into G and P
- Generate and propagate for groups spanning  $i:j$

$$G_{i:j} =$$

$$P_{i:j} =$$

- Base case

$$G_{i:i} \equiv G_i =$$

$$P_{i:i} \equiv P_i =$$

$$G_{0:0} \equiv G_0 =$$

$$P_{0:0} \equiv P_0 =$$

- Sum:

$$S_i =$$

# Generate / Propagate

- Equations often factored into G and P
- Generate and propagate for groups spanning i:j

$$G_{i:j} = G_{i:k} + P_{i:k} \cdot G_{k-1:j}$$

$$P_{i:j} = P_{i:k} \cdot P_{k-1:j} \quad \dots\dots\dots$$

- Base case

$$G_{i:i} \equiv G_i = A_i \cdot B_i$$

$$P_{i:i} \equiv P_i = A_i \oplus B_i$$

$$G_{0:0} \equiv G_0 = C_{in}$$

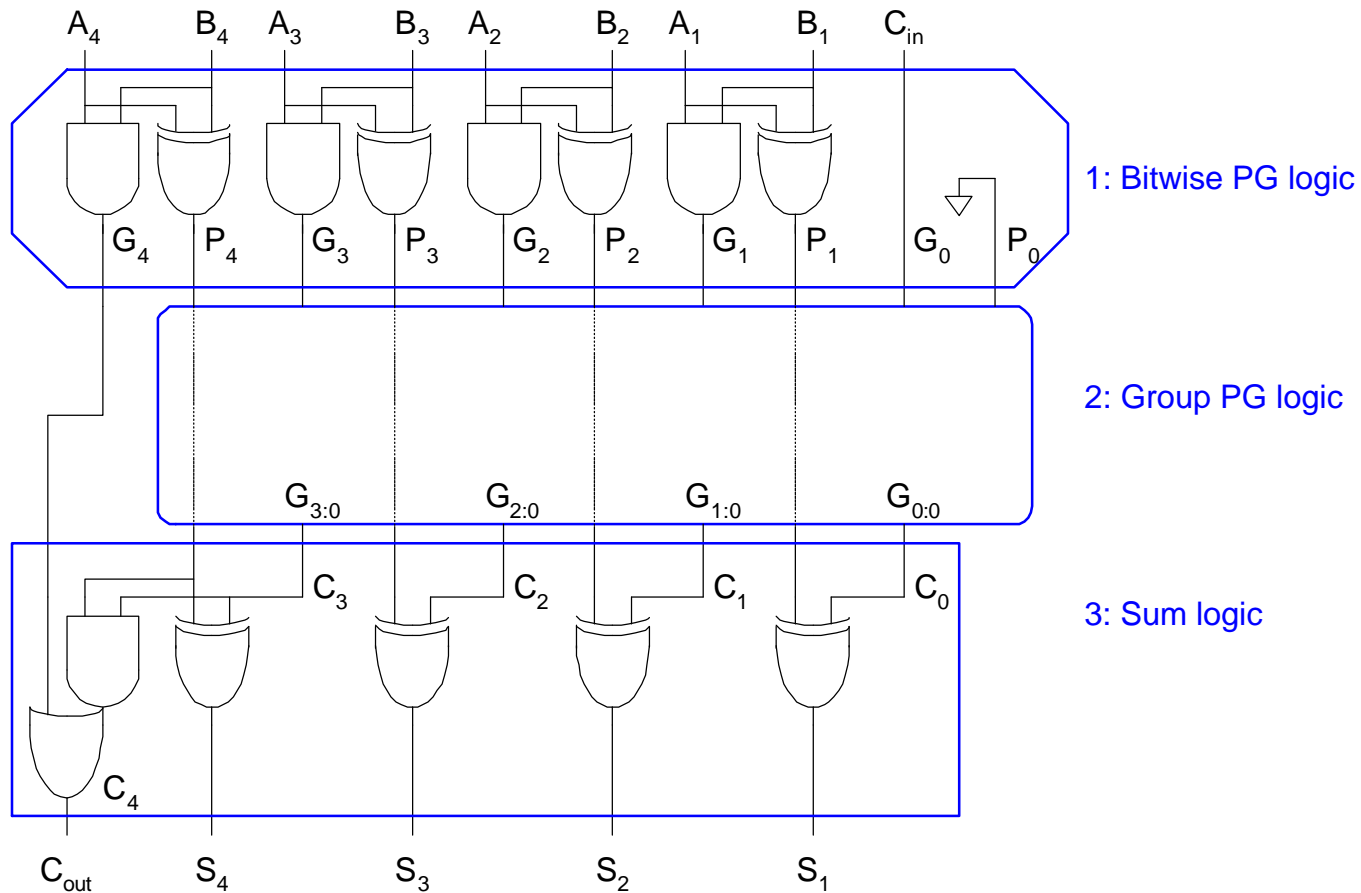
$$P_{0:0} \equiv P_0 = 0$$

- Sum:

$$S_i = P_i \oplus G_{i-1:0}$$

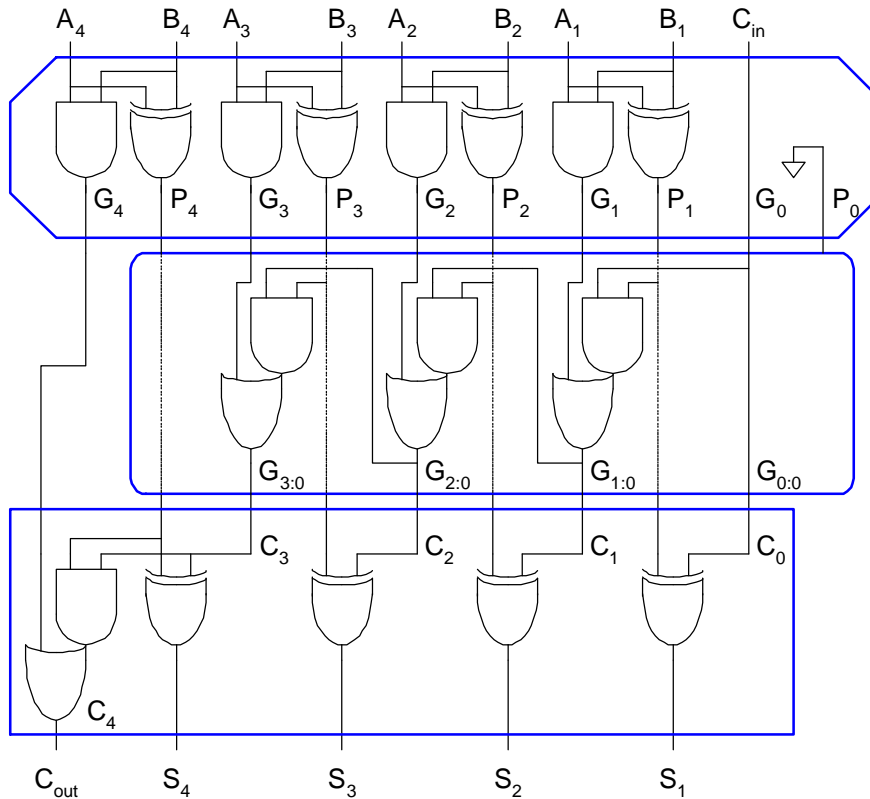


# PG Logic



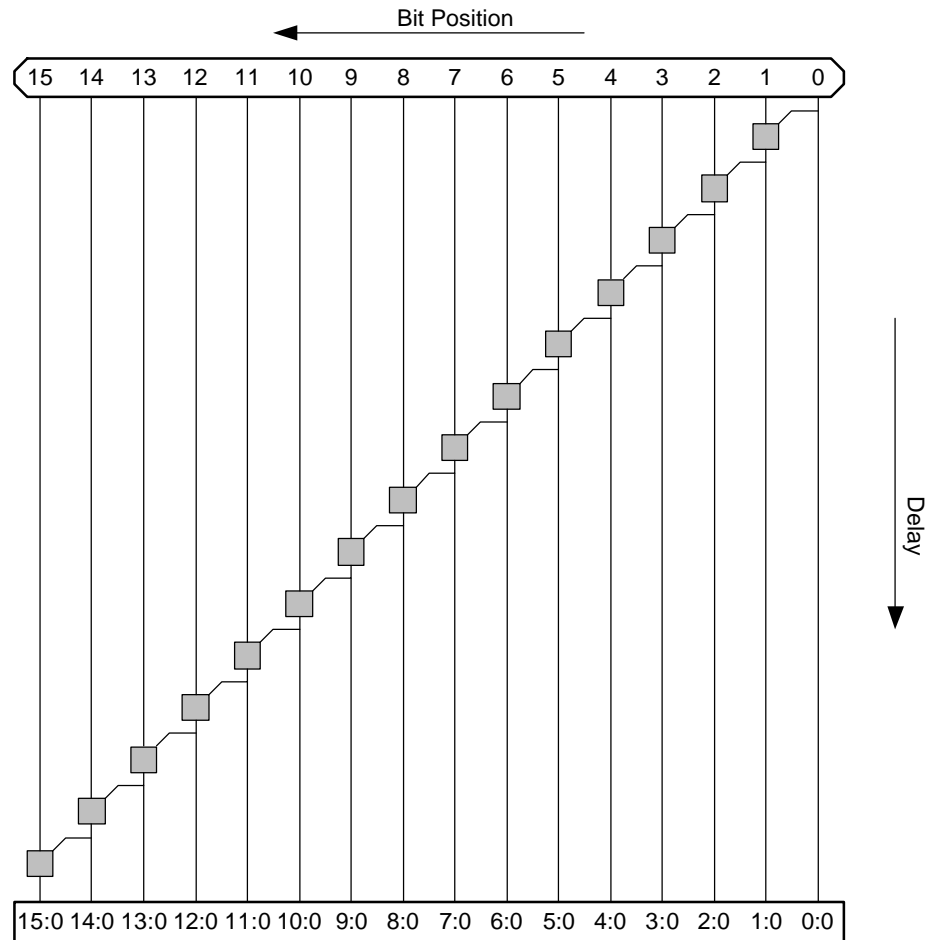
# Carry-Ripple Revisited

$$G_{i:0} = G_i + P_i \cdot G_{i-1:0}$$



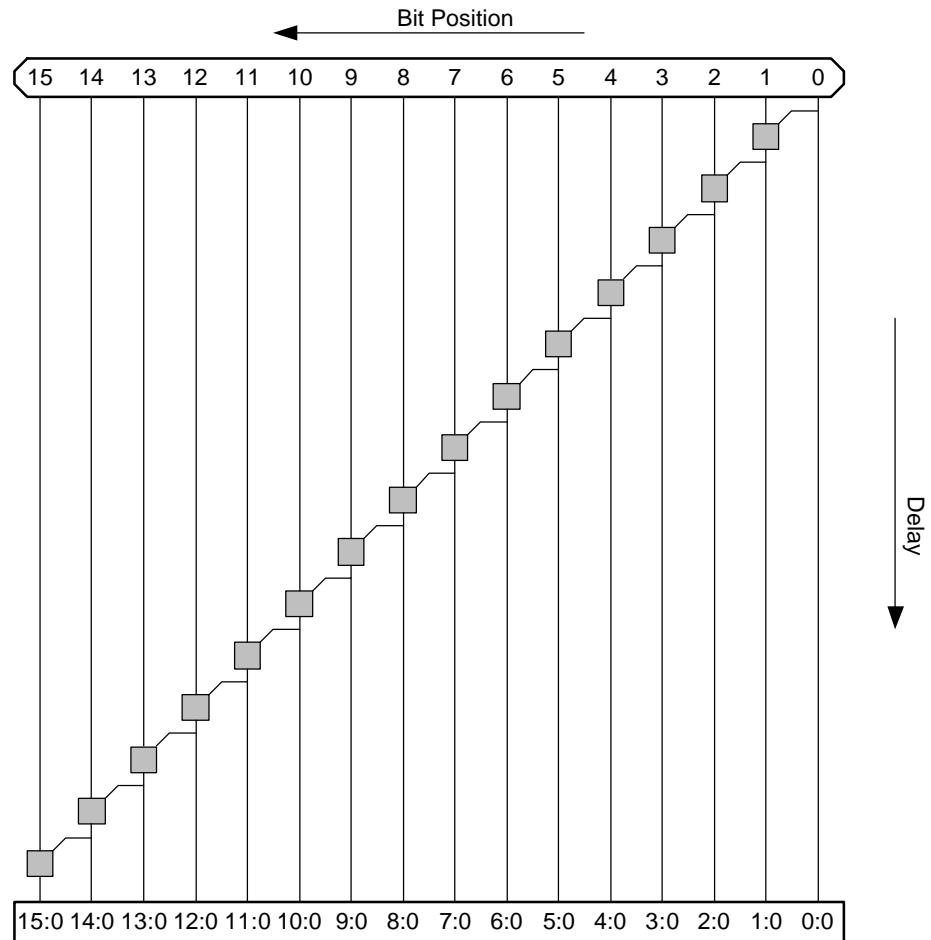
# Carry-Ripple PG Diagram

$t_{\text{ripple}} =$



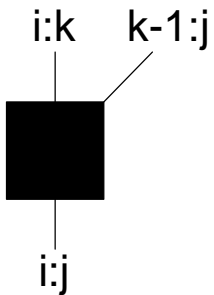
# Carry-Ripple PG Diagram

$$t_{\text{ripple}} = t_{pg} + (N - 1)t_{AO} + t_{\text{xor}}$$

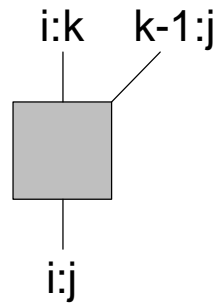


# PG Diagram Notation

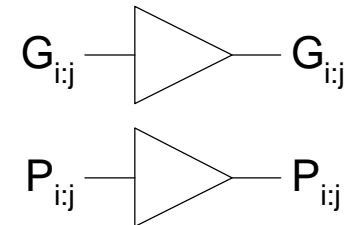
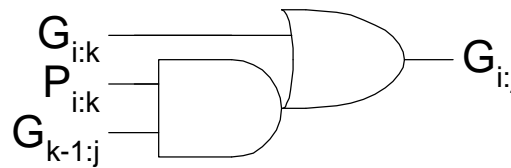
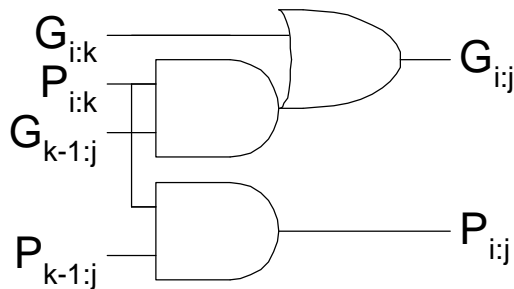
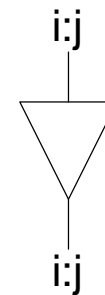
Black cell



Gray cell

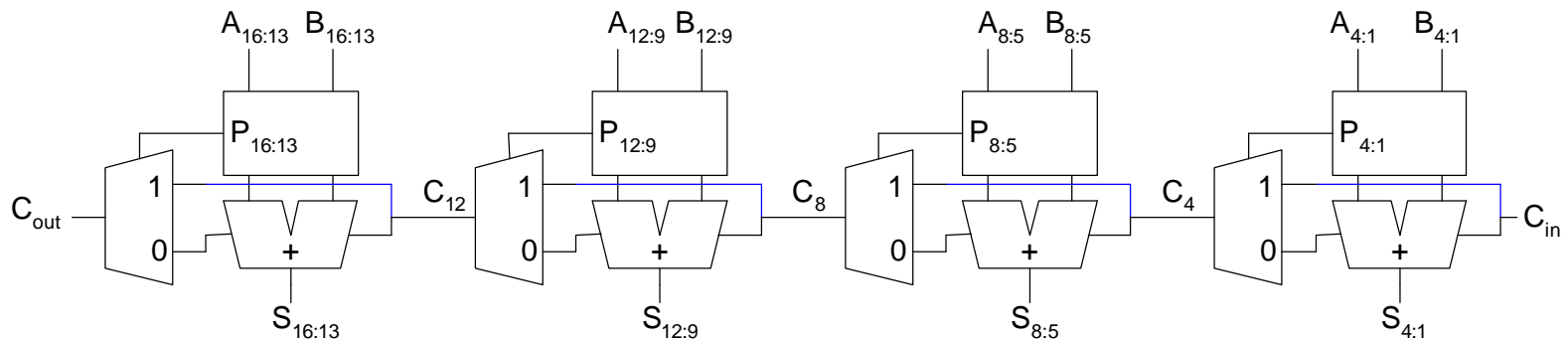


Buffer

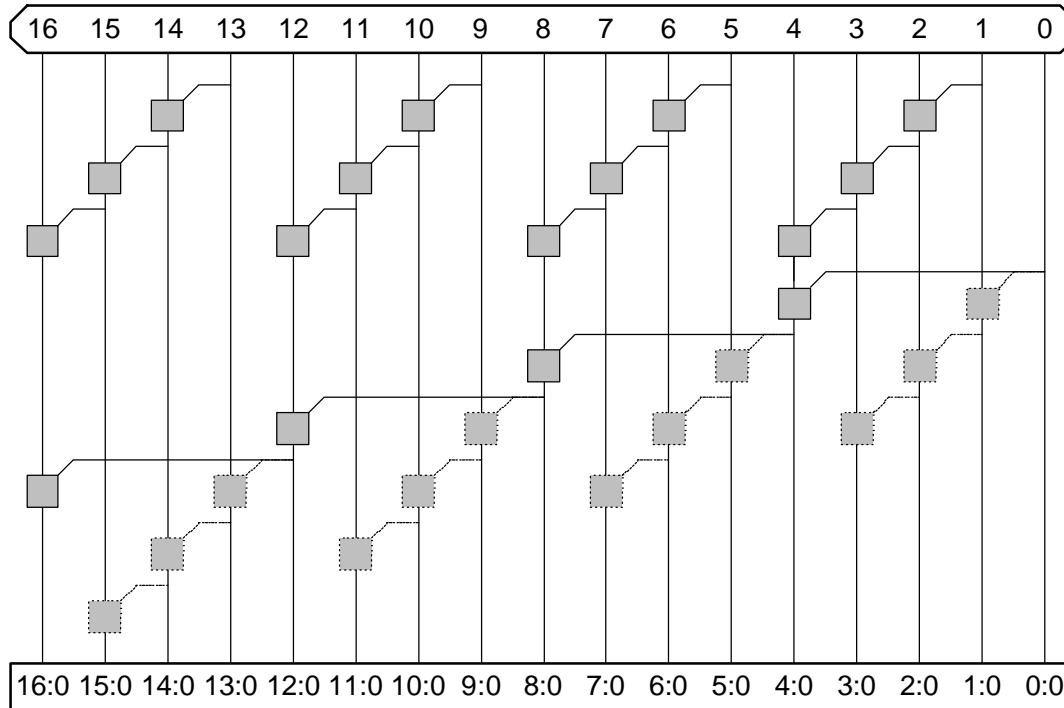


# Carry-Skip Adder

- ❑ Carry-ripple is slow through all N stages
- ❑ Carry-skip allows carry to skip over groups of n bits
  - Decision based on n-bit propagate signal



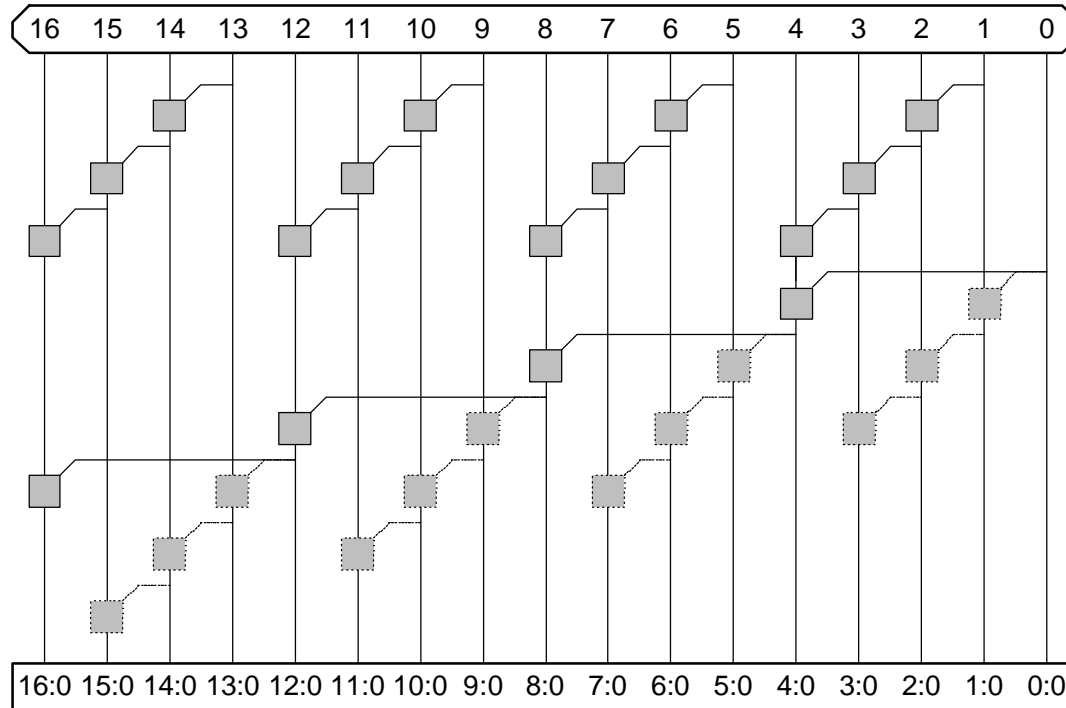
# Carry-Skip PG Diagram



For  $k$   $n$ -bit groups ( $N = nk$ )

$$t_{\text{skip}} =$$

# Carry-Skip PG Diagram

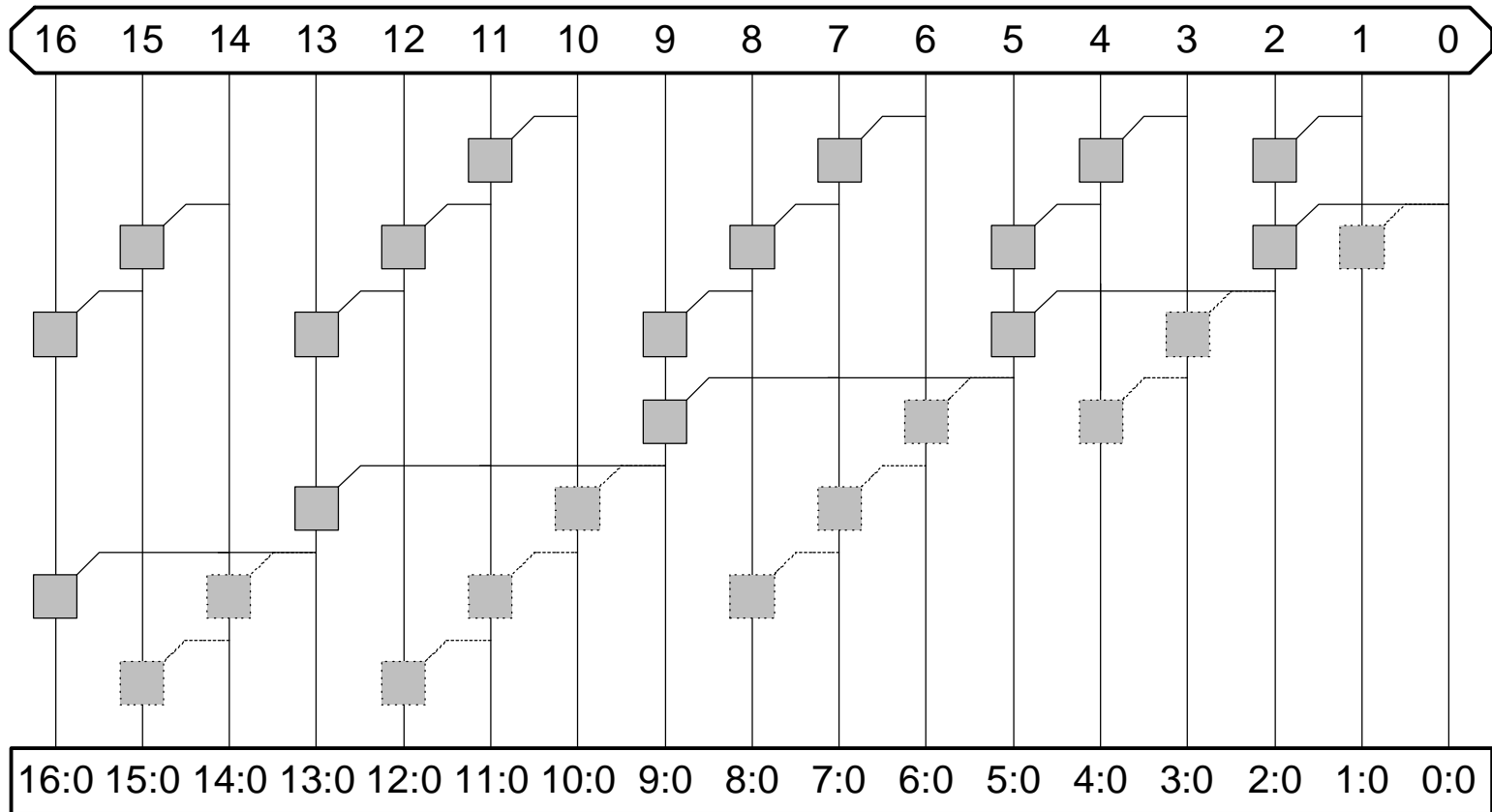


For  $k$   $n$ -bit groups ( $N = nk$ )

$$t_{\text{skip}} = t_{pg} + [2(n-1) + (k-1)]t_{AO} + t_{\text{xor}}$$



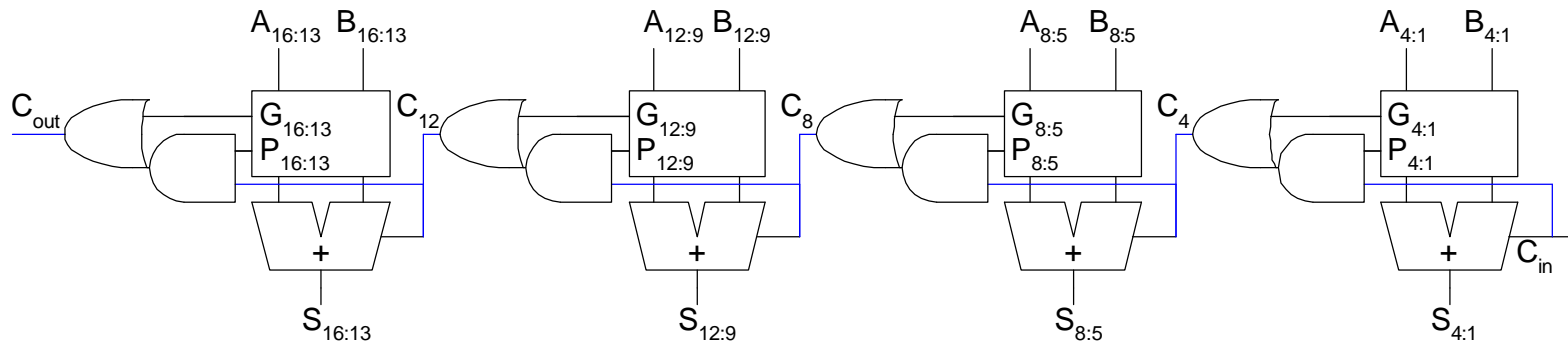
# Variable Group Size



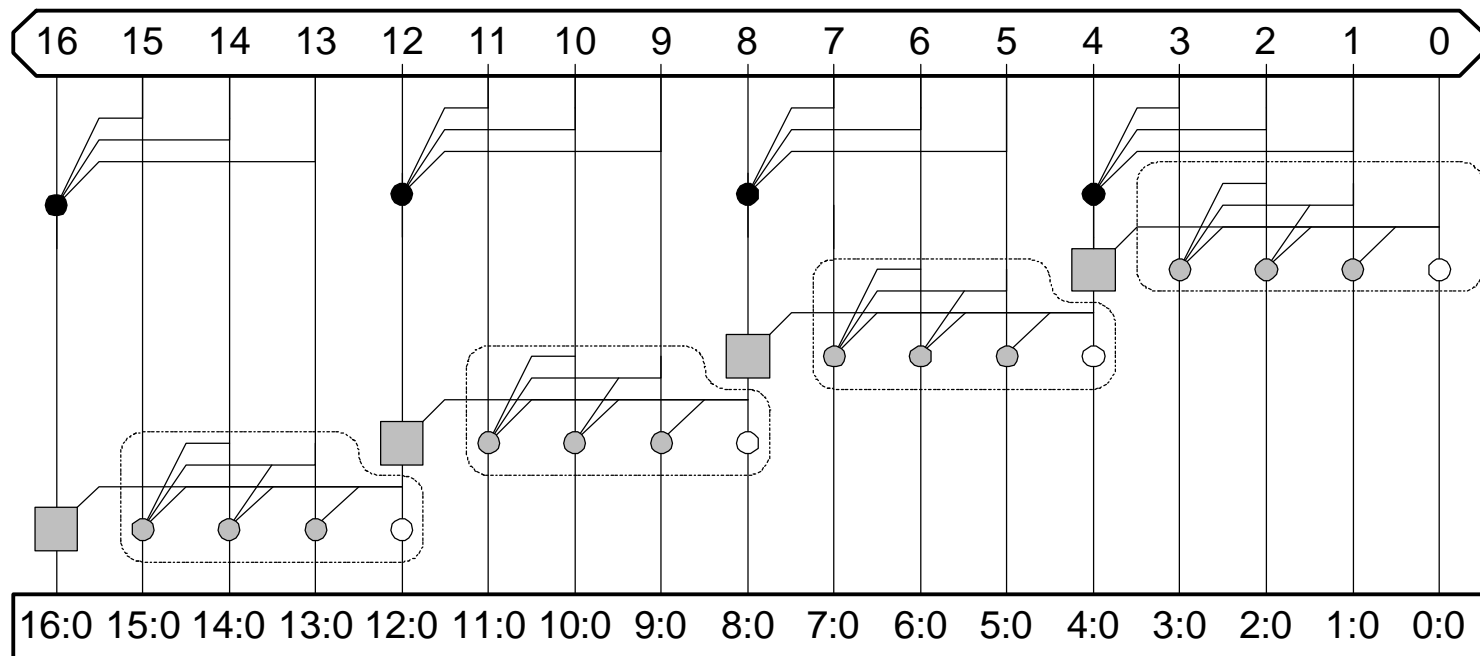
Delay grows as  $O(\sqrt{N})$

# Carry-Lookahead Adder

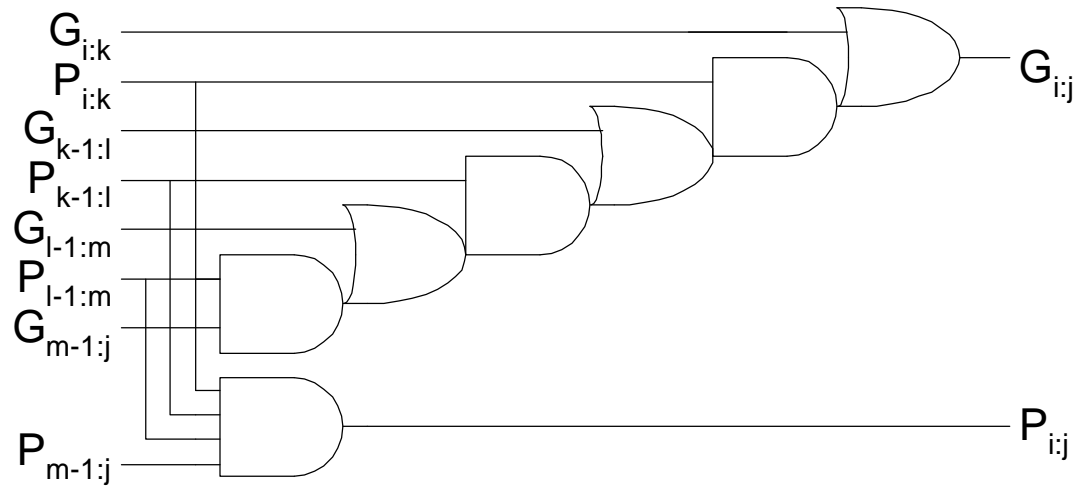
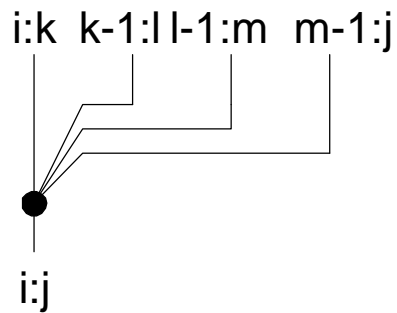
- ❑ Carry-lookahead adder computes  $G_{i:0}$  for many bits in parallel.
- ❑ Uses higher-valency cells with more than two inputs.



# CLA PG Diagram

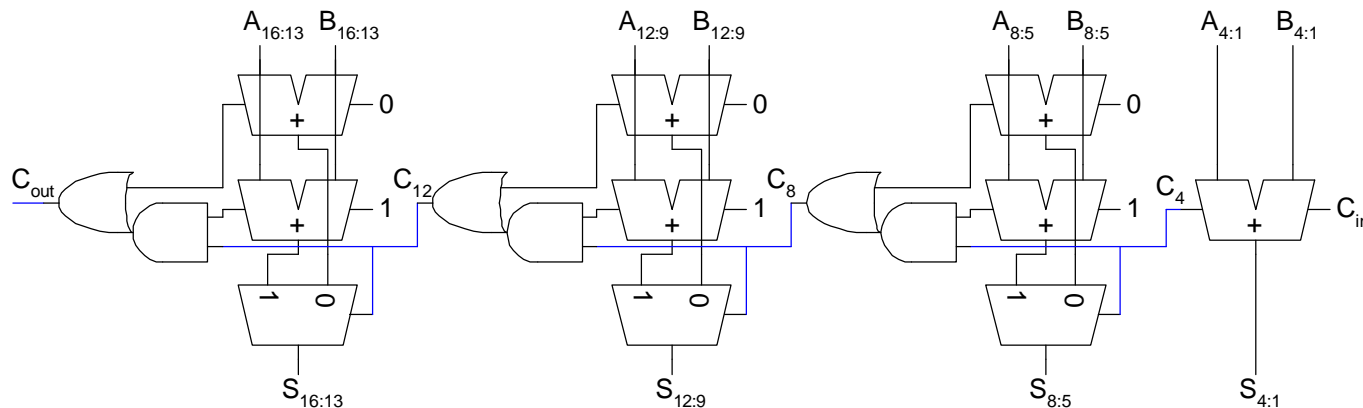


# Higher-Valency Cells



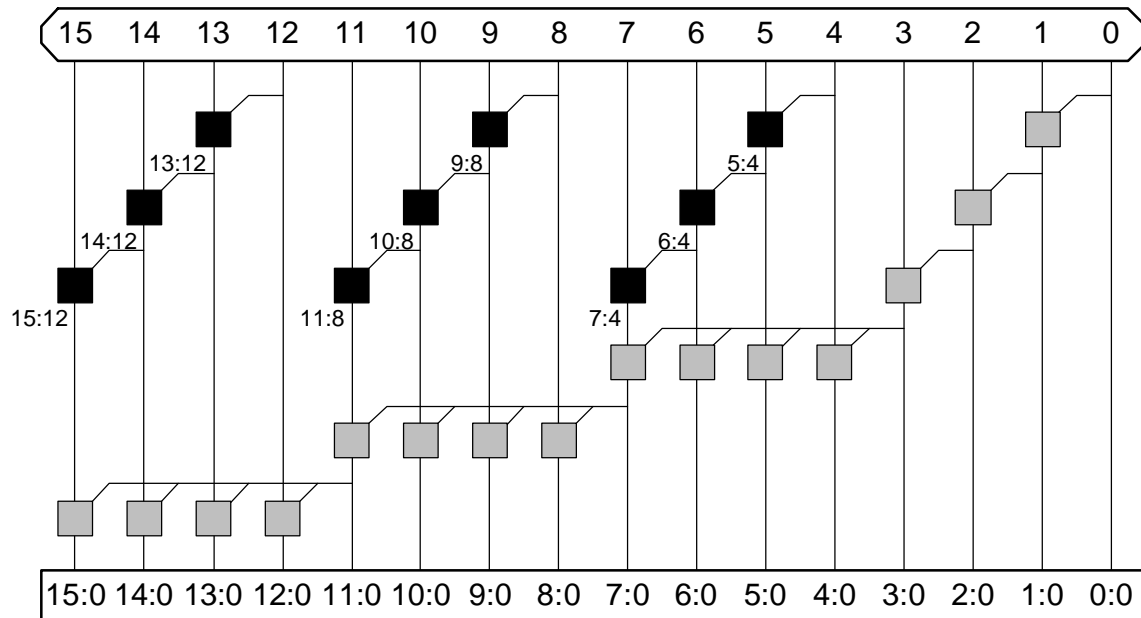
# Carry-Select Adder

- ❑ Trick for critical paths dependent on late input X
  - Precompute two possible outputs for  $X = 0, 1$
  - Select proper output when  $X$  arrives
- ❑ Carry-select adder precomputes n-bit sums
  - For both possible carries into n-bit group



# Carry-Increment Adder

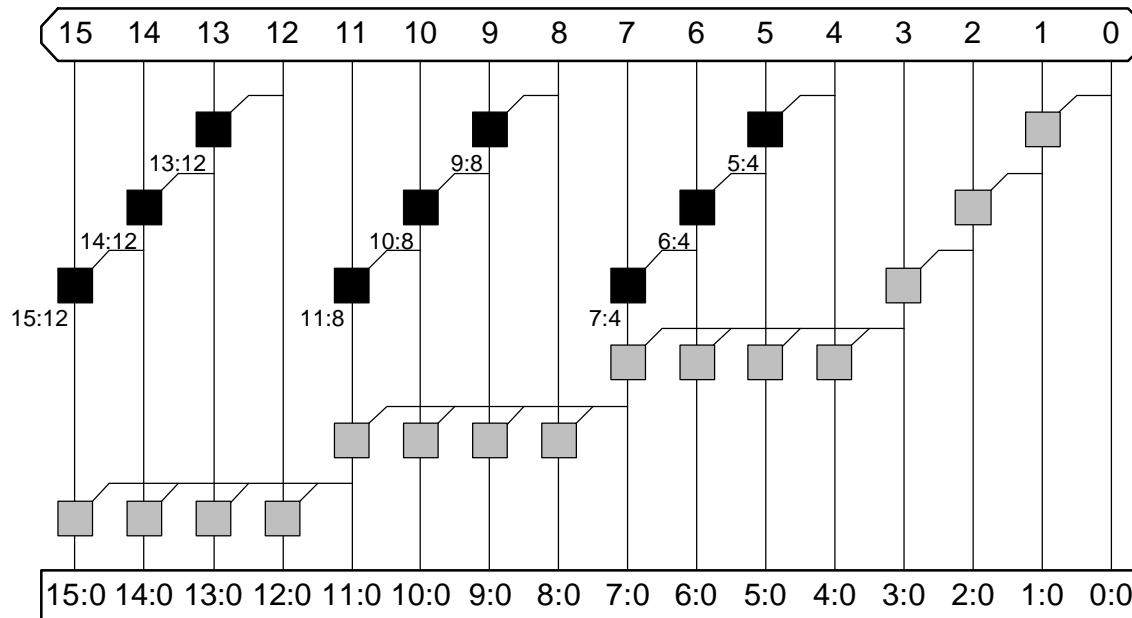
- Factor initial PG and final XOR out of carry-select



$$t_{\text{increment}} =$$

# Carry-Increment Adder

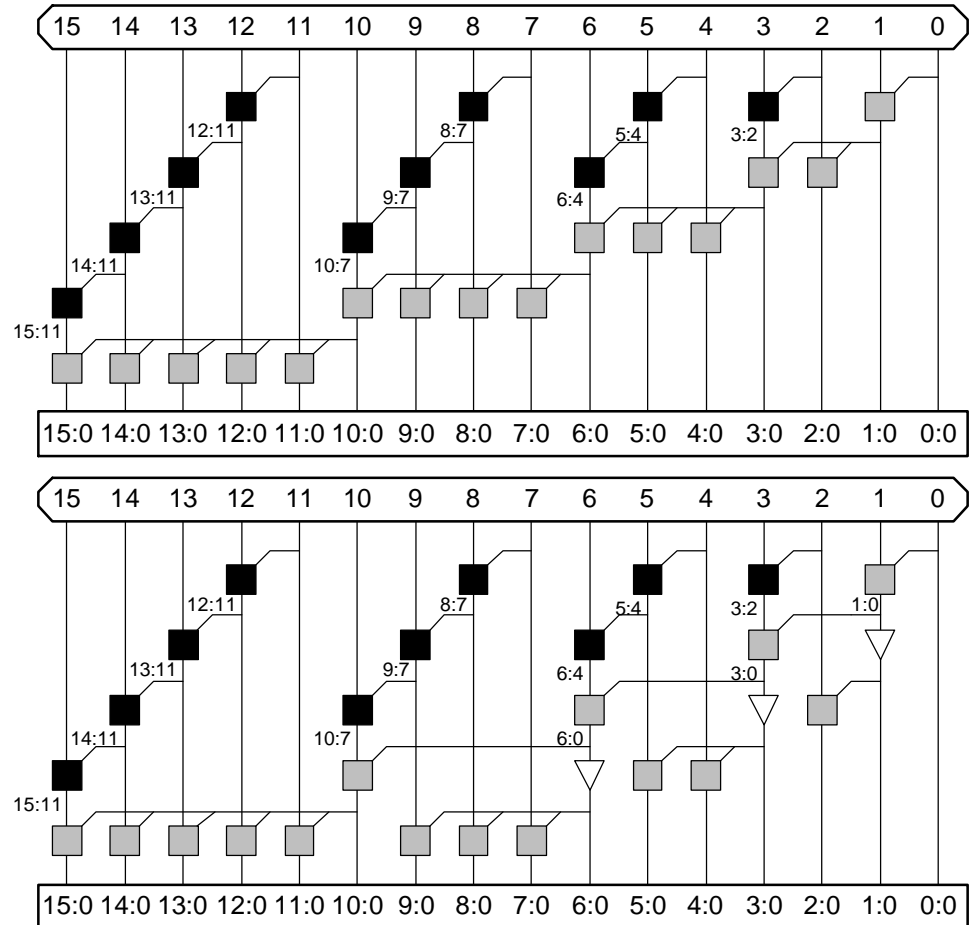
- Factor initial PG and final XOR out of carry-select



$$t_{\text{increment}} = t_{pg} + \left[ (n-1) + (k-1) \right] t_{AO} + t_{xor}$$

# Variable Group Size

- Also buffer noncritical signals

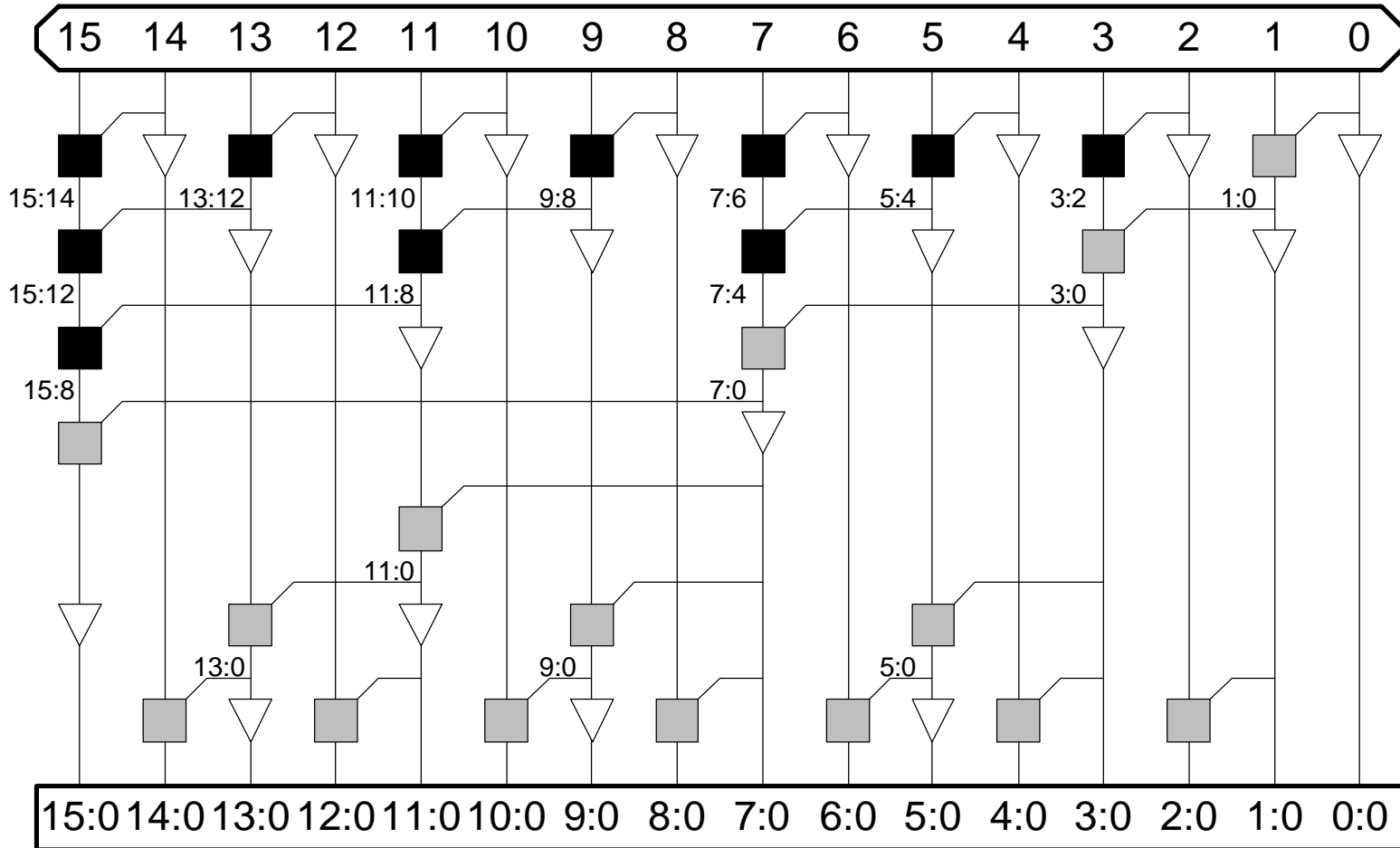




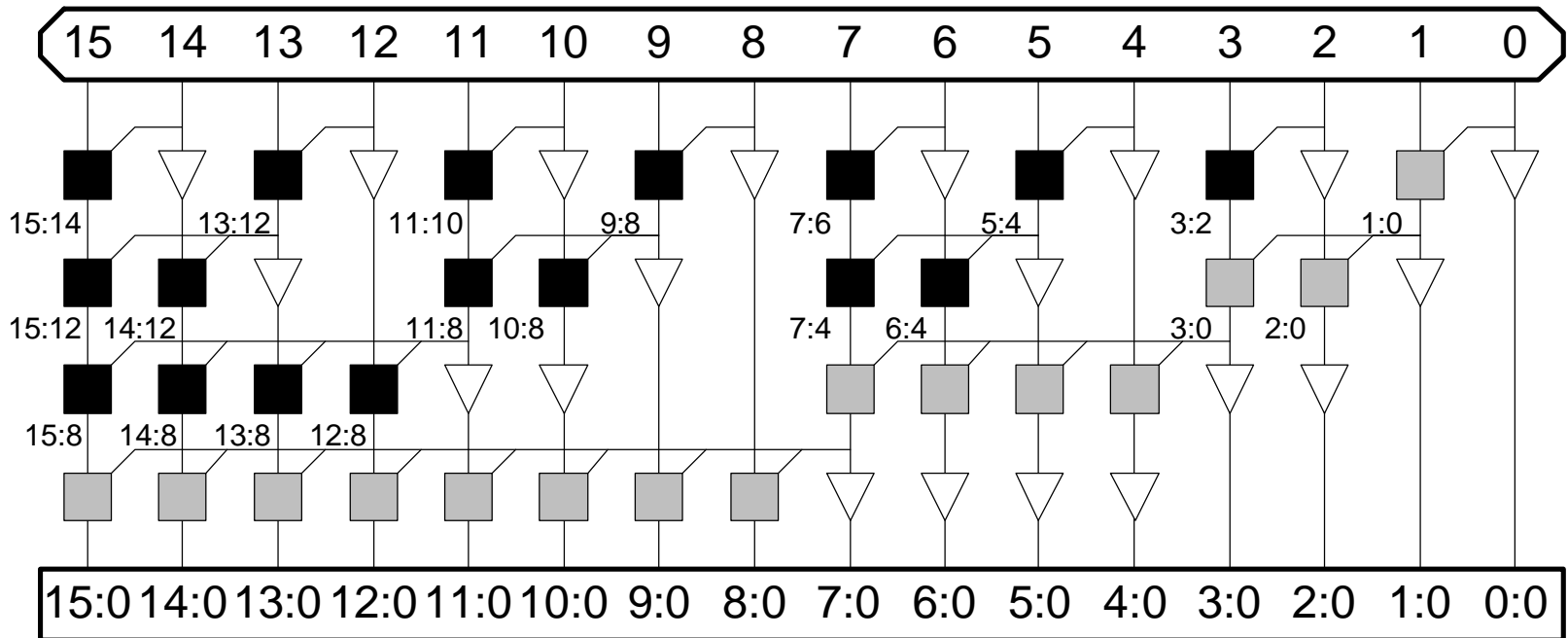
# Tree Adder

- ❑ If lookahead is good, lookahead across lookahead!
  - Recursive lookahead gives  $O(\log N)$  delay
- ❑ Many variations on tree adders

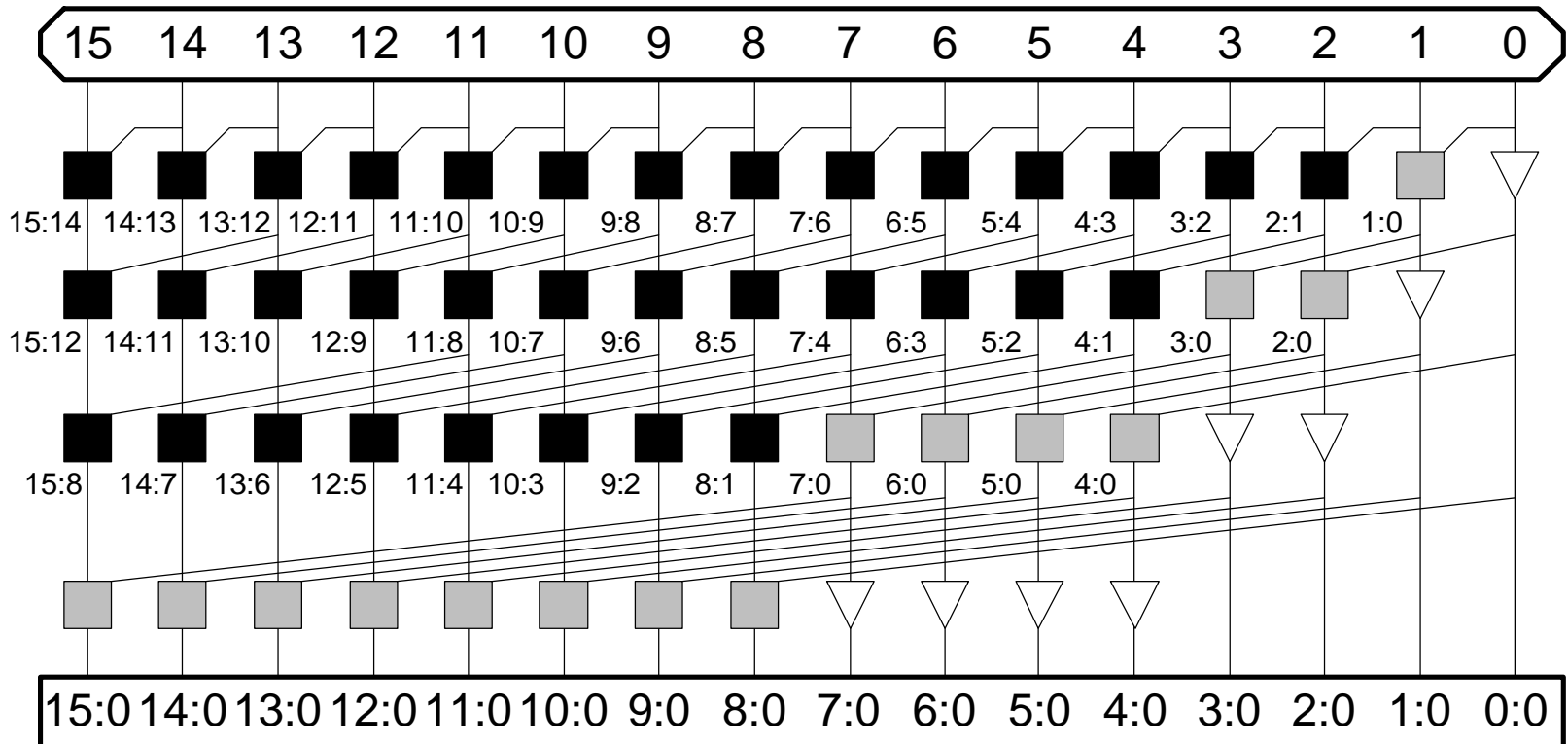
# Brent-Kung



# Sklansky



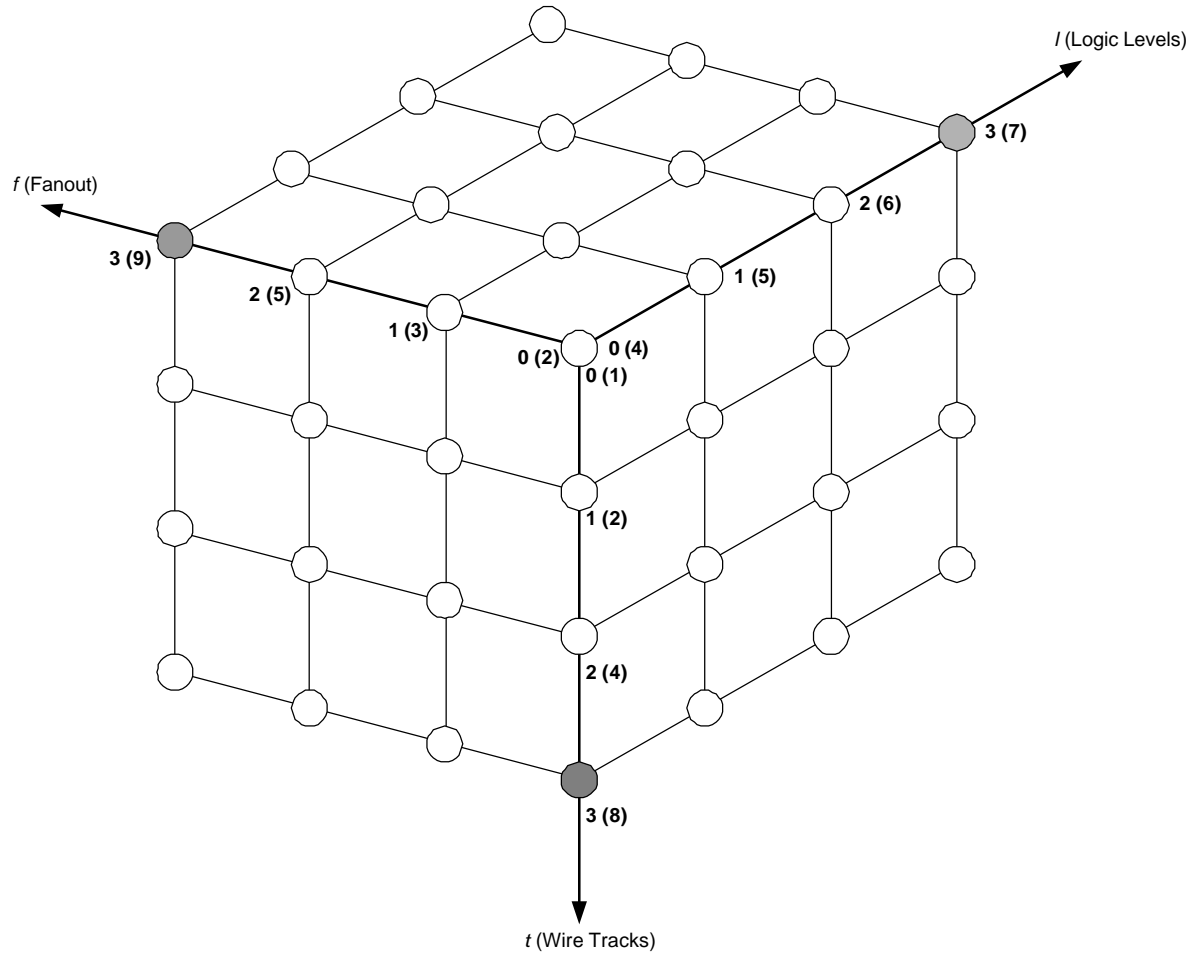
# Kogge-Stone



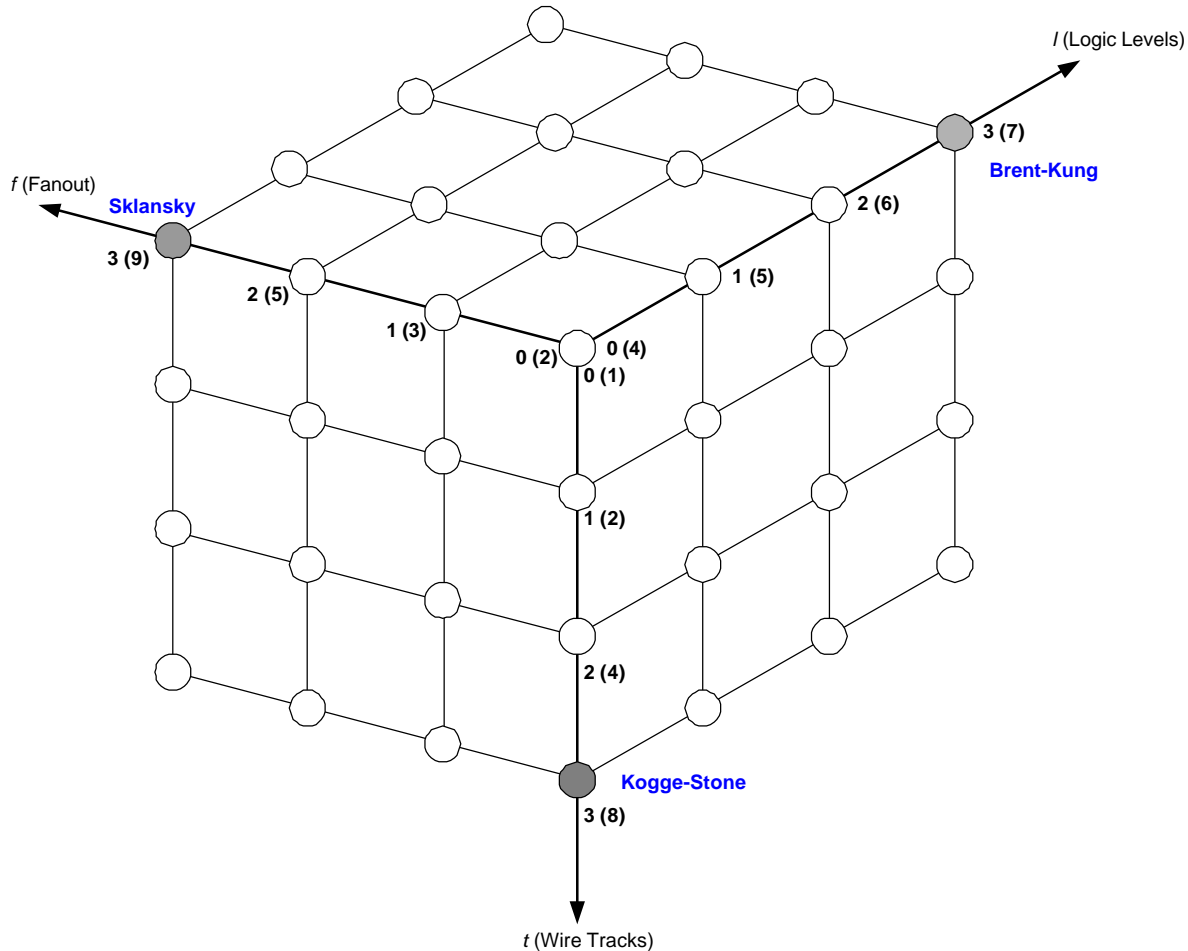
# Tree Adder Taxonomy

- ❑ Ideal N-bit tree adder would have
  - $L = \log N$  logic levels
  - Fanout never exceeding 2
  - No more than one wiring track between levels
- ❑ Describe adder with 3-D taxonomy ( $l, f, t$ )
  - Logic levels:  $L + l$
  - Fanout:  $2^f + 1$
  - Wiring tracks:  $2^t$
- ❑ Known tree adders sit on plane defined by
$$l + f + t = L - 1$$

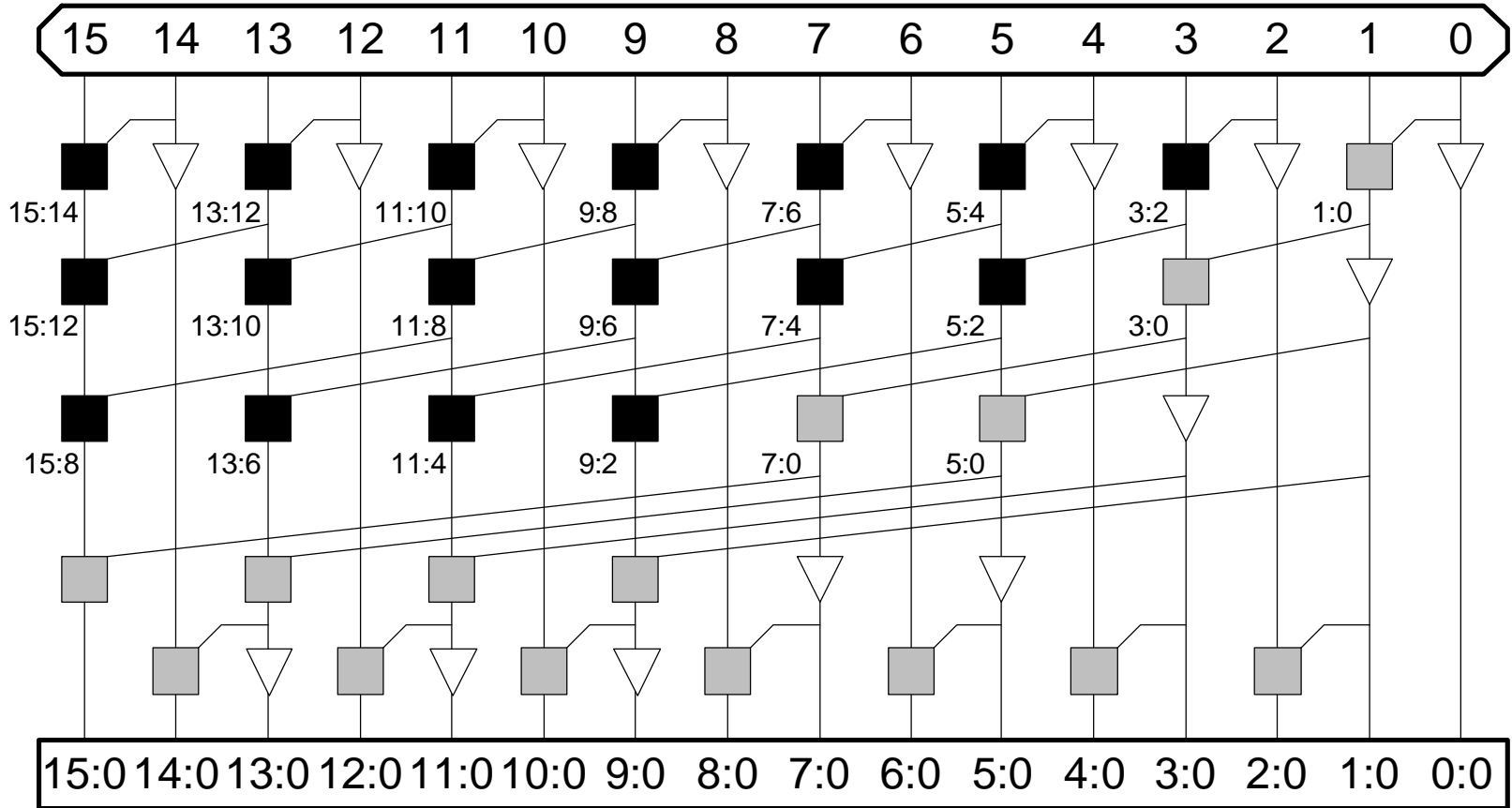
# Tree Adder Taxonomy



# Tree Adder Taxonomy

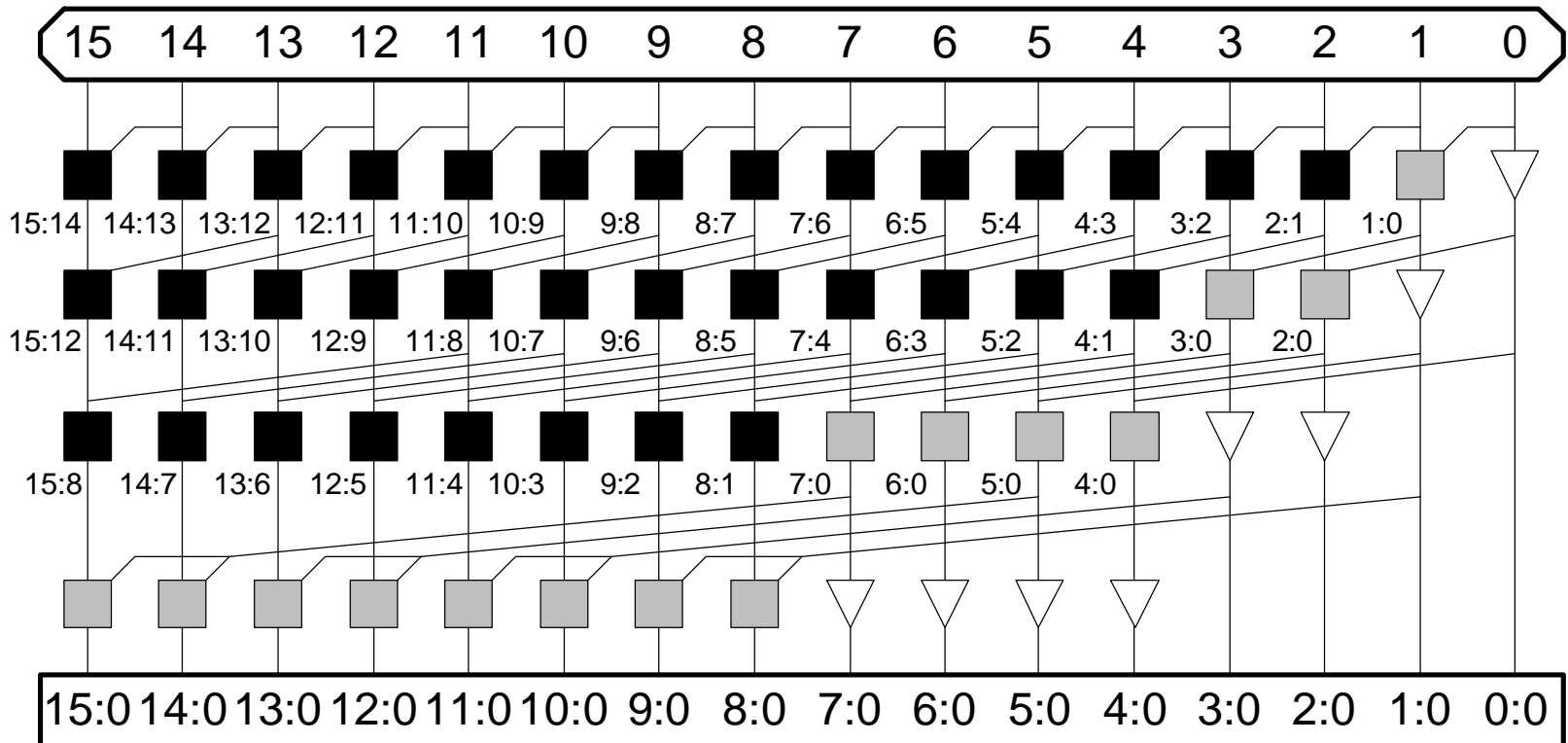


# Han-Carlson

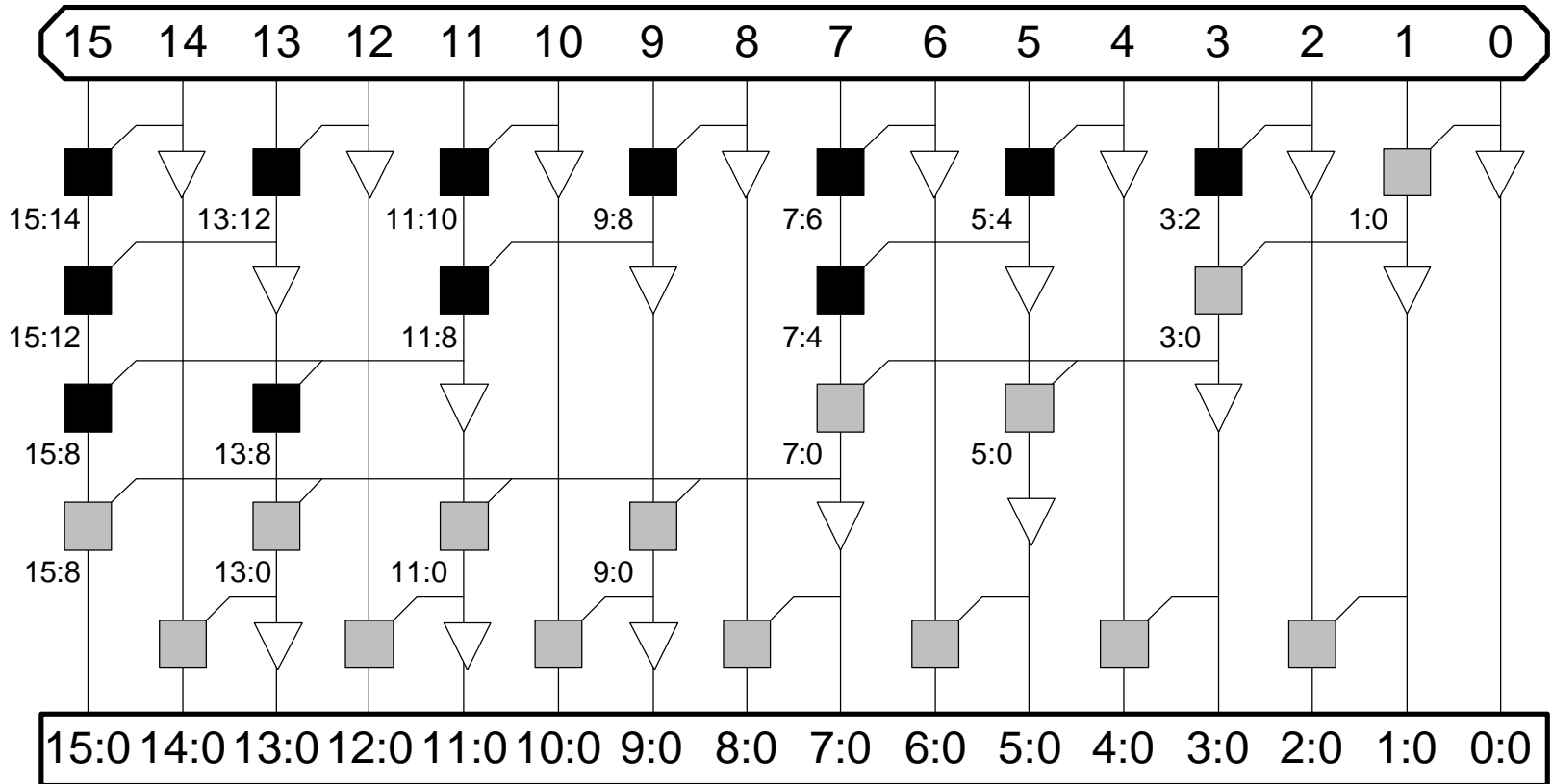




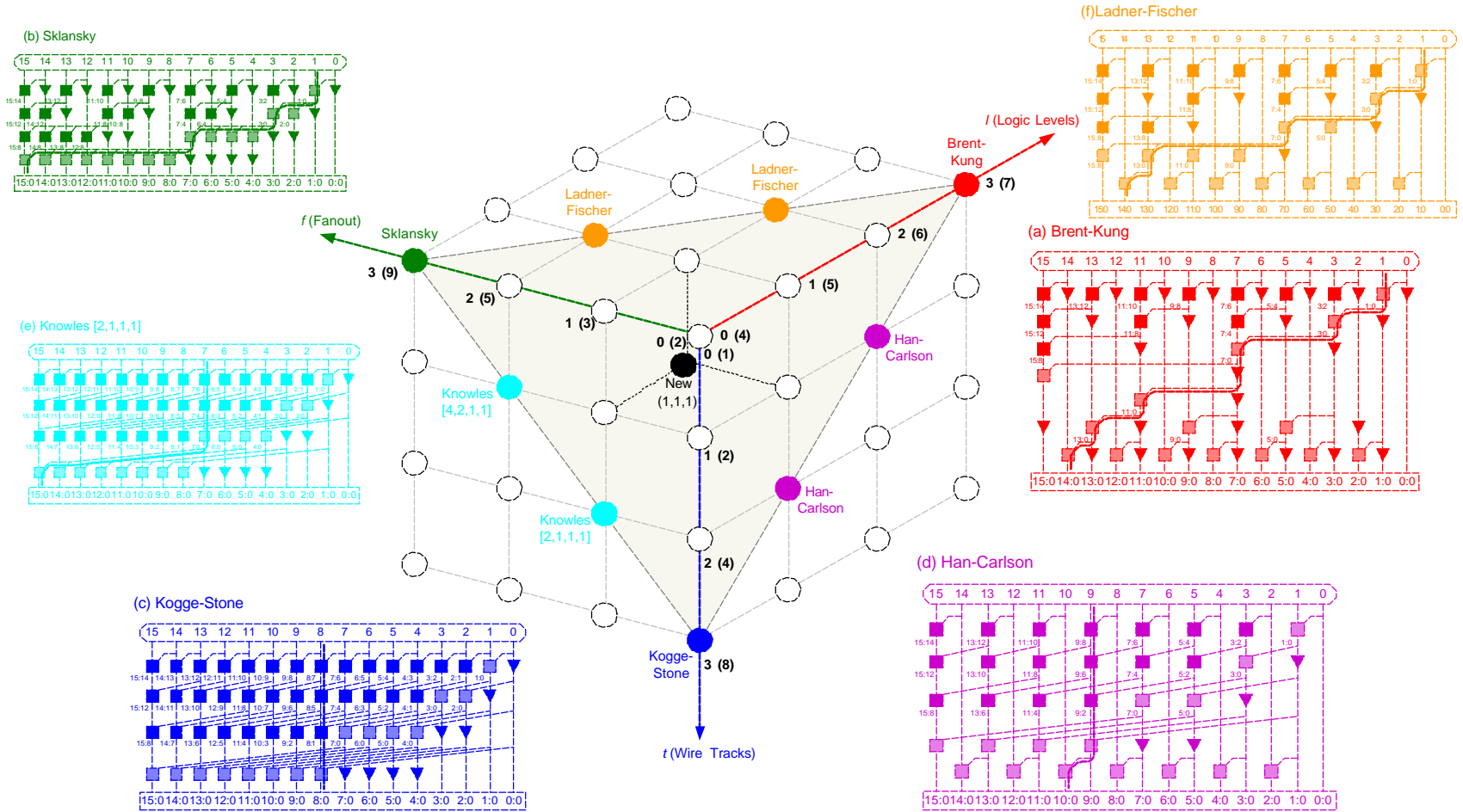
# Knowles [2, 1, 1, 1]



# Ladner-Fischer



# Taxonomy Revisited



# Summary

Adder architectures offer area / power / delay tradeoffs.  
Choose the best one for your application.

Architecture	Classification	Logic Levels	Max Fanout	Tracks	Cells
Carry-Ripple		$N-1$	1	1	$N$
Carry-Skip $n=4$		$N/4 + 5$	2	1	$1.25N$
Carry-Inc. $n=4$		$N/4 + 2$	4	1	$2N$
Brent-Kung	$(L-1, 0, 0)$	$2\log_2 N - 1$	2	1	$2N$
Sklansky	$(0, L-1, 0)$	$\log_2 N$	$N/2 + 1$	1	$0.5 N \log_2 N$
Kogge-Stone	$(0, 0, L-1)$	$\log_2 N$	2	$N/2$	$N \log_2 N$