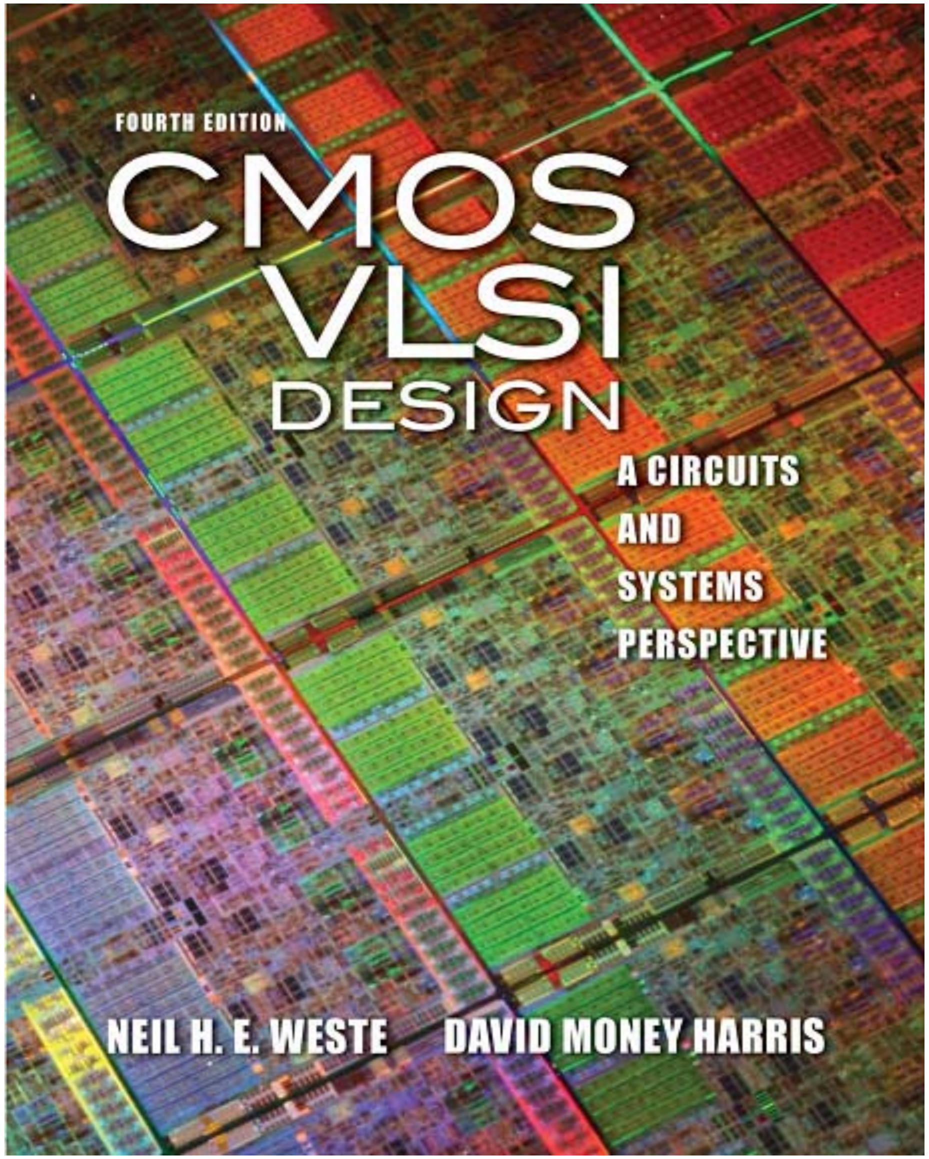


Lecture 12: Adders

Outline

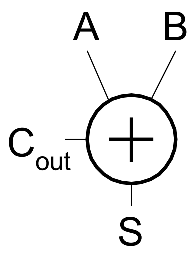
- ❑ Single-bit Addition
- ❑ Carry-Ripple Adder
- ❑ Carry-Skip Adder
- ❑ Carry-Lookahead Adder
- ❑ Carry-Select Adder
- ❑ Carry-Increment Adder
- ❑ Tree Adder

Single-Bit Addition

Half Adder

$$S = A \oplus B$$

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

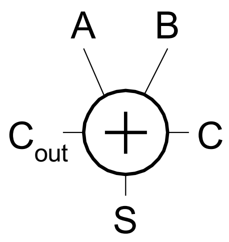


A	B	C_{out}	S
0	0		
0	1		
1	0		
1	1		

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	1		
0	1	0		
0	1	1		
1	0	0		
1	0	1		
1	1	0		
1	1	1		

PGK

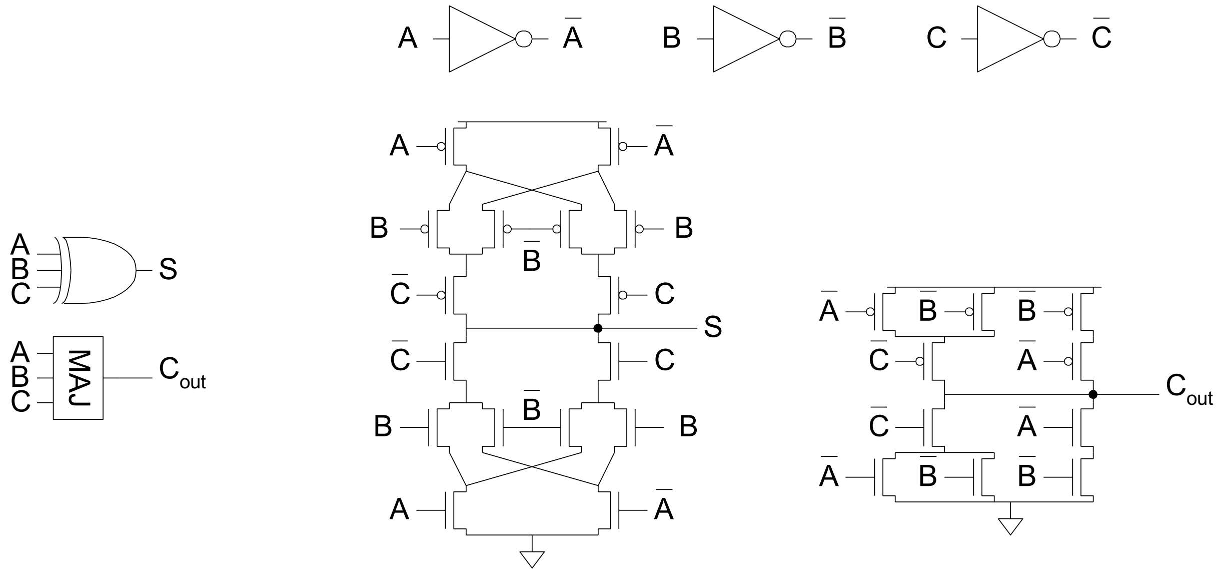
- For a full adder, define what happens to carries
  (in terms of A and B)
  - Generate: C_{out} = 1 independent of C
    - G =
  - Propagate: C_{out} = C
    - P =
  - Kill: C_{out} = 0 independent of C
    - K =

Full Adder Design I

- Brute force implementation from eqns

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

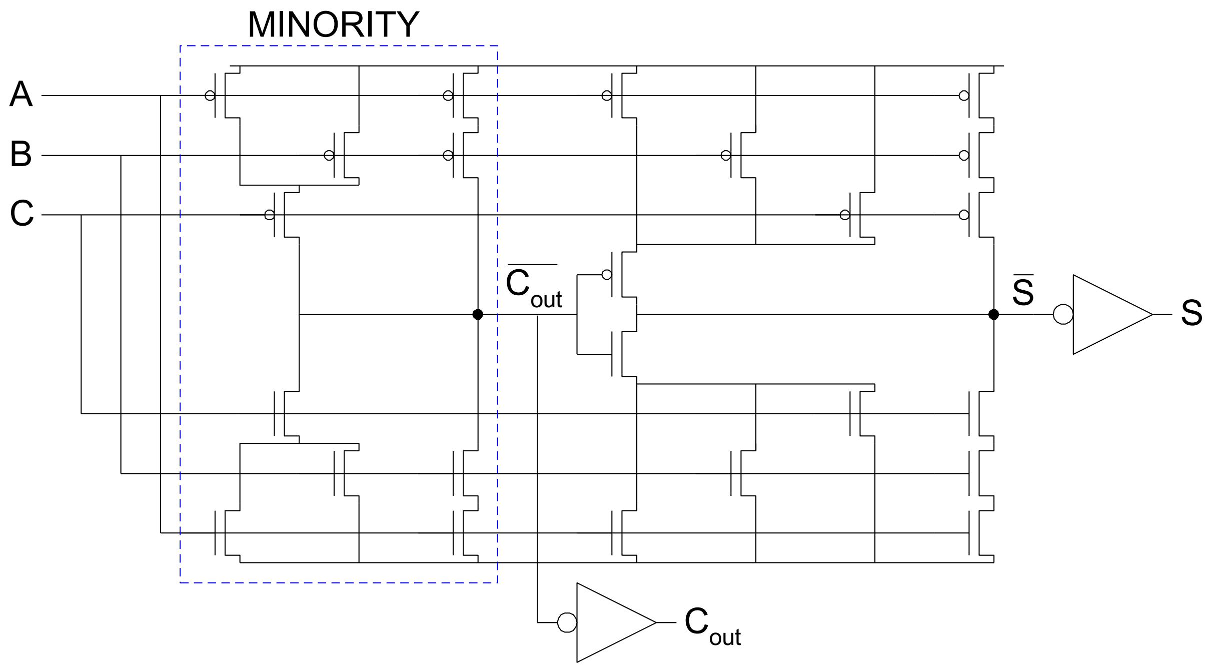
$$C_{\text{out}} = MAJ(A, B, C)$$



Full Adder Design II

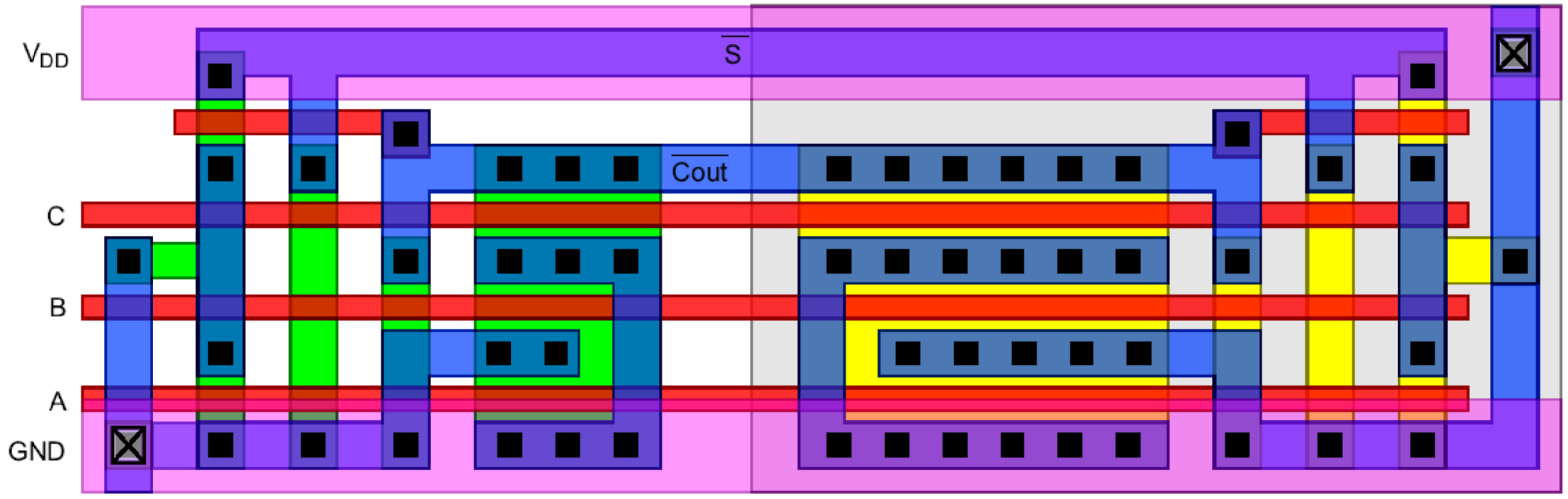
- ❑ Factor S in terms of C_{out}

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



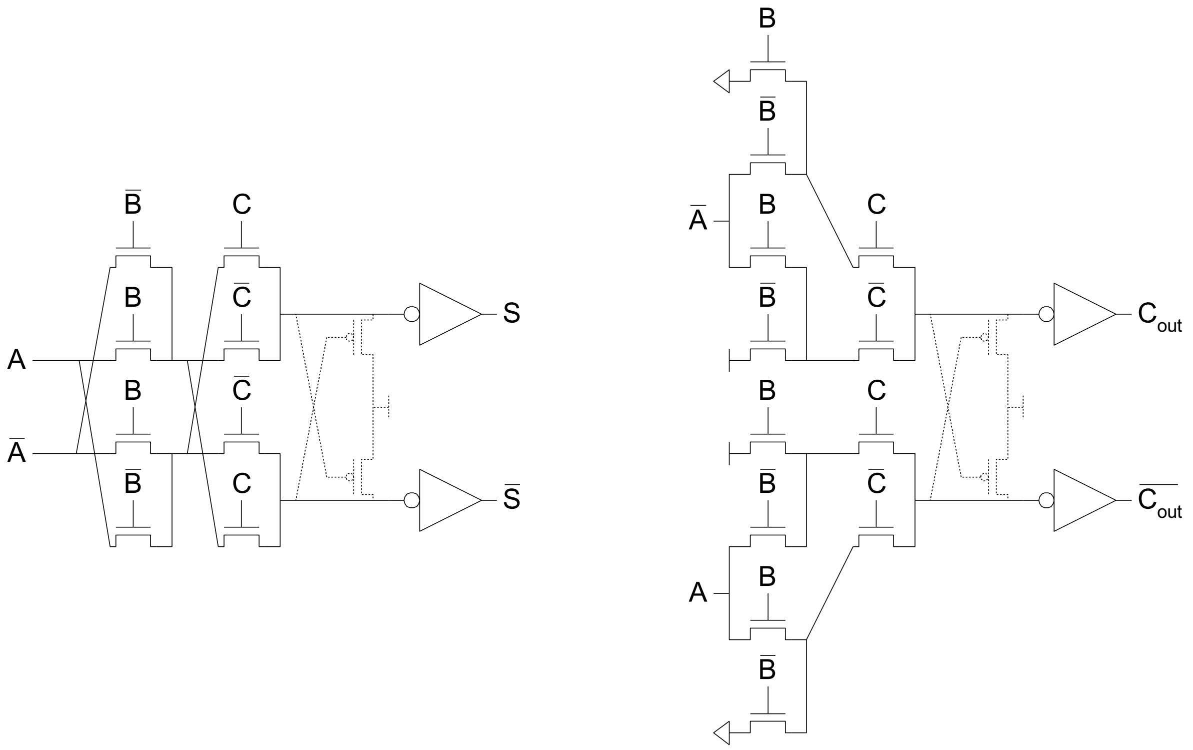
Layout

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



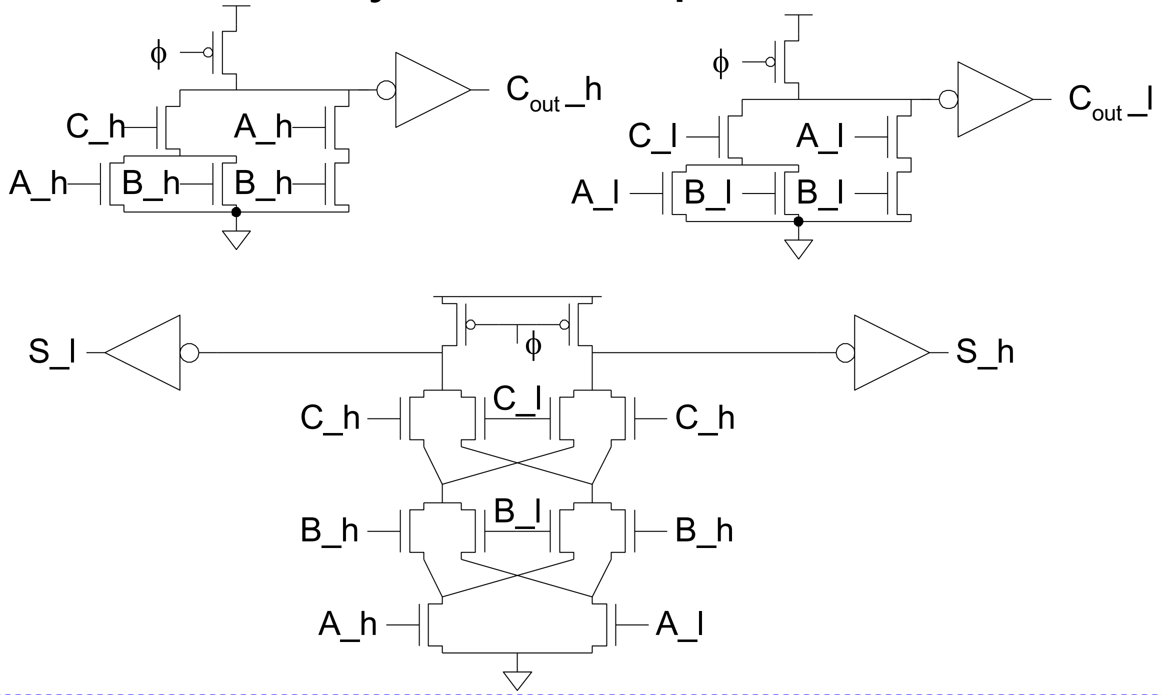
Full Adder Design III

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



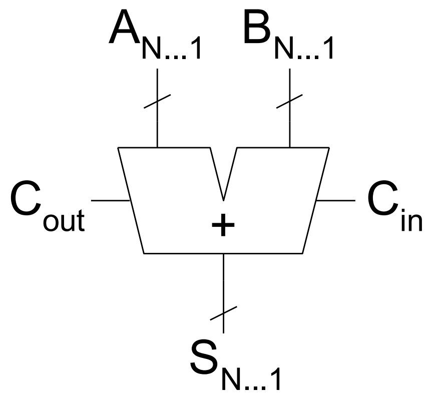
Full Adder Design IV

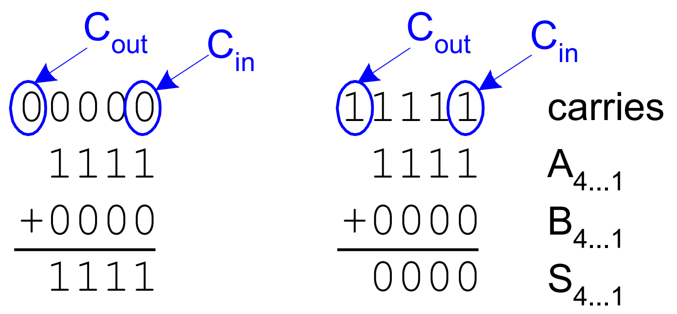
- Dual-rail domino
  - Very fast, but large and power hungry
  - Used in very fast multipliers



Carry Propagate Adders

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

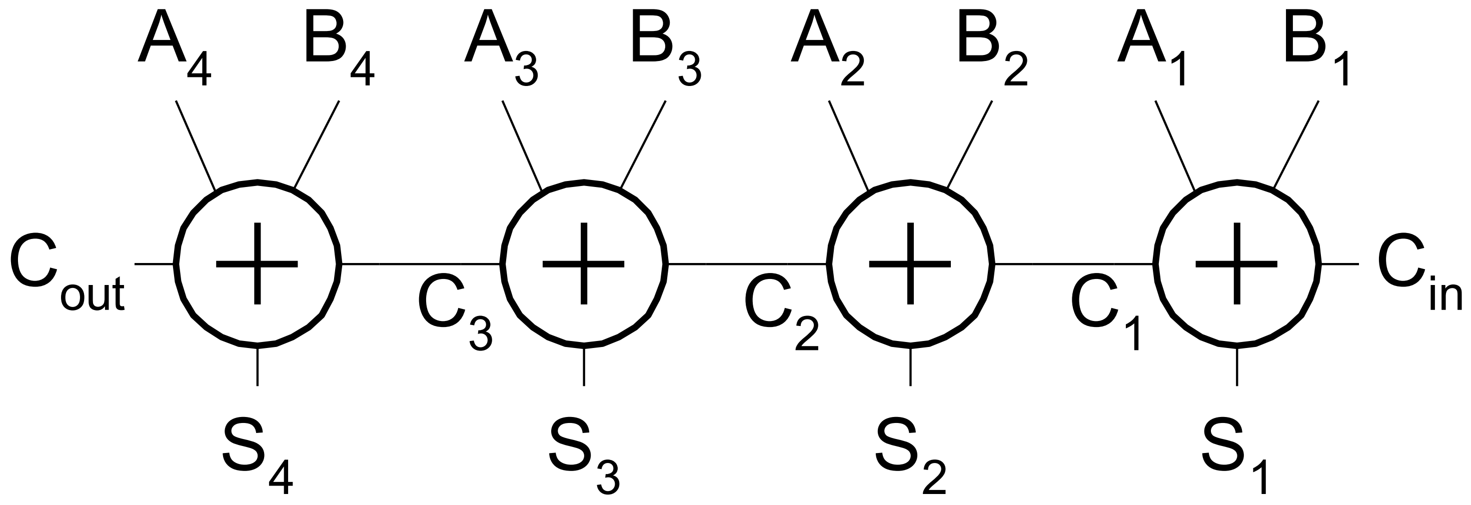




00000	11111	carries
1111	1111	$A_{4...1}$
+0000	+0000	$B_{4...1}$
1111	0000	$S_{4...1}$

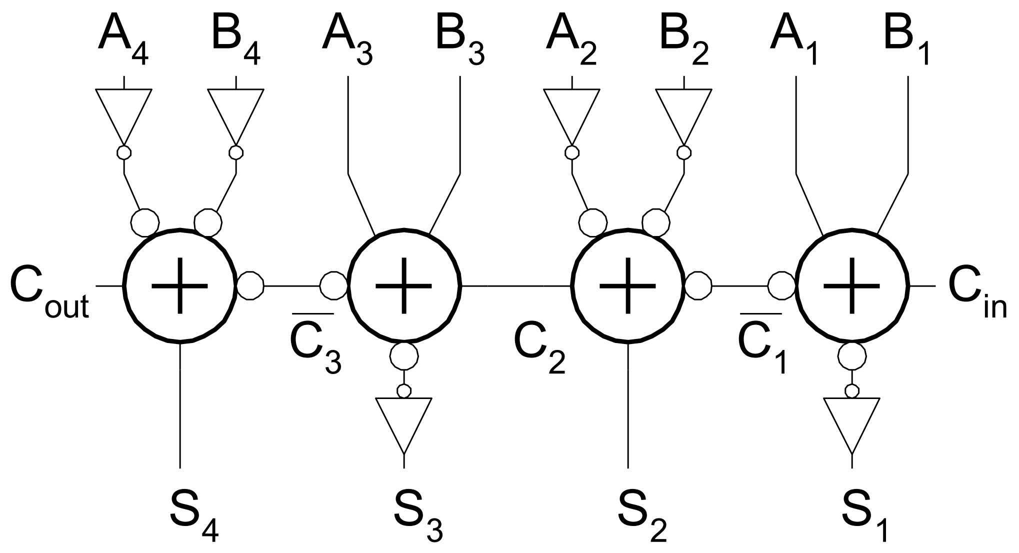
Carry-Ripple Adder

- 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

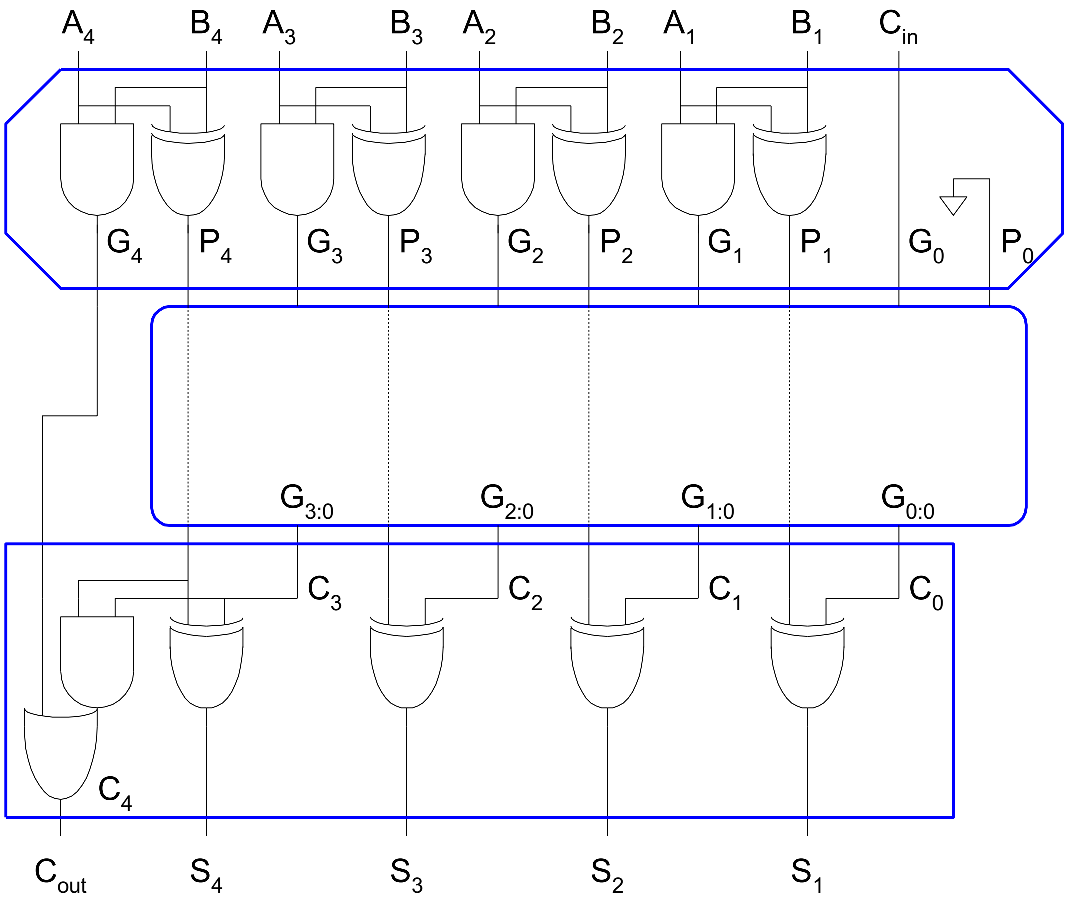
$$G_{i:i} \equiv \qquad G_{0:0} \equiv$$

$$P_{i:i} \equiv \qquad P_{0:0} \equiv$$

- Sum:

$$S_i =$$

PG Logic



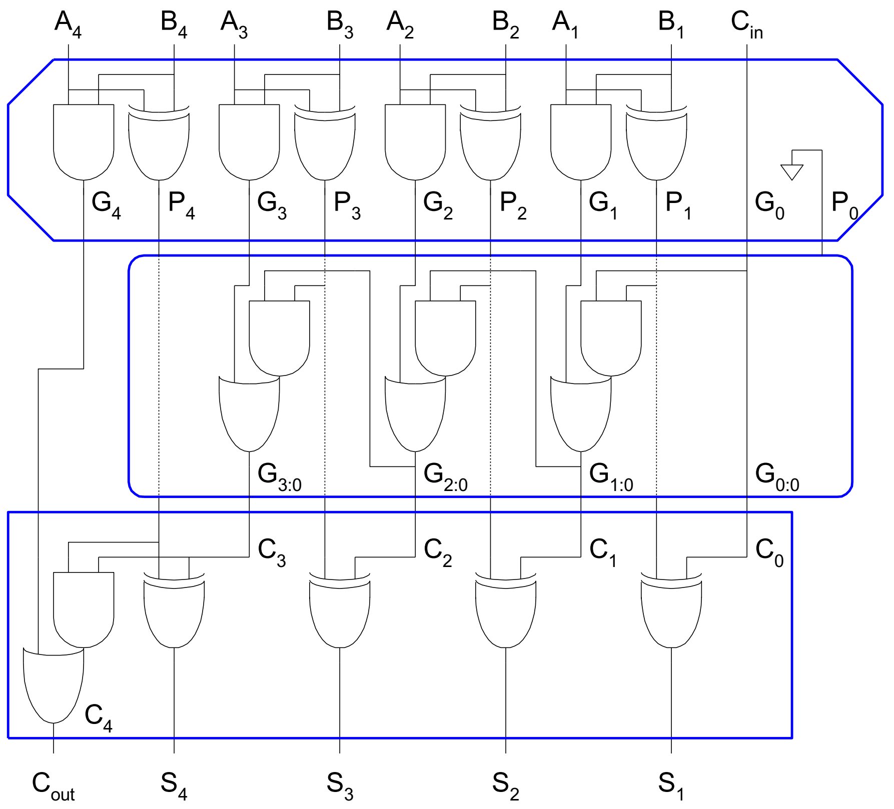
1: Bitwise PG logic

2: Group PG logic

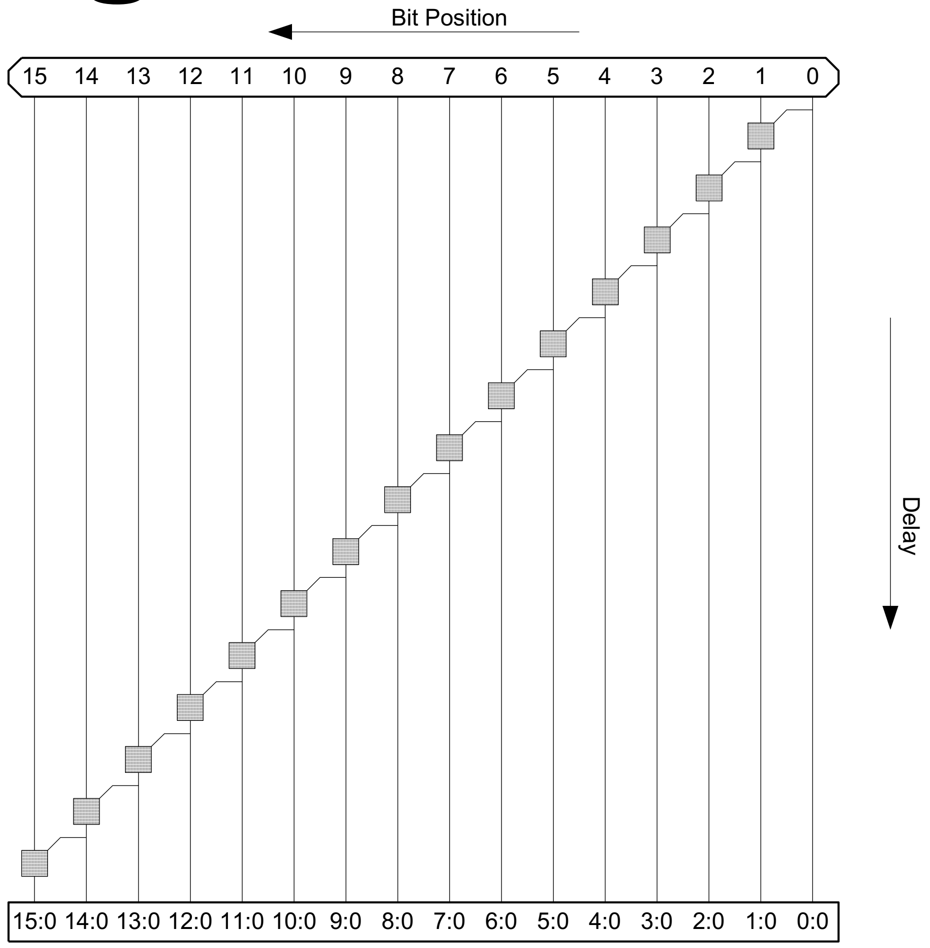
3: Sum logic

Carry-Ripple Revisited

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

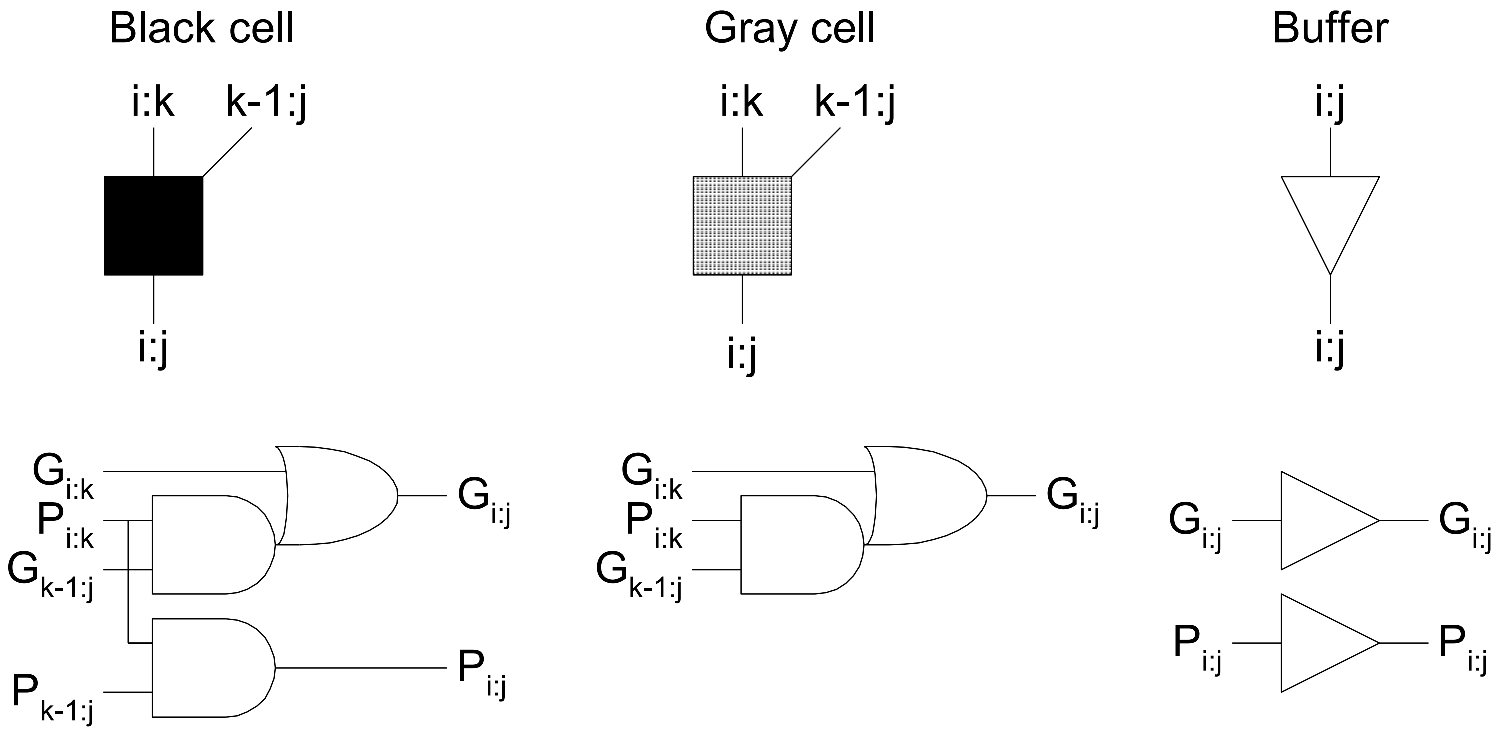


Carry-Ripple PG Diagram



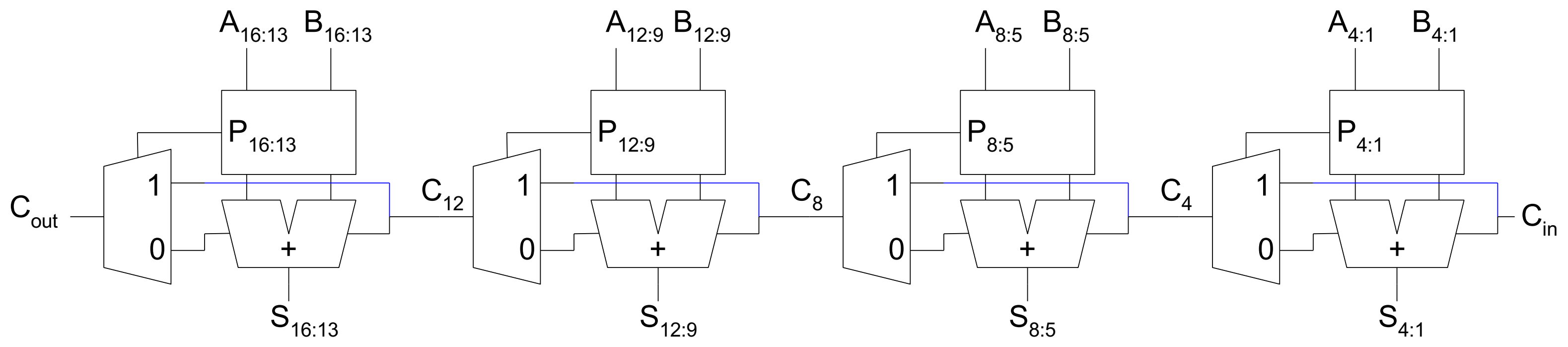
$t_{\text{ripple}} =$

PG Diagram Notation

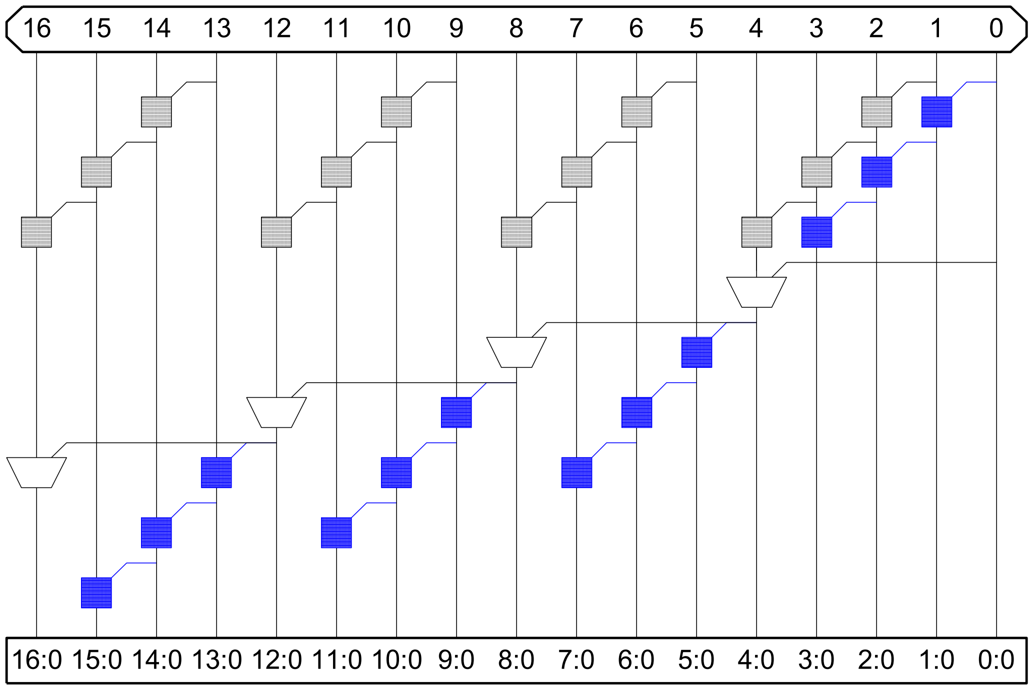


Carry-Skip Adder

- 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



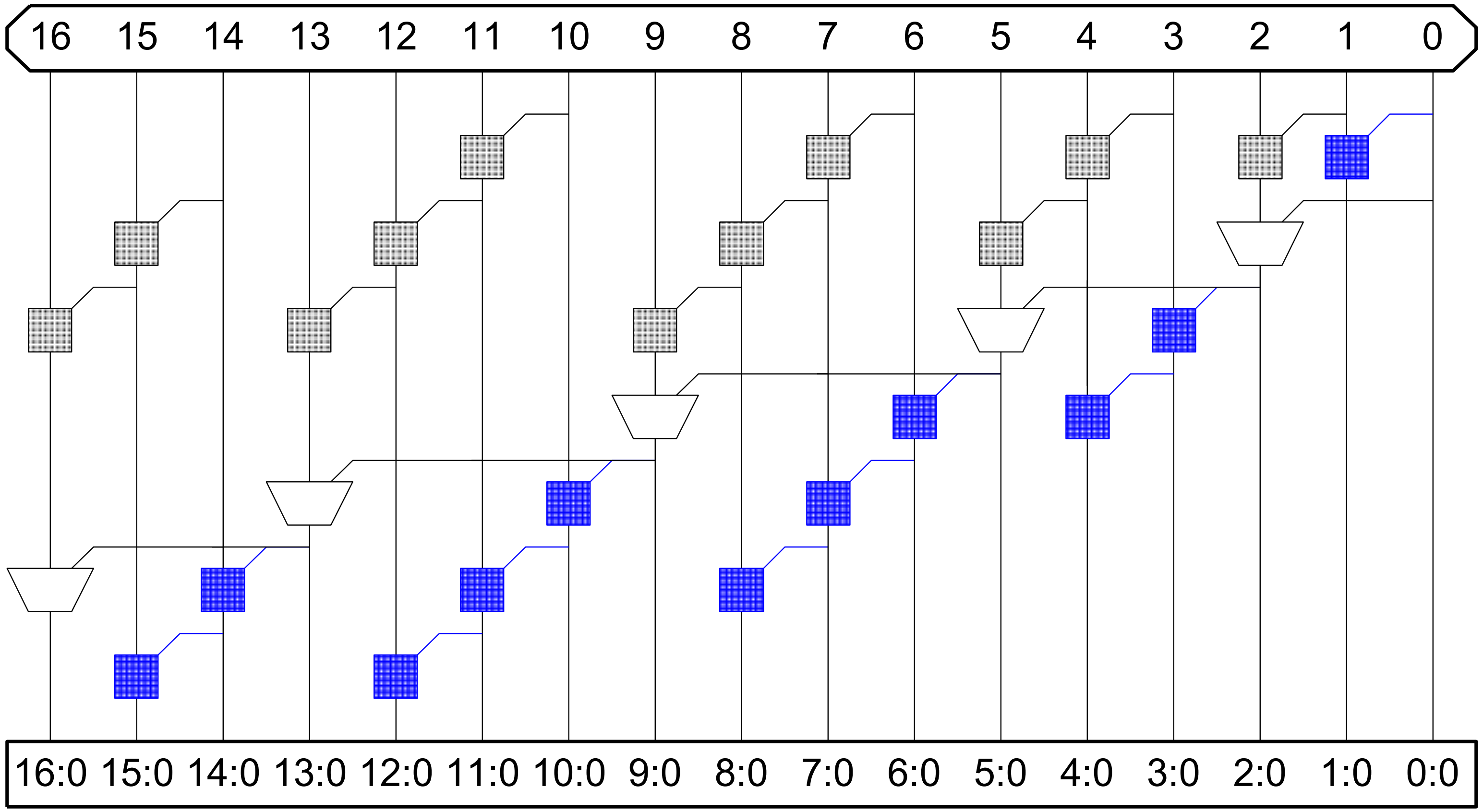
Carry-Skip PG Diagram



For k n-bit groups (N = nk)

$t_{\text{skip}} =$

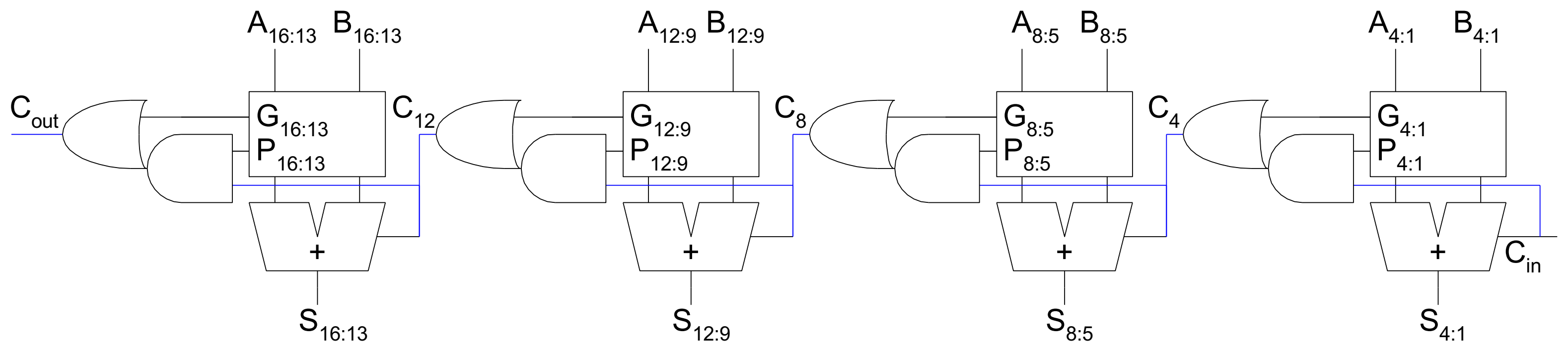
Variable Group Size



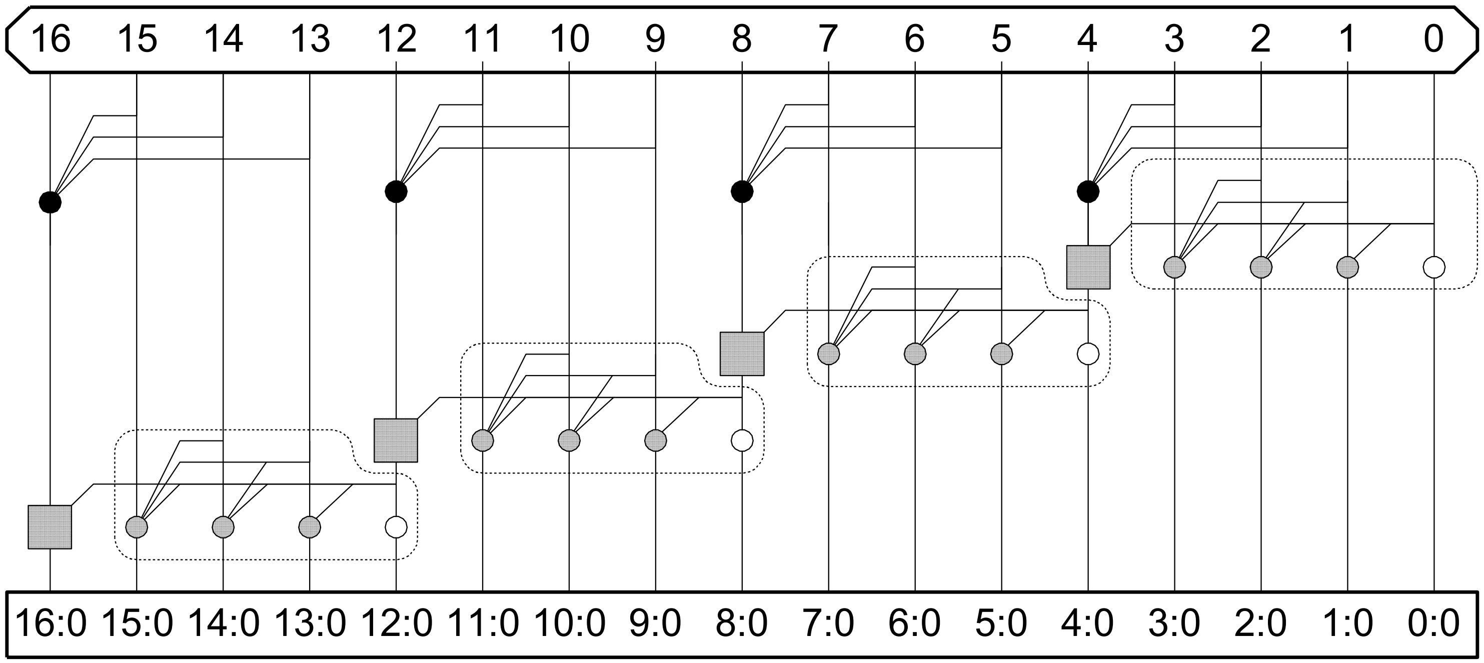
Delay grows as O(sqrt(N))

Carry-Lookahead Adder

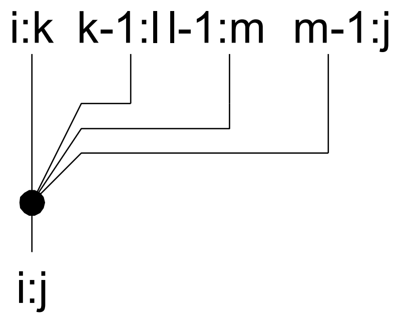
- Carry-lookahead adder computes $G_{i:0}$ for many bits in parallel.
- Uses higher-valency cells with more than two inputs.

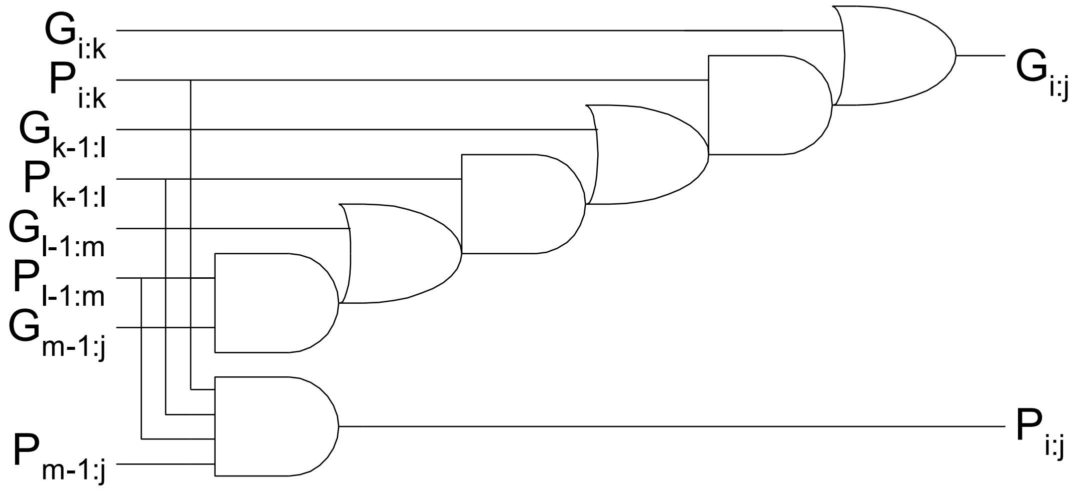


CLA PG Diagram



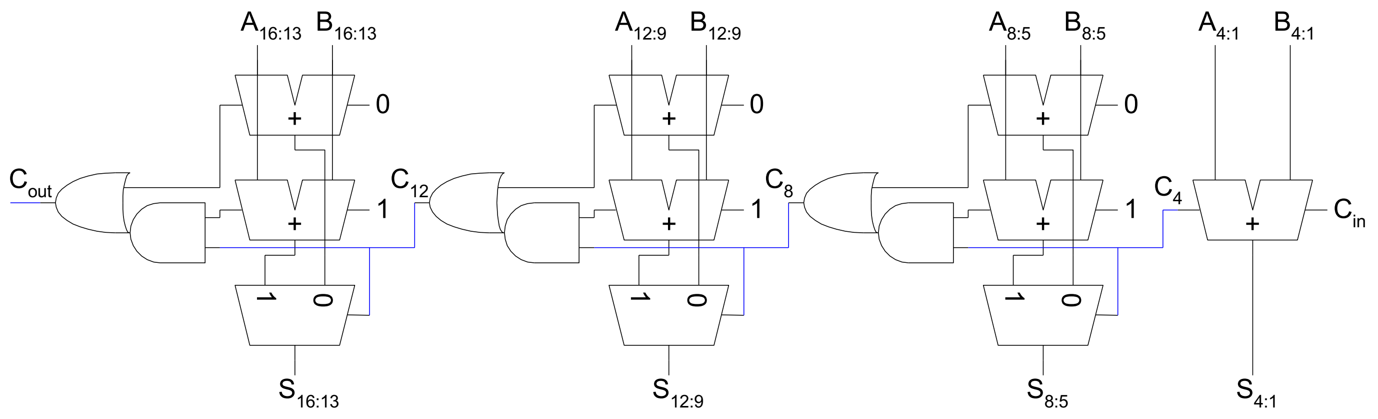
Higher-Valency Cells





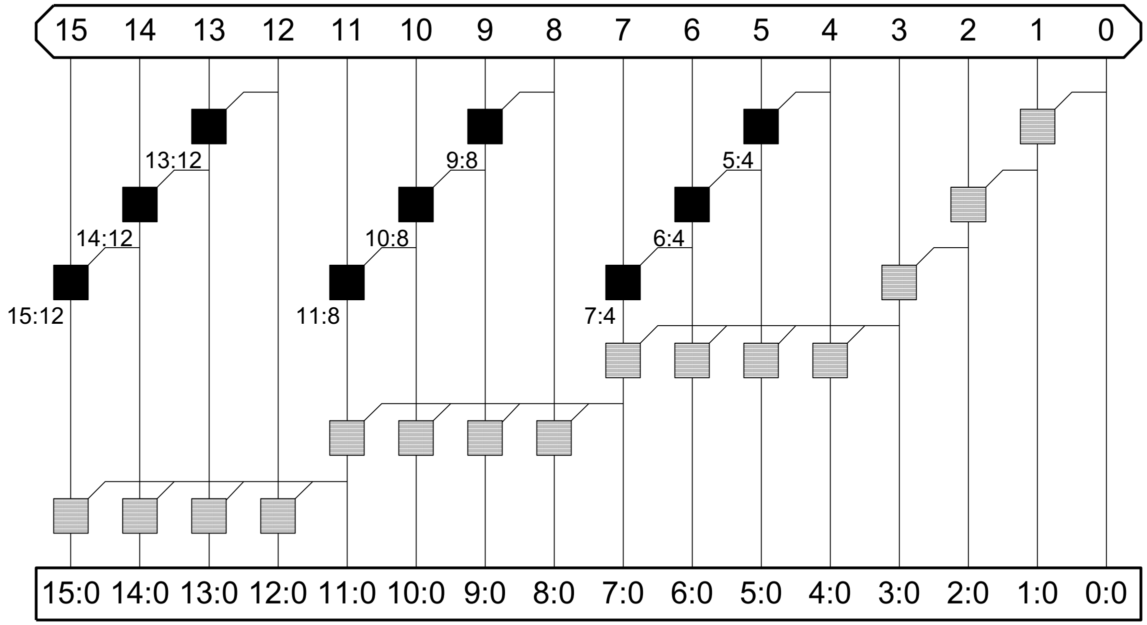
Carry-Select Adder

- 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

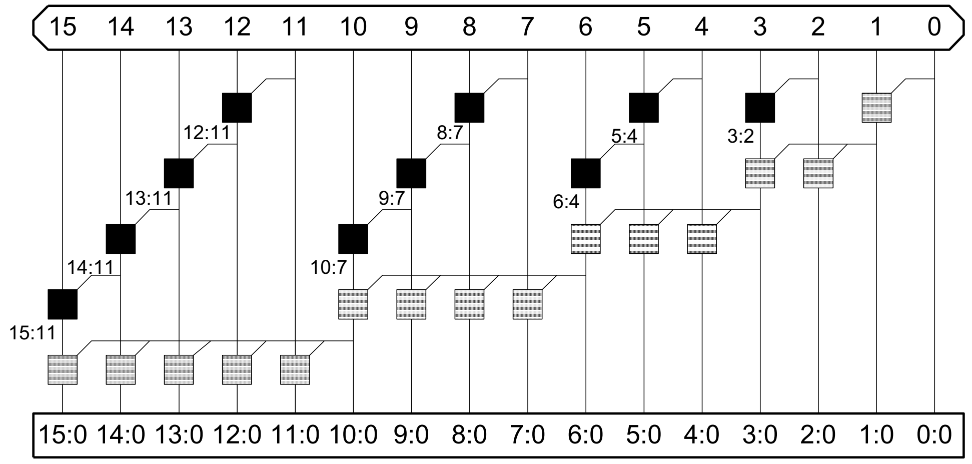
- Factor initial PG and final XOR out of carry-select

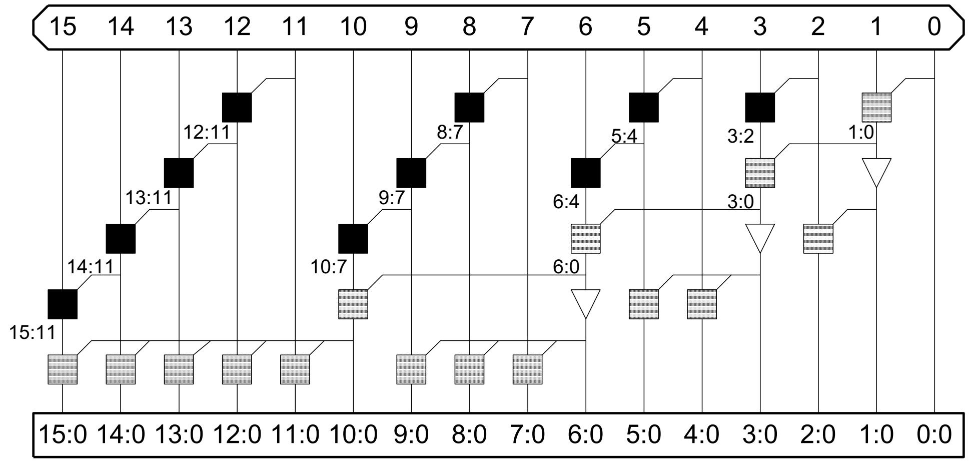


$t_{\text{increment}} =$

Variable Group Size

- Also buffer noncritical signals

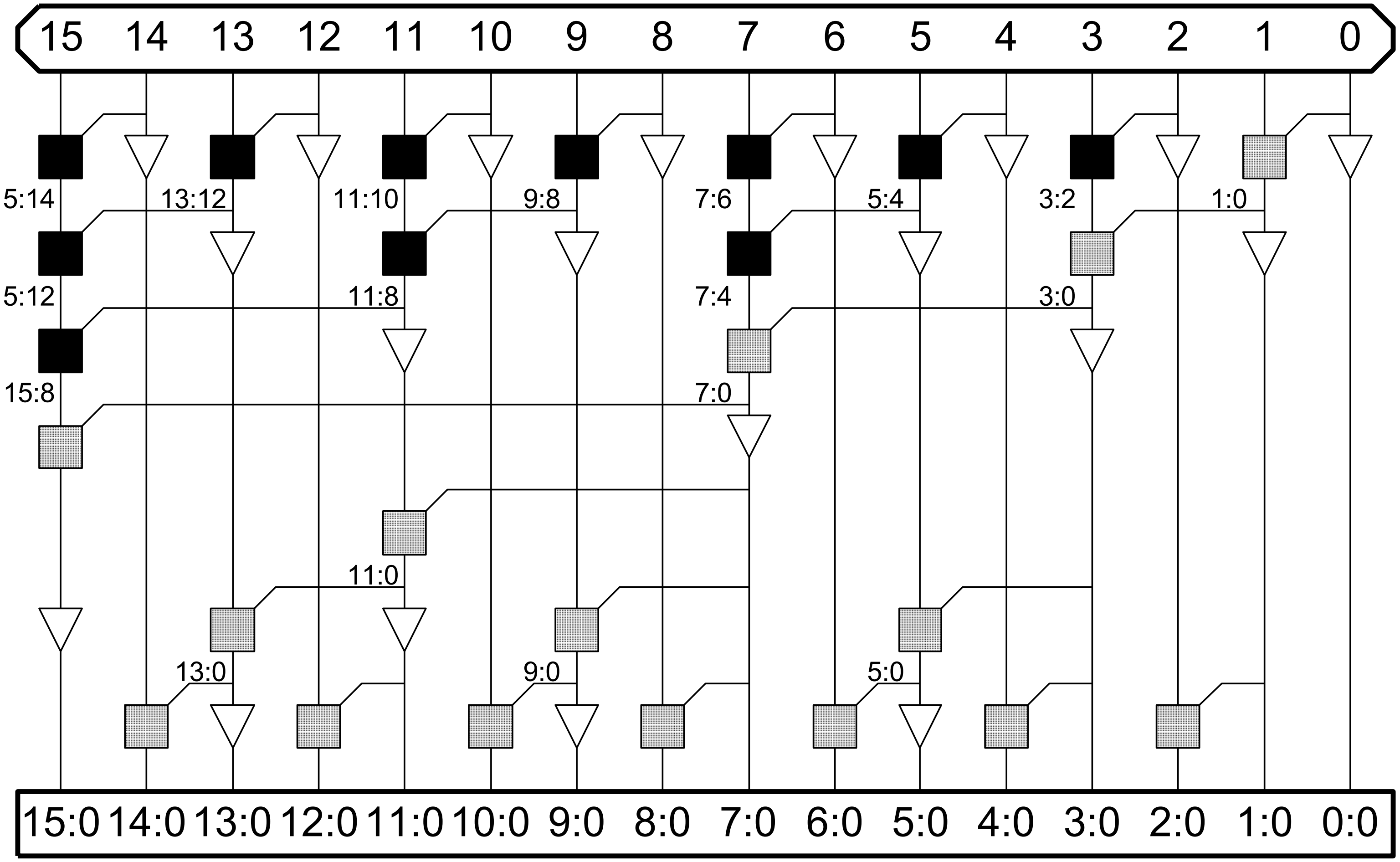




Tree Adder

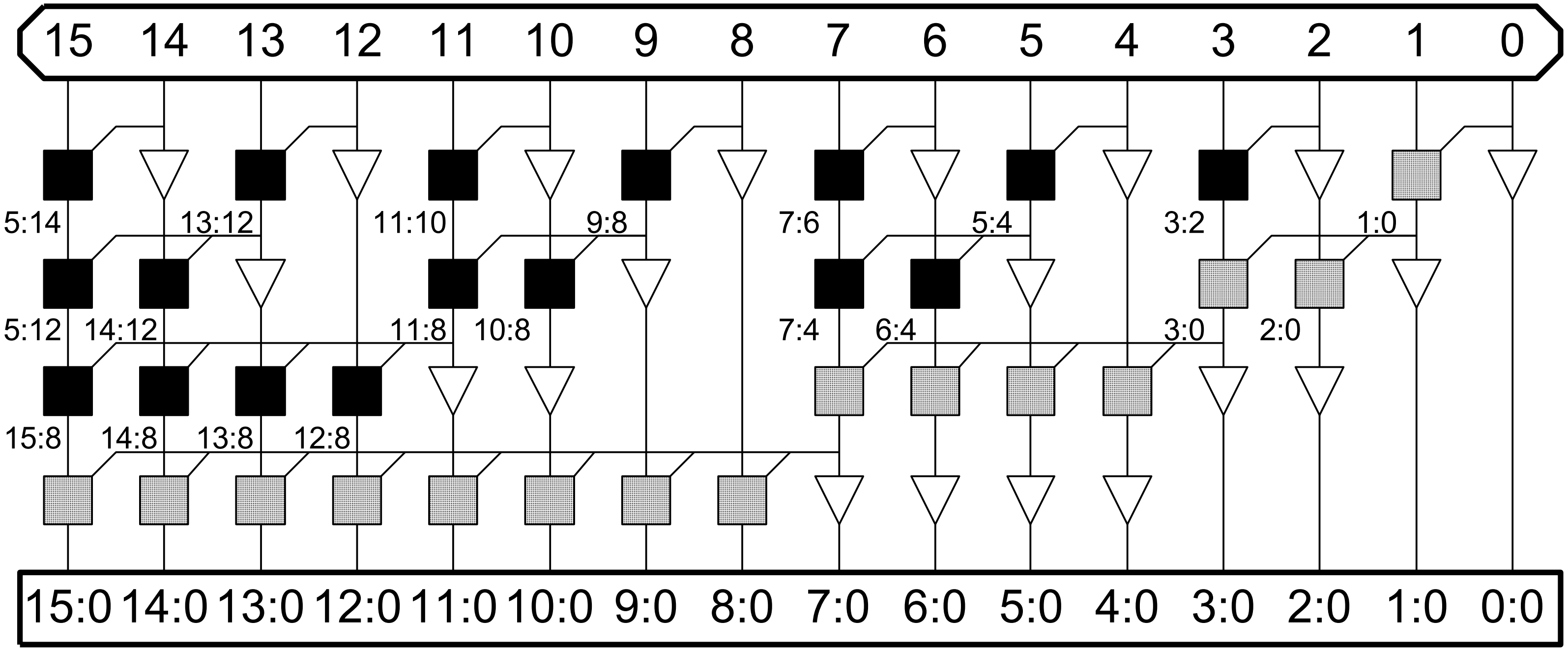
- If lookahead is good, lookahead across lookahead!
  - Recursive lookahead gives O(log N) delay
- Many variations on tree adders

Brent-Kung



15 14 13 12 11 10 9 8 7 6 5 4 3 2 1 0
15:14
13:12
11:10
9:8
7:6
5:4
3:2
1:0
15:12
11:8
7:4
3:0
15:8
7:0
11:0
13:0
9:0
5:0
15:0 14:0 13:0 12:0 11:0 10:0 9:0 8:0 7:0 6:0 5:0 4:0 3:0 2:0 1:0 0:0

Sklansky


15 14 13 12 11 10 9 8 7 6 5 4 3 2 1 0
15:14
13:12
11:10
9:8
7:6
5:4
3:2
1:0
15:12
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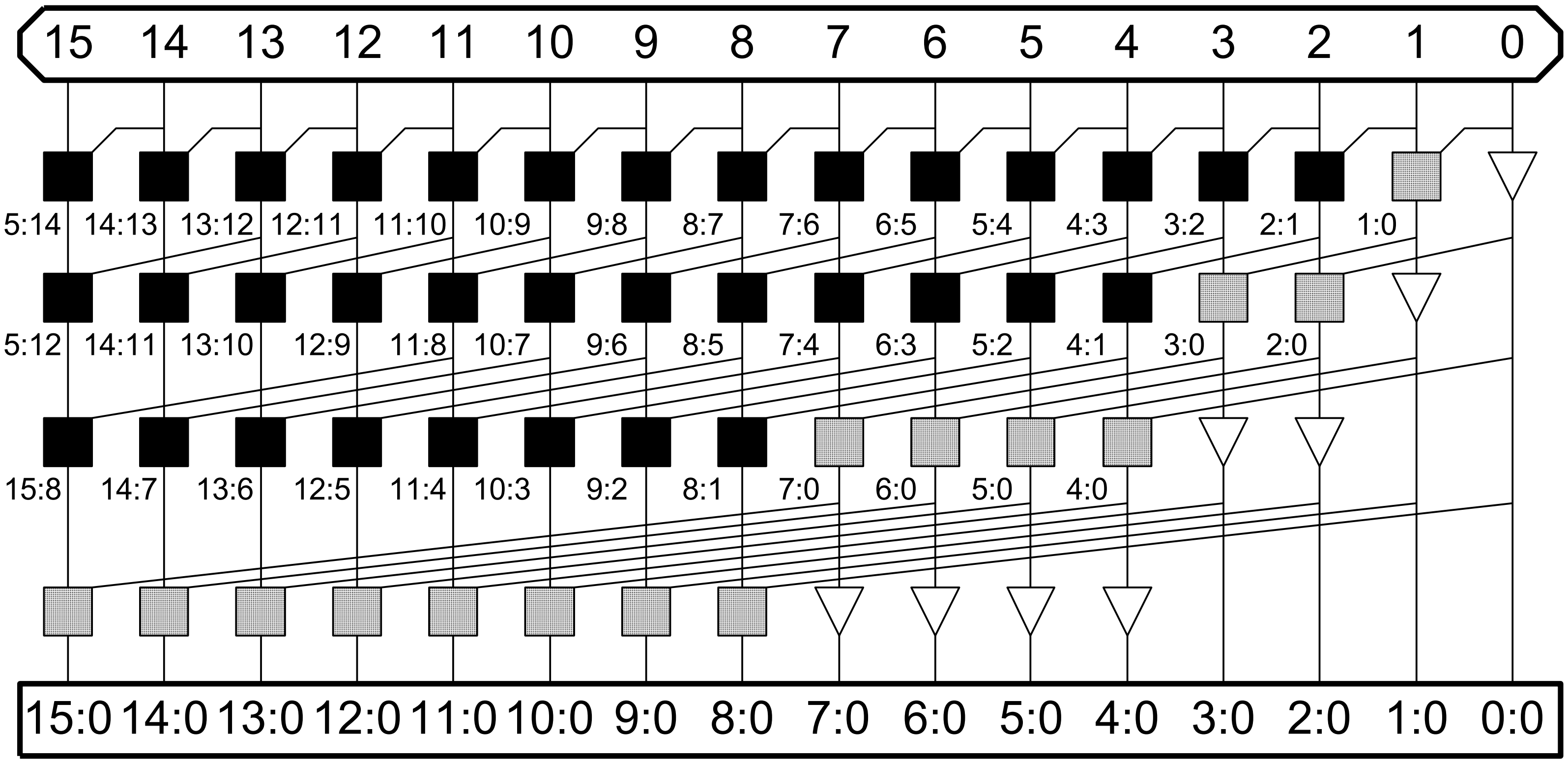
11:8
10:8
7:4
6:4
3:0
2:0
15:8
14:8
13:8
12:8
15:0 14:0 13:0 12:0 11:0 10:0 9:0 8:0 7:0 6:0 5:0 4:0 3:0 2:0 1:0 0:0

Kogge-Stone



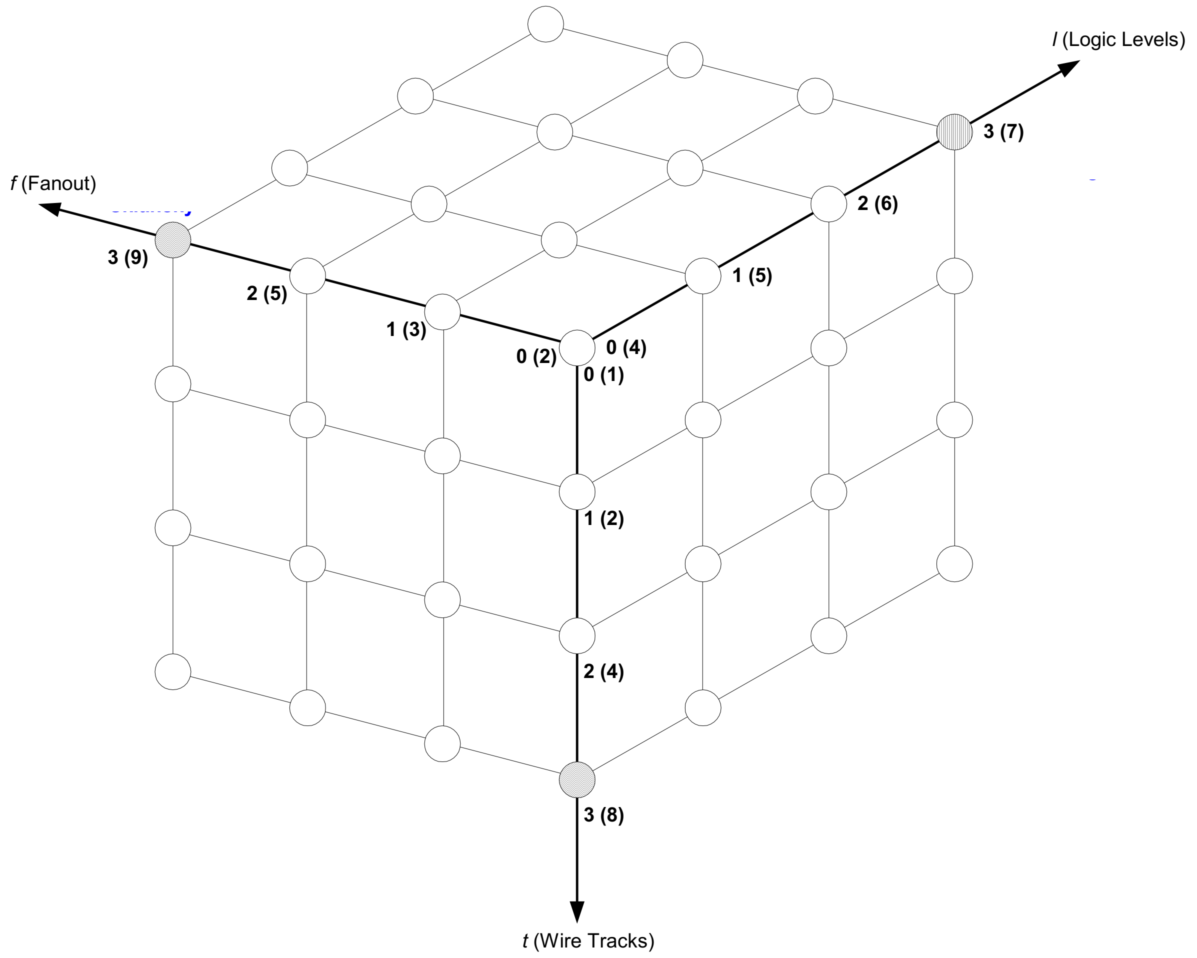
15 14 13 12 11 10 9 8 7 6 5 4 3 2 1 0
15:14 14:13 13:12 12:11 11:10 10:9 9:8 8:7 7:6 6:5 5:4 4:3 3:2 2:1 1:0
15:12 14:11 13:10 12:9 11:8 10:7 9:6 8:5 7:4 6:3 5:2 4:1 3:0 2:0
15:8 14:7 13:6 12:5 11:4 10:3 9:2 8:1 7:0 6:0 5:0 4:0
15:0 14:0 13:0 12:0 11:0 10:0 9:0 8:0 7:0 6:0 5:0 4:0 3:0 2:0 1:0 0:0

Tree Adder Taxonomy

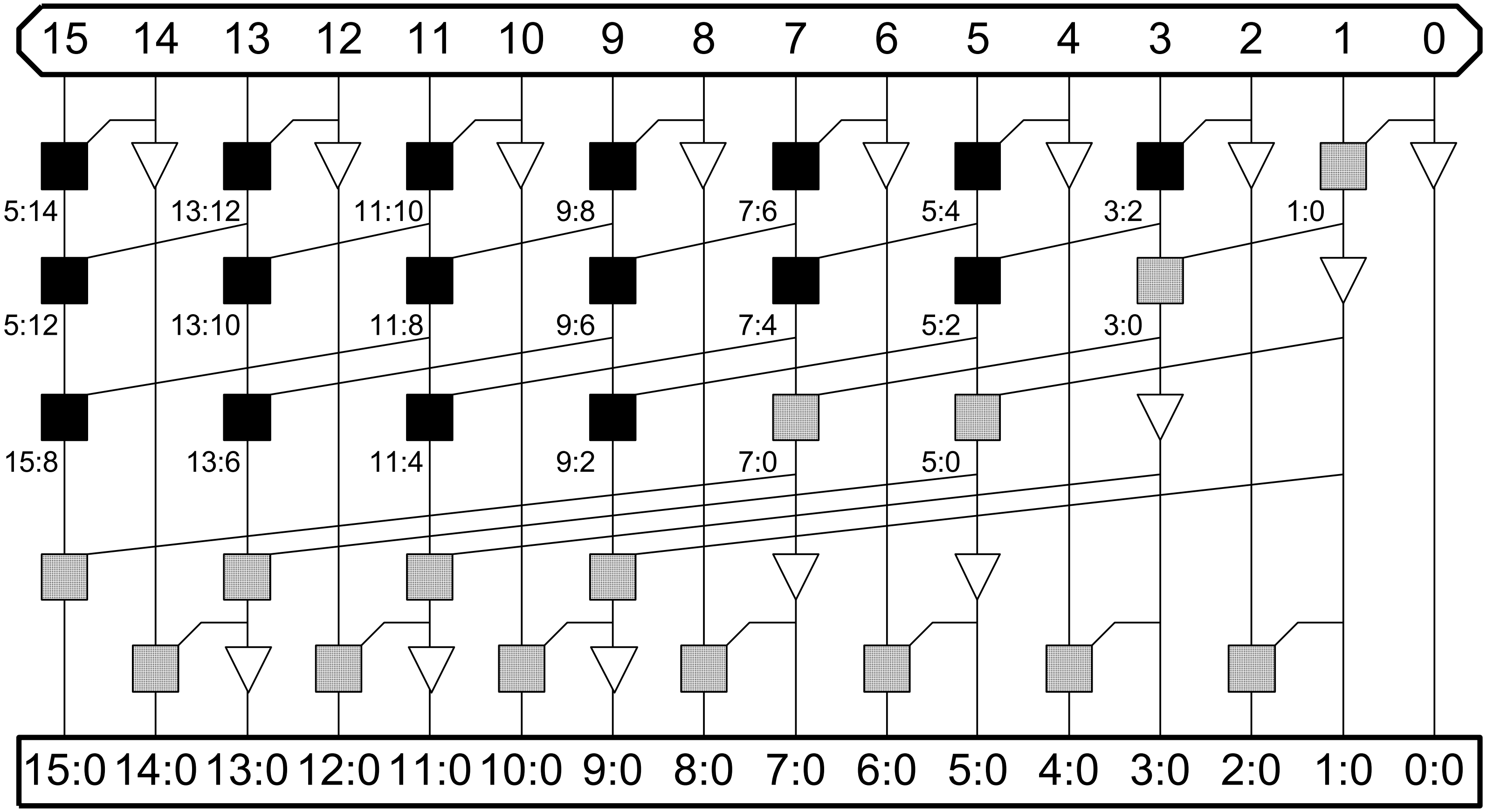
- Ideal N-bit tree adder would have
  - $L = \log N$ logic levels
  - Fanout never exceeding 2
  - No more than one wiring track between levels
- Describe adder with 3-D taxonomy (l, f, t)
  - Logic levels: $L + l$
  - Fanout: $2^f + 1$
  - Wiring tracks: 2^t
- Known tree adders sit on plane defined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

$$l + f + t = L\text{-}1$$

Tree Adder Taxonomy



Han-Carlson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3:0
15:8
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9:2
7:0
5:0
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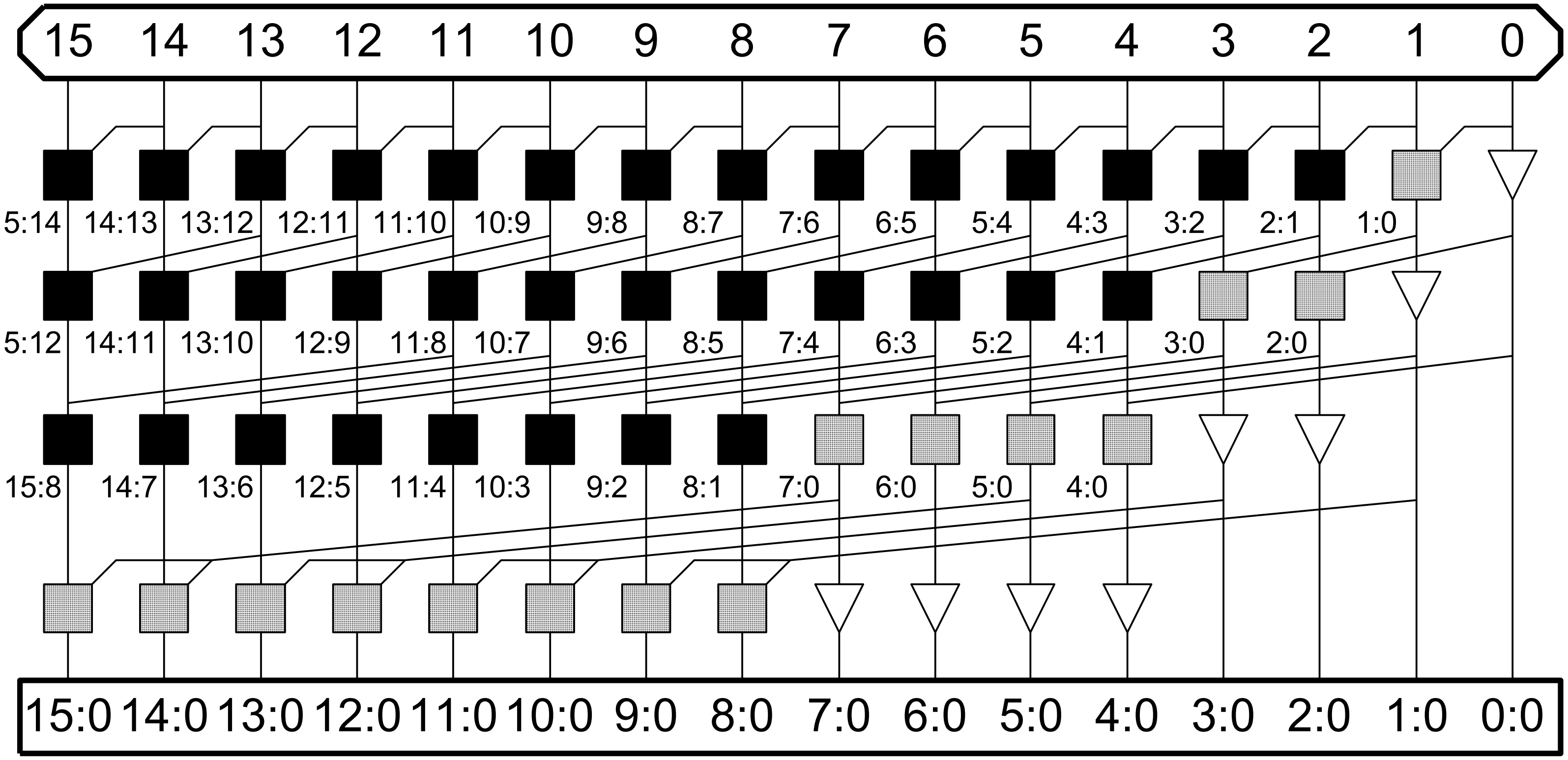
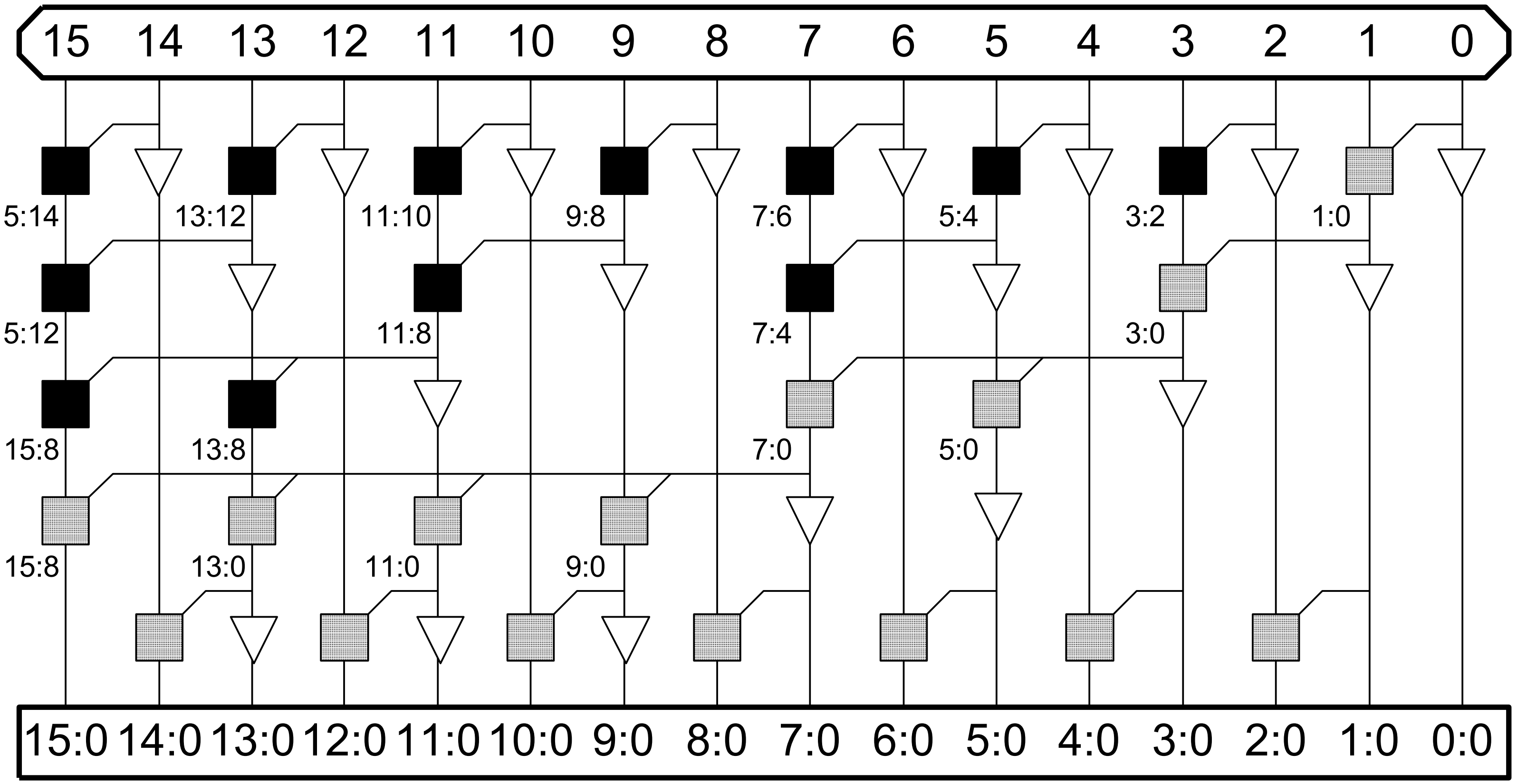
11:0
10:0
9:0
8:0
7:0
6:0
5:0
4:0
3:0
2:0
1:0
0:0

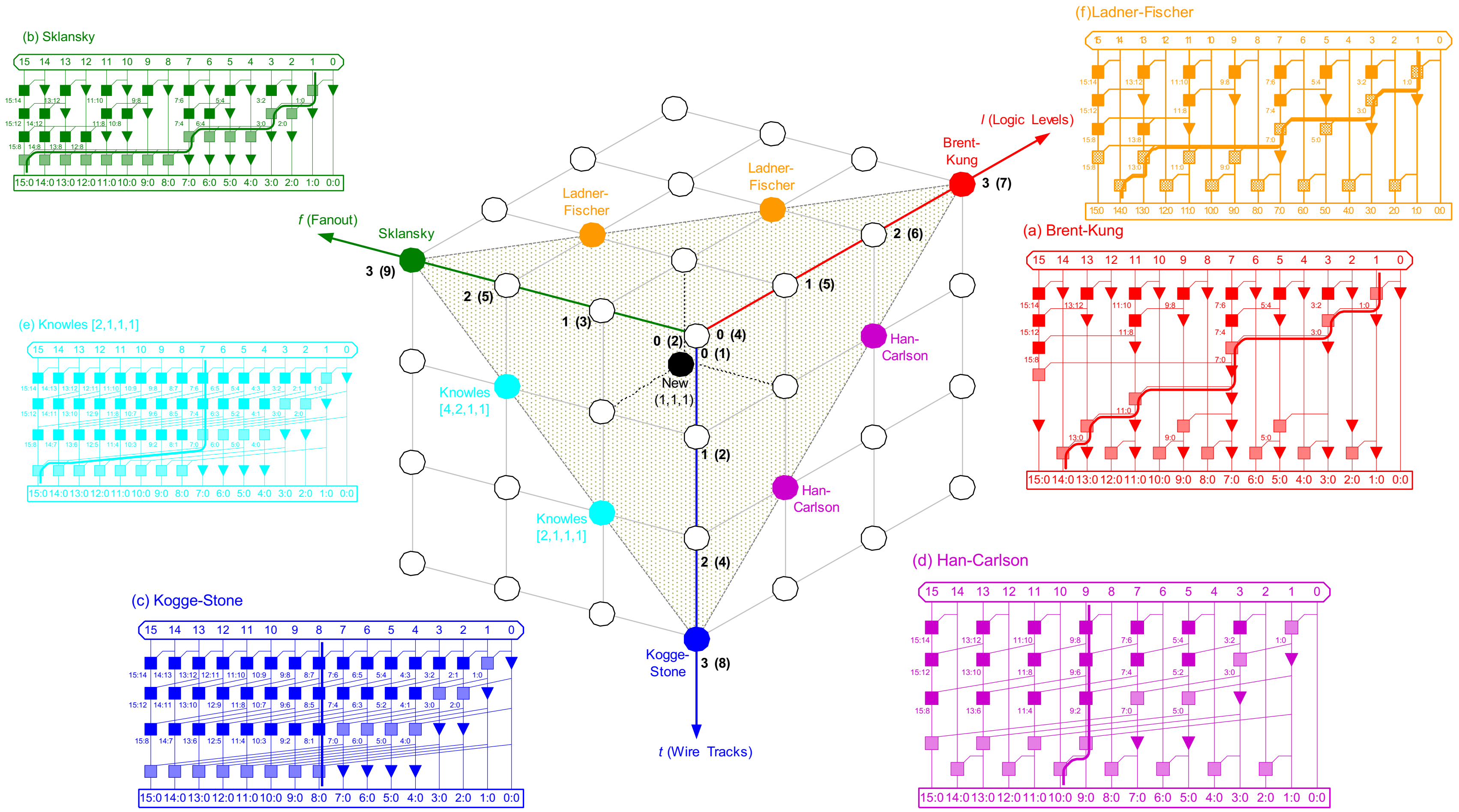
Knowles [2, 1, 1, 1]



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	$N\log_2 N$