8. Design of Adders

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VLSI Design
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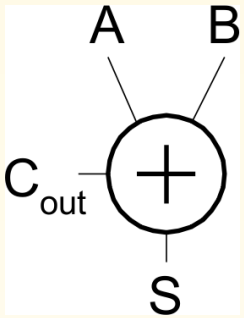
Single-Bit Addition

Half Adder

$$S = A \oplus B$$

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

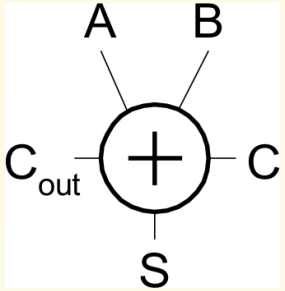


A	B	C_{out}	S
0	0	0	0
0	1	0	1
1	0	0	1
1	1	1	0

Full Adder

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

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



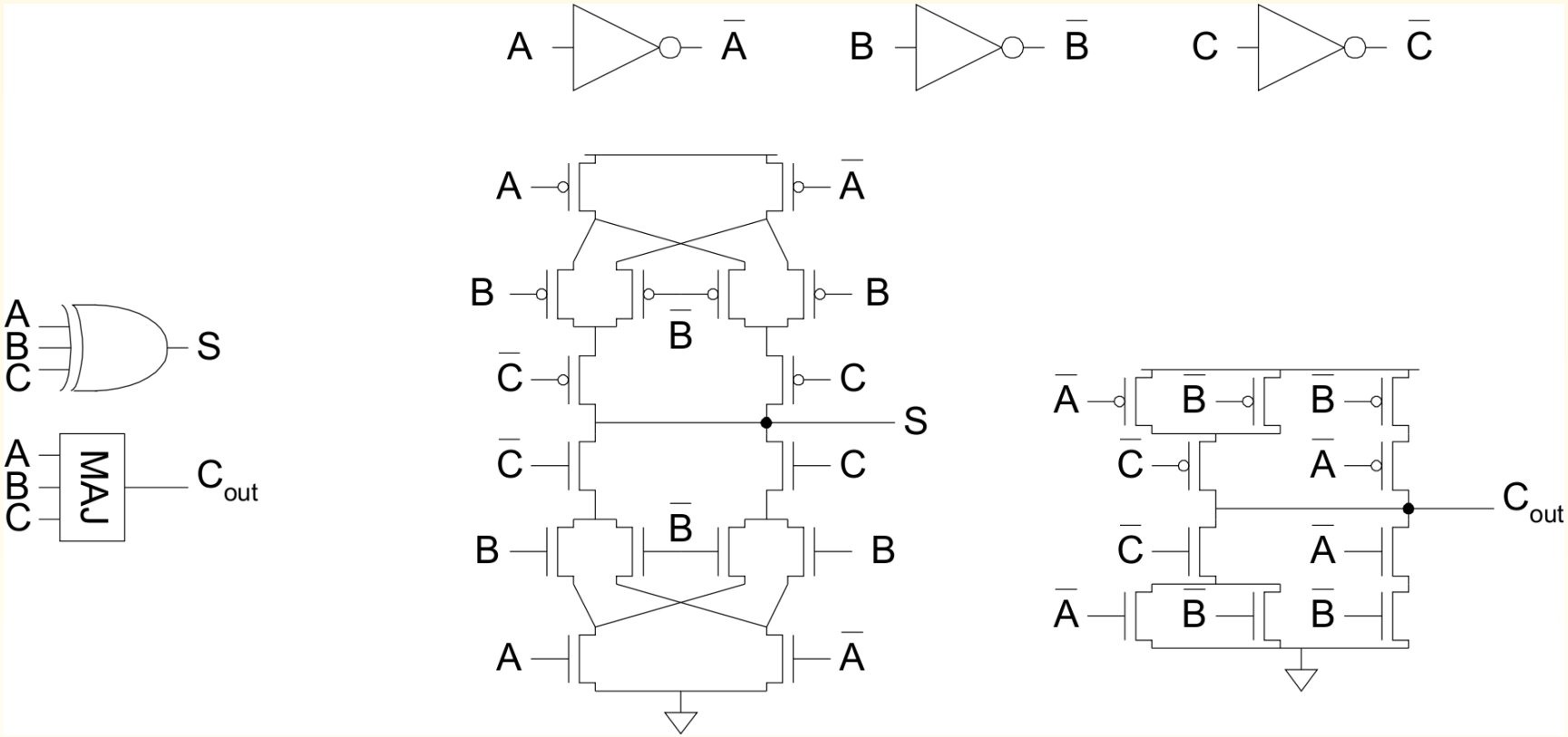
A	B	C	C_{out}	S
0	0	0	0	0
0	0	1	0	1
0	1	0	0	1
0	1	1	1	0
1	0	0	0	1
1	0	1	1	0
1	1	0	1	0
1	1	1	1	1

Full Adder Design I

Brute force implementation from equations

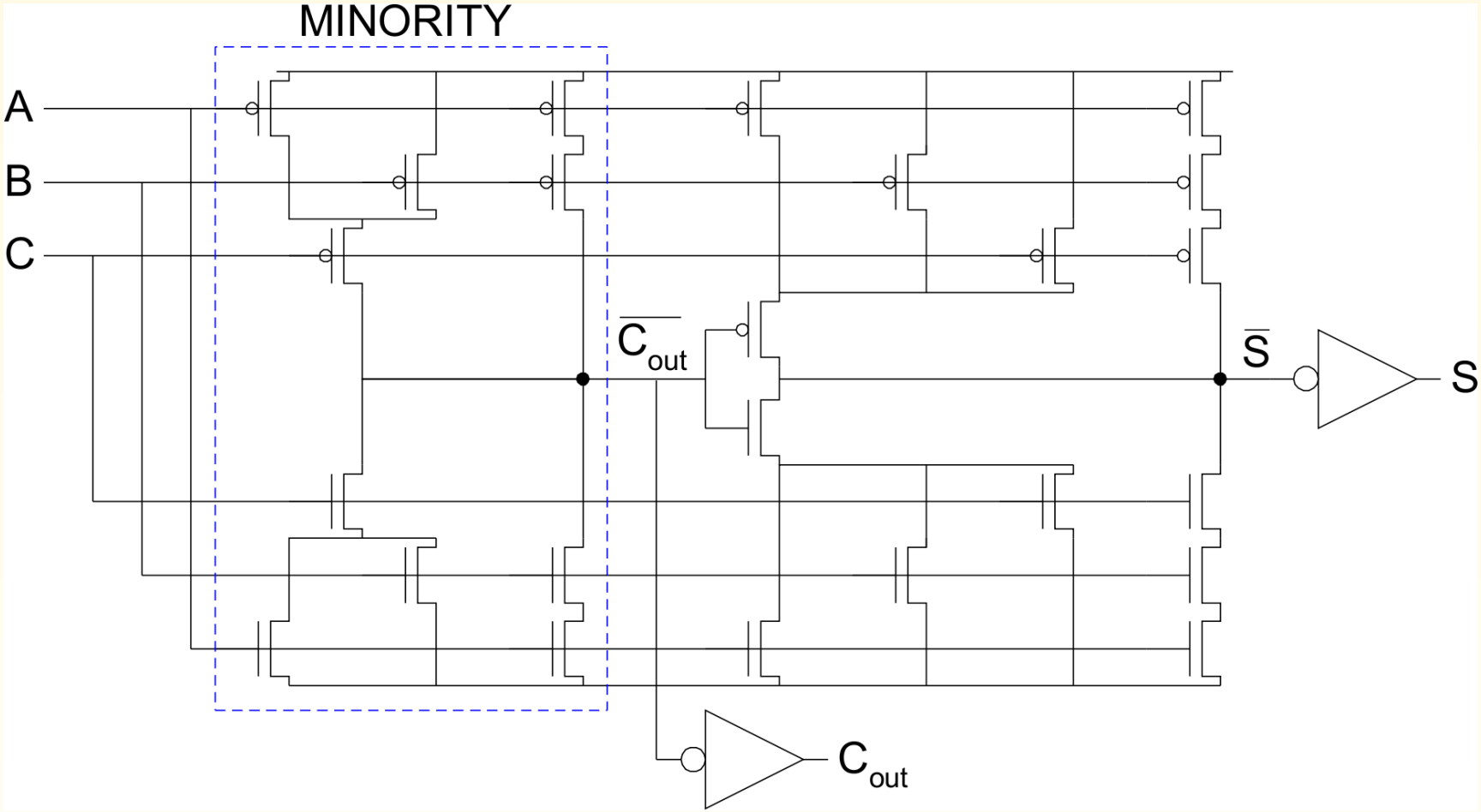
$S = A \oplus B \oplus C$

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



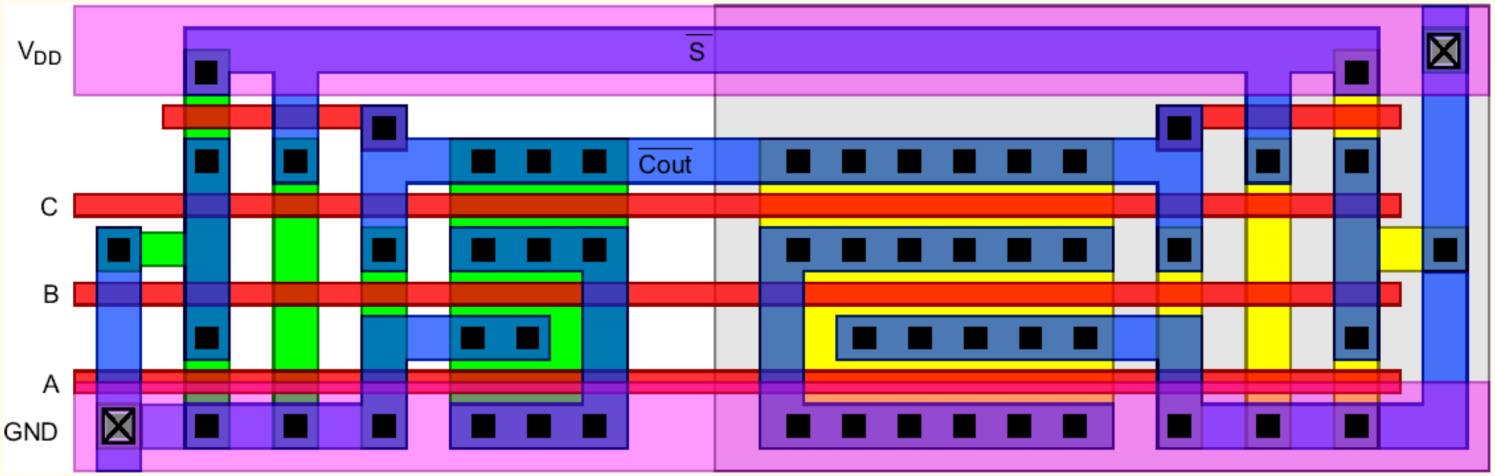
Full Adder Design II

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



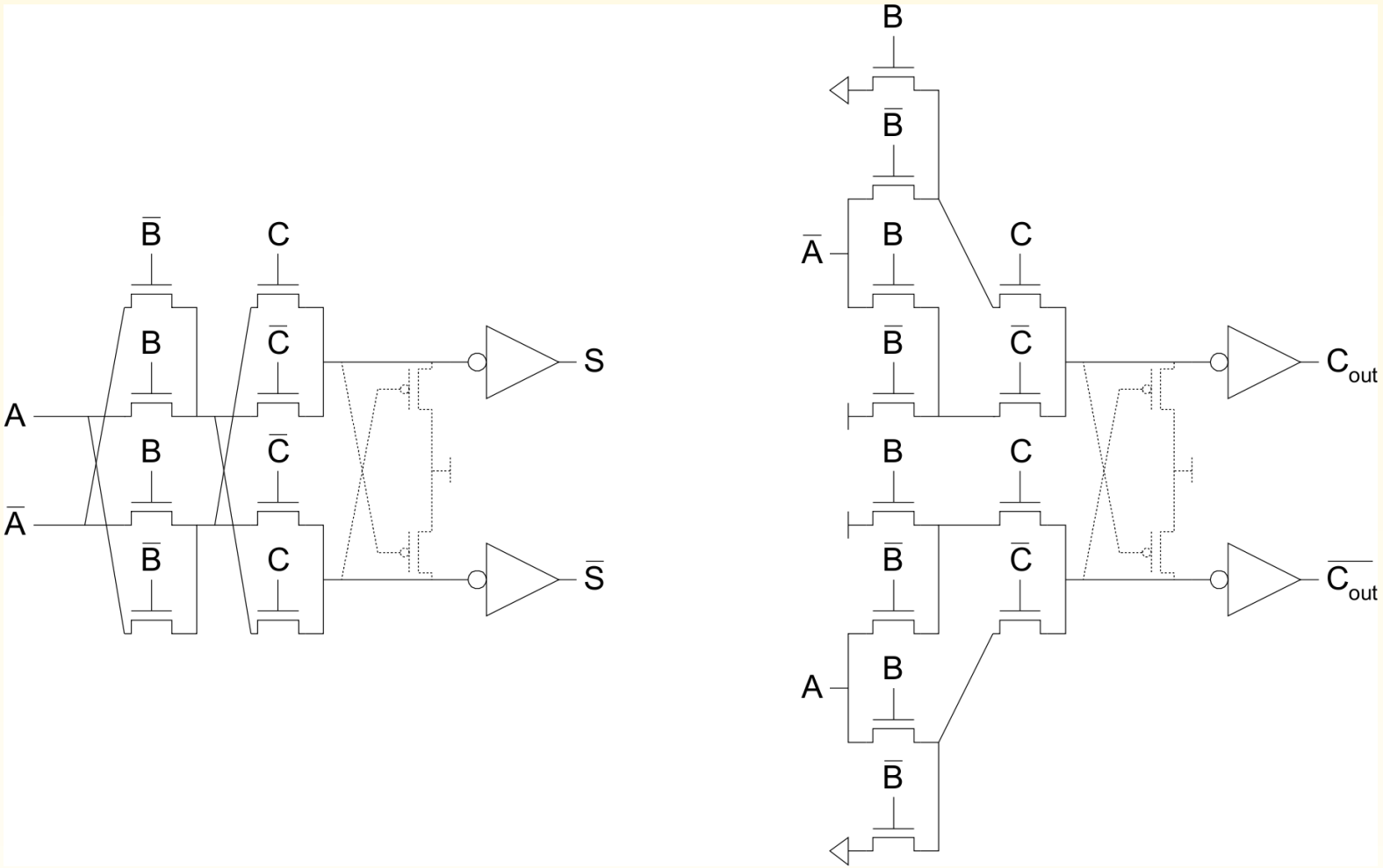
Layout of Full Adder

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



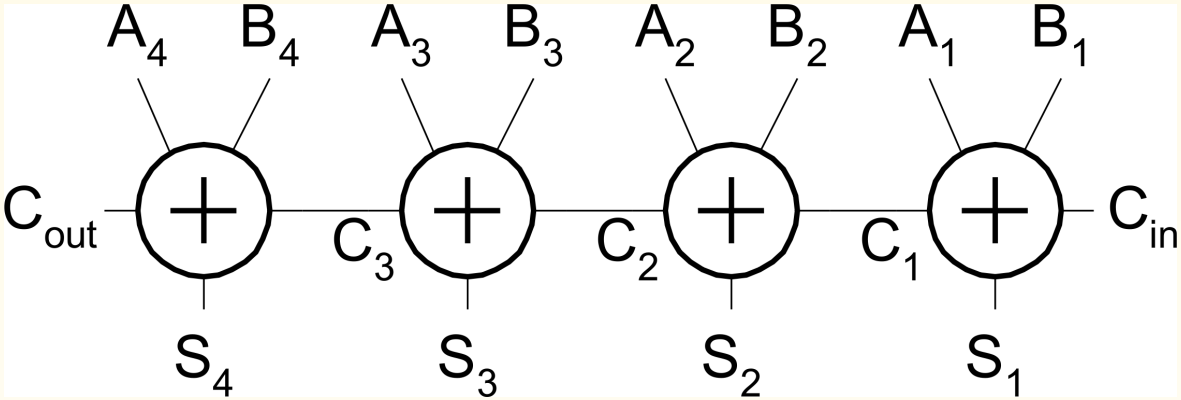
Full Adder Design III

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



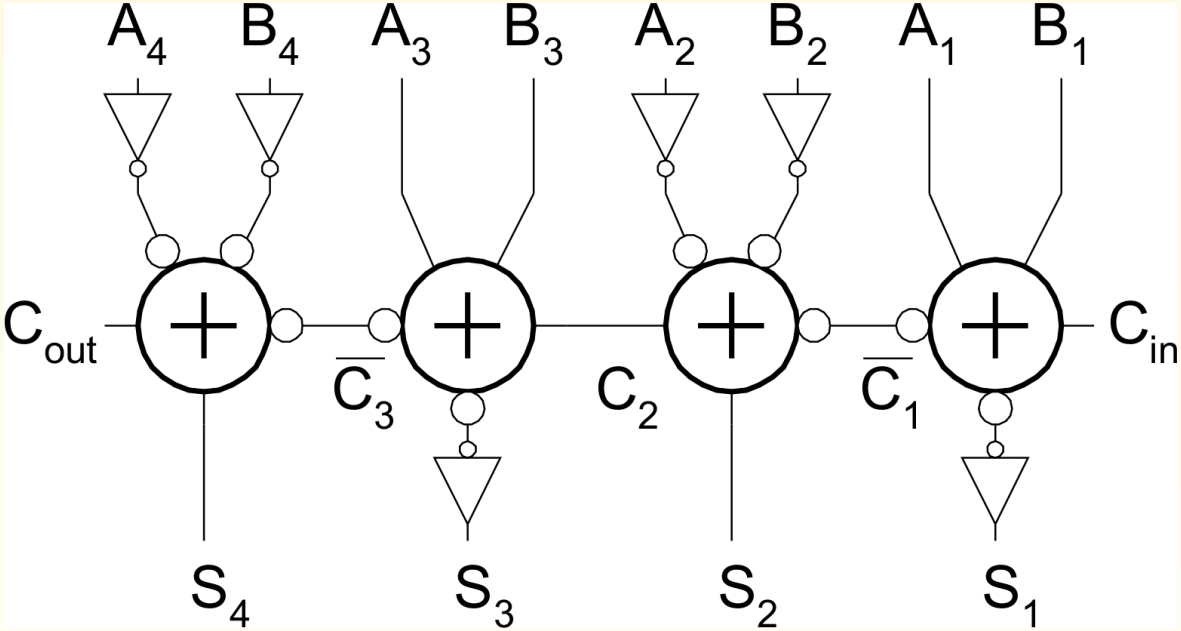
Ripple Carry Adder

- Simplest design: cascade full adders
  - Critical path goes from C_{in} to C_{out}
  - Design full adder to have fast carry (small delay for carry signal)



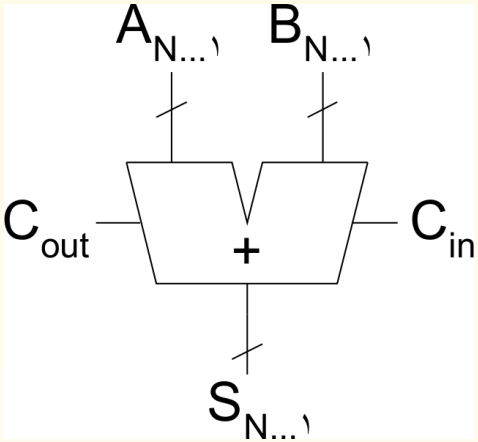
Deal with Inversions to Speed Up Carry Path

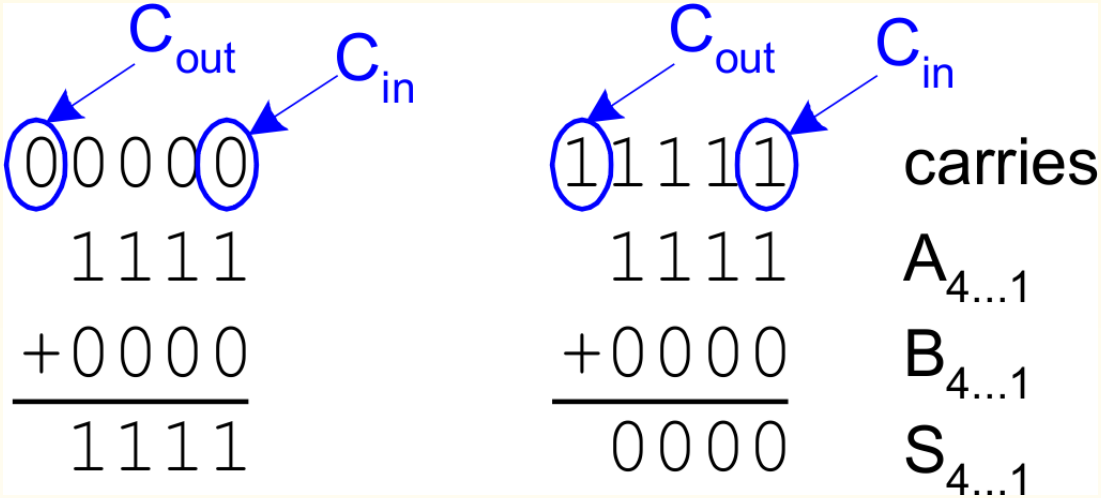
- Critical path passes through majority gate
  - Built from minority + inverter
  - Eliminate inverter and use inverting full adder



Carry Propagate Adders

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





Carry Propagate, Generate, Kill (P, G, K)

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
  - $K = \overline{A} \cdot \overline{B}$

Generate and Propagate for groups spanning i:j

- $G_{i:j} = G_{i:k} + P_{i:k} \cdot G_{k-1:j}$
- $P_{i:j} = P_{i:k} \cdot P_{k-1:j}$
- Base Case
  - $G_{i:i} \equiv G_i = A_i \cdot B_i, \qquad G_{0:0} = G_0 = C_{in}$
  - $P_{i:i} \equiv P_i = A_i \oplus B_i, \qquad P_{0:0} = P_0 = 0$
- Sum: $S_i = P_i \oplus G_{i-1:0}$

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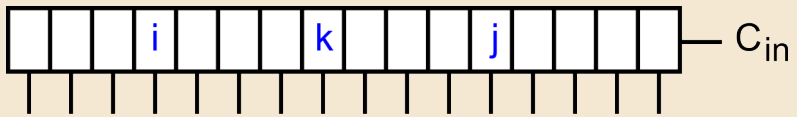

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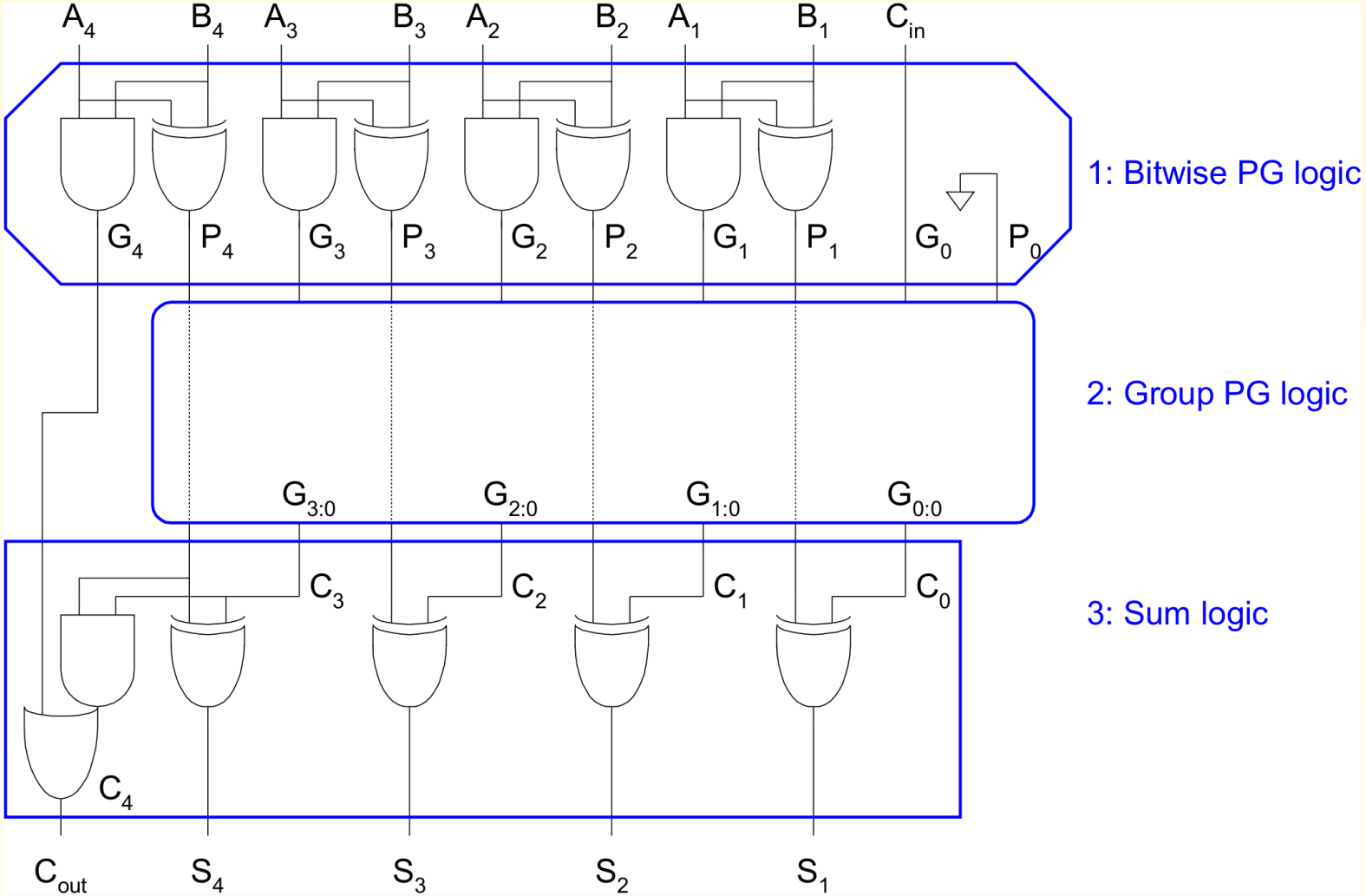
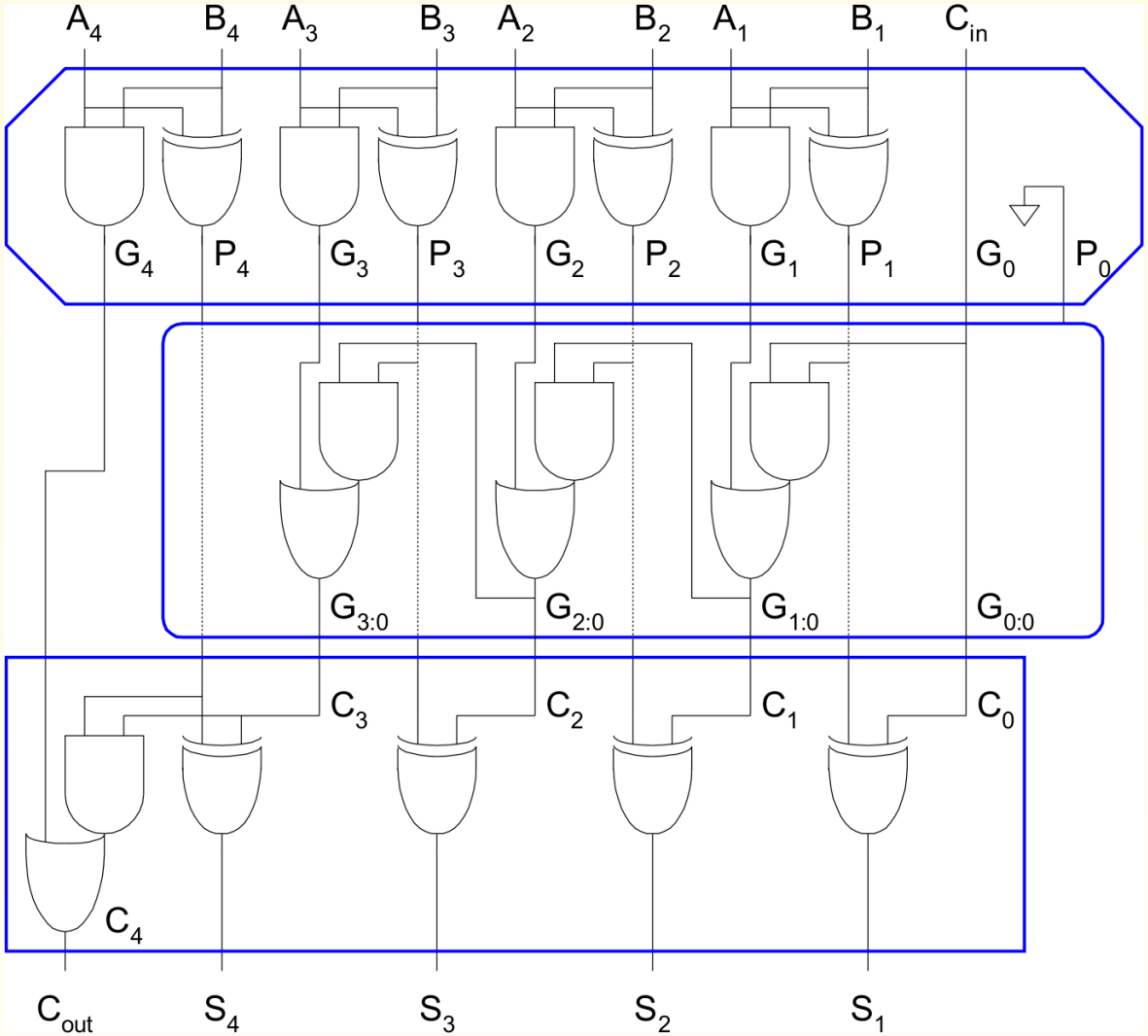
PG Logic


A4
B4
A3
B3
A2
B2
A1
B1
Cin
G4
P4
G3
P3
G2
P2
G1
P1
G0
P0
1: Bitwise PG logic
G3:0
G2:0
G1:0
G0:0
2: Group PG logic
C3
C2
C1
C0
C4
3: Sum logic
Cout
S4
S3
S2
S1

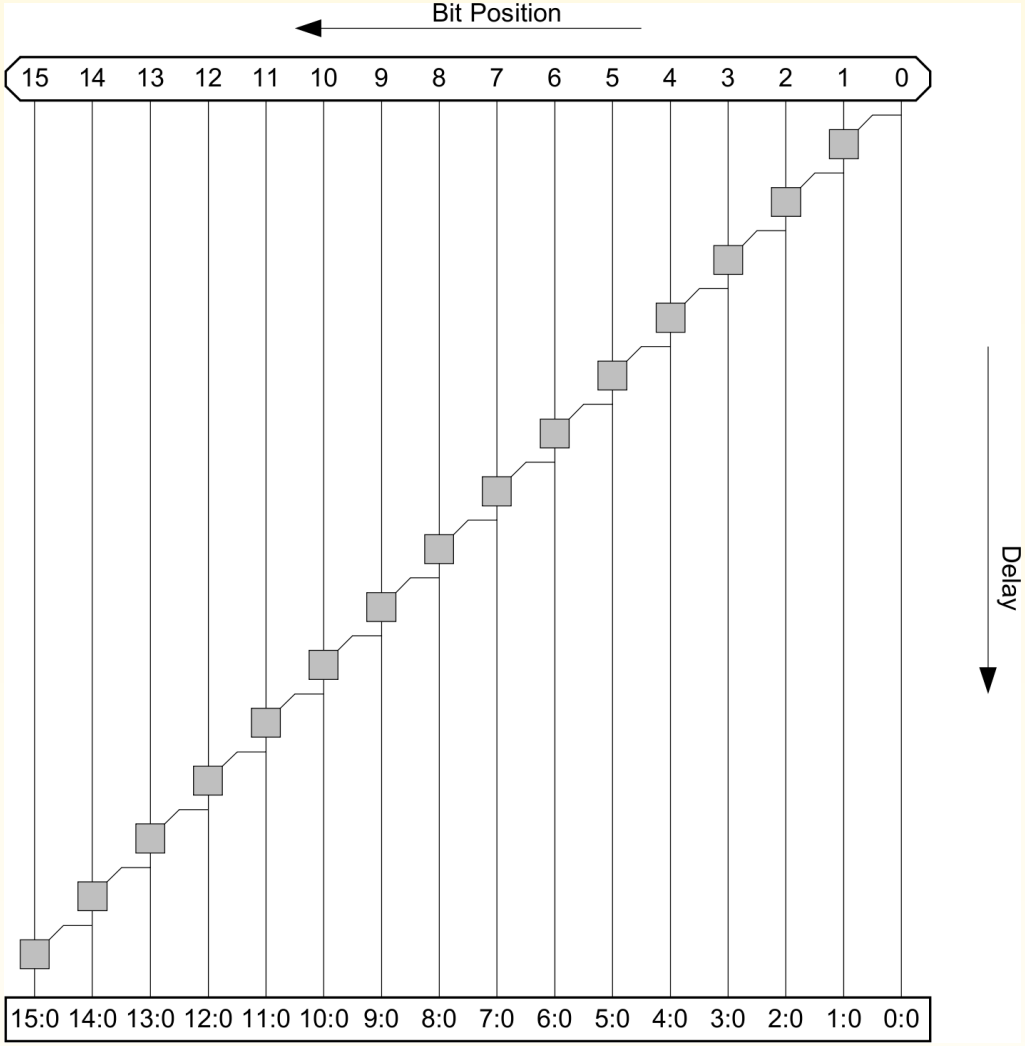
Ripple Carry Adder Revisited in the PG Framework

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

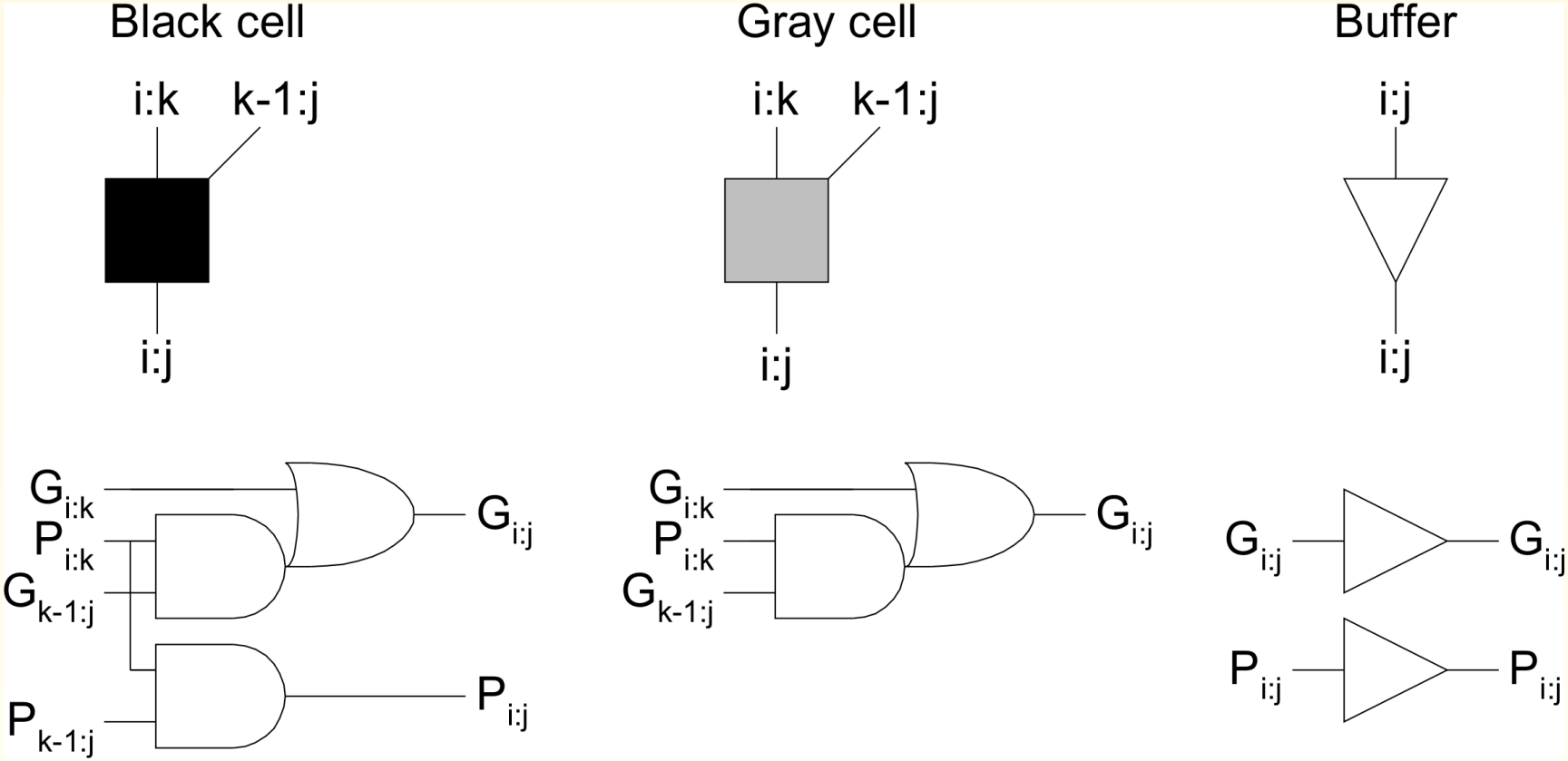


Ripple Carry PG Diagram

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

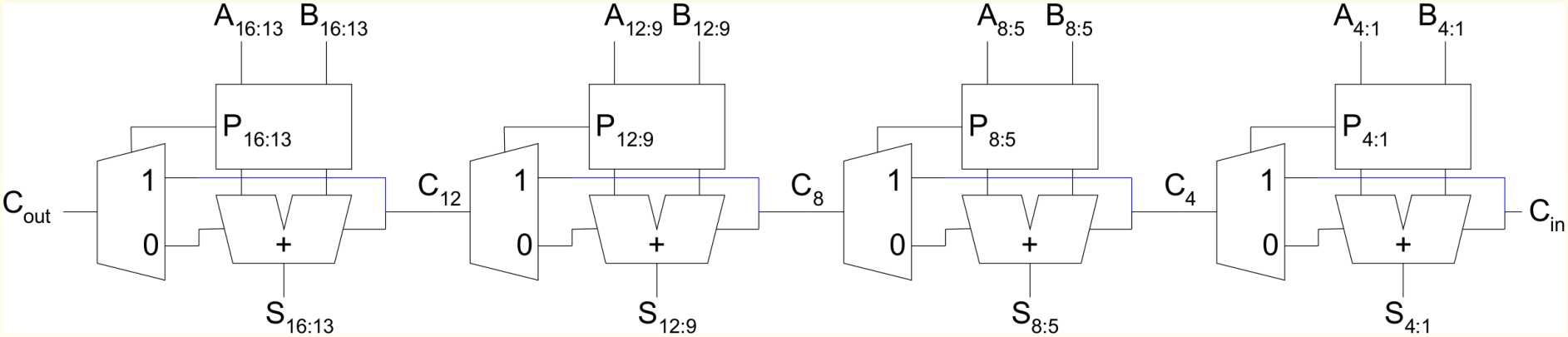


PG Diagram Notation

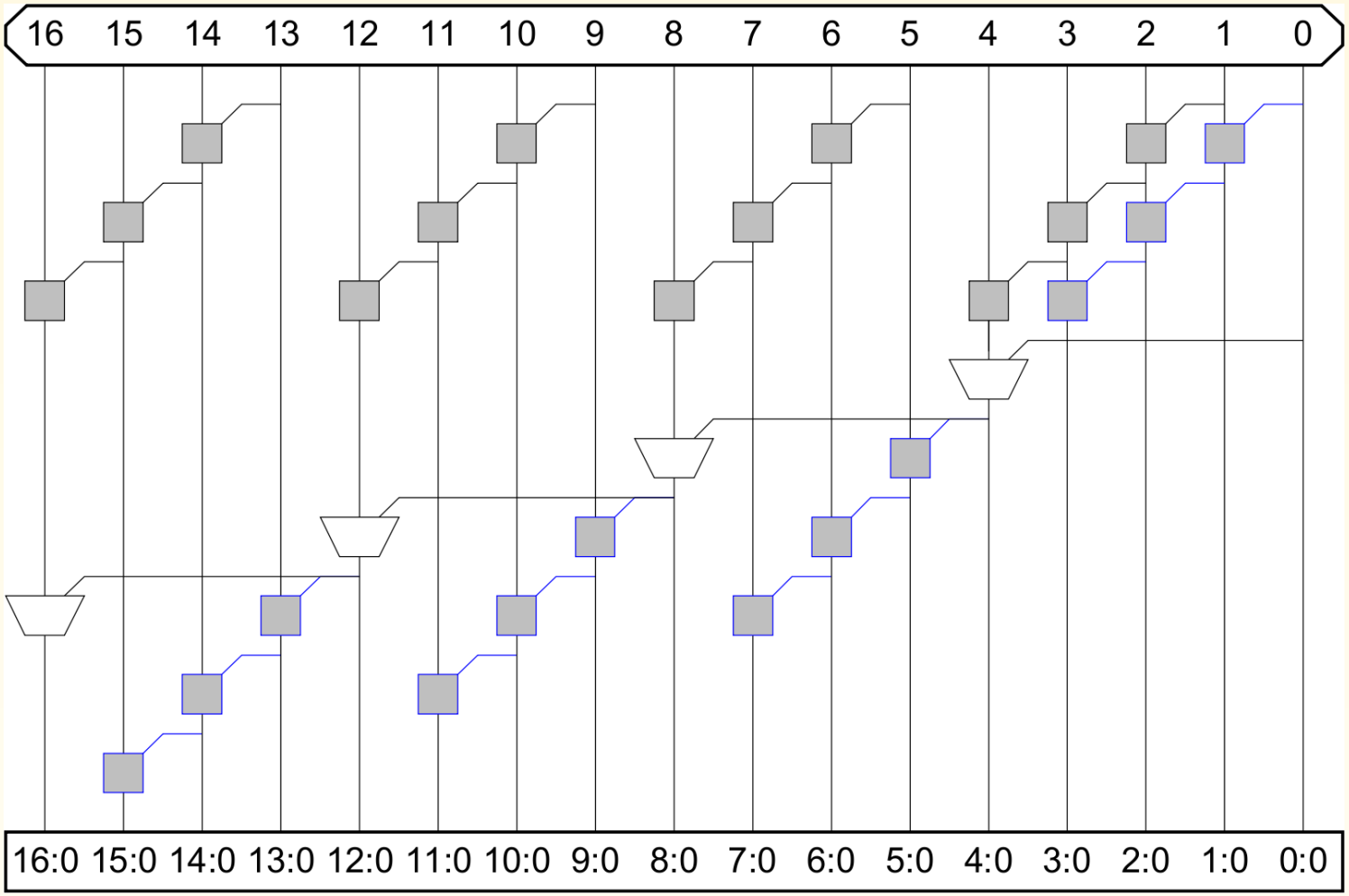


Carry-Skip Adder

- 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

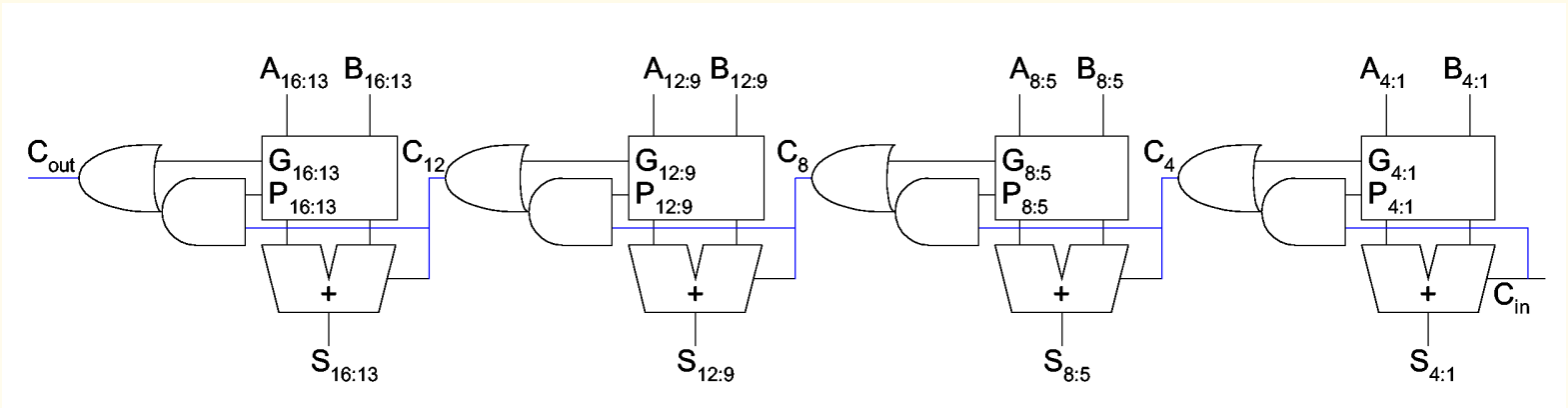


For k n-bit groups ($N = nk$)

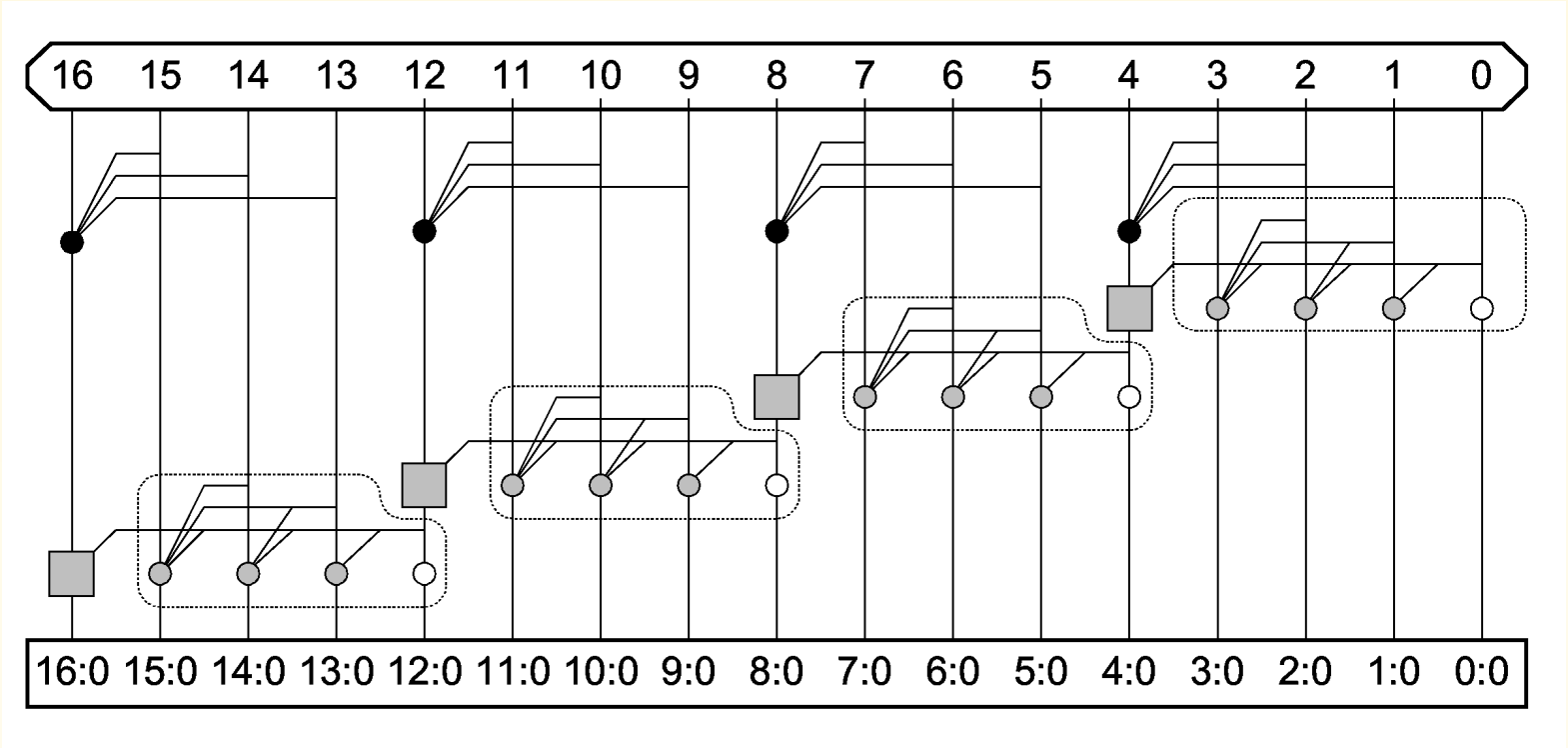
$$t_{skip} = t_{pg} + [2(n-1) + (k-1)]\, t_{AO} + t_{xor}$$

Carry-Lookahead Adder (CLA)

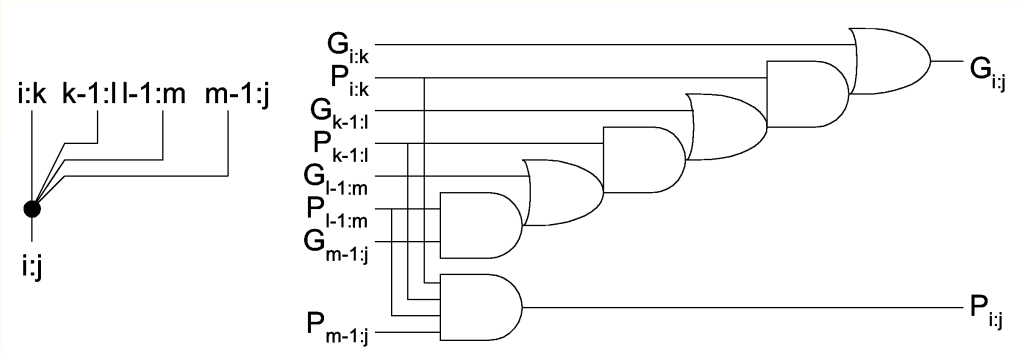
- Carry-lookahead adder computes $G_{i:0}$ for many bits in parallel
- Uses higher-valency cells with more than two inputs



CLA PG Diagram

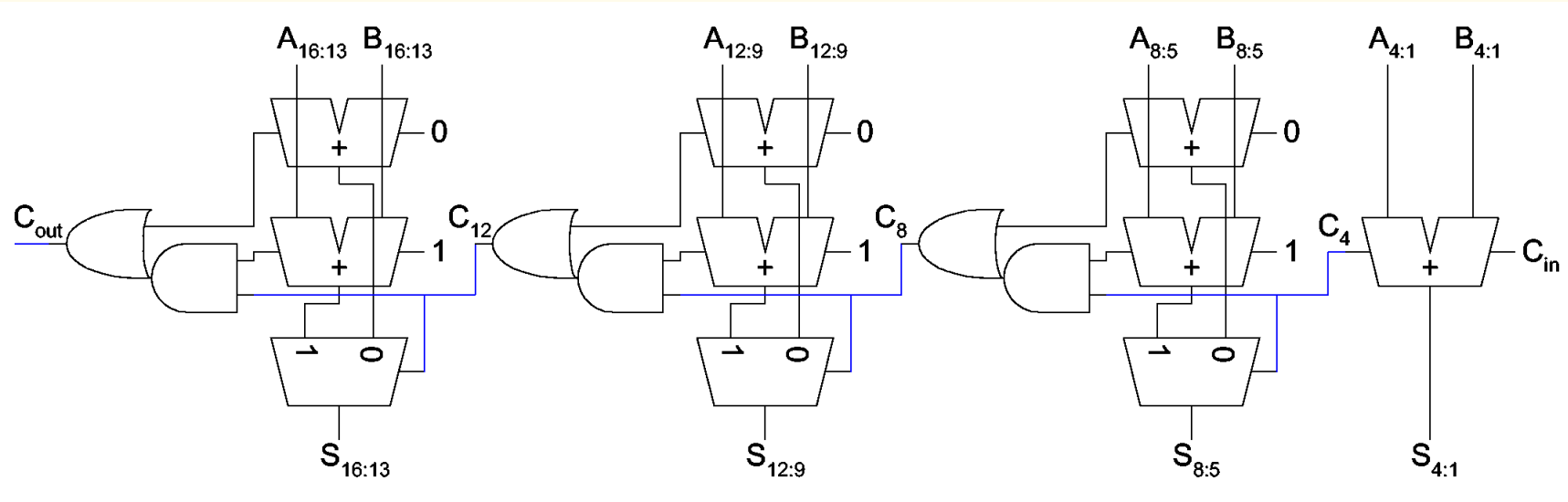


Higher Valency Cells



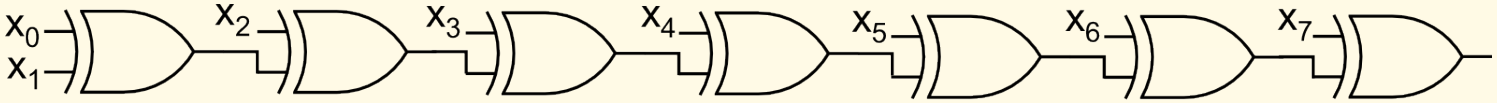
Carry-Select Adder

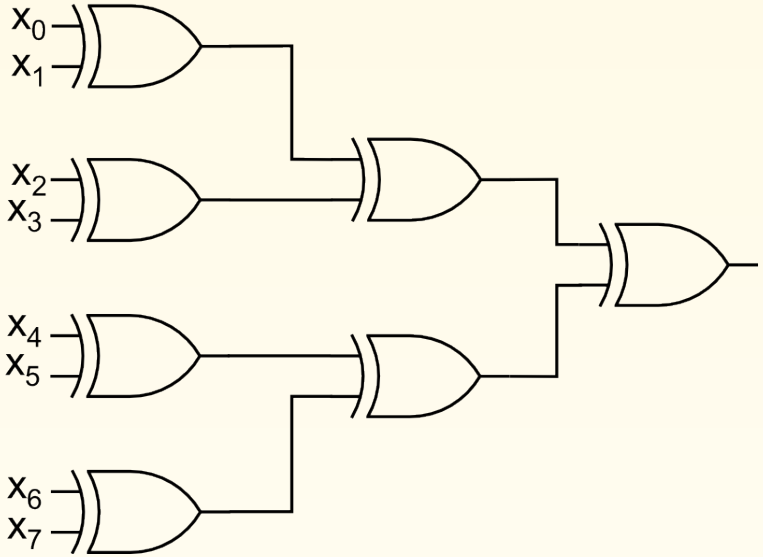
- Trick for critical paths dependent on late input X
  - Precompute two possible outputs for X = 0, 1
  - Select proper output when X arrives
- Carry-select adder precomputes n-bit sums for both possible carries into n-bit group



Tree Adders

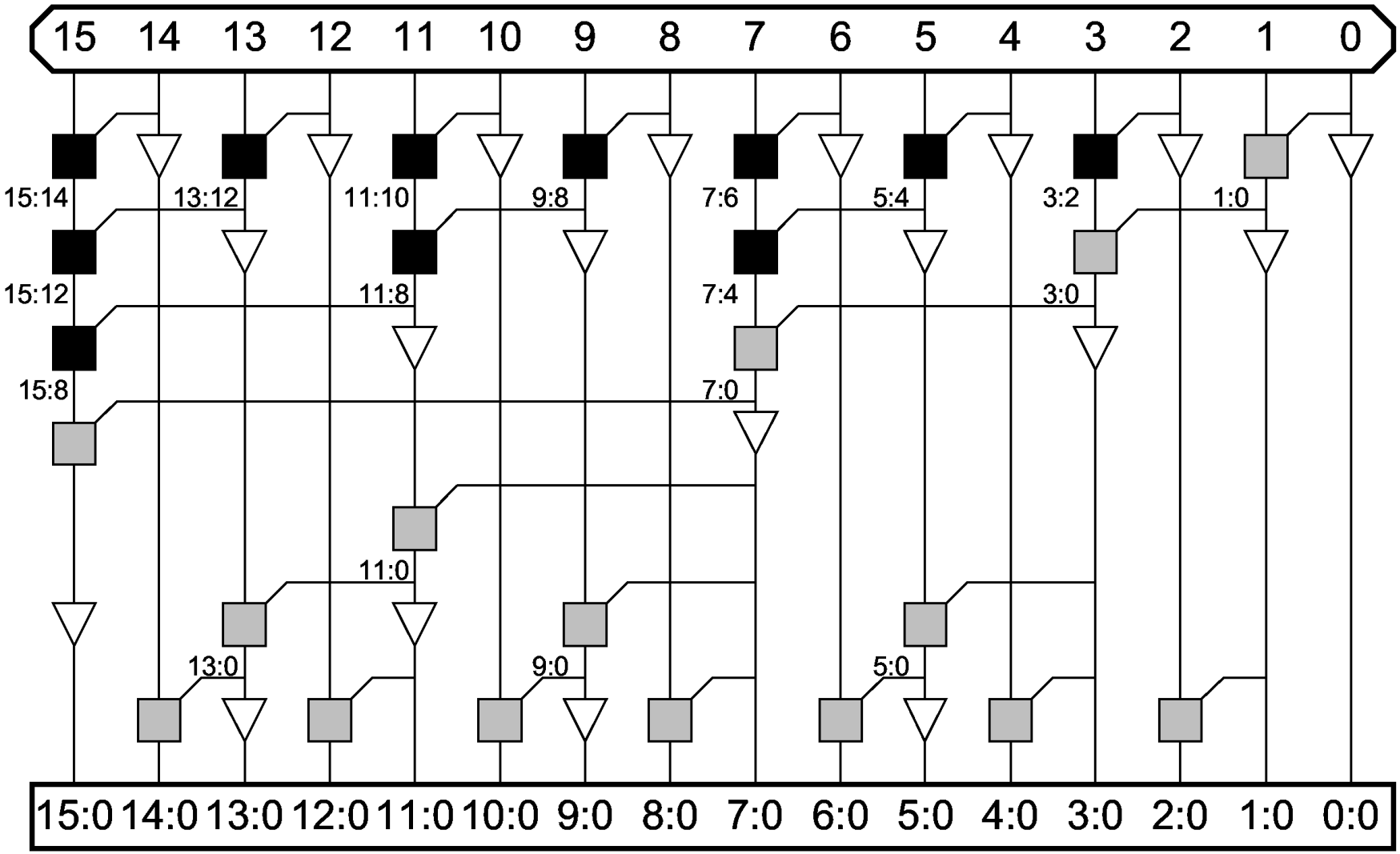
- Tree structures can be used to speed up computations
- Look at computing the XOR of 8 bits using 2-input XOR-gates



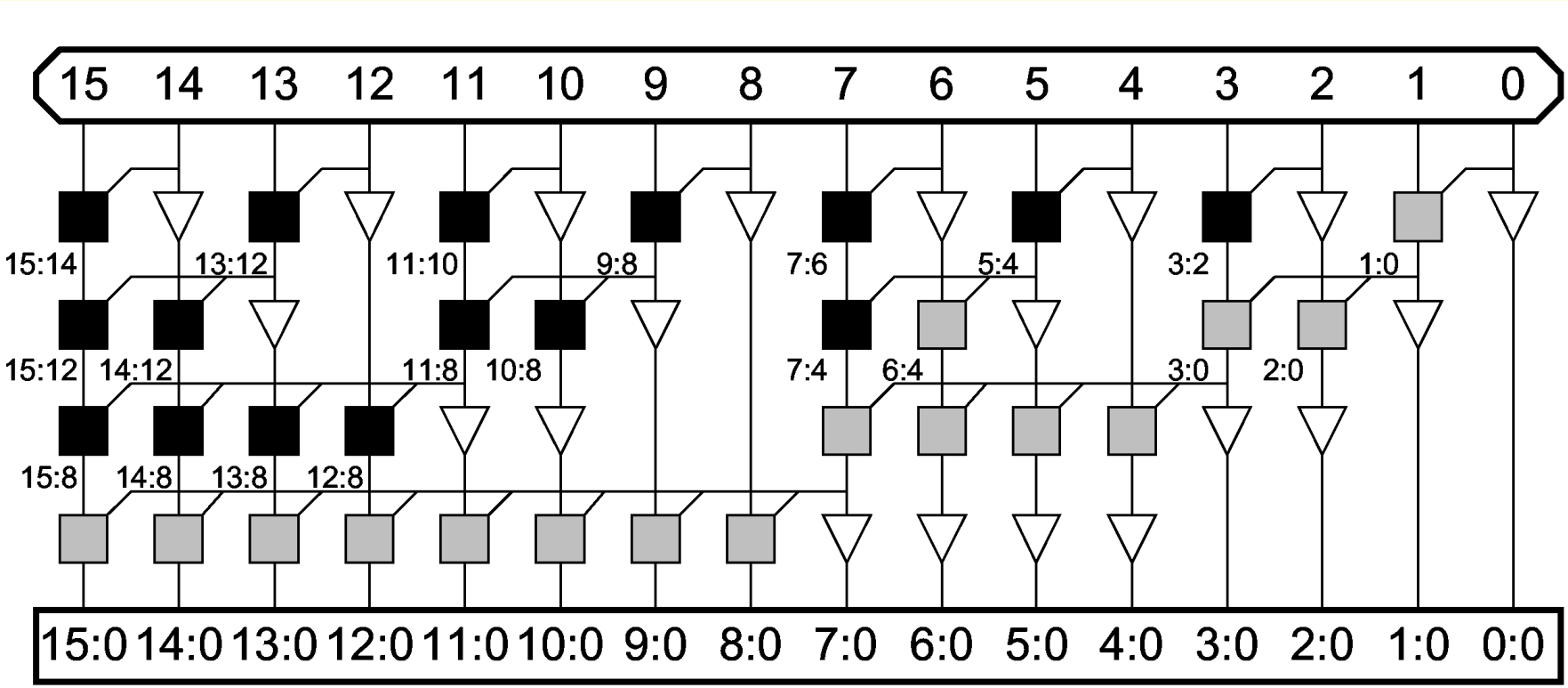


- If lookahead is good for adders, lookahead across lookahead!
  - Recursive lookahead gives O(log N) delay
- Many variations on tree adders

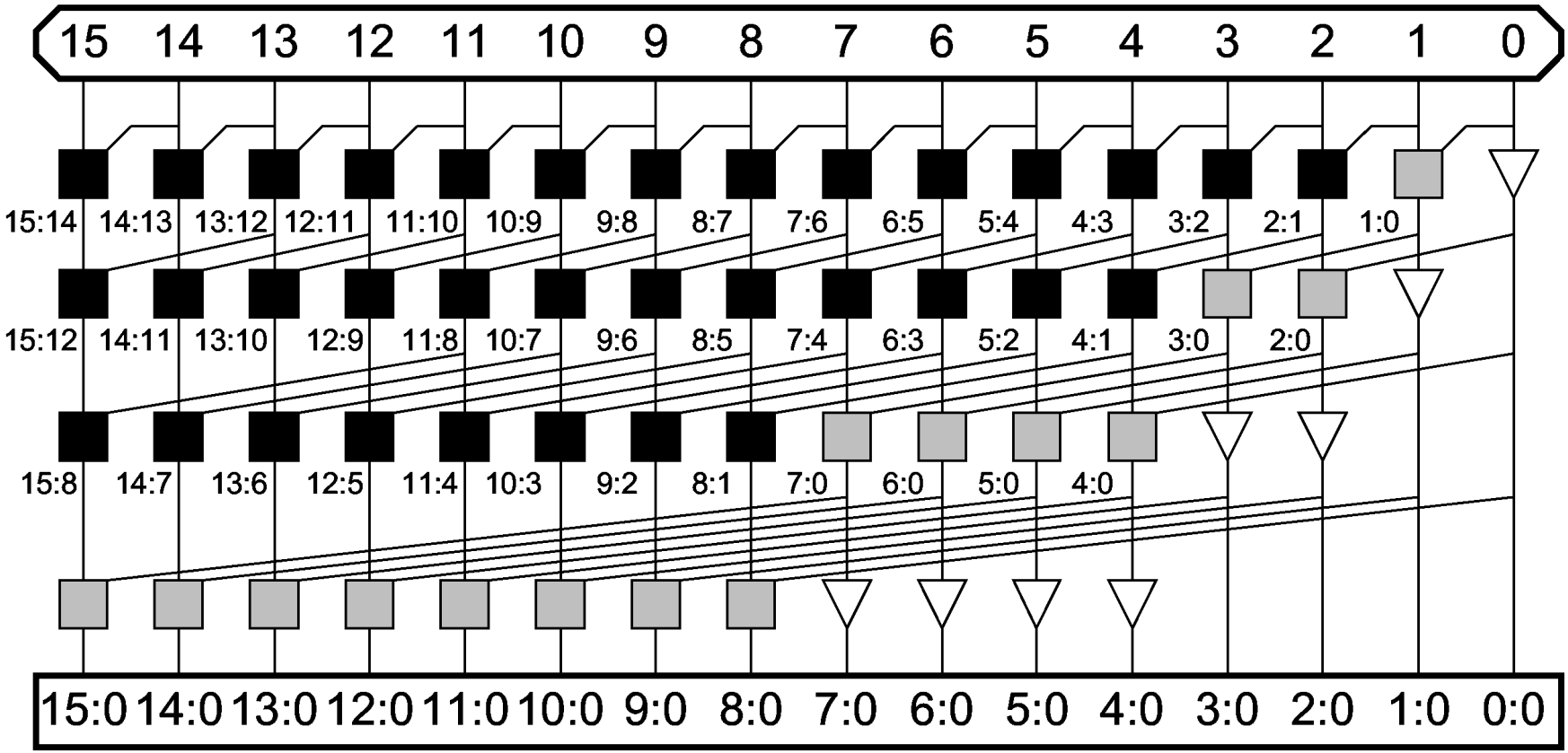
Brent-Kung Adder



Sklansky Adder



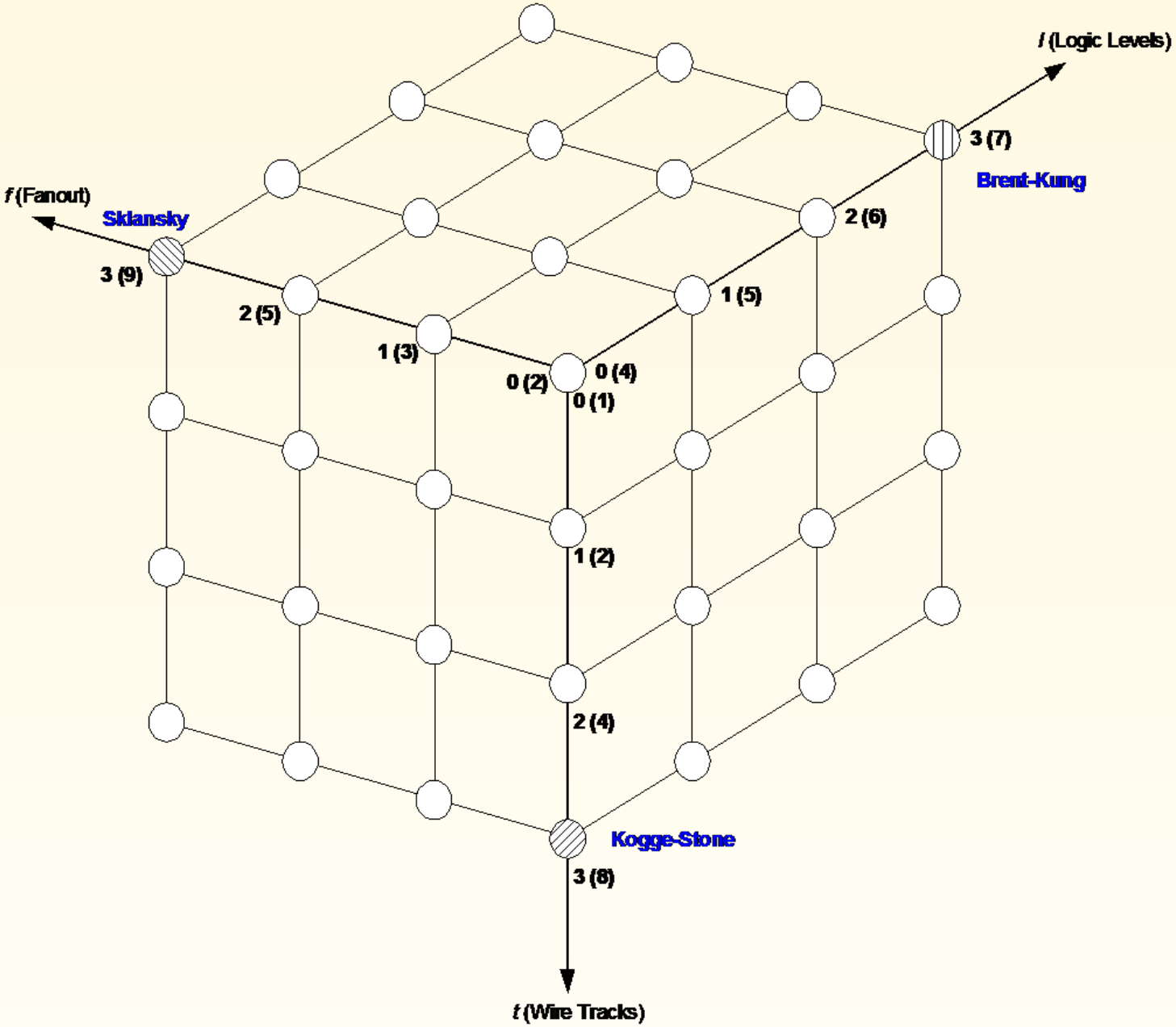
Kogge-Stone Adder



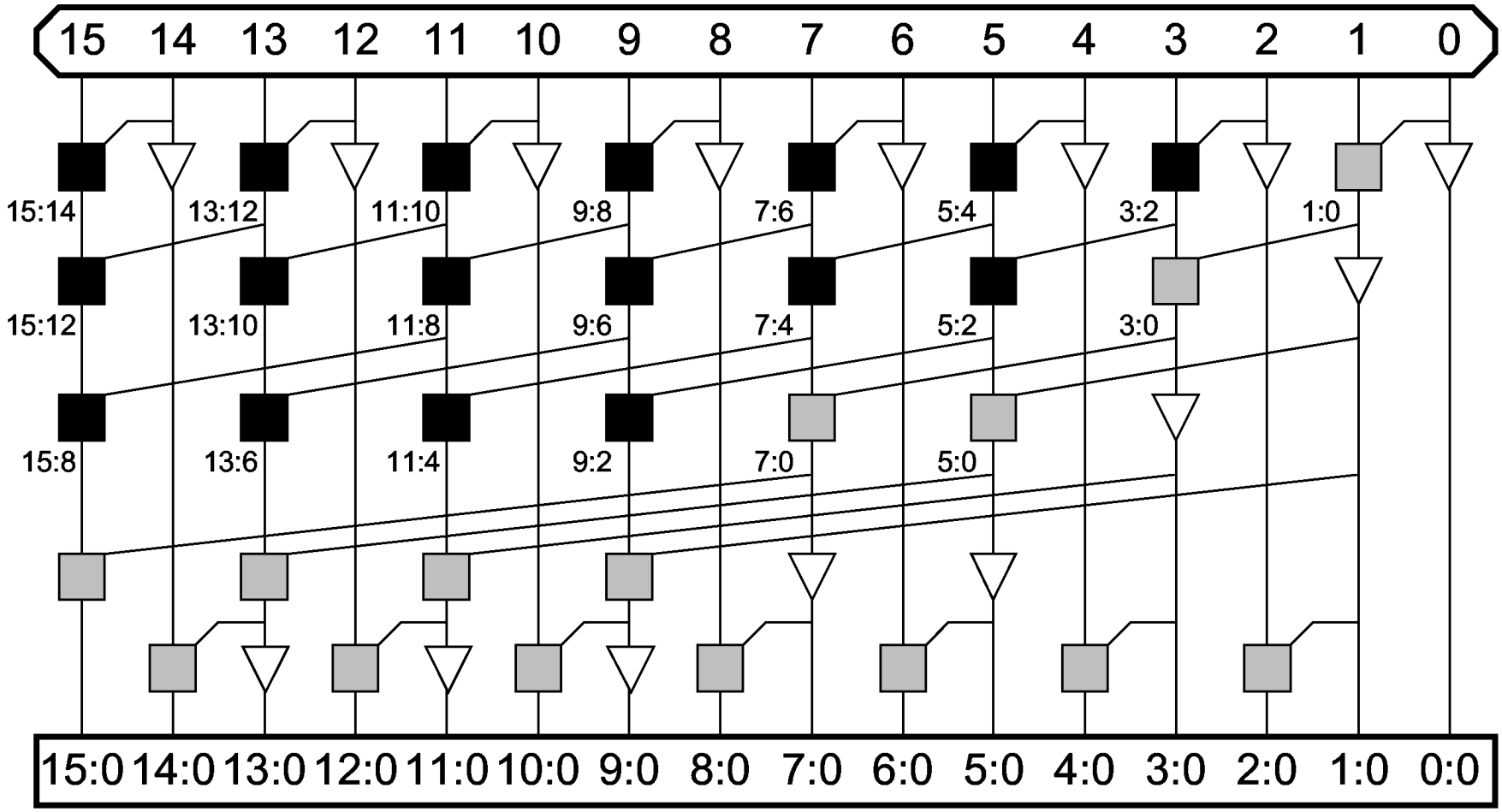
Tree Adder Taxonomy

- 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: $2f + 1$
  - Wiring tracks: 2^t
- Known tree adders sit on plane defined by $l + f + t = L - 1$

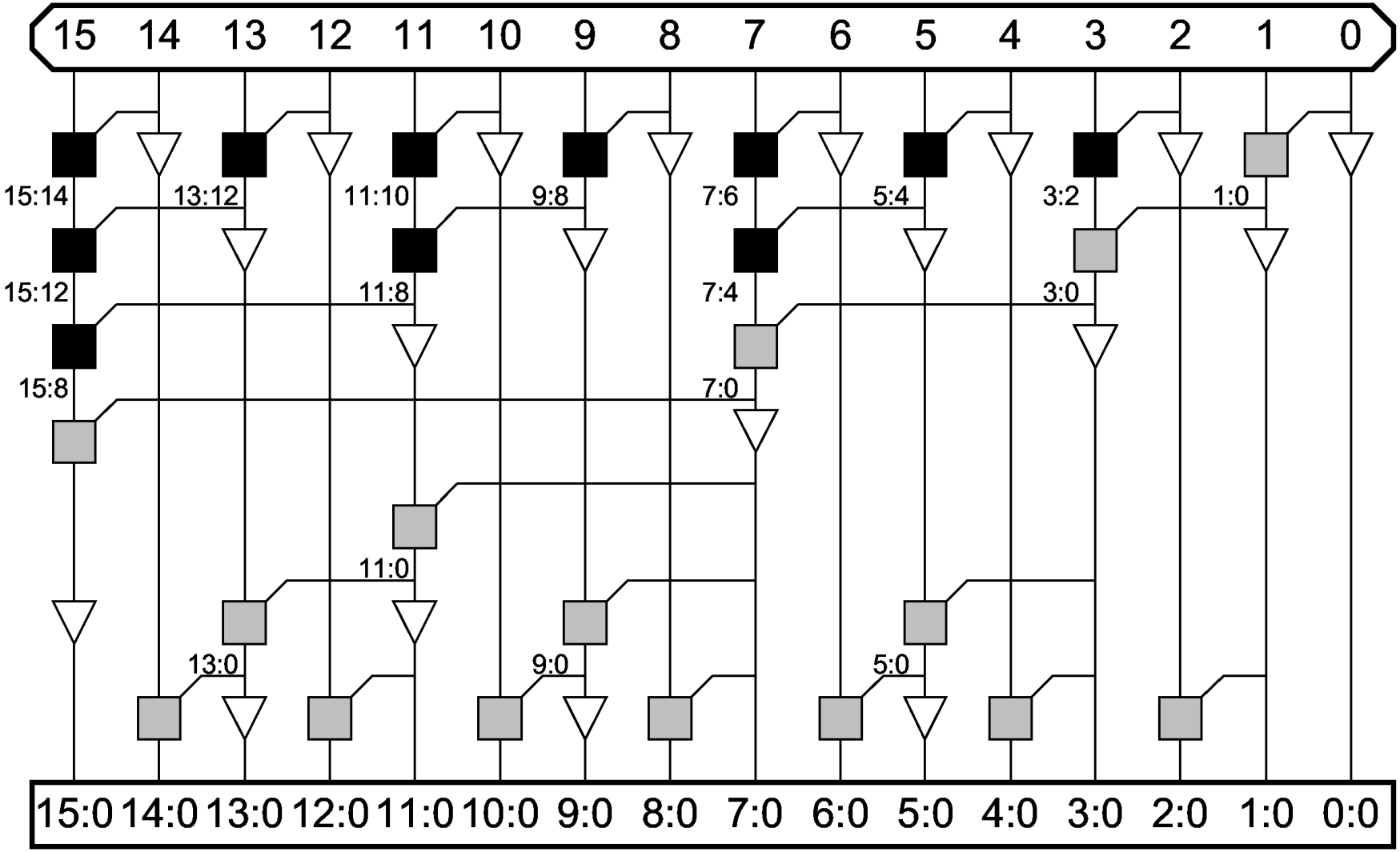
Tree Adder Taxonomy, Cont'd



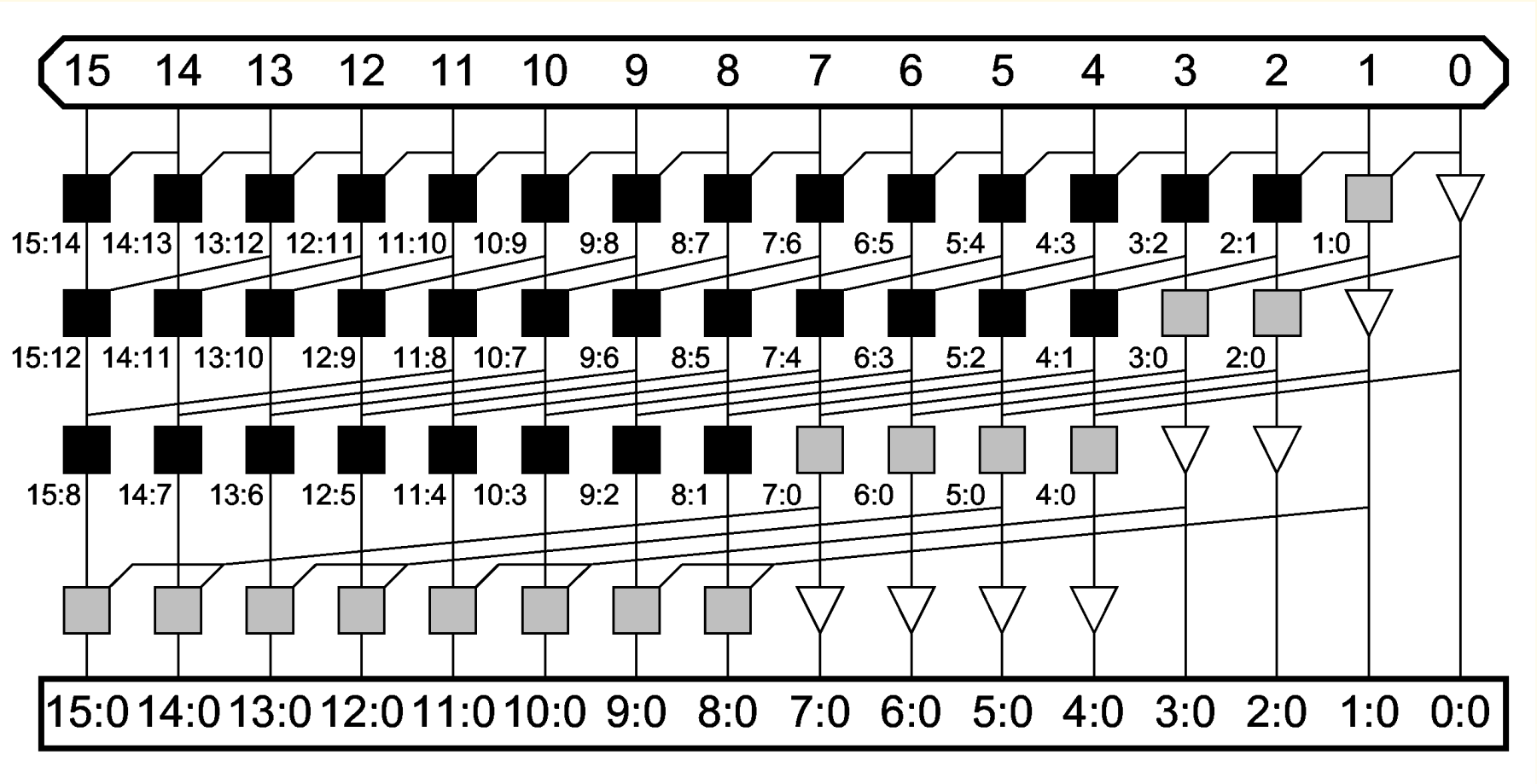
Han-Carlson Adder



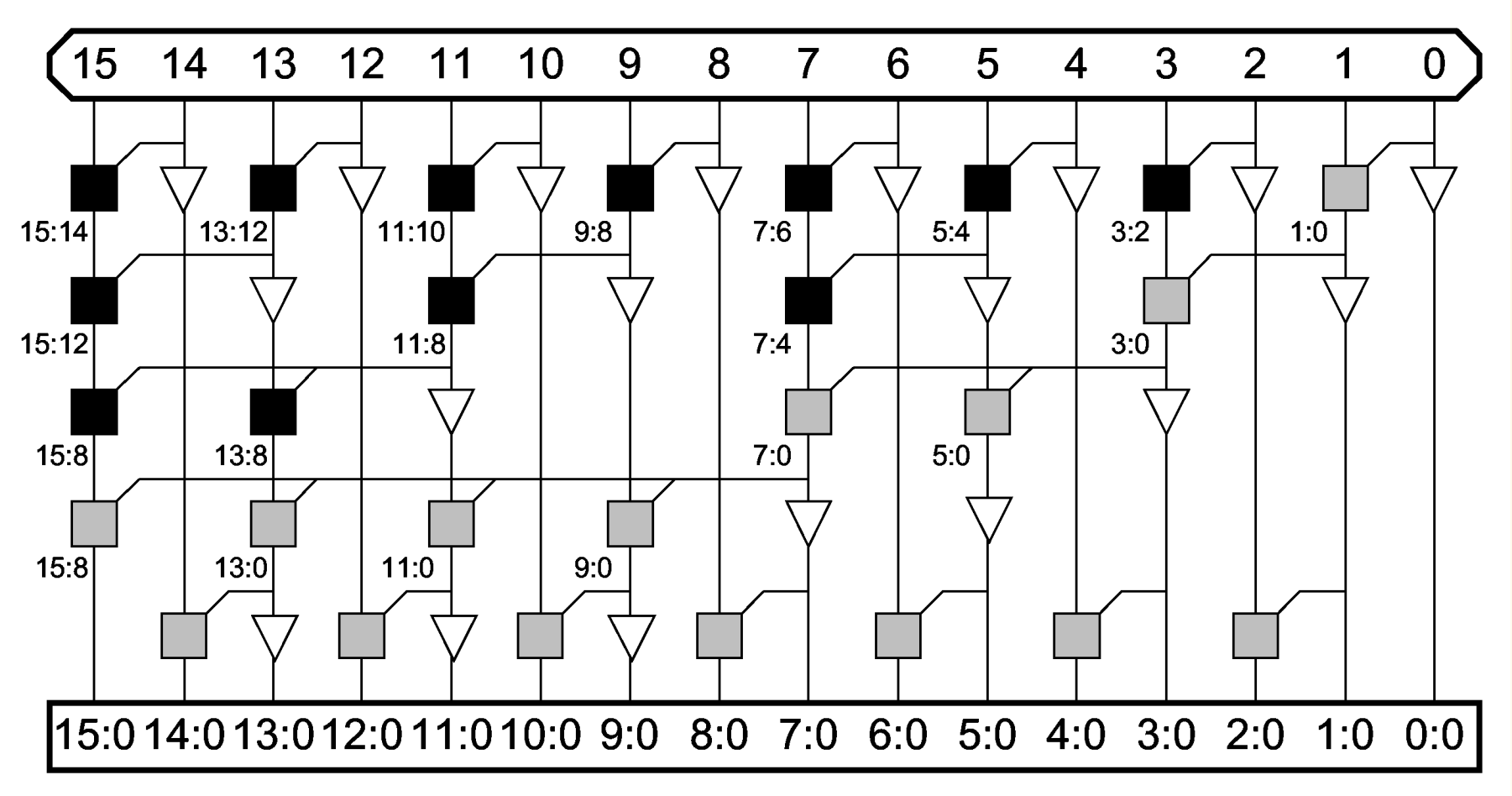
Brent-Kung Adder



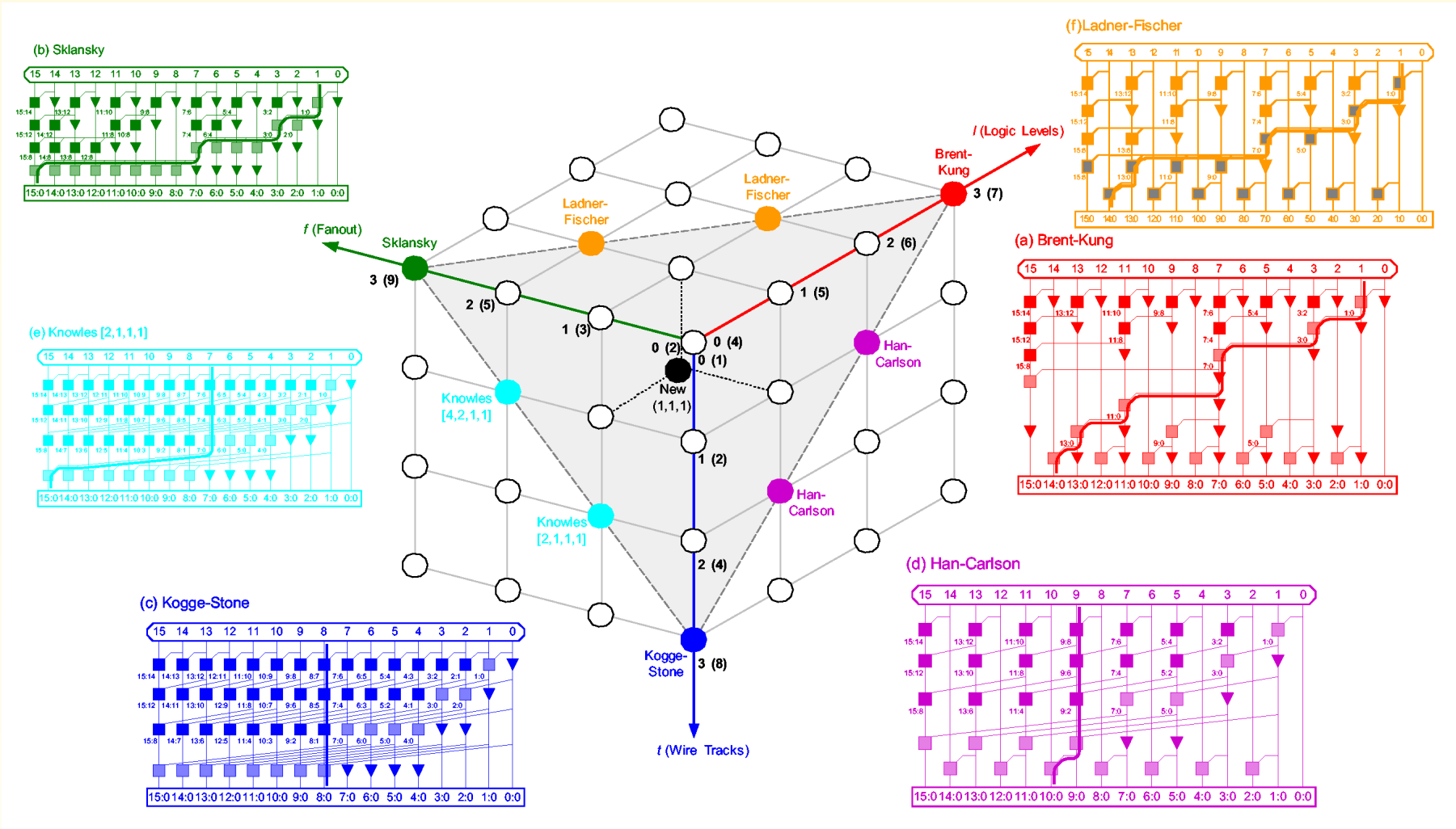
Knowles [2,1,1,1] Adder



Ladner-Fischer Adder



Tree Adder Taxonomy Revisited



Summary of Adders

Adder architectures offer area/power/delay tradeoffs

Choose the best one for your application

Architecture	Classification	Logic levels	Max. fanout	Tracks	Cells
Ripple Carry		$N-1$	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)	$2log_2N-1$	2	1	$2N$
Sklansky	(0,L-1,0)	log_2N	$N/2+1$	1	$0.5Nlog_2N$
Kogge-Stone	(0,0,L-1)	log_2N	2	$N/2$	$Nlog_2N$