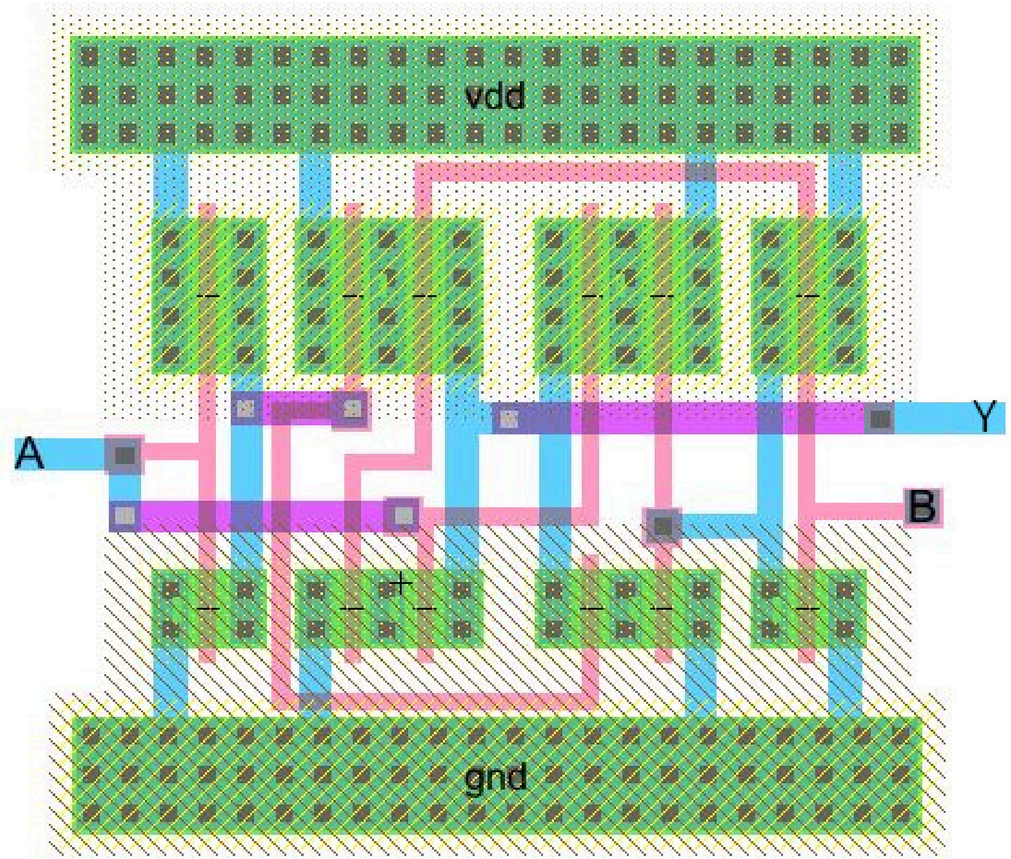
Hardware, part 1

Levels of abstraction in IC design

Levels of abstraction

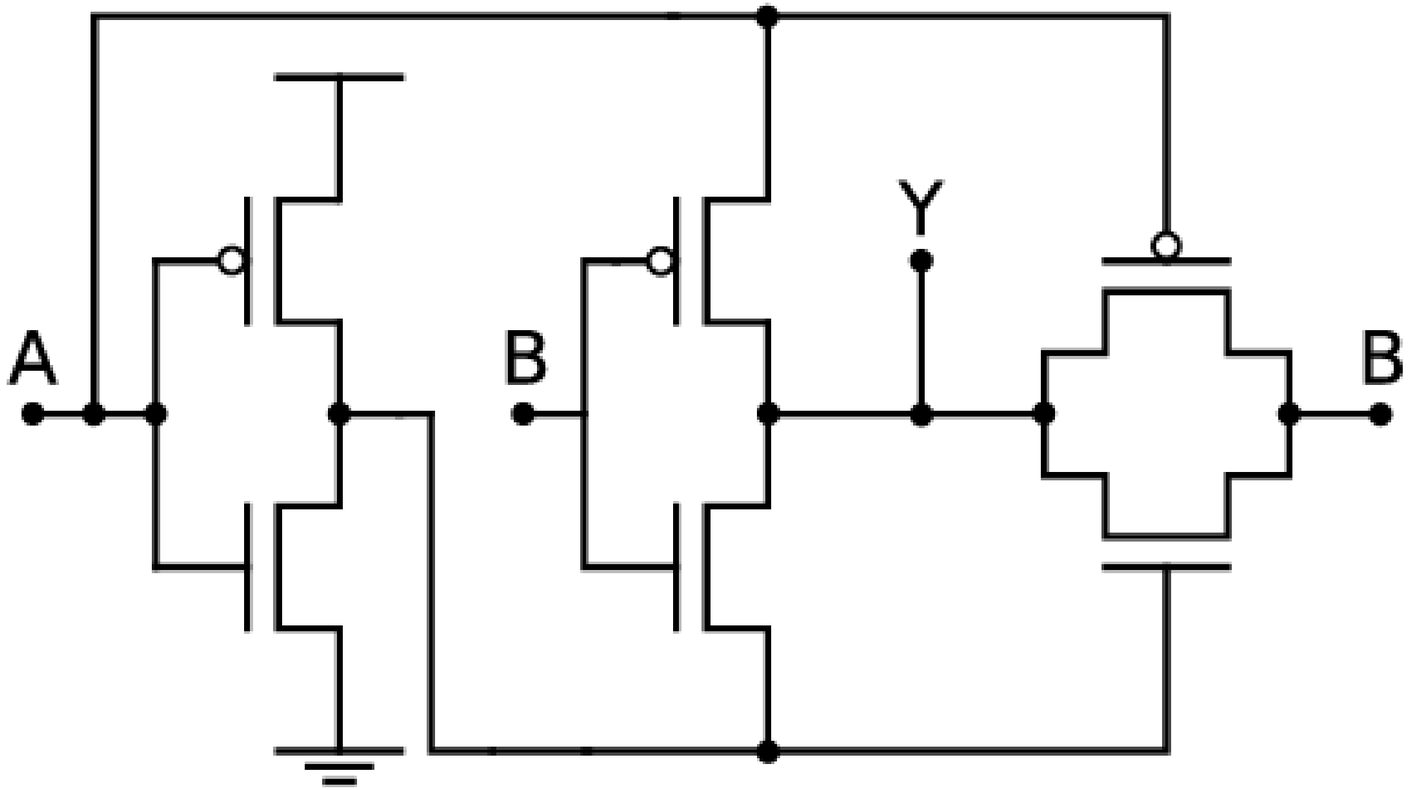
0. integrated circuit (IC) layout
1. transistors
2. logic gates
3. “intellectual property” (IP) block

0. IC layout



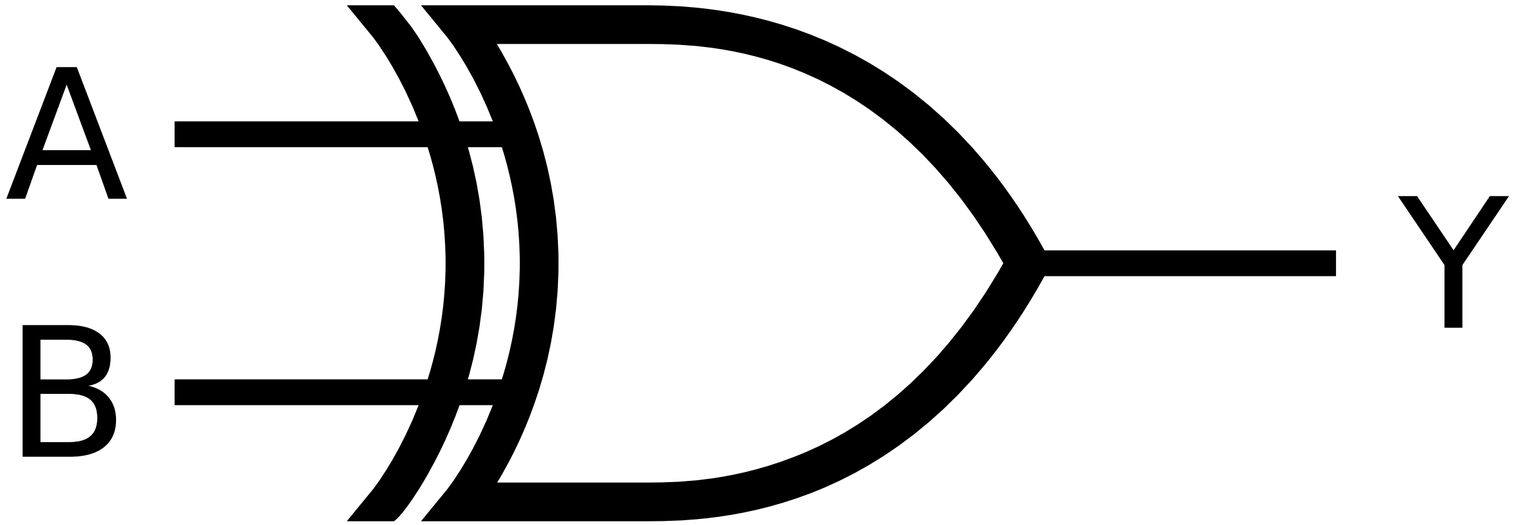
`Y := A xor B` (IC layout)

1. Transistors



`Y := A xor B` (transistors)

2. Logic gates



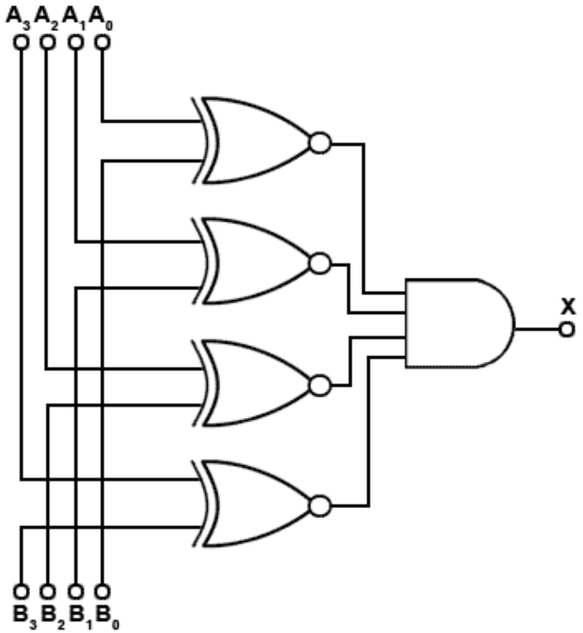
`Y := A xor B` (logic gate)

3. IP blocks

4-bit equality comparator:

$$\begin{aligned} \text{assuming} \quad \texttt{a} &= A_3 \times 2^3 + A_2 \times 2^2 + A_1 \times 2^1 + A_0 \times 2^0 \\ \text{and} \quad \texttt{b} &= B_3 \times 2^3 + B_2 \times 2^2 + B_1 \times 2^1 + B_0 \times 2^0 \end{aligned}$$

```
if a == b then x := 1
if a != b then x := 0
```



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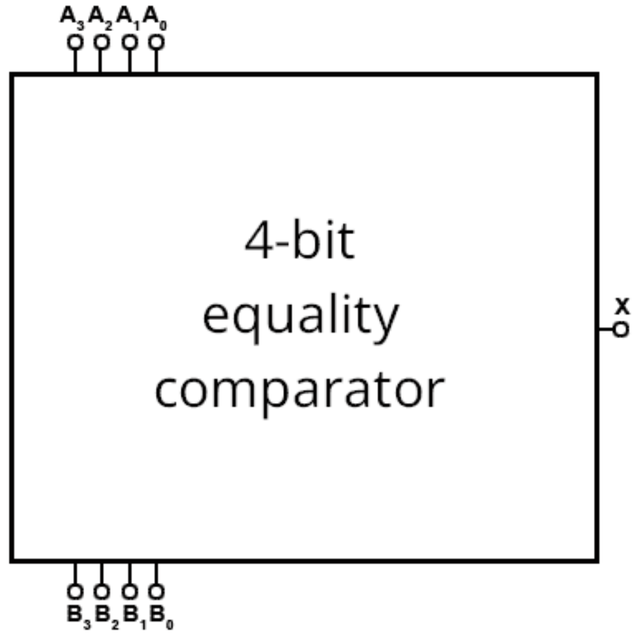

Example: n-bit addition

```
carry
a       …  0  1  1  0
b       …  0  1  1  1
-------------------------
a + b
```

Example: n-bit addition

carry				0	
a	…	0	1	1	0
b	…	0	1	1	1
a + b					1

Example: n-bit addition

carry			1	0	
a	…	0	1	1	0
b	…	0	1	1	1
a + b				0	1

Example: n-bit addition

carry		1	1	0	
a	…	0	1	1	0
b	…	0	1	1	1
a + b			1	0	1

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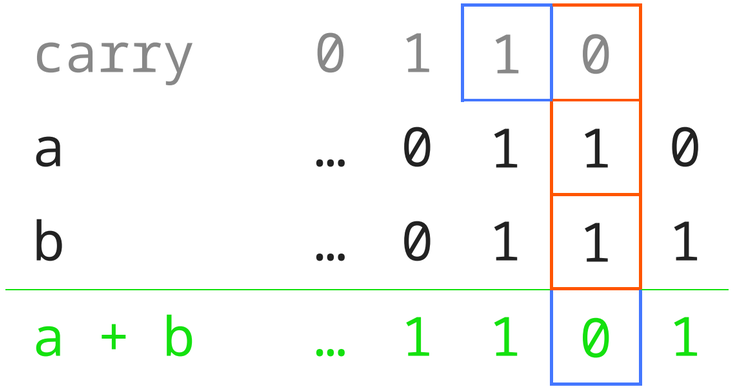
carry		0	1	1	0
a	…	0	1	1	0
b	…	0	1	1	1
a + b	…	1	1	0	1

Example: n-bit addition



The 1-bit “full adder”

- Input:
  - 1 bit of `carry`: C_{in}
  - 1 bit of a: A
  - 1 bit of b: B
- Output:
  - 1 bit of `carry`: C_{out}
  - 1 bit of the sum a + b: S
- Operation: Compute C_{out} and S such that

$$A + B + C_{\text{in}} = C_{\text{out}} \times 2 + S$$

carry	…	1	1	0	
a	…	0	1	1	0
b	…	0	1	1	1
a + b	…	1	1	0	1

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Truth table:

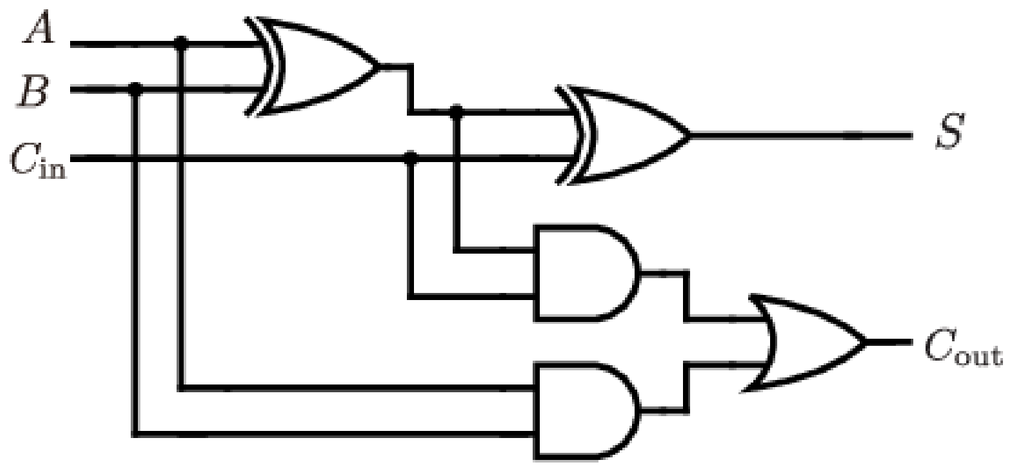
C_{in}	A	B	C_{out}	S
0	0	0	0	0
0	0	1	0	1
0	1	0	0	1
0	1	1	1	0
1	0	0	0	1
1	0	1	1	0
1	1	0	1	0
1	1	1	1	1

The 1-bit “full adder”

Boolean expressions:

- S := A xor B xor C_{in}
- C_{out} := (A and B) or ((A xor B) and C_{in})

Logic diagram:



Truth table:

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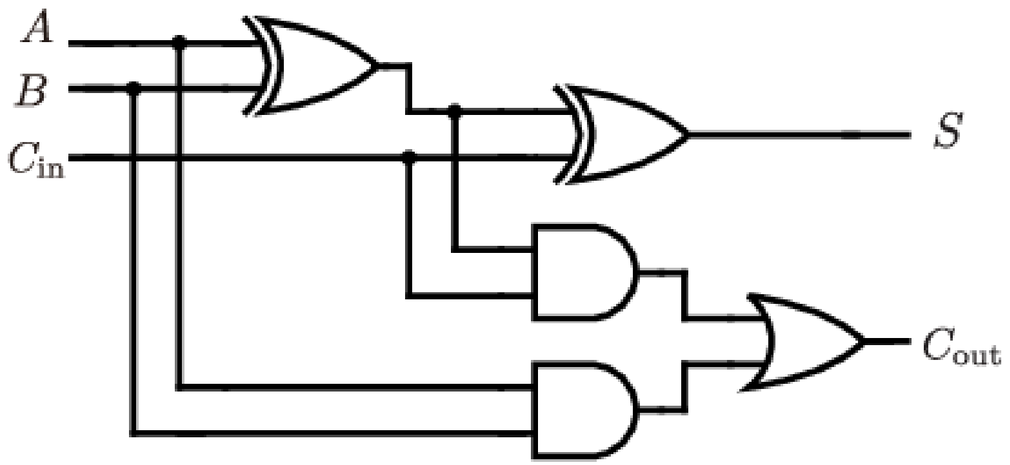
0	0	1	0	1
0	1	0	0	1
0	1	1	1	0
1	0	0	0	1
1	0	1	1	0
1	1	0	1	0
1	1	1	1	1

The 1-bit “full adder”

Notes:

- Called “full” in contrast to the “1-bit half adder” which has no C_{in}.
- There can be multiple valid Boolean expressions (and logic diagrams)



The 1-bit “full adder”

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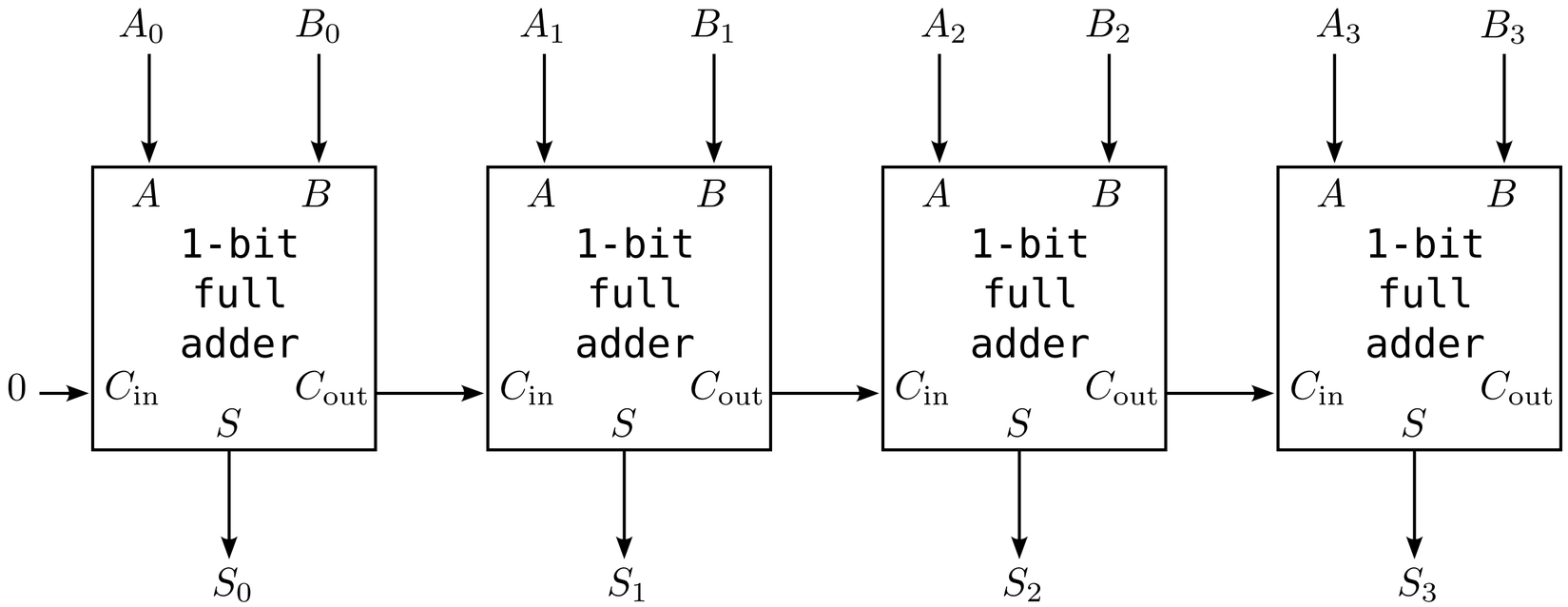
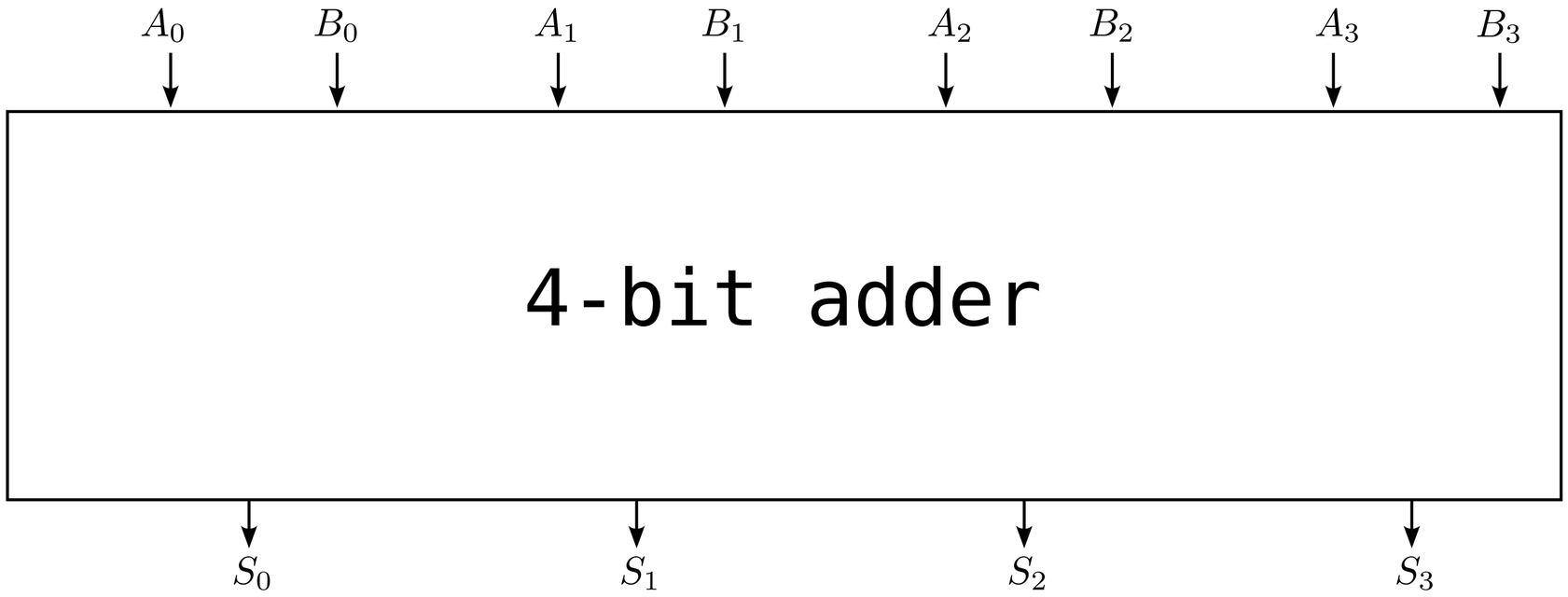
4-bit adder


A_0
B_0
A_1
B_1
A_2
B_2
A_3
B_3
A
B
1-bit full adder
C_{in}
C_{out}
S
0
S_0
S_1
S_2
S_3

4-bit adder



How IP blocks are designed

IP blocks are designed (and combined) in hardware description languages (“HDL”):

Verilog, VHDL and derivatives

HDL is then translated into IC layouts by specialized tools.

```
interface adder_if();
  logic        rstn;
  logic [7:0]  a;
  logic [7:0]  b;
  logic [7:0]  out;
  logic        carry;
endinterface

module adder(adder_if i);
  always_comb begin
    if (i.rstn) begin
      i.out <= 0;
      i.carry <= 0;
    end else begin
      {i.carry, i.out} <= i.a + i.b;
    end
  end
endmodule
```

SystemVerilog code for an 8-bit adder

The IC design and manufacturing industry

Foundries

- “**foundry**” or “fabrication plant” (“**fab**”): factory in which ICs are manufactured, and by extension, companies who own such plants (e.g. Intel, TSMC, Samsung).

- “**process node**”: marketing name given by foundries to a particular version of their manufacturing process – usually a “**feature size**”: the size of some parts of the transistors (e.g. 5nm, 7nm, etc.) – but not directly comparable across companies.

  Smaller tansistors means:

  - more transistors (per unit of area)
  - lower power consumption
  - faster ICs (propagation delay↓, power consumption↓, heat dissipation↓)

Types of industry players

- **fabless**: company that does not own fabrication plants (e.g. ARM, AMD, Apple, nVidia).

  Such companies either:

  - sell the designs of their IP blocks (ARM), or
  - subcontract foundries to manufacture their designs for them (AMD, Apple, nVidia).

- **“pure-play” foundries** (e.g. TSMC): foundries who manufacture other companies’ designs.

- **integrated device manufacturer (IDM)** (e.g. Intel): designs and manufactures its own ICs.

Recent history of the industry

- In the early 2000s, Intel (US), AMD (US) and IBM (US) have the best manufacturing technology. All three are IDMs – they design and manufacture in-house.

- Around 2008, AMD (US) spins off its foundry (as "GlobalFoundries") and became fabless.

  Note: first iPhone released in 2007 in the US

- In the 2010s, TSMC (Taiwan) emerges as a major foundry for Apple (US), nVidia (US) and AMD.

- In 2014, IBM sells its manufacturing business to GlobalFoundries.

- As of 2026, GlobalFoundries is still one of the largest pure-play foundries but it has fallen behind in terms of technology (by 5-10 years).

State of the industry

- Since ~2018, TSMC (Taiwan) has had the best process node, ahead of Samsung (Korea) and Intel (US).
- TSMC's advantage in large part due to early bet on extreme ultra-violet ("EUV") technology. Now, Samsung and Intel also use EUV tech.
- ASML (Netherlands) is currently the only supplier of production-grade EUV-capable machines.
- Apple (US), AMD (US), nVidia (US), Qualcomm (US) all mostly subcontract TSMC to fabricate their top-of-the-line ICs.

High-bandwidth memory

- SK hynix, Samsung, and Micron are currently the only manufacturers of top-of-the-line high-bandwidth memory
  - HBM3e (used in AMD MI300, and in nVidia Hopper and Blackwell)
  - HBM4 (used in AMD MI400 and later, and in upcoming nVidia Vera Rubin)

- All three rely on ASML's EUV machines.