Intro to Digital Design
FSM Design, MUXes, Adders

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Relevant Course Information

- Lab 6 – Connecting multiple FSMs in Tug of War game
  - *Bigger* step up in difficulty from Lab 5
  - Putting together complex system – interconnections!
  - Bonus points for smaller resource usage

Clock Divider (not for simulation)

- Why/how does this work?

```
// divided_clocks[0]=25MHz, [1]=12.5Mhz, ...
module clock_divider (clock, divided_clocks);
  input  logic        clock;
  output logic [31:0] divided_clocks;

  initial
    divided_clocks = 0;

  always_ff @(posedge clock)
    divided_clocks <= divided_clocks + 1;

endmodule  // clock_divider
```

Outline

- **FSM Design**
- Multiplexors
- Adders

FSM Design Process

1) Understand the problem

2) Draw the state diagram

3) Use state diagram to produce state table

4) Implement the combinational control logic

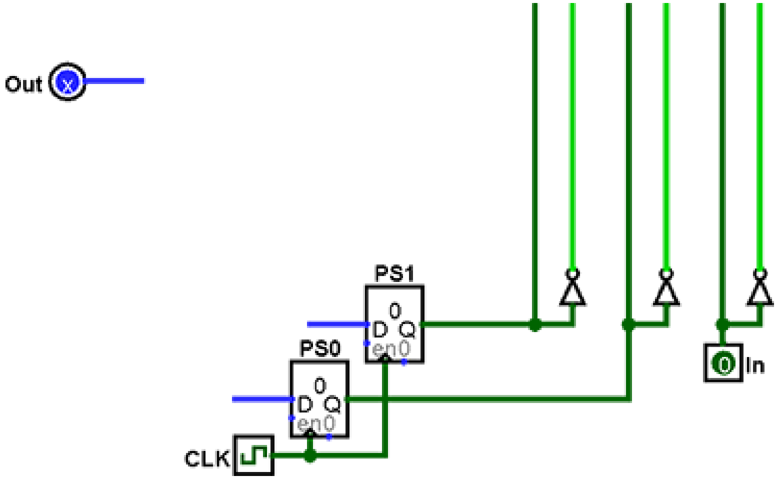
Practice: String Recognizer FSM

- Recognize the string `101` with the following behavior
  - Input: `1 0 0 1 0 1 0 1 1 0 0 1 0`
  - Output: `0 0 0 0 0 1 0 1 0 0 0 0 0`
- State diagram to implementation:

	00	01	11	10
0				
1				

	00	01	11	10
0				
1				

	00	01	11	10
0				
1				



HDL Organization

- Most problems are best solved with multiple pieces – how to best organize your system and code?
- Everything is computed in parallel
  - We use routing elements (next lecture) to select between (or ignore) multiple outcomes/parts
  - This is why we use block diagrams and waveforms
- A module is not a *function*, it is closest to a *class*
  - Something that you ***instantiate***, not something that you ***call*** – hardware cannot appear and disappear spontaneously
  - Should treat modules as ***resource managers*** rather than temporary helpers
    - This can include having internal modules

Block Diagrams

- Block diagrams are the basic design tool for digital logic.
  - The diagram itself is a module → inputs and outputs shown and connected
  - Major components are represented by blocks ("black boxes") with their internals abstracted away → each block becomes its own module
  - All ports for each block should be shown and labeled and connected to the appropriate part(s) of the rest of the system → sets your port connections
  - Wires and other basic building blocks can be added/shown as needed

- From Wikipedia: The goal is to "[end] in block diagrams detailed enough that each individual block can be easily implemented."
  - For designs that involve multiple modules, should always create your block diagram *before* coding anything!

Subdividing FSMs Example

- “Psychic Tester”
  - Machine generates a 4-bit pattern
  - User tries to guess 8 patterns in a row to be deemed psychic

- States?

Example: Plan First with Block Diagram

- Pieces?
  - Generate/pick pattern
  - User input (guess)
  - Check guess
  - Count correct guesses

Example: Implementation & Testing

1) Create individual submodules

2) Create submodules test benches – test as usual
   - CL – run through all input combinations
   - SL – take every transition that you care about

3) Create top-level module
   - Create instance of each submodule
   - Create wires/nets to connect signals between submodules, inputs, and outputs

4) Create top-level test bench
   - Goal is to check the interconnections between submodules – does input/state change in one submodule trigger the expected change in other submodules?

Outline

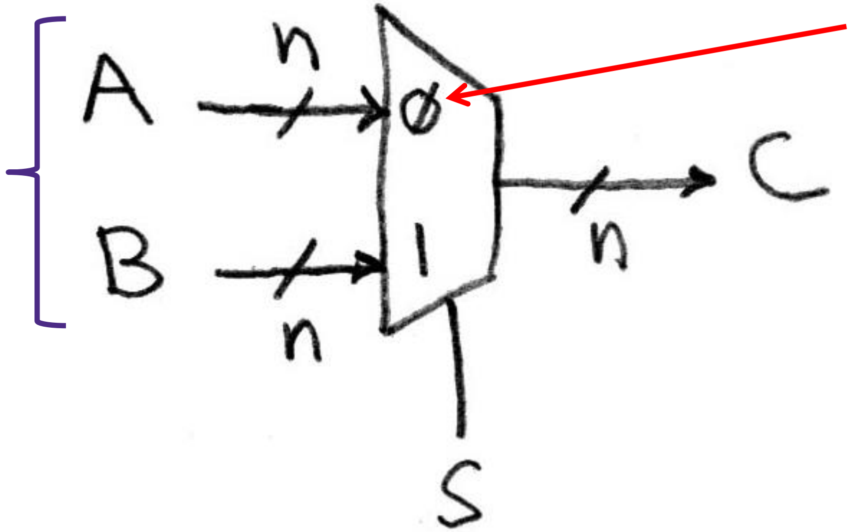
- FSM Design
- **Multiplexors**
- Adders

Data Multiplexor

- Multiplexor ("MUX") is a *selector*
  - Direct one of many ($N = 2^s$) n-bit wide inputs onto output
  - Called a n-bit, N-to-1 MUX

- <u>Example</u>: n-bit 2-to-1 MUX
  - Input S (s bits wide) selects between two inputs of n bits each

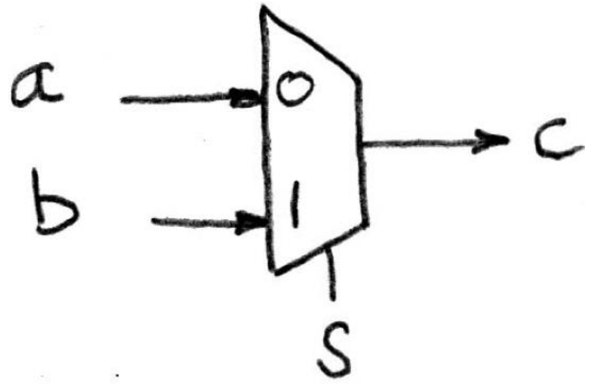
N inputs



This input is passed to output if selector bits match shown value

Review: Implementing a 1-bit 2-to-1 MUX

- **Schematic:**



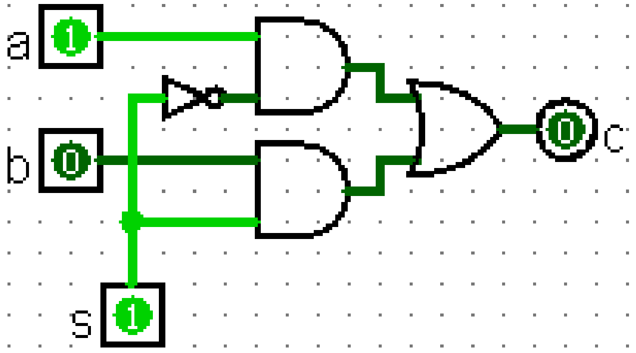
- **Truth Table:**

s	a	b	c
0	0	0	0
0	0	1	0
0	1	0	1
0	1	1	1
1	0	0	0
1	0	1	1
1	1	0	0
1	1	1	1

- **Boolean Algebra:**

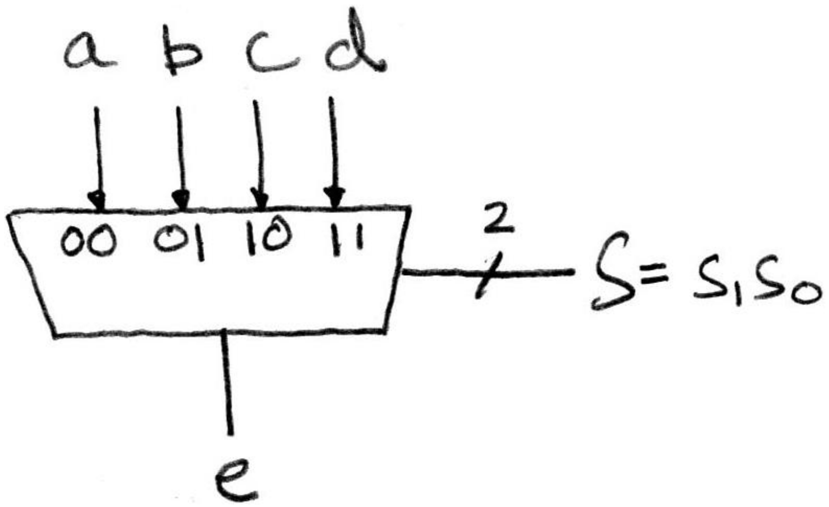
$$\begin{aligned} c &= \overline{s}a\overline{b} + \overline{s}ab + s\overline{a}b + sab \\ &= \overline{s}(a\overline{b} + ab) + s(\overline{a}b + ab) \\ &= \overline{s}(a(\overline{b} + b)) + s((\overline{a} + a)b) \\ &= \overline{s}(a(1) + s((1)b) \\ &= \overline{s}a + sb \end{aligned}$$

- **Circuit Diagram:**



1-bit 4-to-1 MUX

- **Schematic:**



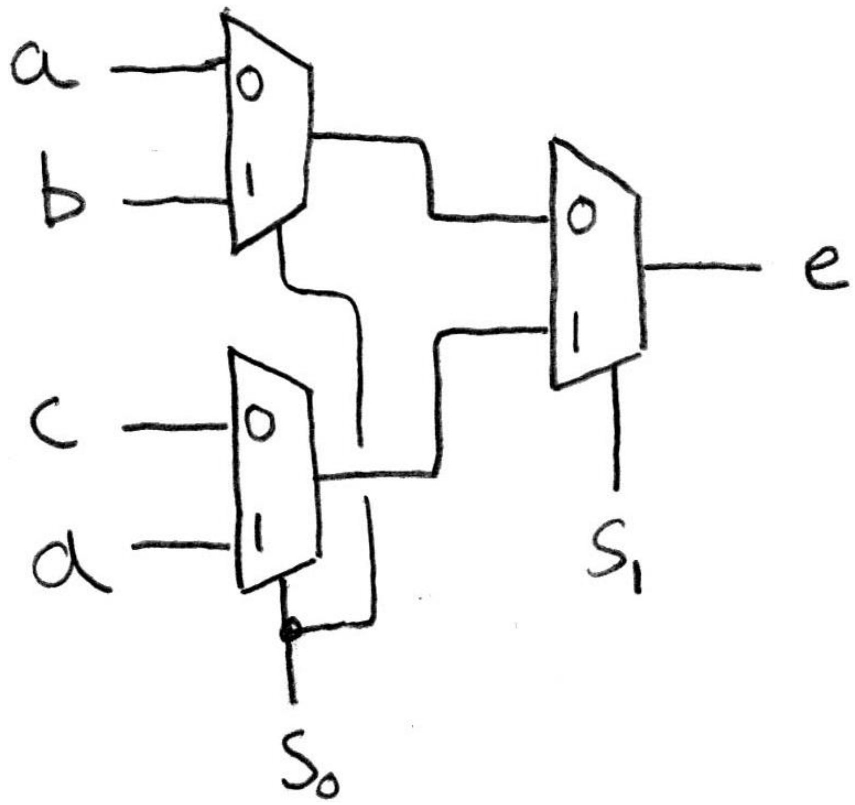
- **Truth Table:** How many rows?

- **Boolean Expression:**

$$e = \overline{s_1}\,\overline{s_0}a + \overline{s_1}s_0 b + s_1\overline{s_0}c + s_1 s_0 d$$

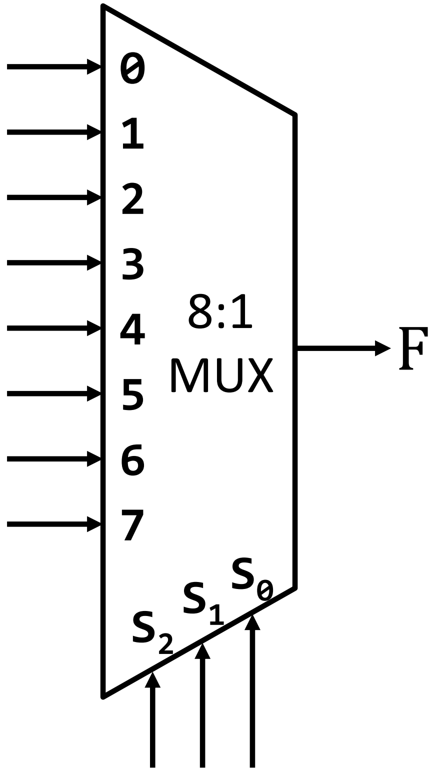
1-bit 4-to-1 MUX

- Can we leverage what we've previously built?
  - Alternative hierarchical approach:



Multiplexers in General Logic

- Implement $F = X\overline{Y}Z + Y\overline{Z}$ with a 8:1 MUX



Technology Break

Outline

- FSM Design
- Multiplexors
- **Adders**

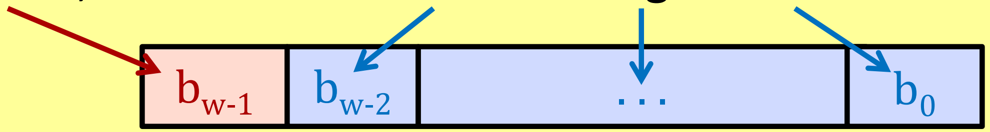
Review: Unsigned Integers

- Unsigned values follow the standard base 2 system
  - $b_7b_6b_5b_4b_3b_2b_1b_0 = b_7 2^7 + b_6 2^6 + \cdots + b_1 2^1 + b_0 2^0$
- In n bits, represent integers 0 to 2^n-1
- Add and subtract using the normal "carry" and "borrow" rules, just in binary

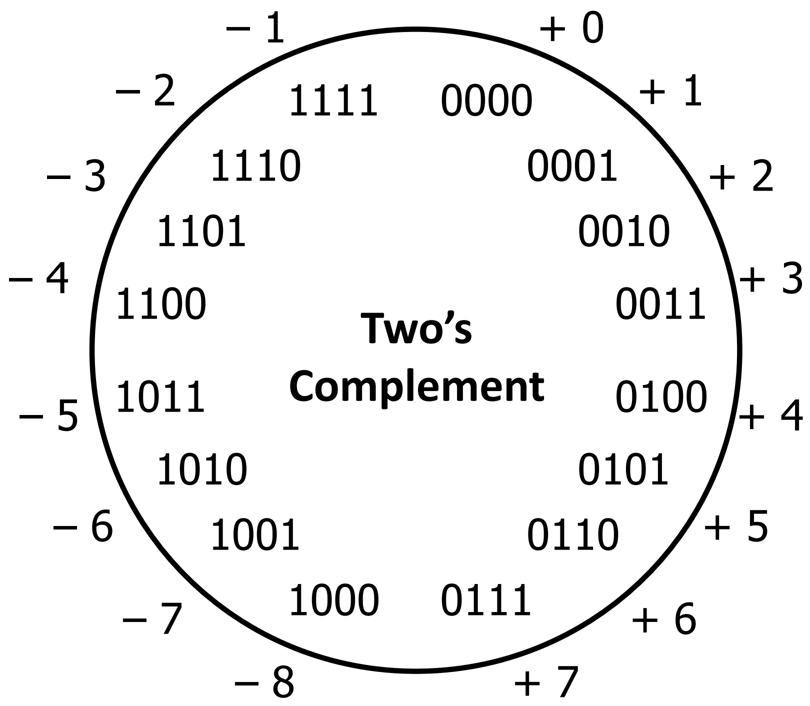
```
  63     00111111          64     01000000
+  8    +00001000        -  8    -00001000
  71     01000111          56     00111000
```

Review: Two's Complement (Signed)

b_{w-1} has weight -2^{w-1}, other bits have usual weights $+2^{i}$



- **Properties:**
  - In n bits, represent integers -2^{n-1} to $2^{n-1}-1$
  - Positive number encodings match unsigned numbers
  - Single zero (encoding = all zeros)
- **Negation procedure:**
  - Take the bitwise complement and then add one
    `( ~x + 1 == -x )`



Addition and Subtraction in Hardware

- The same bit manipulations work for both unsigned and two's complement numbers!
  - Perform subtraction via adding the negated 2nd operand:
    $\mathrm{A} - \mathrm{B} = \mathrm{A} + (-\mathrm{B}) = \mathrm{A} + (\sim\mathrm{B}) + 1$

- 4-bit examples:

	Two's	Un
0 0 1 0	+2	2
+ 1 1 0 0	-4	12

	Two's	Un
1 0 0 0	-8	8
+ 0 1 0 0	+4	4

	Two's	Un
0 1 1 0	+6	6
- 0 0 1 0	+2	2

	Two's	Un
1 1 1 1	-1	15
- 1 1 1 0	-2	14

Half Adder (1 bit)

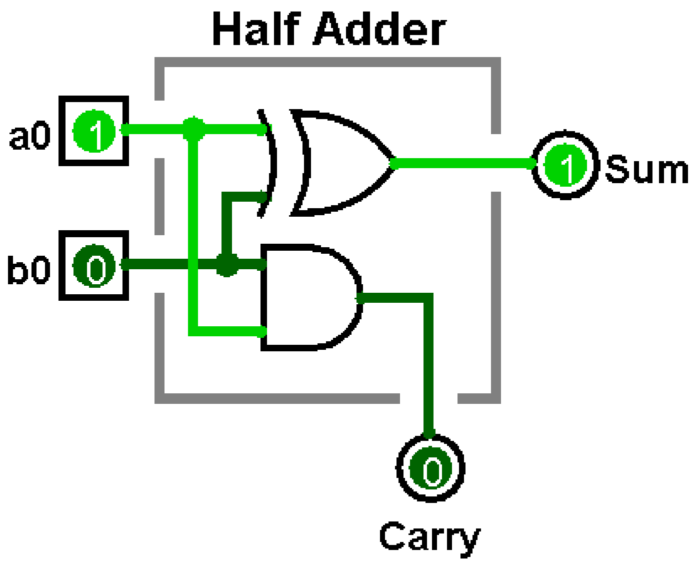
	a_3	a_2	a_1	a_0
+	b_3	b_2	b_1	b_0
	s_3	s_2	s_1	s_0

$\text{Carry} = a_0 b_0$

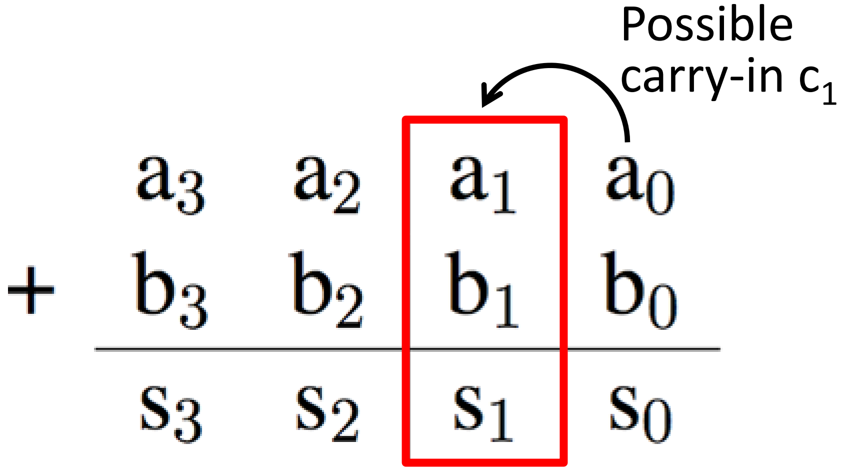
$\text{Sum} = a_0 \oplus b_0$

Carry-out bit

a_0	b_0	c_1	s_0
0	0	0	0
0	1	0	1
1	0	0	1
1	1	1	0



Full Adder (1 bit)

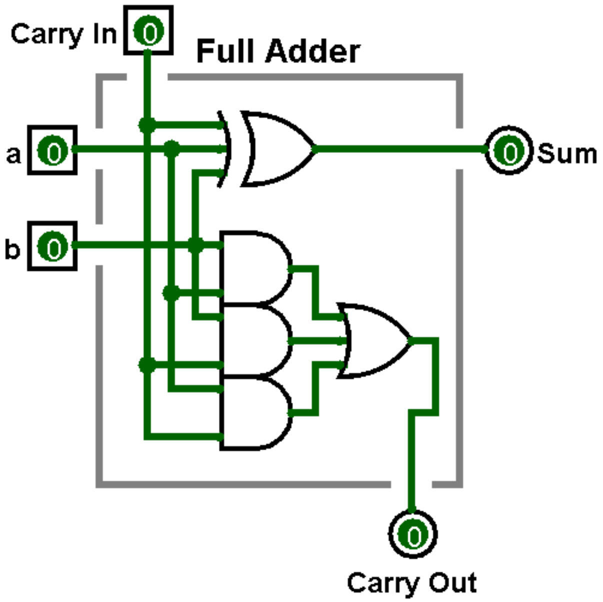


$$s_i = \mathrm{XOR}(a_i, b_i, c_i)$$

$$c_{i+1} = \mathrm{MAJ}(a_i, b_i, c_i) = a_i b_i + a_i c_i + b_i c_i$$

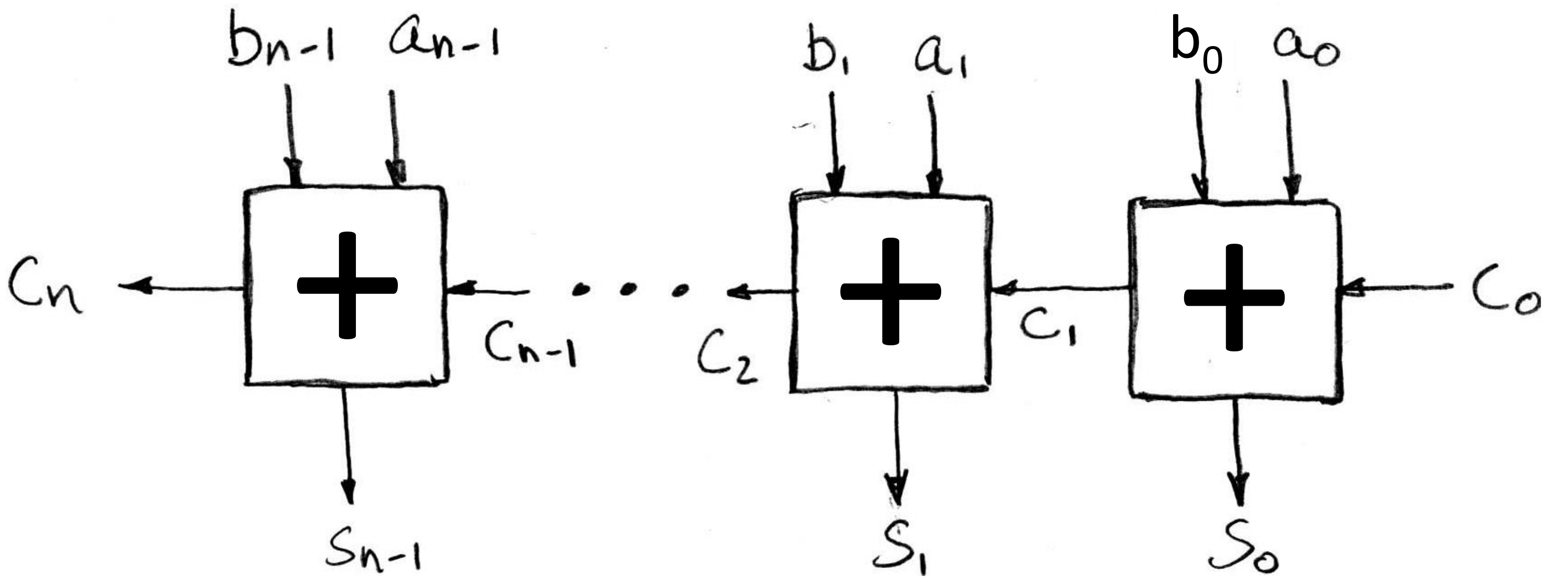
Carry-in → c_i; Carry-out → c_{i+1}

c_i	a_i	b_i	c_{i+1}	s_i
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



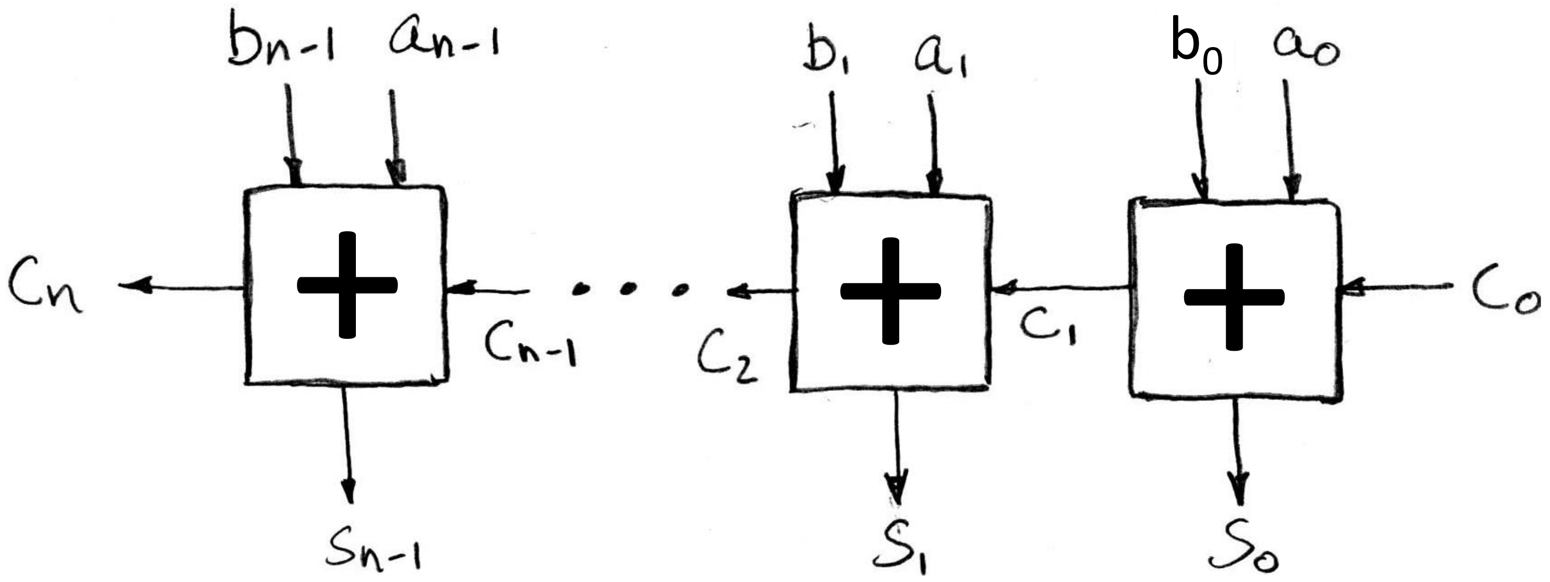
Multi-Bit Adder (N bits)

- Chain 1-bit adders by connecting CarryOut_i to CarryIn_{i+1}:

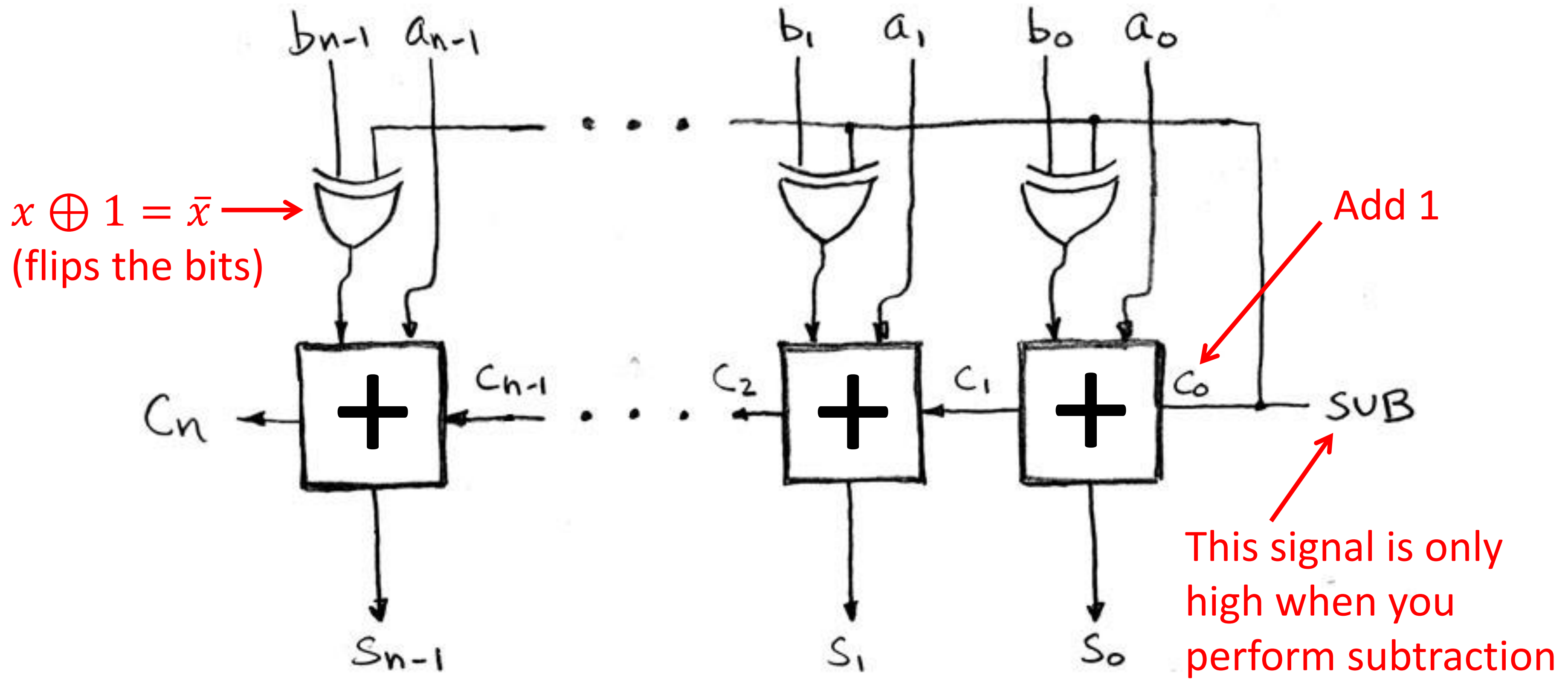


Subtraction?

- Can we use our multi-bit adder to do subtraction?
  - Flip the bits and add 1?
    - $X \oplus 1 = \overline{X}$
    - CarryIn_0 (using full adder in all positions)



Multi-bit Adder/Subtractor



Detecting Arithmetic Overflow

- **Overflow:** When a calculation produces a result that can't be represented in the current encoding scheme
  - Integer range limited by fixed width
  - Can occur in both the positive and negative directions

- **Unsigned Overflow**
  - Result of add/sub is > UMax or < Umin

- **Signed Overflow**
  - Result of add/sub is > TMax or < TMin
  - (+) + (+) = (–) or (–) + (–) = (+)

Signed Overflow Examples

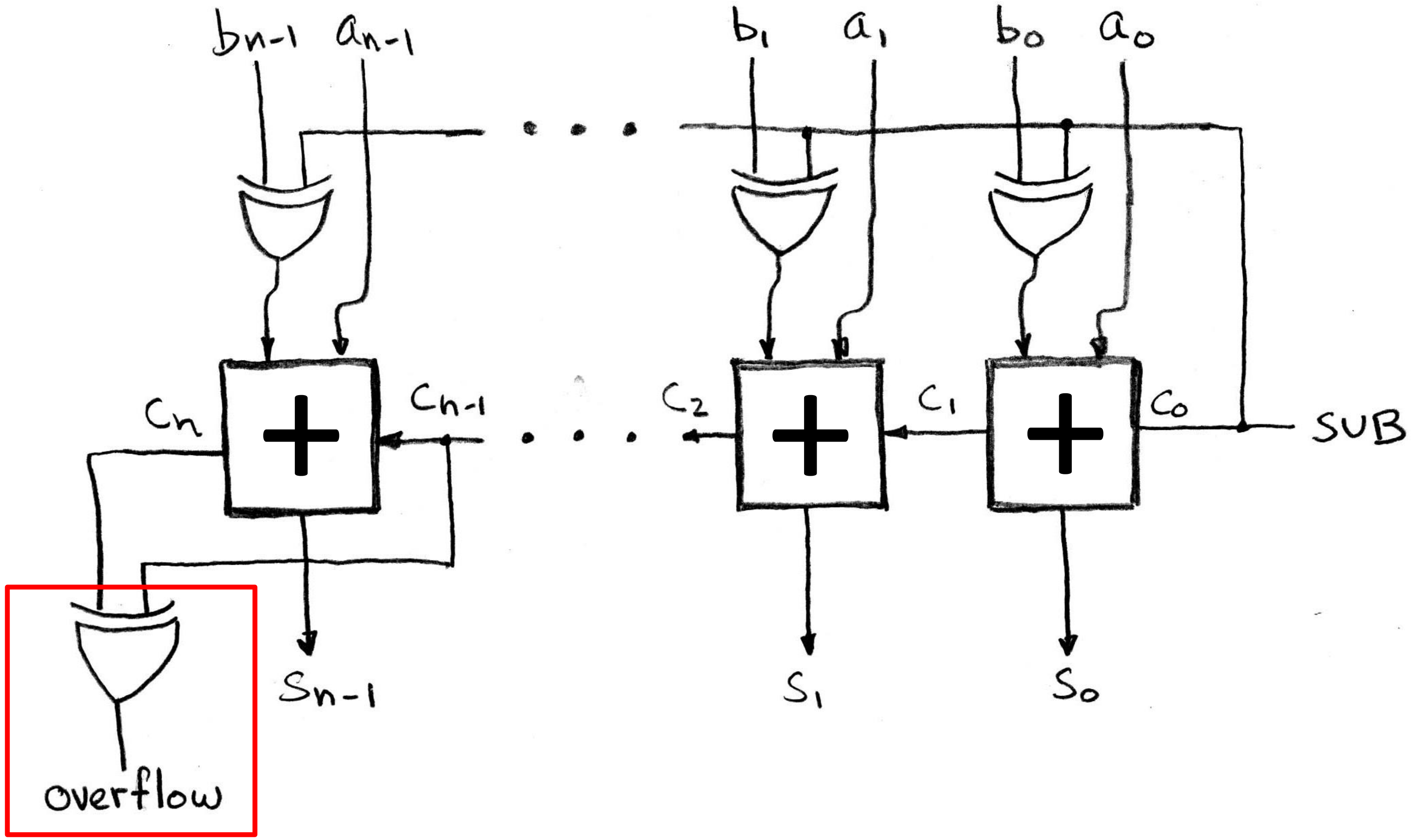
```
          Two's
  0 1 0 1  +5
+ 0 0 1 1  +3
---------
```

```
          Two's
  1 0 0 1  -7
+ 1 1 1 0  -2
---------
```

```
          Two's
  0 1 0 1  +5
+ 0 0 1 0  +2
---------
```

```
          Two's
  1 1 0 0  -4
+ 0 1 0 0   4
---------
```

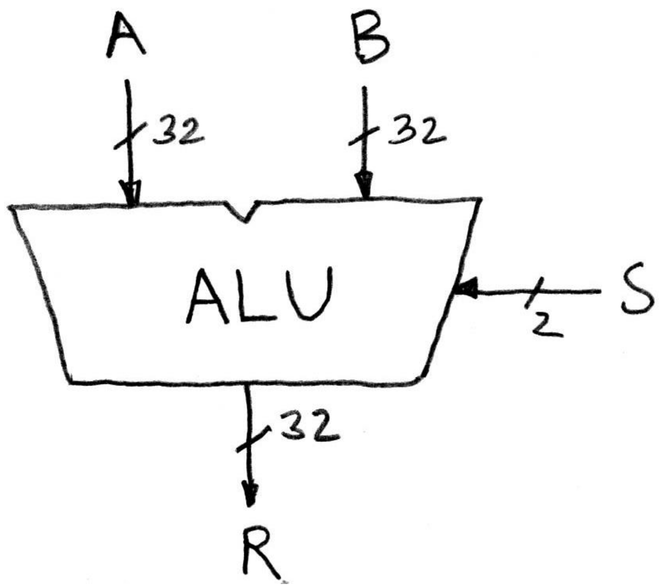
Multi-bit Adder/Subtractor with Overflow



Arithmetic and Logic Unit (ALU)

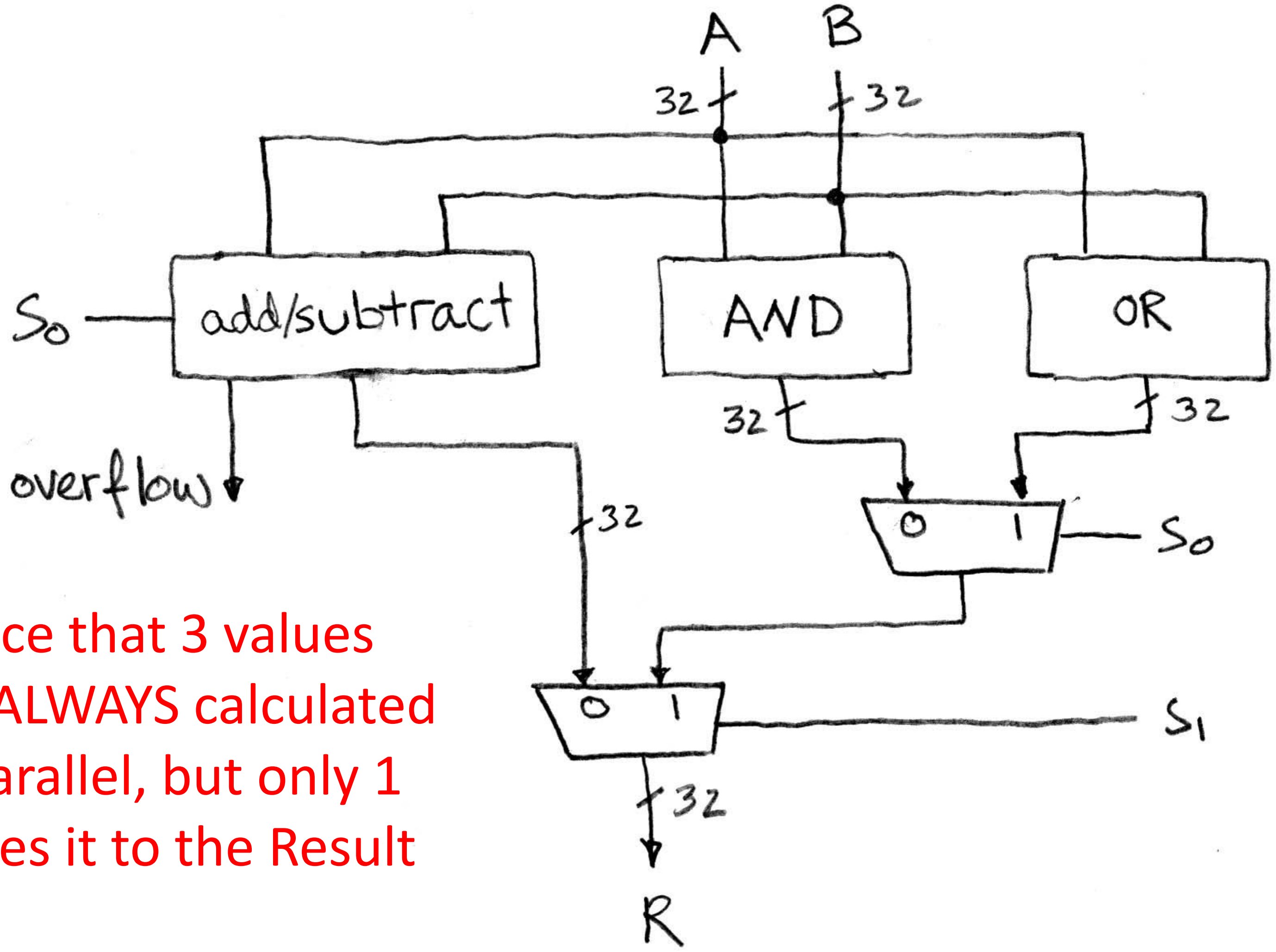
- Processors contain a special logic block called the "Arithmetic and Logic Unit" (ALU)
  - Here's an easy one that does ADD, SUB, bitwise AND, and bitwise OR (for 32-bit numbers)

- **Schematic:**



when S=00, R = A+B
when S=01, R = A−B
when S=10, R = A&B
when S=11, R = A|B

Simple ALU Schematic



Notice that 3 values are ALWAYS calculated in parallel, but only 1 makes it to the Result

1-bit Adders in Verilog

- What's wrong with this?
  - Truncation!

```
module halfadd1 (s, a, b);
  output logic s;
  input  logic a, b;

  always_comb begin
    s = a + b;
  end
endmodule
```

- Fixed:
  - Use of `{sig, …, sig}` for *concatenation*

```
module halfadd2 (c, s, a, b);
  output logic c, s;
  input  logic a, b;

  always_comb begin
    {c, s} = a + b;
  end
endmodule
```

Ripple-Carry Adder in Verilog

```
module fulladd (cout, s, cin, a, b);
  output logic cout, s;
  input  logic cin, a, b;

  always_comb begin
    {cout, s} = cin + a + b;
  end
endmodule
```

- Chain full adders?

```
module add2 (cout, s, cin, a, b);
  output logic cout; output logic [1:0] s;
  input  logic cin;  input  logic [1:0] a, b;
  logic  c1;

  fulladd b1 (cout, s[1], c1,  a[1], b[1]);
  fulladd b0 (c1,   s[0], cin, a[0], b[0]);
endmodule
```

Add/Sub in Verilog (parameterized)

- Variable-width add/sub (with overflow, carry)

```
module addN #(parameter N=32) (OF, CF, S, sub, A, B);
  output logic         OF, CF;
  output logic [N-1:0] S;
  input  logic         sub;
  input  logic [N-1:0] A, B;
  logic  [N-1:0] D;    // possibly flipped B
  logic          C2;   // second-to-last carry-out

  always_comb begin
    D = B ^ {N{sub}};  // replication operator
    {C2, S[N-2:0]} = A[N-2:0] + D[N-2:0] + sub;
    {CF, S[N-1]} = A[N-1] + D[N-1] + C2;
    OF = CF ^ C2;
  end
endmodule  // addN
```

  - Here using OF = overflow flag, CF = carry flag (from condition flags in x86-64 CPUs)

Add/Sub in Verilog (parameterized)

```
module addN_tb ();
  parameter N = 4;
  logic          sub;
  logic [N-1:0] A, B;
  logic          OF, CF;
  logic [N-1:0] S;

  addN #(.N(N)) dut (.OF, .CF, .S, .sub, .A, .B);

  initial begin
    #100;  sub = 0;  A = 4'b0101;  B = 4'b0010;  //  5 +  2
    #100;  sub = 0;  A = 4'b1101;  B = 4'b1011;  // -3 + -5
    #100;  sub = 0;  A = 4'b0101;  B = 4'b0011;  //  5 +  3
    #100;  sub = 0;  A = 4'b1001;  B = 4'b1110;  // -7 + -2
    #100;  sub = 1;  A = 4'b0101;  B = 4'b1110;  //  5 -(-2)
    #100;  sub = 1;  A = 4'b1101;  B = 4'b0101;  // -3 -  5
    #100;  sub = 1;  A = 4'b0101;  B = 4'b1101;  //  5 -(-3)
    #100;  sub = 1;  A = 4'b1001;  B = 4'b0010;  // -7 -  2
    #100;
  end
endmodule  // addN_tb
```