ECE/CS 552: Arithmetic and Logic

Lecture notes based in part on slides created by Mark Hill, David Wood, Guri Sohi, John Shen and Jim Smith

Basic Arithmetic and the ALU

- Number representations: 2’s complement, unsigned
- Addition/Subtraction
- Add/Sub ALU
  - Full adder, ripple carry, subtraction
- Logical operations
  - and, or, xor, nor, shifts
- Overflow

Basic Arithmetic and the ALU

- Covered later in the semester:
  - Integer multiplication, division
  - Floating point arithmetic
- These are not crucial for the project

Background

- Recall
  - n bits enables 2^n unique combinations
- Notation: $b_{31}\ b_{30} \ldots b_3\ b_2\ b_1\ b_0$
- No inherent meaning
  - $f(b_{31} \ldots b_0)$ => integer value
  - $f(b_{31} \ldots b_0)$ => control signals

Background

- 32-bit types include
  - Unsigned integers
  - Signed integers
  - Single-precision floating point
  - MIPS instructions (refer to book)

Unsigned Integers

- $f(b_{31}...b_0) = b_{31} \times 2^{31} + ... + b_1 \times 2^1 + b_0 \times 2^0$
- Treat as normal binary number

  E.g. 0…01101010101

  $= 1 \times 2^7 + 1 \times 2^6 + 0 \times 2^5 + 1 \times 2^4 + 1 \times 2^3 + 0 \times 2^1 + 1 \times 2^0$

  $= 128 + 64 + 16 + 4 + 1 = 213$
- Max $f(111...11) = 2^{32} – 1 = 4,294,967,295$
- Min $f(000...00) = 0$
- Range $[0,2^{32}-1]$ => # values $(2^{32}-1) – 0 + 1 = 2^{32}$

Signed Integers

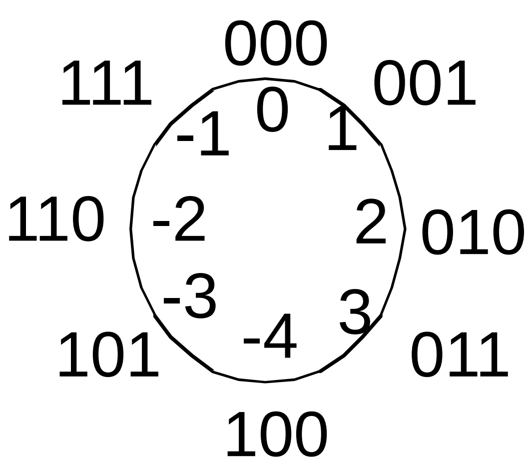
- 2's complement

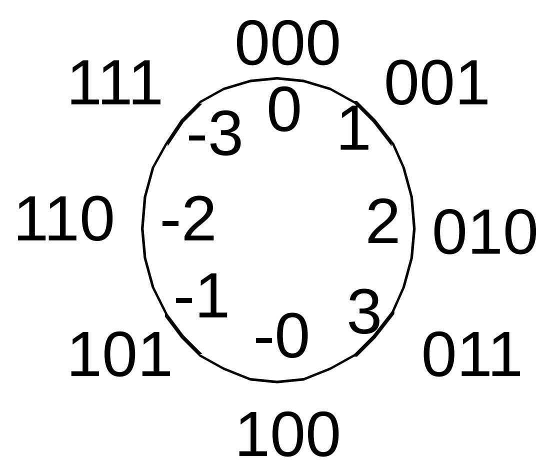
  $f(b_{31}\ldots b_0) = -b_{31} \times 2^{31} + \ldots b_1 \times 2^1 + b_0 \times 2^0$

- Max f(0111…11) = $2^{31} - 1$ = 2147483647
- Min f(100…00) = -2^{31} = -2147483648 (asymmetric)
- Range$[-2^{31}, 2^{31}-1]$ => # values$(2^{31}-1 - -2^{31}) = 2^{32}$
- Invert bits and add one: e.g. –6
  - 000…0110 => 111…1001 + 1 => 111…1010

Why 2’s Complement

- Why not use sign-magnitude?
- 2’s complement makes hardware simpler
- Just like humans don’t work with Roman numerals
- Representation affects ease of calculation, not correctness of answer





Addition and Subtraction

- 4-bit unsigned example

0	0	1	1		3
1	0	1	0		10
1	1	0	1		13

- 4-bit 2’s complement – ignoring overflow

0	0	1	1		3
1	0	1	0		-6
1	1	0	1		-3

Subtraction

- A – B = A + 2's complement of B
- E.g. 3 – 2

0	0	1	1		3
1	1	1	0		-2
0	0	0	1		1

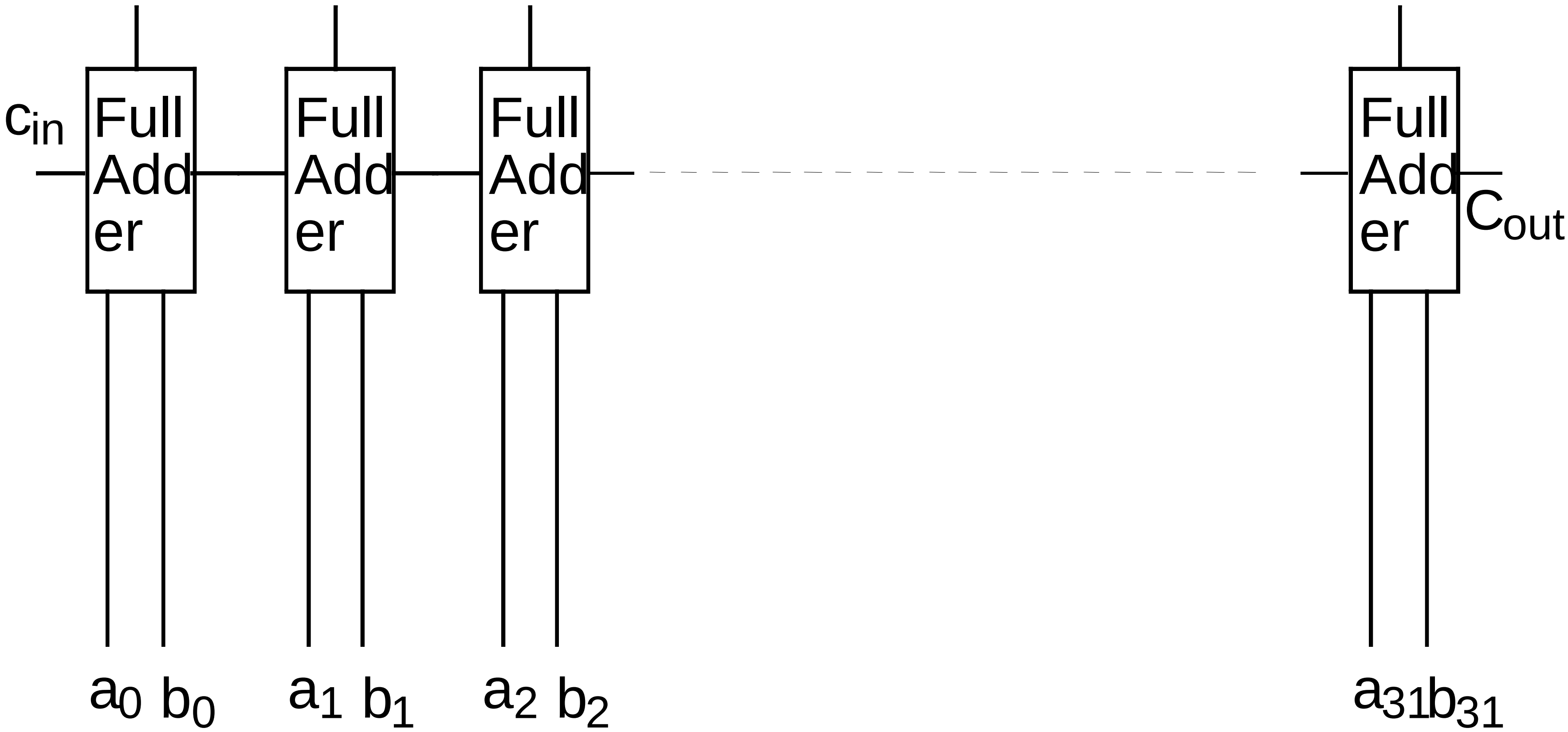
Full Adder

- Full adder $(a,b,c_{in}) => (c_{out}, s)$
- c_{out} = two or more of (a, b, c_{in})
- s = exactly one or three of (a,b,c_{in})

a	b	c_{in}	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

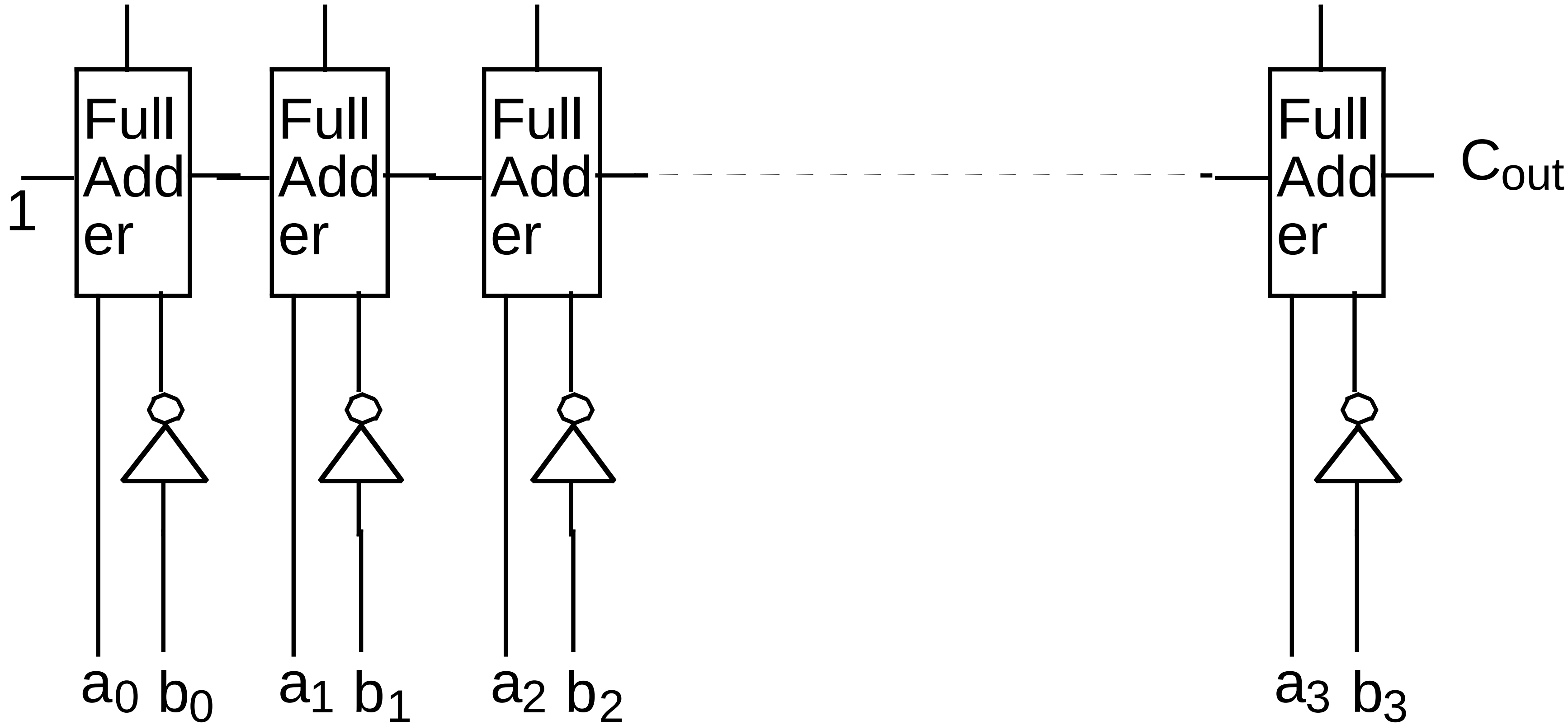
Ripple-carry Adder

- Just concatenate the full adders



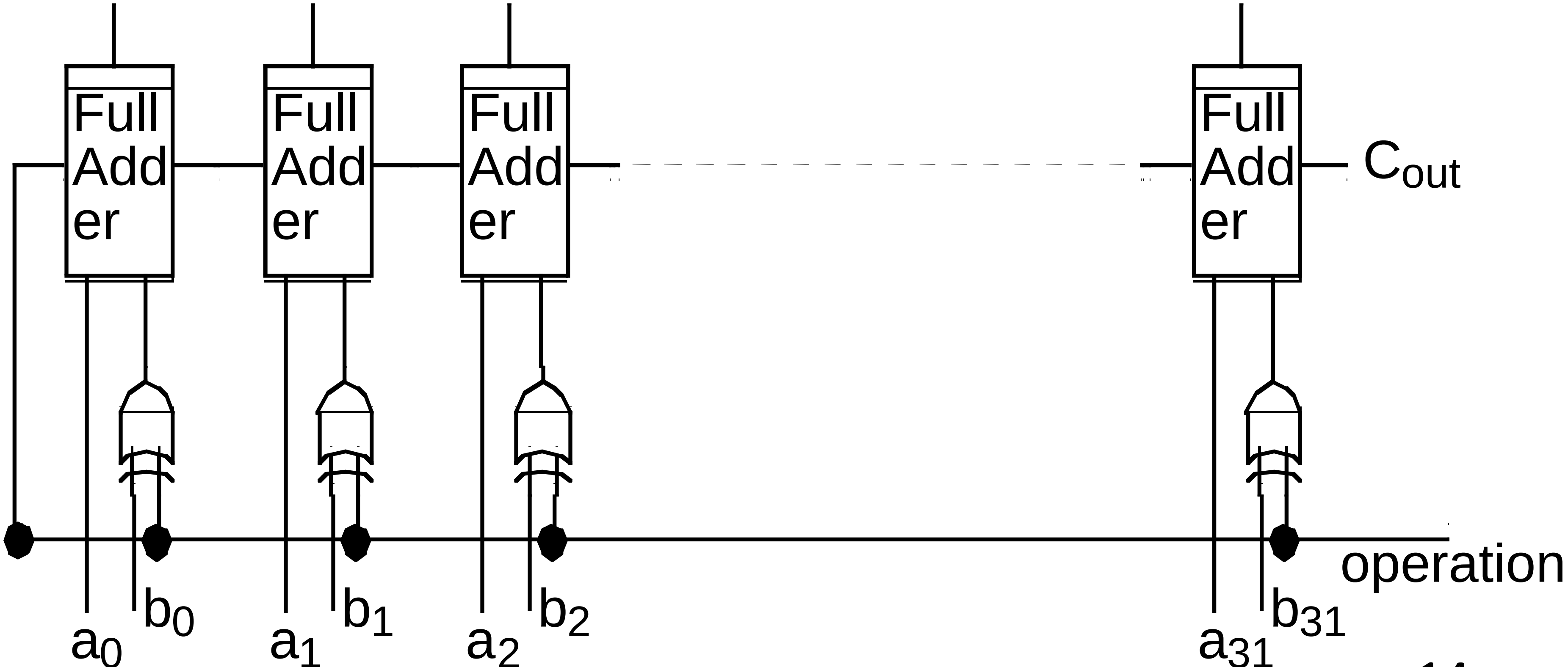
Ripple-carry Subtractor

- $A - B = A + (-B)$ => invert B and set c_{in} to 1



Combined Ripple-carry Adder/Subtractor

- Control = 1 => subtract
- XOR B with control and set c_{in0} to control

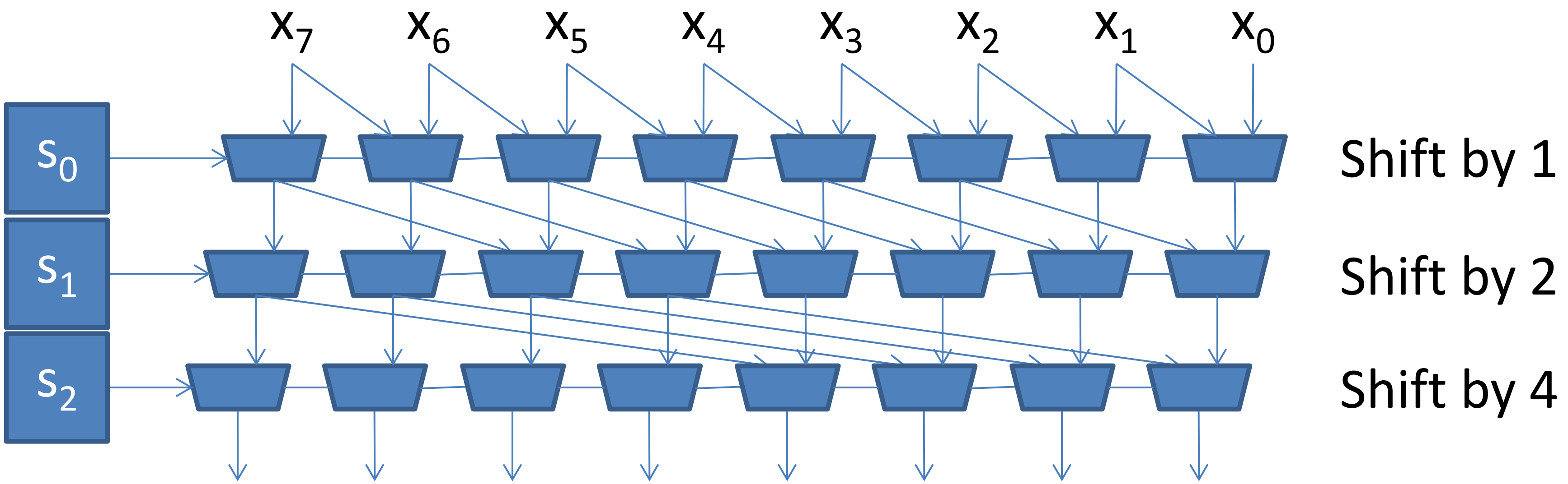


Logical Operations

- Bitwise AND, OR, XOR, NOR
  - Implement w/ 32 gates in parallel

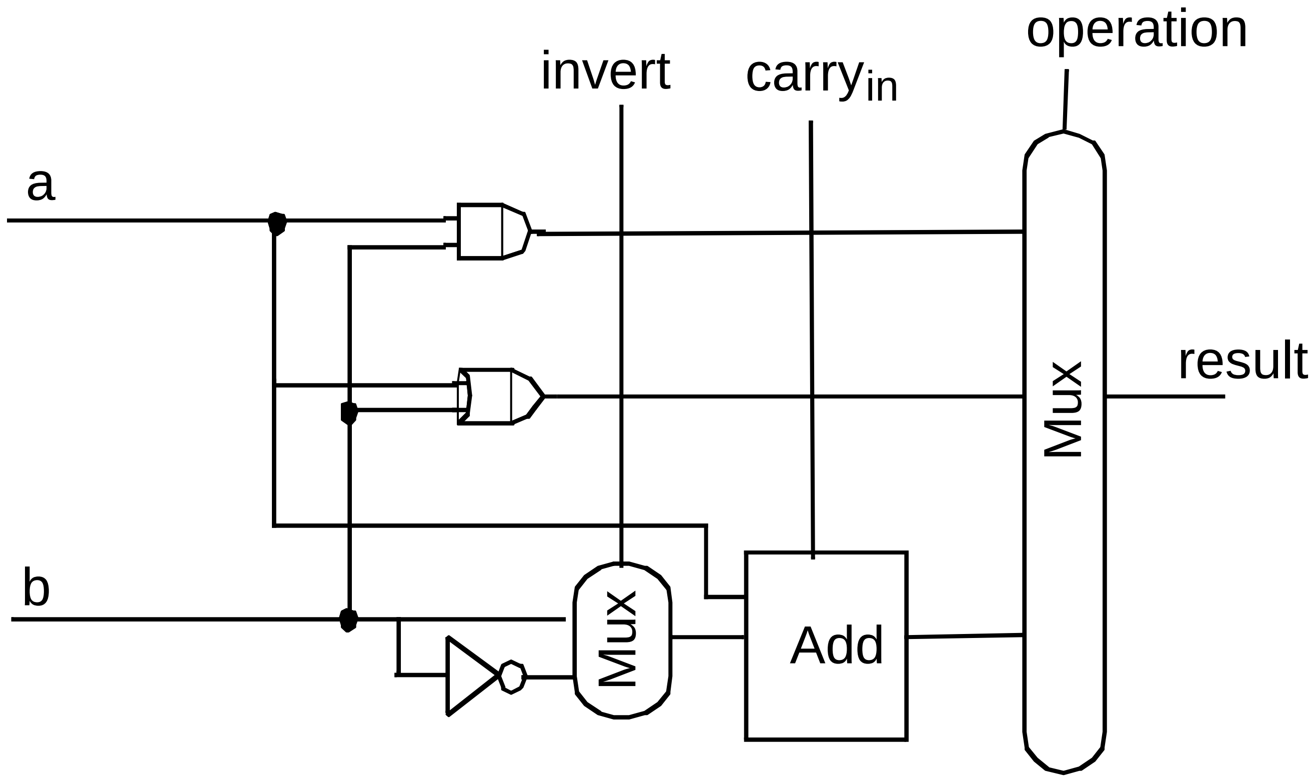
- Shifts and rotates
  - rol => rotate left (MSB->LSB)
  - ror => rotate right (LSB->MSB)
  - sll -> shift left logical (0->LSB)
  - srl -> shift right logical (0->LSB)
  - sra -> shift right arithmetic (old MSB->new MSB)

Shifter



- Right shift logic shown: missing inputs are 0
  - Left shift logic similar
- Rotate: wraparound instead of 0 inputs

All Together



Overflow

- With n bits only 2^n combinations
  - Unsigned range $[0, 2^n-1]$
  - 2's complement range $[-2^{n-1}, 2^{n-1}-1]$
- Unsigned Add

  5 + 6 > 7: 101 + 110 => 1011

  f(3:0) = a(2:0) + b(2:0) => overflow = f(3)

  Carryout from MSB

Overflow

- More involved for 2's complement

  -1 + -1 = -2:

  111 + 111 = 1110

  110 = -2 is correct
- Can't just use carry-out to signal overflow

Addition Overflow

- When is overflow NOT possible?

  (p1, p2) > 0 and (n1, n2) < 0

  p1 + p2

  p1 + n1 not possible

  n1 + p2 not possible

  n1 + n2

- Just checking signs of inputs is not sufficient

Addition Overflow

- 2 + 3 = 5 > 4: 010 + 011 = 101 =? –3 < 0
  - Sum of two positive numbers should not be negative
    - Conclude: overflow
- -1 + -4: 111 + 100 = 011 > 0
  - Sum of two negative numbers should not be positive
    - Conclude: overflow

Overflow = f(2) * ~(a2)*~(b2) + ~f(2) * a(2) * b(2)

Subtraction Overflow

- No overflow on a-b if signs are the same
- Neg – pos => neg ;; overflow otherwise
- Pos – neg => pos ;; overflow otherwise

Overflow = f(2) * ~(a2)*(b2) + ~f(2) * a(2) * ~b(2)

What to do on Overflow?

- Ignore ! (C language semantics)
  - What about Java? (try/catch?)
- Flag – condition code
- Sticky flag – e.g. for floating point
  - Otherwise gets in the way of fast hardware
- Trap – possibly maskable
  - MIPS has e.g. add that traps, addu that does not
  - Useful for extended precision in software

Zero and Negative

- Zero = ~[f(2) + f(1) + f(0)]
- Negative = f(2) (sign bit)

Zero and Negative

- May also want correct answer even on overflow
- Negative = (a < b) = (a – b) < 0 even if overflow
- E.g. is –4 < 2?

  100 – 010 = 1010 (-4 – 2 = -6): Overflow!

- Work it out: negative = f(2) XOR overflow

Summary

- Binary representations, signed/unsigned
- Arithmetic
  - Full adder, ripple-carry, adder/subtractor
  - Overflow, negative
- Logical
  - Shift, and, or
- Next: high-performance adders

– Later: multiply/divide/FP

ECE/CS 552: Carry Lookahead

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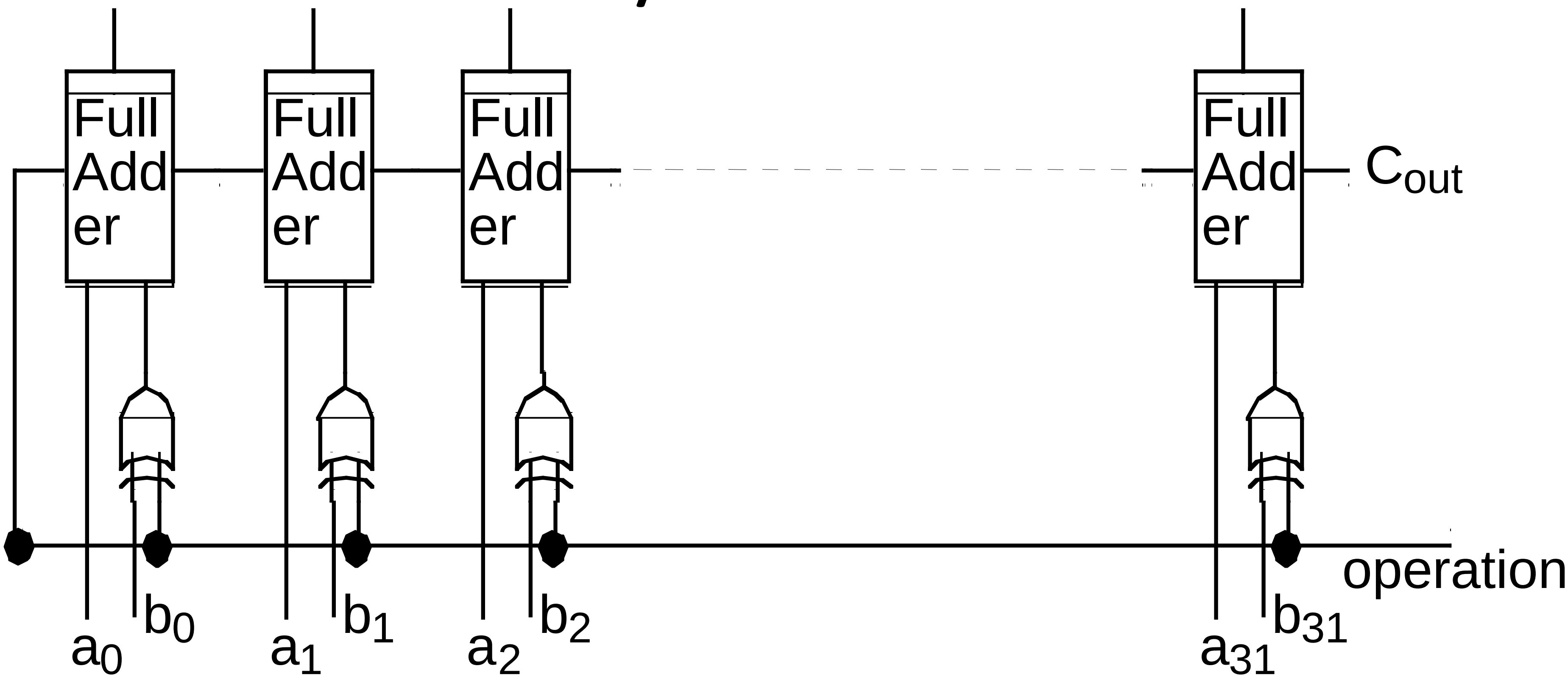
Combined Ripple-carry Adder/Subtractor



- The above ALU is too slow
  - Gate delays for add = 32 x FA + XOR ~= 64

Carry Lookahead

- Theoretically, in parallel
  - $Sum_0 = f(c_{in}, a_0, b_0)$
  - $Sum_i = f(c_{in}, a_i \ldots a_{0,}, b_i \ldots b_0)$
  - $Sum_{31} = f(c_{in}, a_{31} \ldots a_0, b_{31} \ldots b_0)$

- Any boolean function in two levels, right?
  - Wrong! Too much fan-in!

Carry Lookahead

- Need compromise
  - Build tree so delay is $O(\log_2 n)$ for n bits
  - E.g. 2 x 5 gate delays for 32 bits
- We will consider basic concept with
  - 4 bits
  - 16 bits
- Warning: a little convoluted

Carry Lookahead

0101 0100
0011 0110

Need:

both 1 to generate carry

one or both 1s to propagate carry

Define: $g_i = a_i * b_i$ ## carry generate

$p_i = a_i + b_i$ ## carry propagate

Recall: $c_{i+1} = a_i * b_i + a_i * c_i + b_i * c_i$

$= a_i * b_i + (a_i + b_i) * c_i$

$= g_i + p_i * c_i$

Carry Lookahead

- Therefore

$c_1 = g_0 + p_0 * c_0$

$c_2 = g_1 + p_1 * c_1 = g_1 + p_1 * (g_0 + p_0 * c_0)$

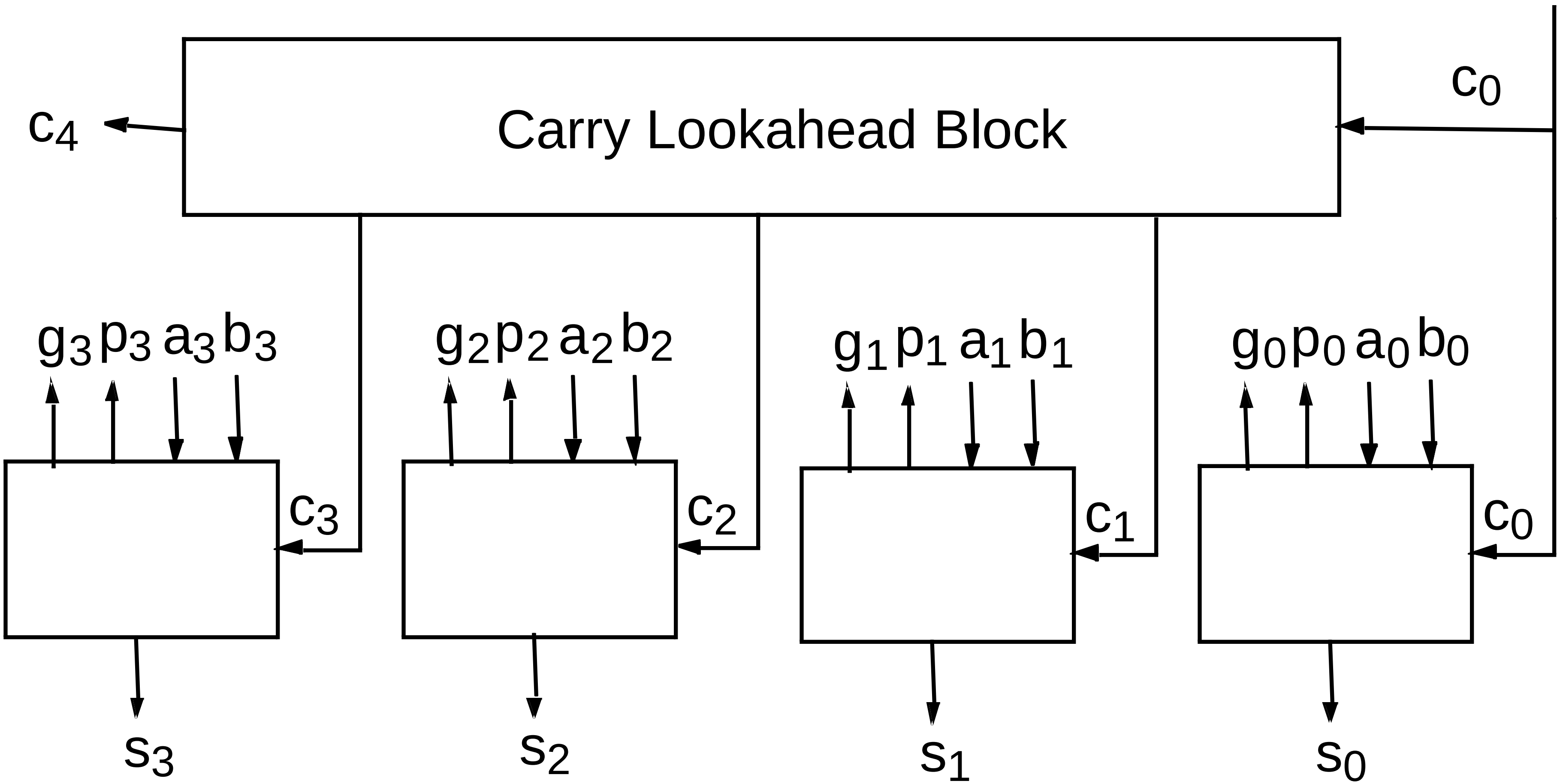
$= g_1 + p_1 * g_0 + p_1 * p_0 * c_0$

$c_3 = g_2 + p_2 * g_1 + p_2 * p_1 * g_0 + p_2 * p_1 * p_0 * c_0$

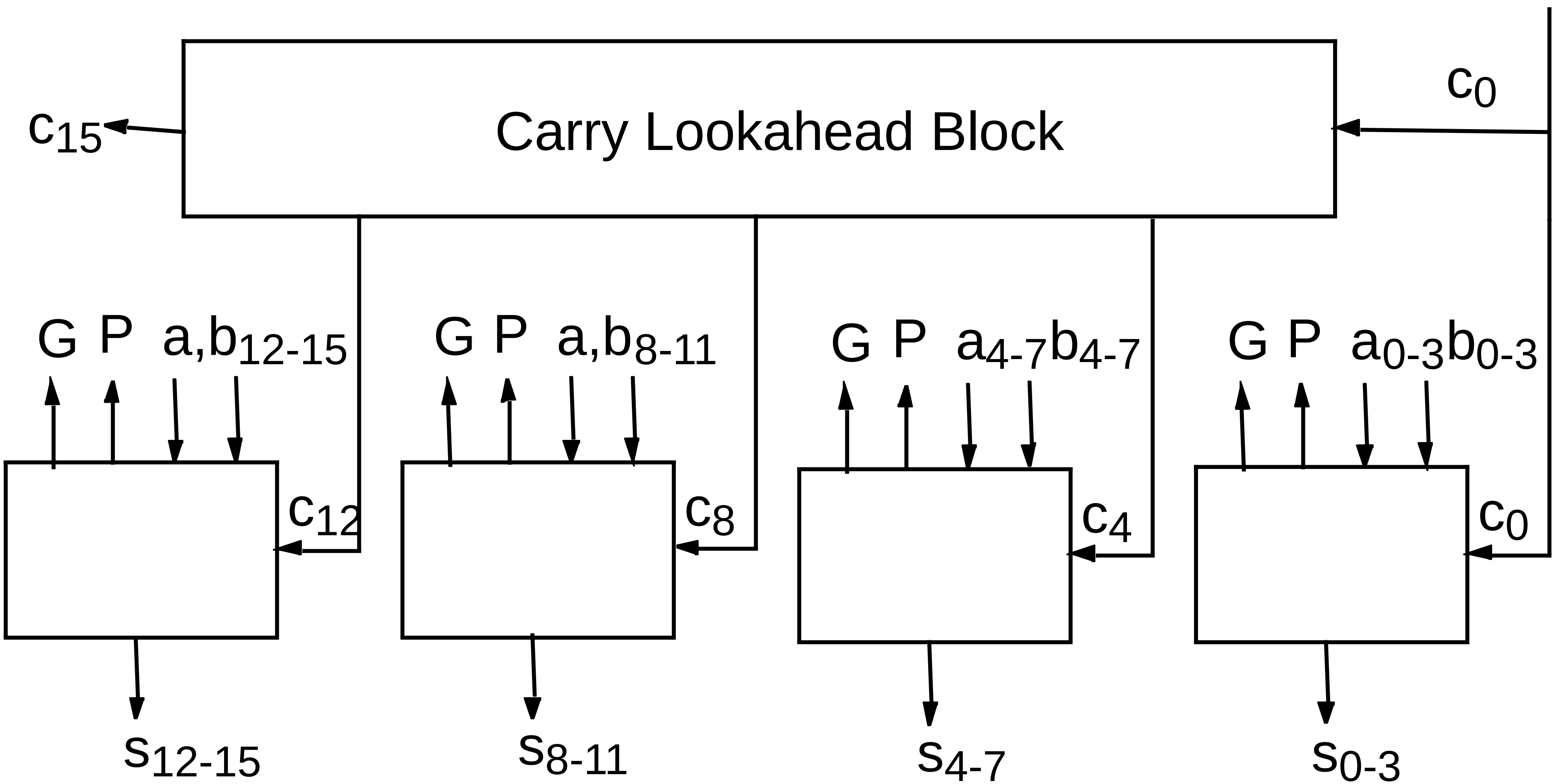
$c_4 = g_3 + p_3*g_2 + p_3*p_2*g_1 + p_3*p_2*p_1*g_0 + p_3*p_2*p_1*p_0*c_0$

- Uses one level to form p_i and g_i, two levels for carry
- But, this needs n+1 fanin at the OR and the rightmost AND

4-bit Carry Lookahead Adder



Hierarchical Carry Lookahead for 16 bits



Hierarchical CLA for 16 bits

Build 16-bit adder from four 4-bit adders

Figure out G and P for 4 bits together

$G_{0,3} = g_3 + p_3 * g_2 + p_3 * p_2 * g_1 + p_3 * p_2 * p_1 * g_0$

$P_{0,3} = p_3 * p_2 * p_1 * p_0$ (Notation a little different from the book)

$G_{4,7} = g_7 + p_7 * g_6 + p_7 * p_6 * g_5 + p_7 * p_6 * p_5 * g_4$

$P_{4,7} = p_7 * p_6 * p_5 * p_4$

$G_{12,15} = g_{15} + p_{15} * g_{14} + p_{15} * p_{14} * g_{13} + p_{15} * p_{14} * p_{13} * g_{12}$

$P_{12,15} = p_{15} * p_{14} * p_{13} * p_{12}$

Carry Lookahead Basics

Fill in the holes in the G's and P's

$G_{i,\,k} = G_{j+1,k} + P_{j+1,\,k} * G_{i,j}$ (assume $i < j+1 < k$)

$P_{i,k} = P_{i,j} * P_{j+1,\,k}$

$G_{0,7} = G_{4,7} + P_{4,7} * G_{0,3}$

$G_{8,15} = G_{12,15} + P_{12,15} * G_{8,11}$

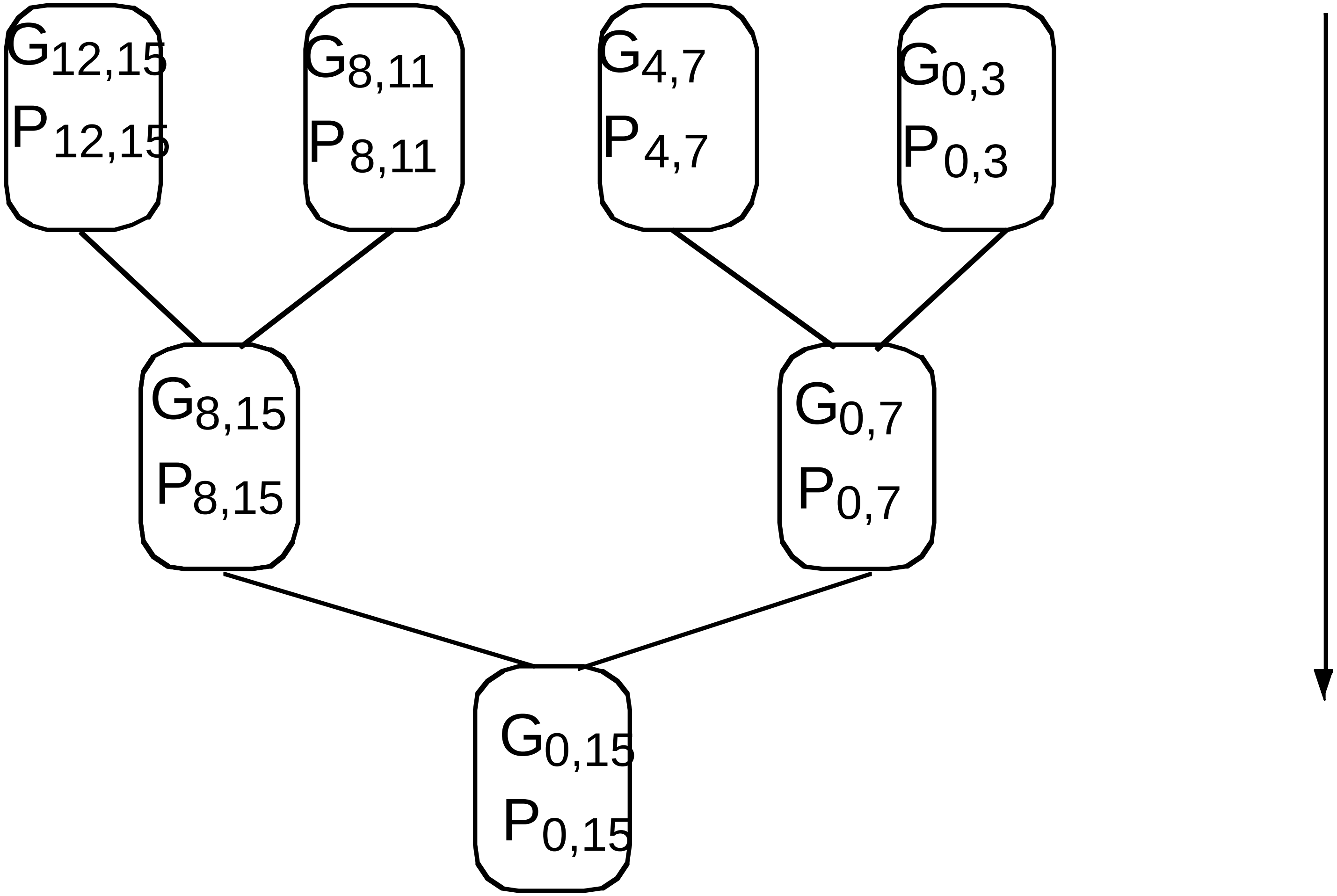
$G_{0,15} = G_{8,15} + P_{8,15} * G_{0,7}$

$P_{0,7} = P_{0,3} * P_{4,7}$

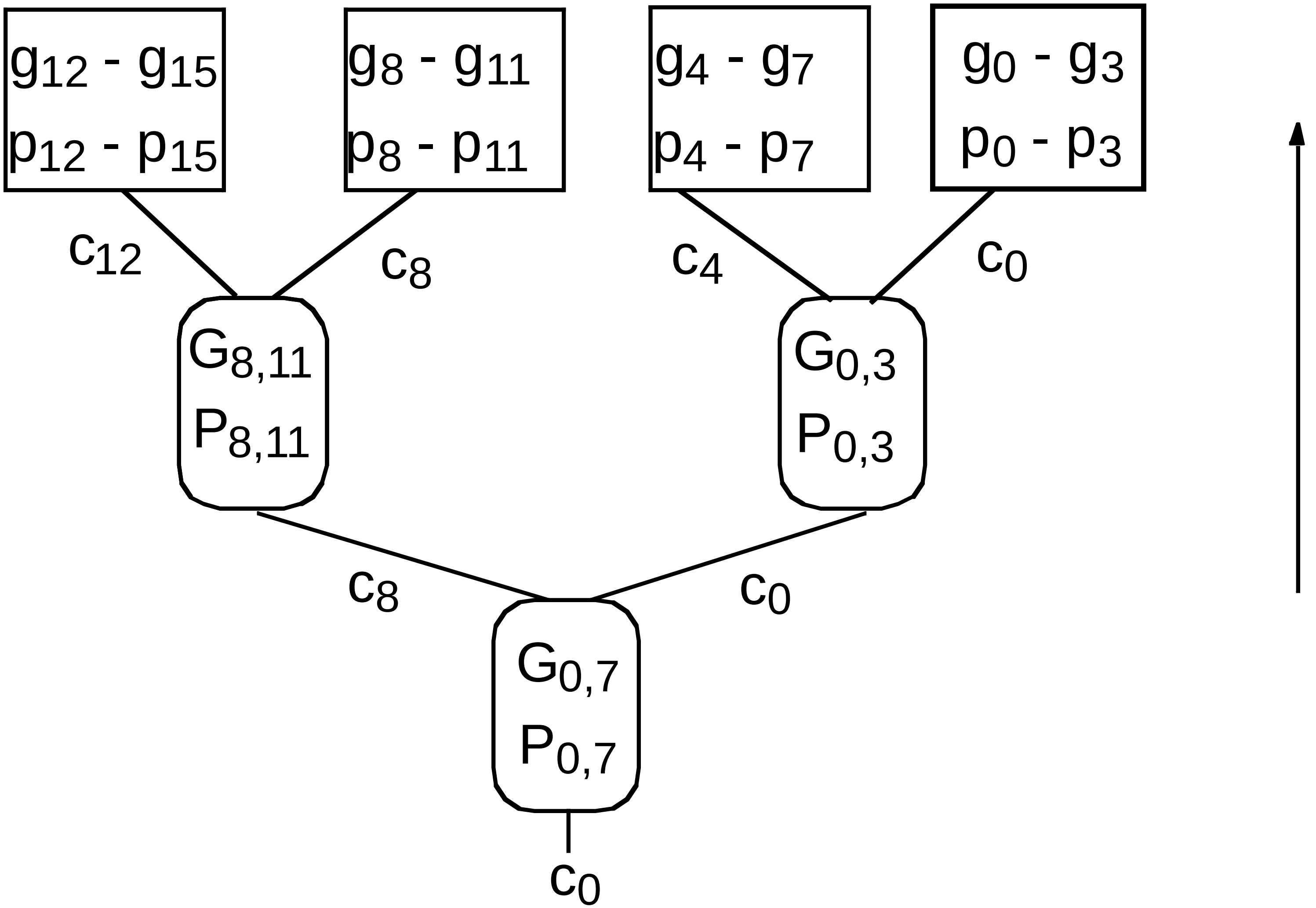
$P_{8,15} = P_{8,11} * P_{12,\,15}$

$P_{0,15} = P_{0,7} * P_{8,\,15}$

CLA: Compute G's and P's

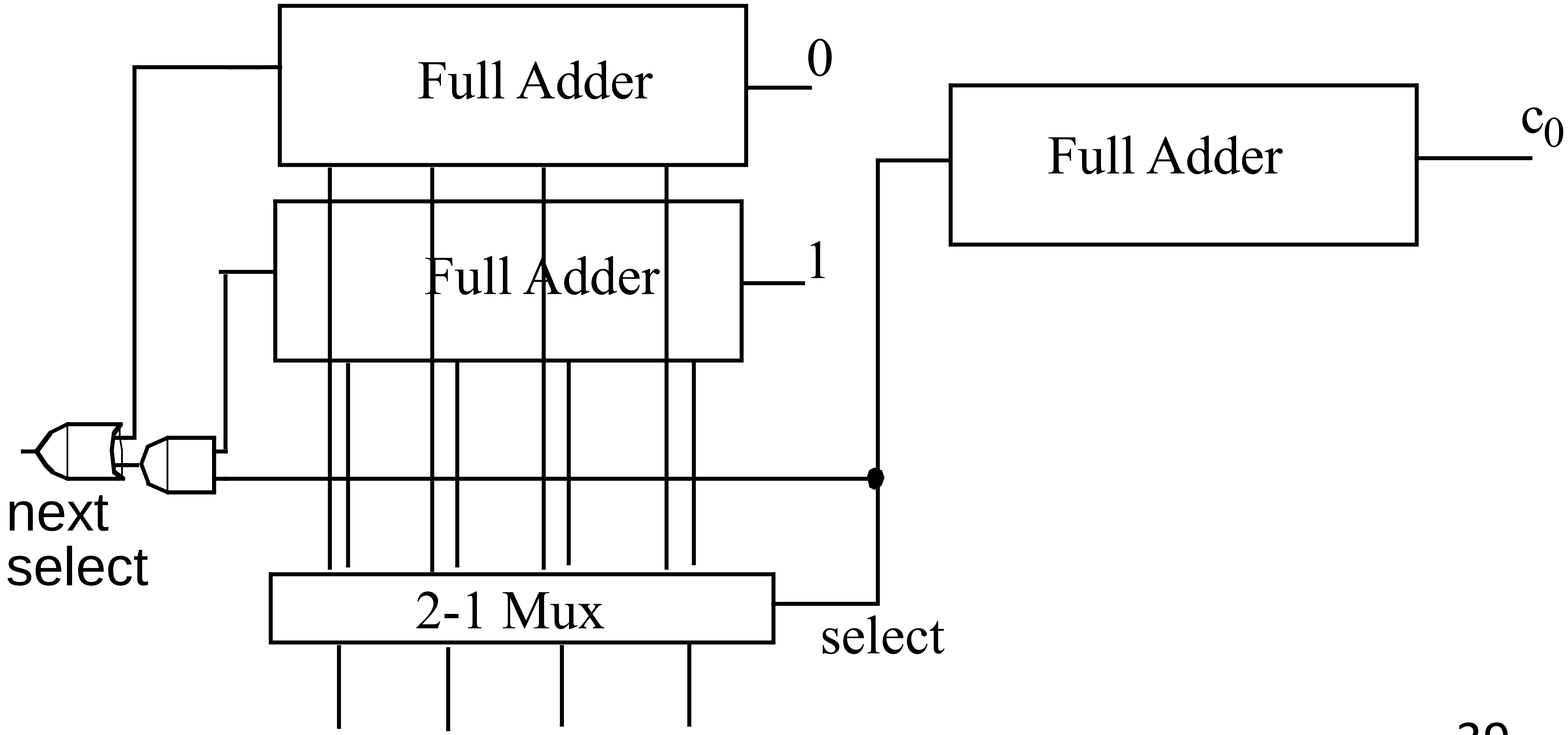


CLA: Compute Carries



Other Adders: Carry Select

- Two adds in parallel; with and without c_{in}
  - When C_{in} is done, select correct result



Other Adders: Carry Save

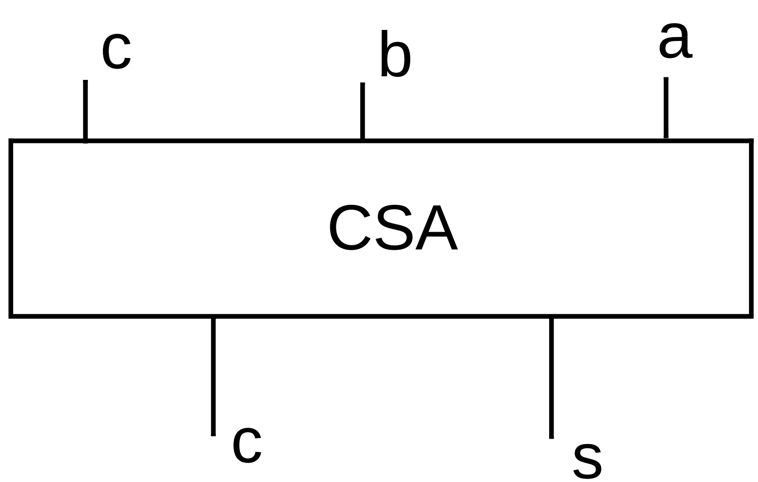
	7	9
+	1	8
C,S	0,8	1,7
Final	8+1=9	7

A + B => S

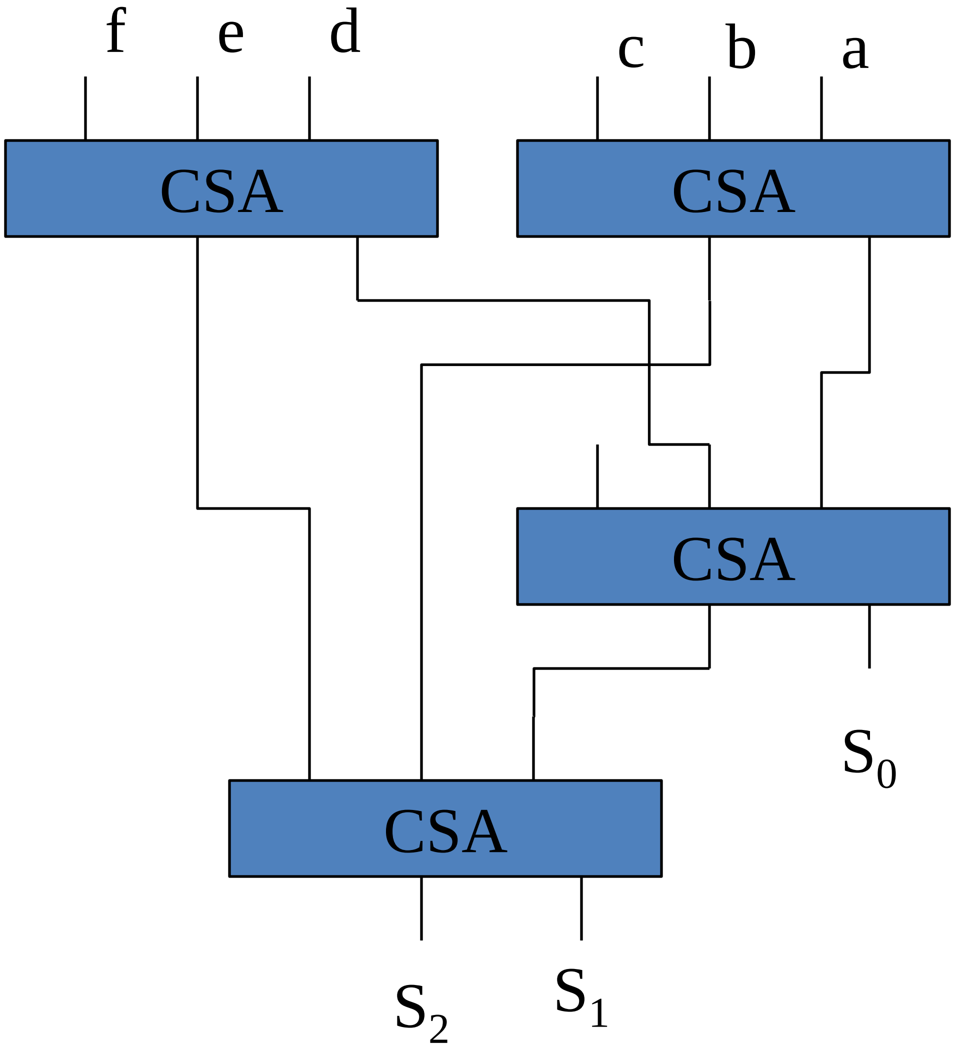
Save carries A + B => S, C_{out}

Use C_{in} A + B + C => S1, S2 (3# to 2# in parallel)

Used in combinational multipliers by building a Wallace Tree



Adding Up Many Bits



Summary

- Carry lookahead
- Carry-select, Carry-save
- State of the art: parallel prefix adders
  – aka. Brent-Kung, Kogge-Stone, …
  – Generalization of CLA
  – Physical design (e.g. wiring) of primary concern
  – Covered in ECE 555