EE1007E : Introduction to Digital Design and ICs

Lecture 2 – Design Process

At HotChips'19 Cerebras announced the largest chip in the world at 8.5 in x 8.5in with 1.2 trillion transistors, and 15kW of power, aimed for training of deep-learning neural networks

At HotChips'21, '22 and '23 they showed the next version in 7nm CMOS, with >2x transistor count

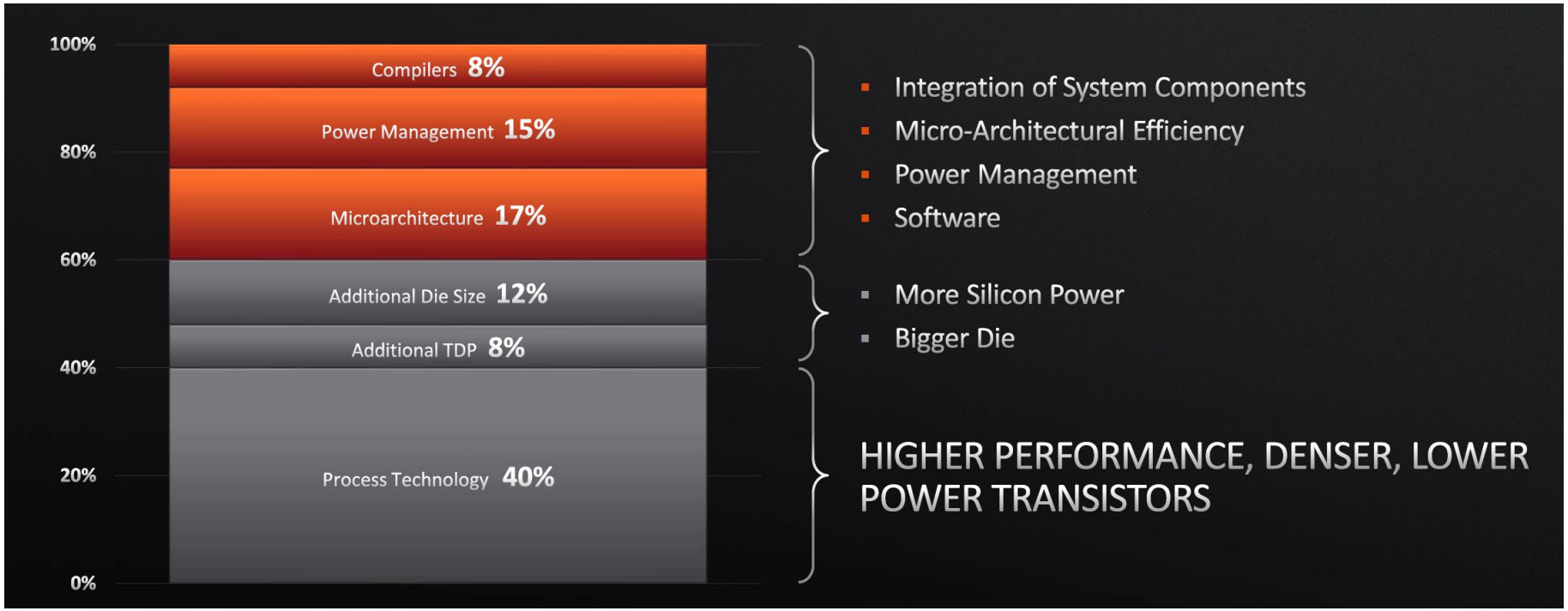
46,225 mm^2 silicon
2.6 Trillion transistors
850,000 AI optimized cores
40 Gigabytes on-chip memory
20 Petabyte/s memory bandwidth
220 Petabit/s fabric bandwidth
7nm Process technology at TSMC

Sean Lie,
HotChips'22

Review

- Moore's law is slowing down
  - There are continued improvements in technology, but at a slower pace
- Dennard's scaling has ended two decades ago
  - All designs are now power limited
- Specialization and customization provides added performance
  - Under power constraints and stagnant technology
- Design costs are high
  - Methodology and better reuse to rescue!
  - Abstraction, modularity, regularity are the keys
    - And creativity!

Putting it in Perspective



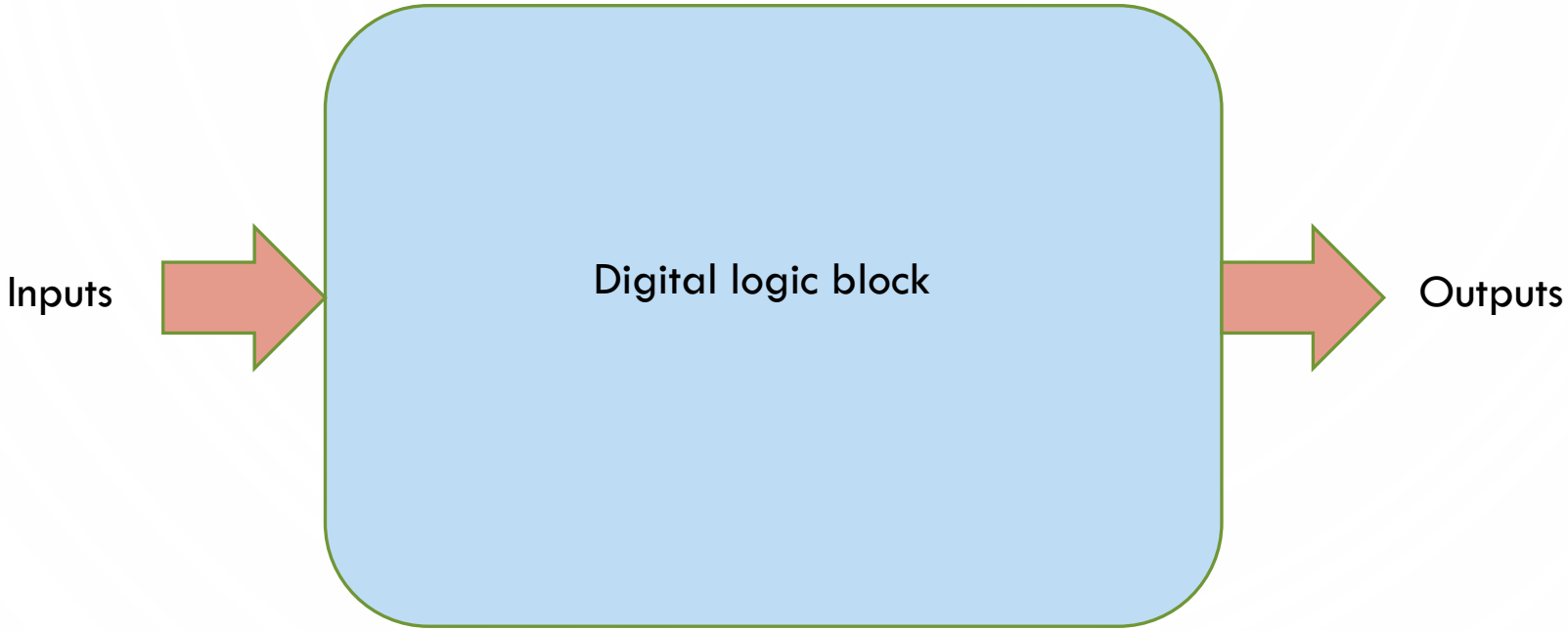
Performance gains
over the past decade

Lisa Su, HotChips'19 keynote

Digital Logic

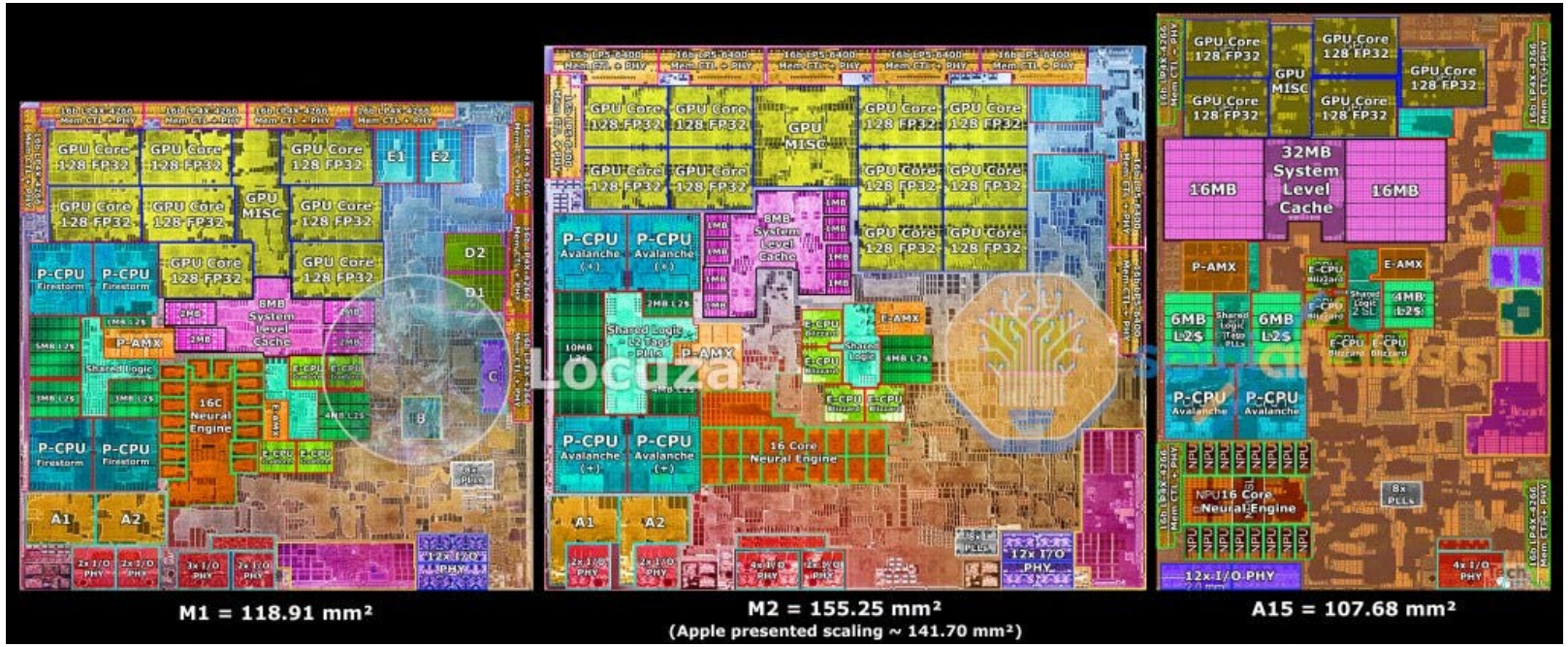
Implementing Digital Systems

- Digital systems implement a set of Boolean equations



- How do we actually implement a complex digital system?

Modern (Mostly) Digital Systems-On-A-Chip



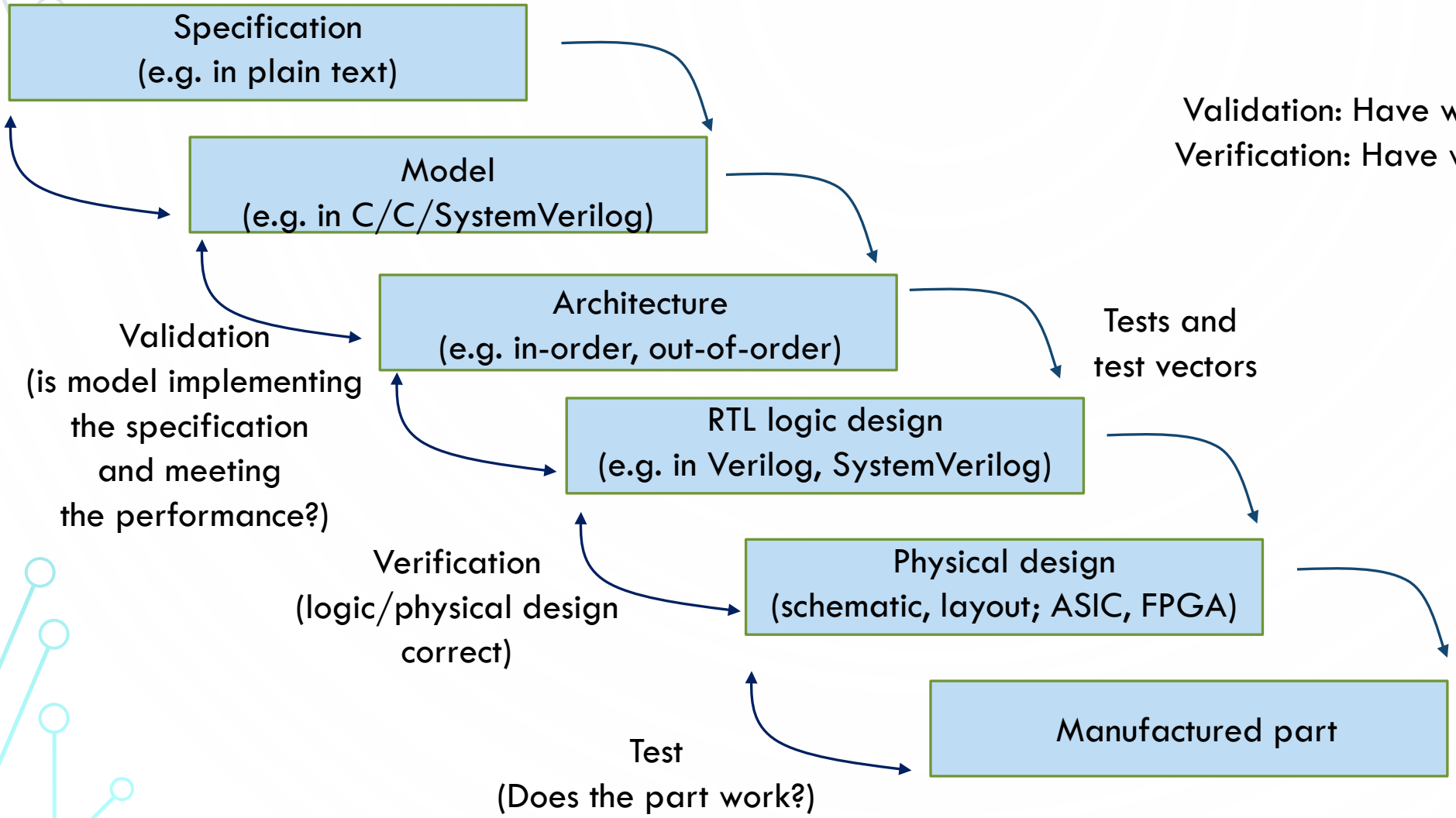
- Multiple large CPUs
- Multiple small CPUs
- GPU
- Neural processing unit (NPU)
- Lots of memory
- DDR memory interfaces

https://www.semianalysis.com/p/apple-m2-die-shot-and-architecture

- TSMC N5 (5nm-class) CMOS

Design Process

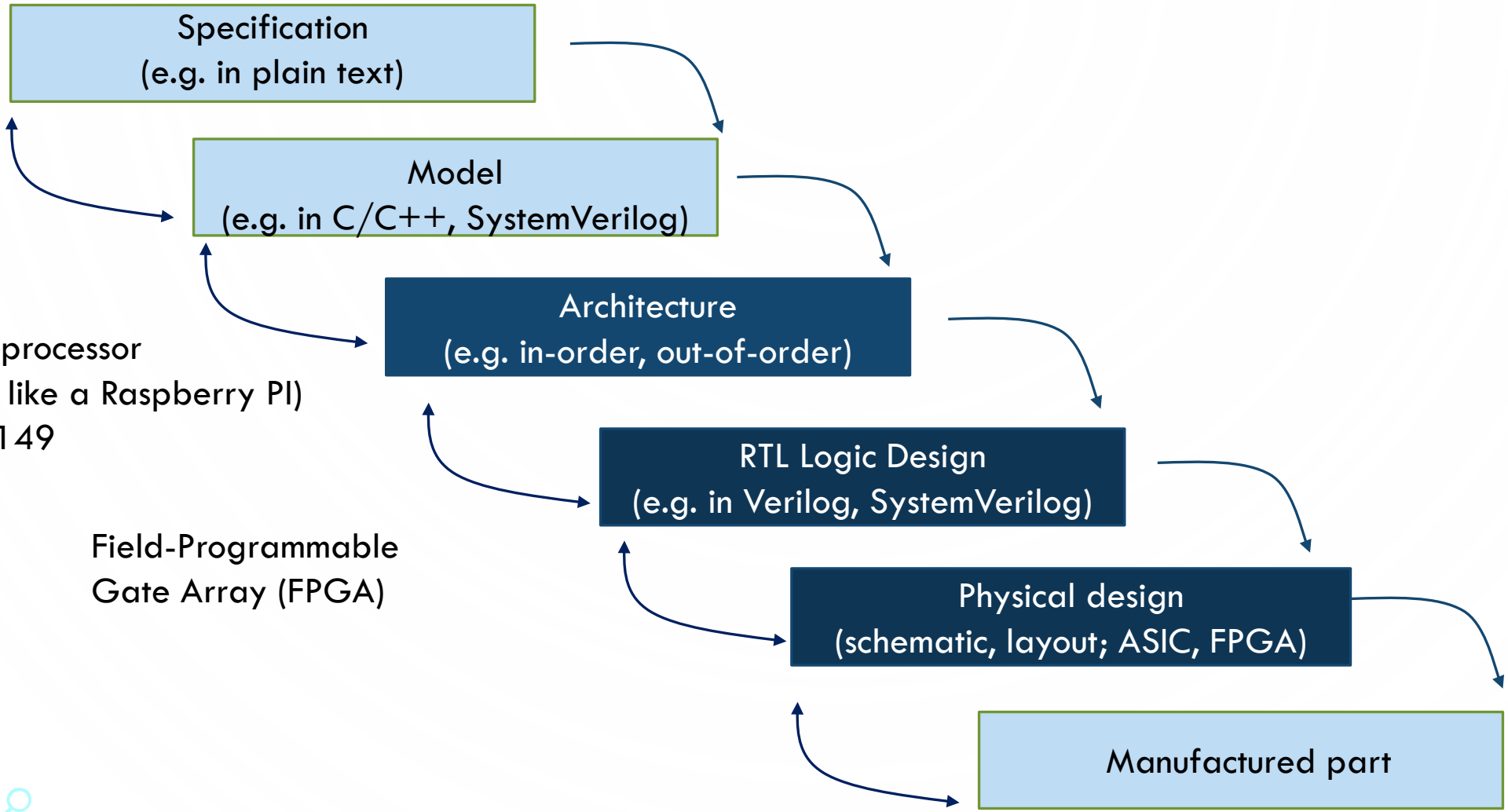
- Design through layers of abstractions



Validation: Have we built the right thing?
Verification: Have we built the thing right?

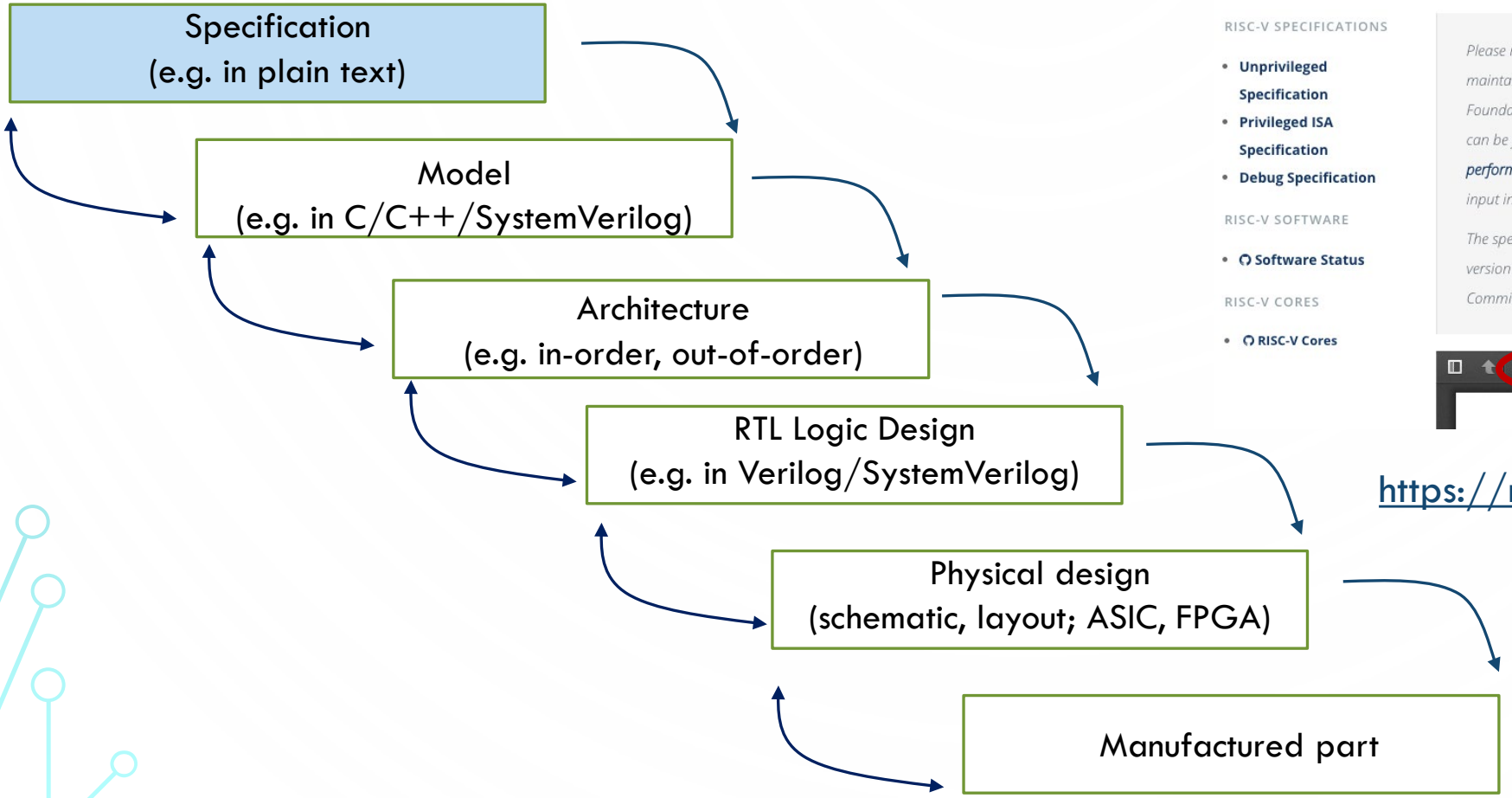
Design Abstractions in EECS151/251A

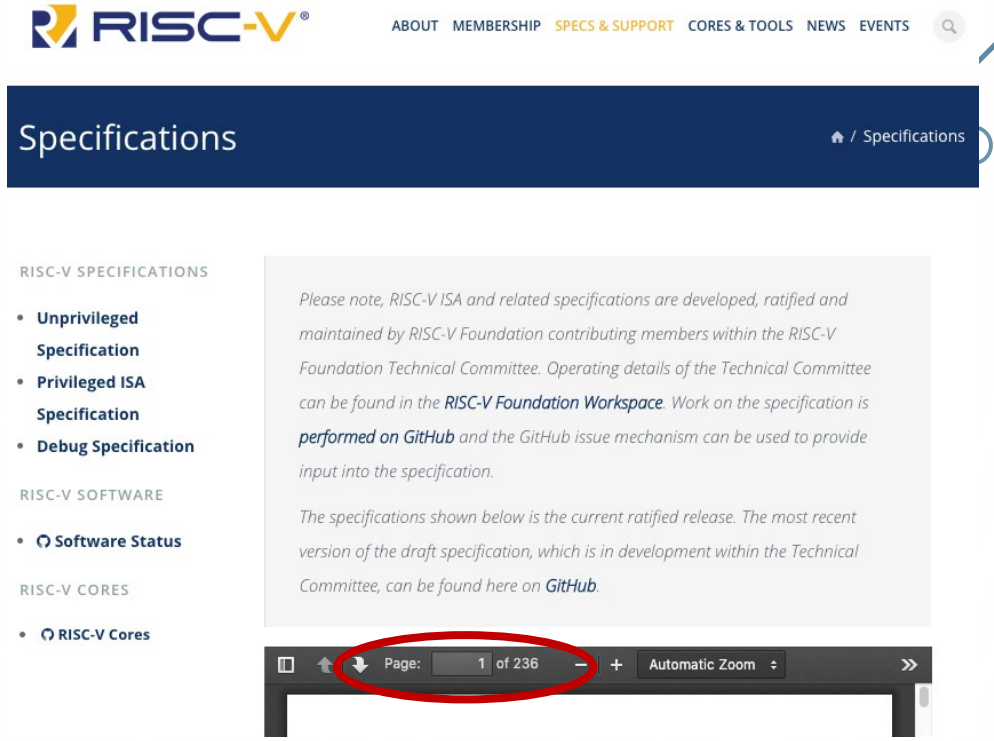
- Design through layers of abstractions



Example: RISC-V Design Process

- Design through layers of abstractions

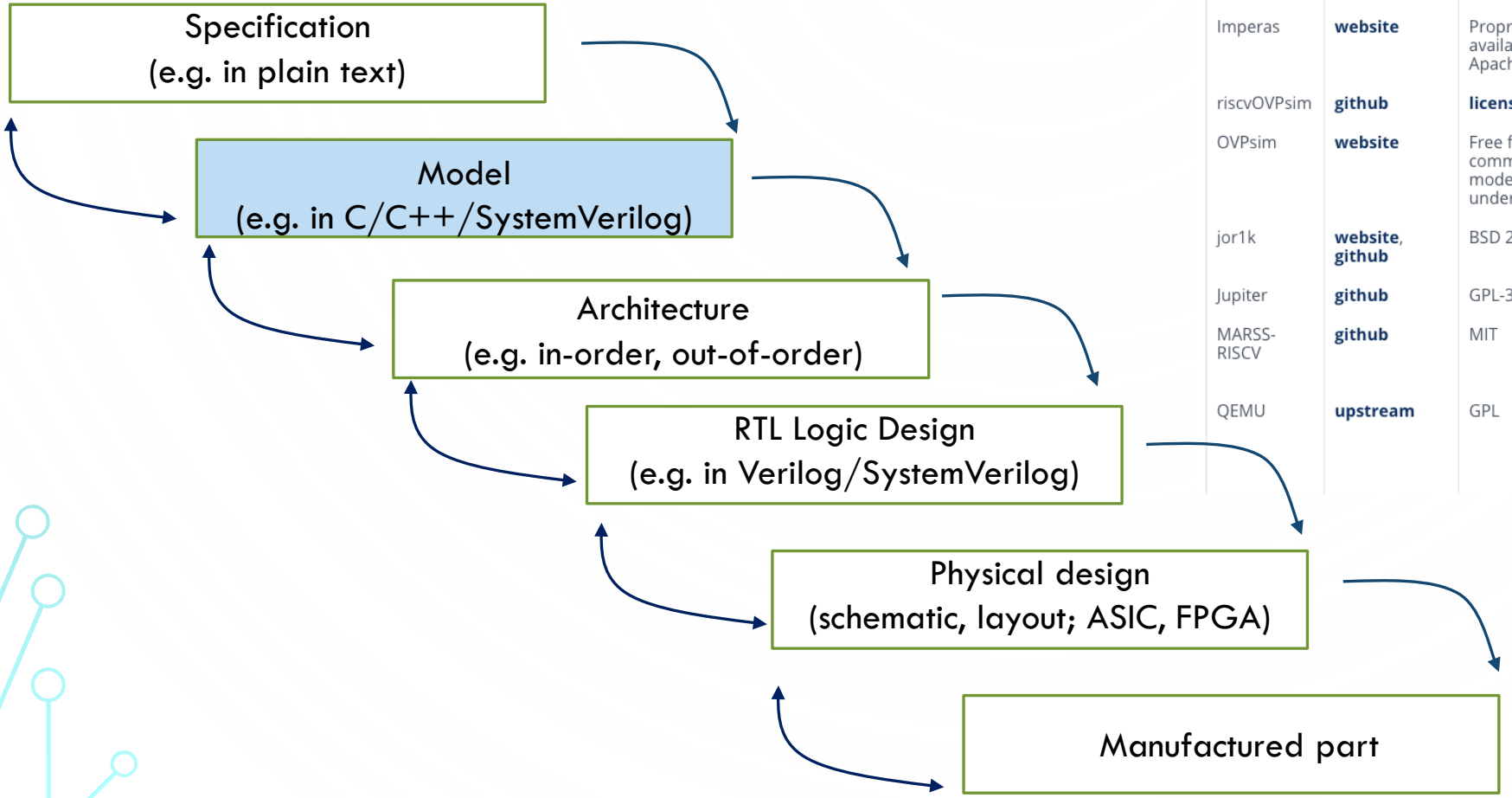




https://riscv.org/specifications/

Example: RISC-V Design Process

- Design through layers of abstractions



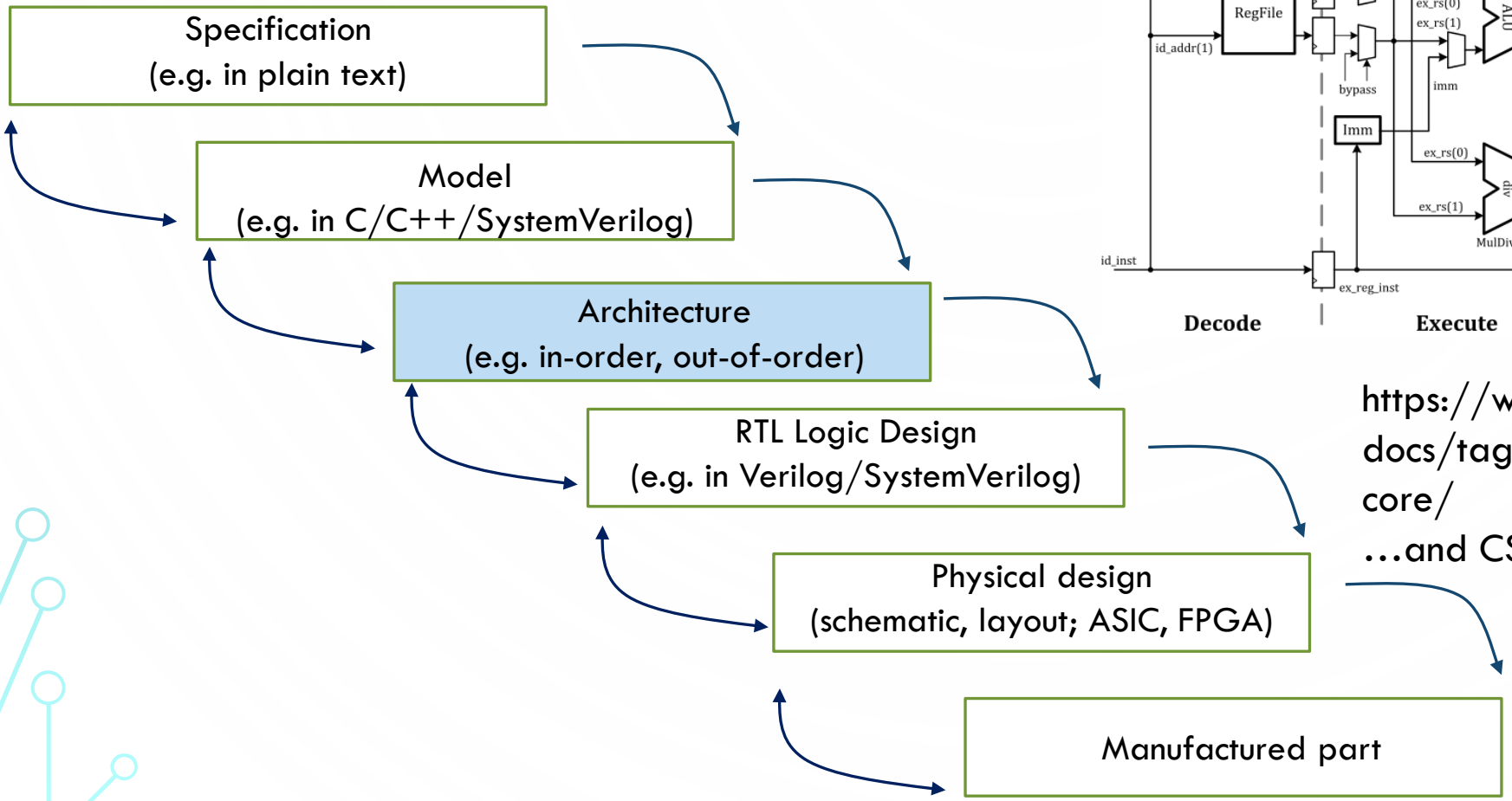
Simulators

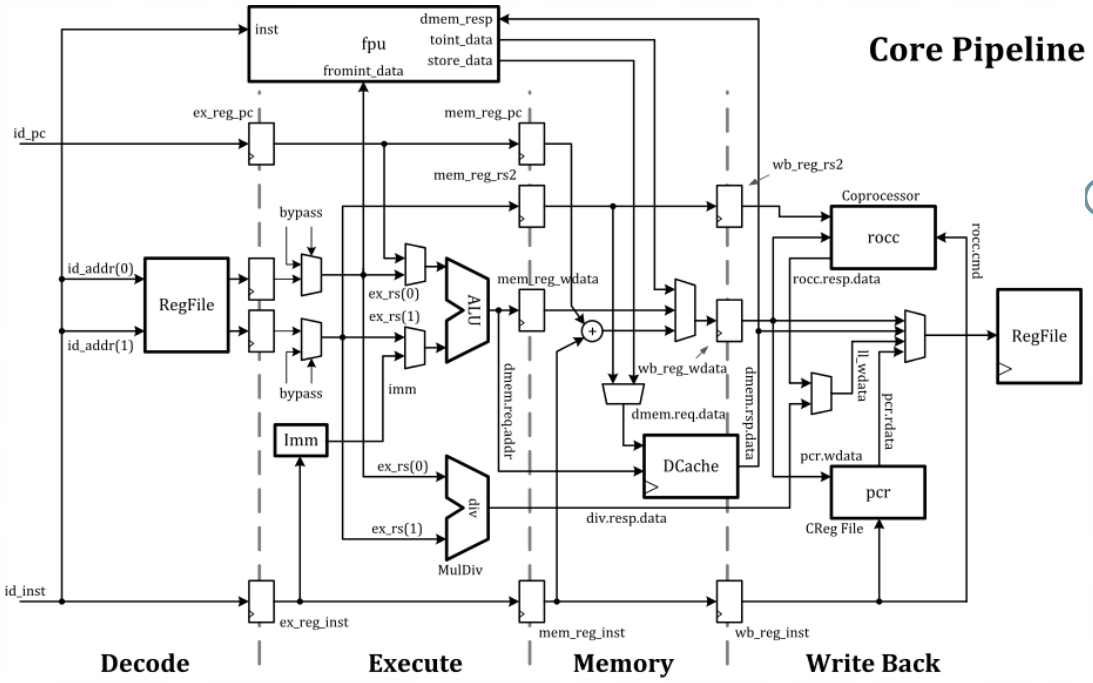
Name	Links	License	Maintainers
DBT-RISE-RISCV	**github**	BSD-3-Clause	**MINRES Technologies**
FireSim	**website**, **mailing list**, **github**, **ISCA 2018 Paper**	BSD	Sagar Karandikar, Howard Mao, Donggyu Kim, David Biancolin, Alon Amid, **Berkeley Architecture Research**
gem5	**SW-dev thread**, **repository**	BSD-style	Alec Roelke (University of Virginia)
Imperas	**website**	Proprietary, models available under Apache 2.0	**Imperas**
riscvOVPsim	**github**	**license**	**Imperas**
OVPsim	**website**	Free for non commercial use, models available under Apache 2.0	**Imperas**
jor1k	**website**, **github**	BSD 2-Clause	Sebastian Macke
Jupiter	**github**	GPL-3.0	Andrés Castellanos
MARSS-RISCV	**github**	MIT	Gaurav N Kothari, Parikshit P Sarnaik, Gokturk Yuksek (State University of New York at Binghamton)
QEMU	**upstream**	GPL	Sagar Karandikar (University of California, Berkeley), Bastian Koppelmann (University of Paderborn), Alex Suykov, Stefan O'Rear and Michael Clark (SiFive)

https://riscv.org/software-status/#simulators

Example: RISC-V Design Process

- Design through layers of abstractions

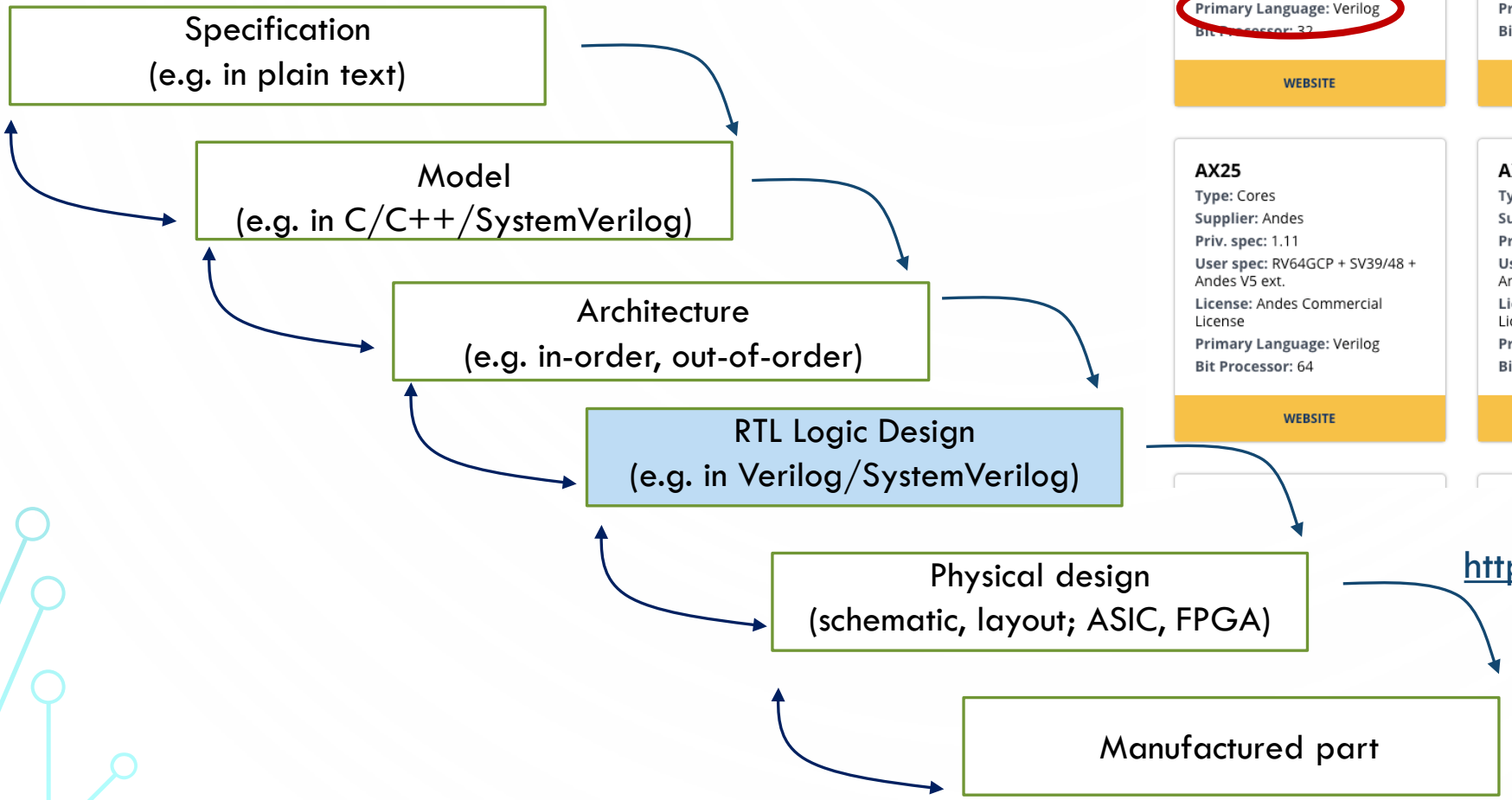


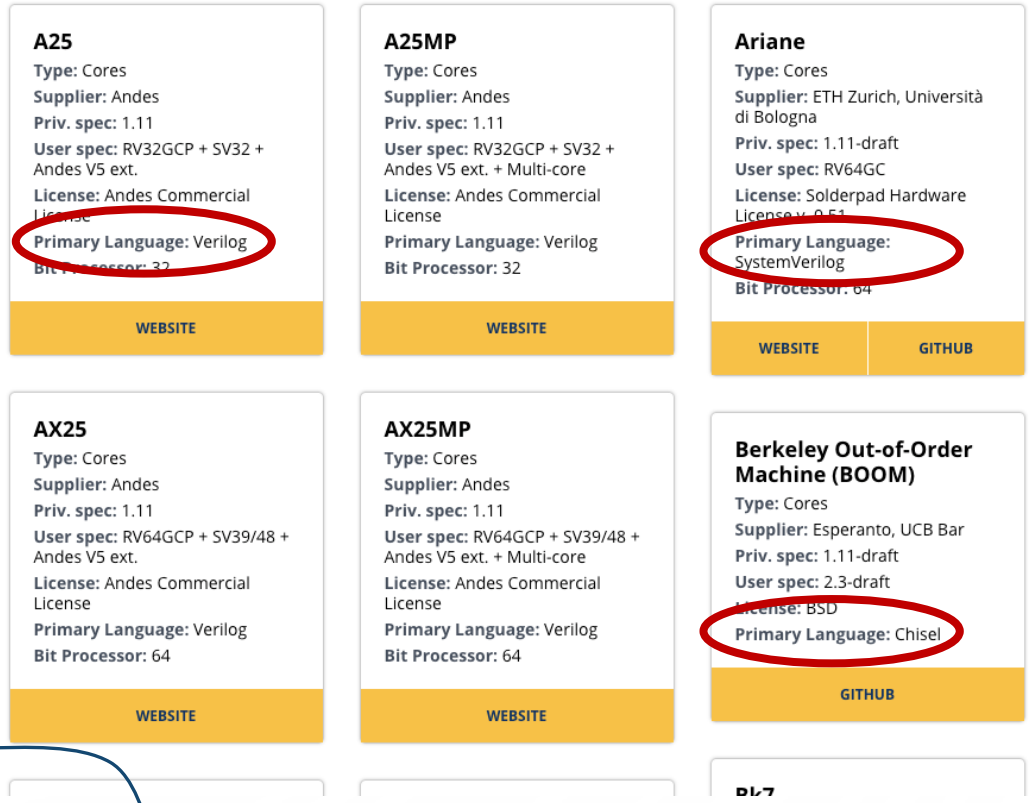


https://www.lowrisc.org/docs/tagged-memory-v0.1/rocket-core/
…and CS152

Example: RISC-V Design Process

- Design through layers of abstractions

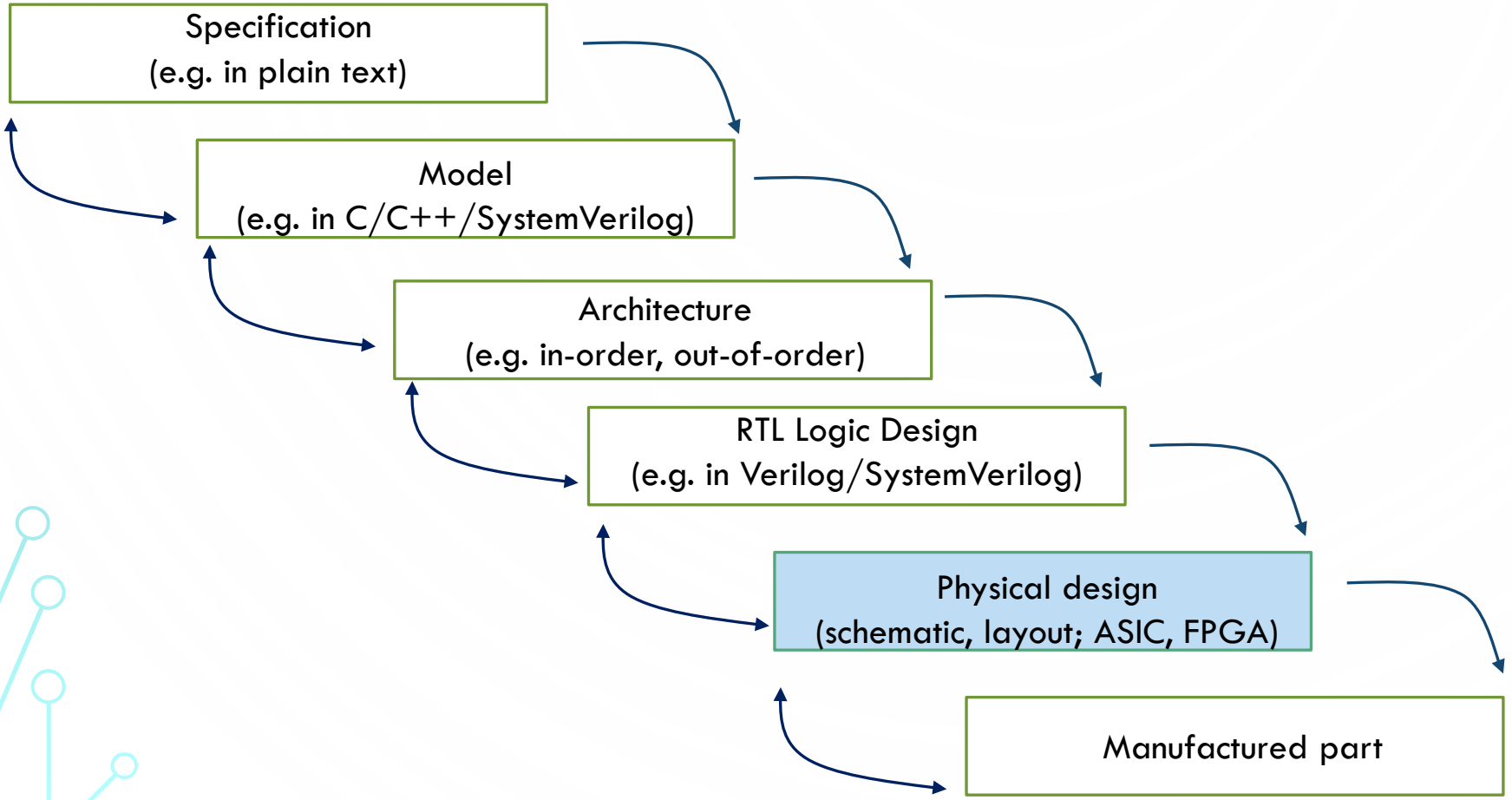


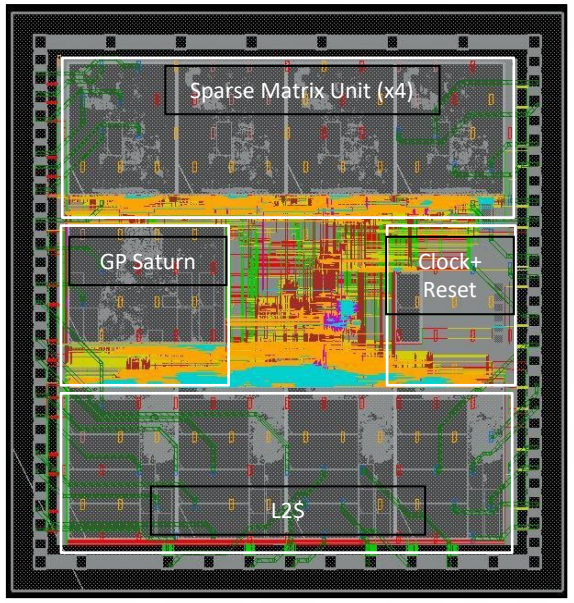


https://riscv.org/risc-v-cores/

Example: RISC-V Design Process

- Design through layers of abstractions

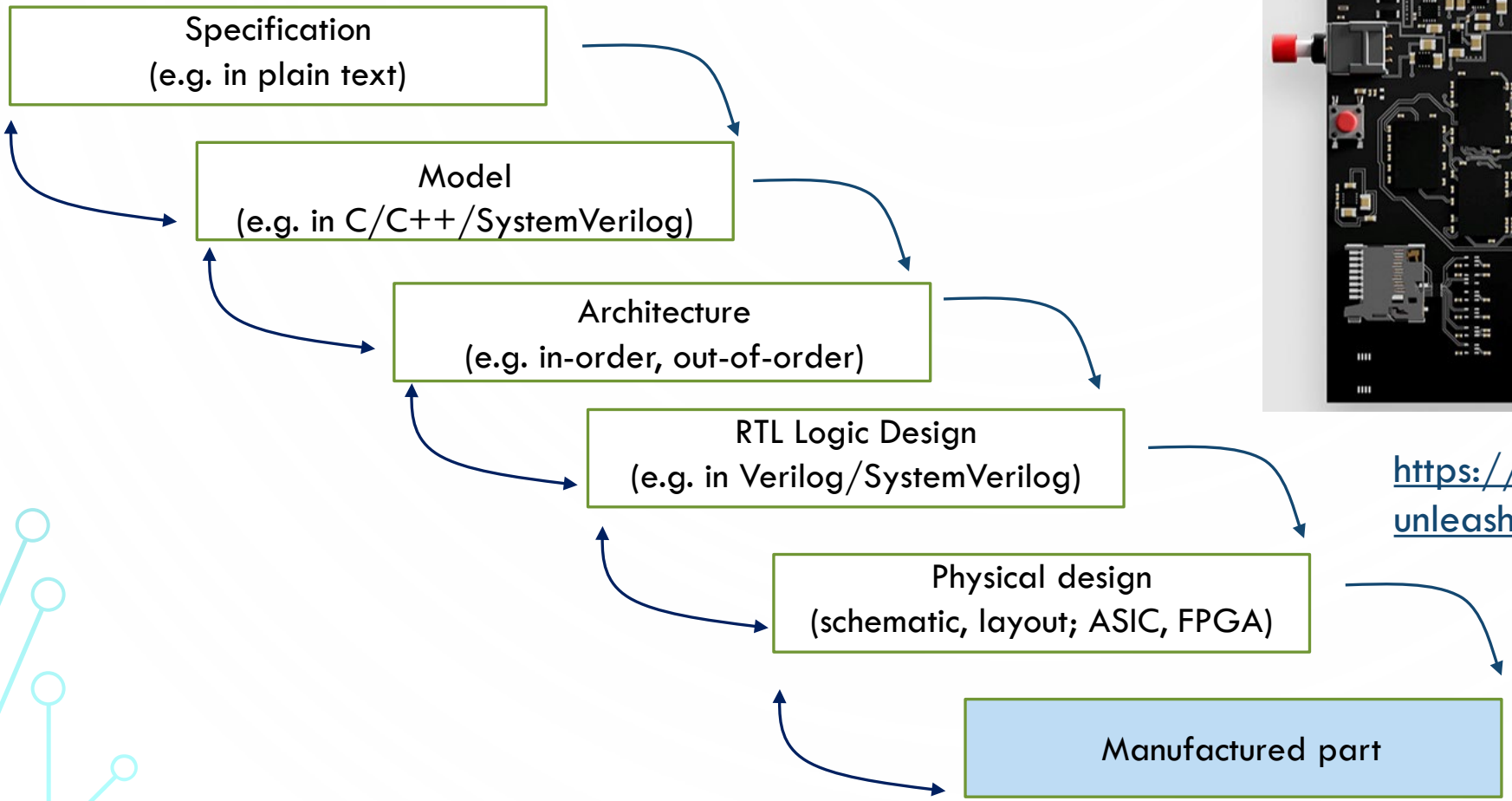


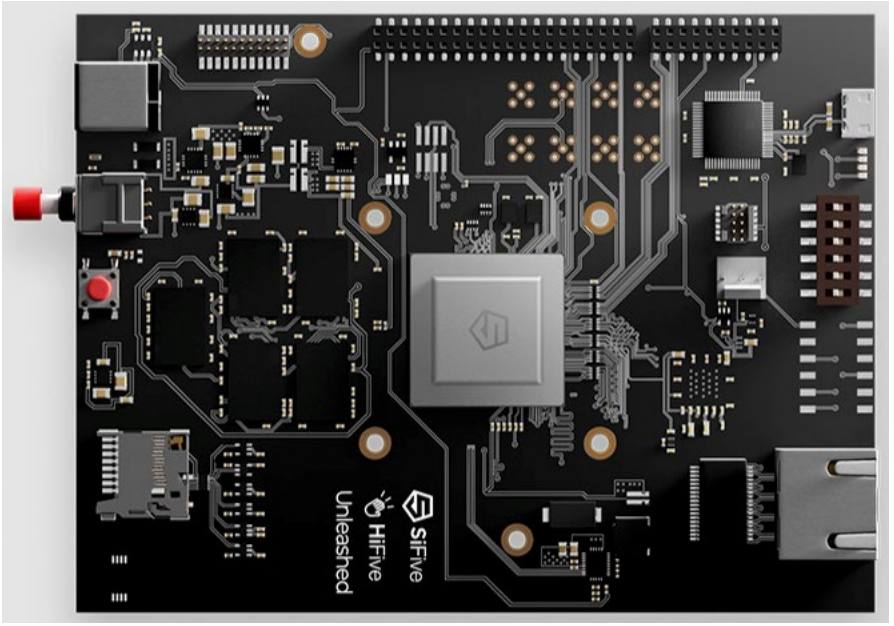


S'22 Class chip
(HotChips'23)

Example: RISC-V Design Process

- Design through layers of abstractions





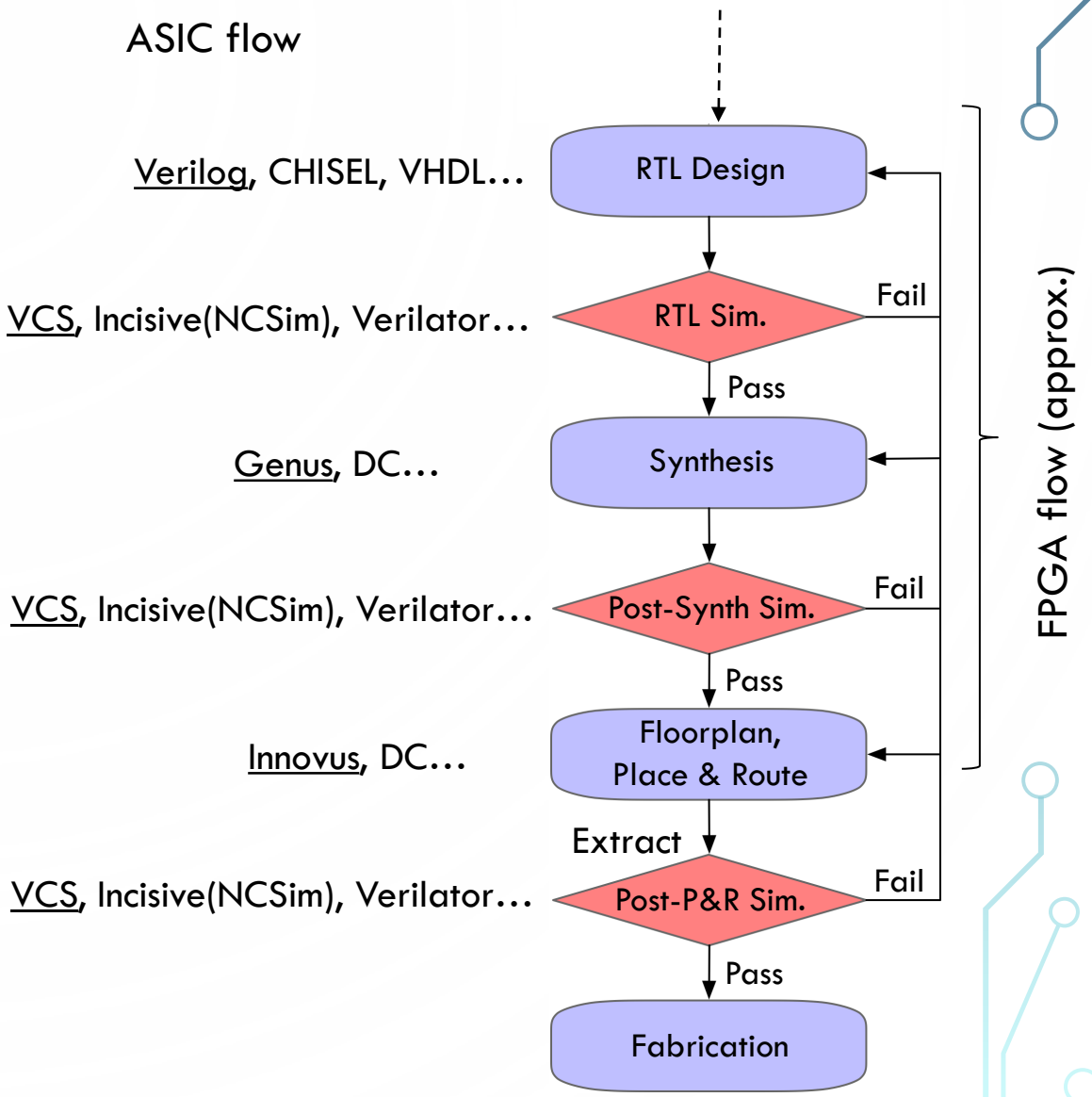
https://www.sifive.com/boards/hifive-unleashed

RTL → Physical Design

RTL Logic Design
(e.g. in Verilog/SystemVerilog)

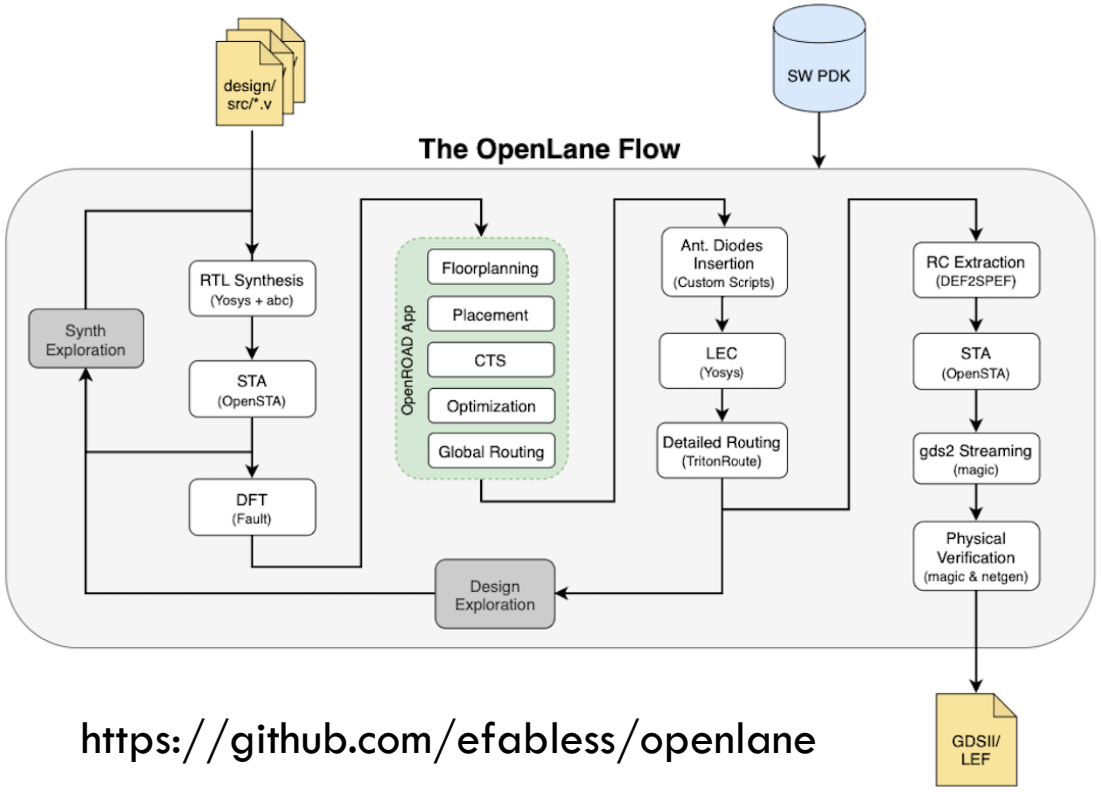
→ Physical design
(schematic, layout; ASIC, FPGA)

- Labs focus on a process of translating RTL to physical ASIC or FPGA by using industry-standard tools.
- Explores the entire design stack.

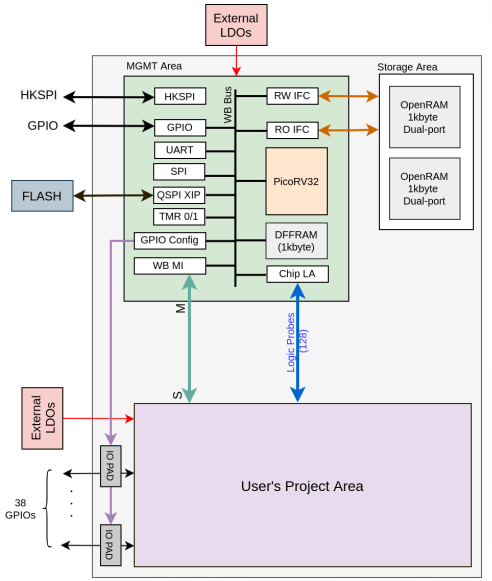


Open-Source Flows

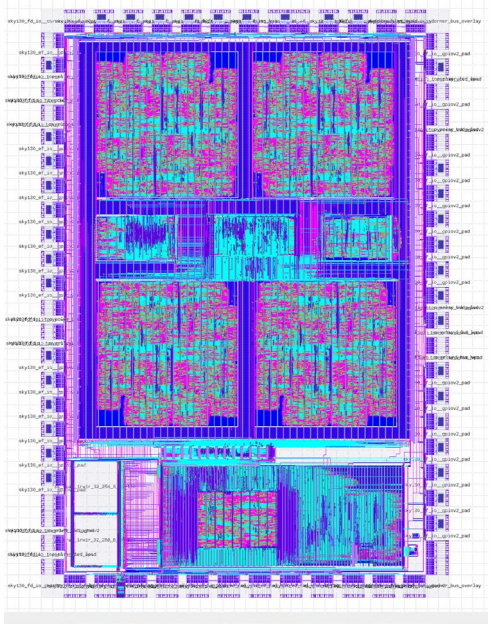
- SkyWater 130nm is an open-source design kit
- OpenROAD (UCSD) and OpenLane (eFabless) are open-source design flows
  - Work with Sky130
  - ASIC labs can target SkyWater130nm with commercial tools



https://github.com/efabless/openlane



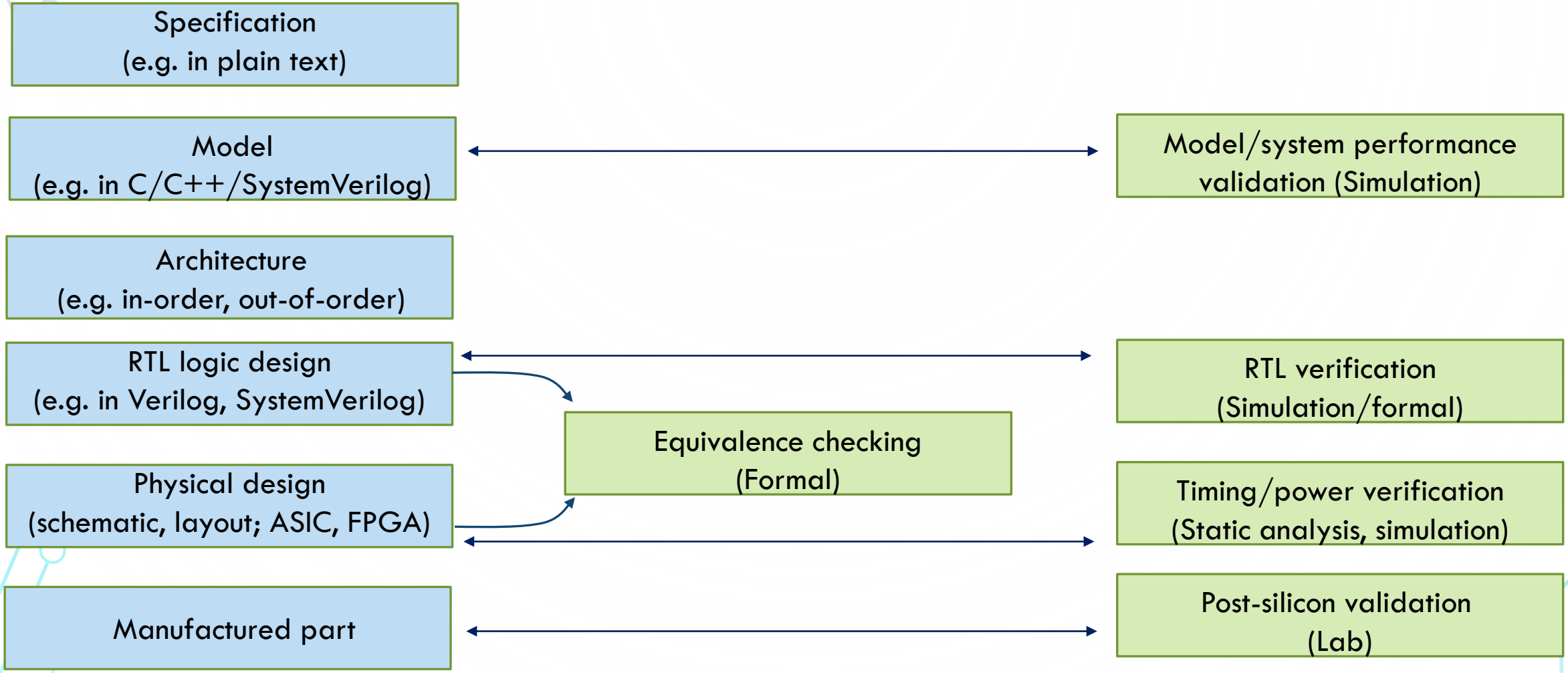
https://github.com/efabless/caravel

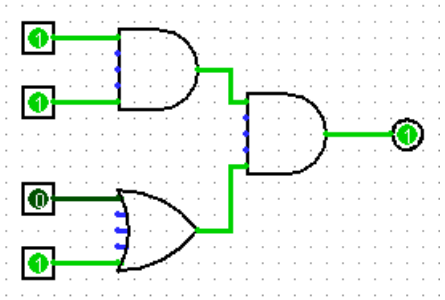


https://efabless.com/projects/35

Design, Verification and Validation

- Design steps
- Verification and validation steps

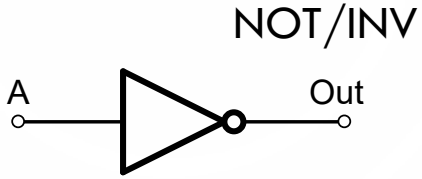
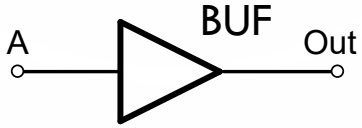
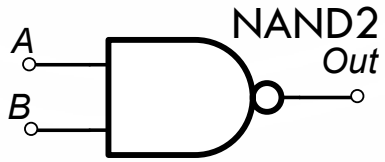
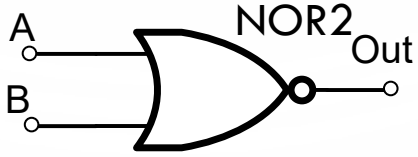




Boolean Logic in A Nutshell

Boolean Logic and Logic Gates (From CS61C/EE16B)

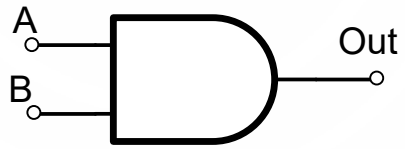
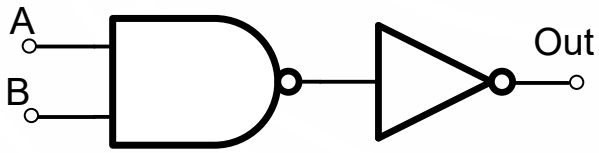
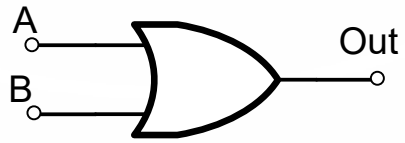
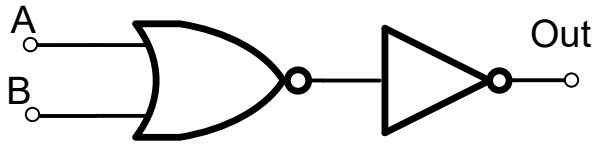
- Logic gates

Name	Boolean equation	Symbol	Truth table
NOT or Inverter	$Out = \overline{A}$		A | Out 0 | 1 1 | 0
Buffer	$Out = A$		A | Out 0 | 0 1 | 1
NAND	$Out = \overline{A \cdot B}$		A | B | Out 0 | 0 | 1 0 | 1 | 1 1 | 0 | 1 1 | 1 | 0
NOR	$Out = \overline{A + B}$		A | B | Out 0 | 0 | 1 0 | 1 | 0 1 | 0 | 0 1 | 1 | 0

Single input

- In CMOS, basic logic gates are inverting

More Logic Gates

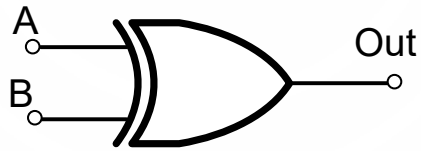
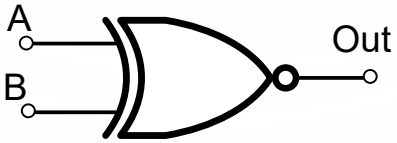
Name	Boolean equation	Symbol
AND	$Out = A \cdot B$	
In CMOS		
OR	$Out = A + B$	
In CMOS		

Truth table

A	B	Out
0	0	0
0	1	0
1	0	0
1	1	1

A	B	Out
0	0	0
0	1	1
1	0	1
1	1	1

More Logic Gates

Name	Boolean equation	Symbol
Exclusive OR XOR	$Out = A \oplus B$	
Exclusive NOR XNOR	$Out = \overline{A \oplus B}$	

Truth table

A	B	Out
0	0	0
0	1	1
1	0	1
1	1	0

A	B	Out
0	0	1
0	1	0
1	0	0
1	1	1

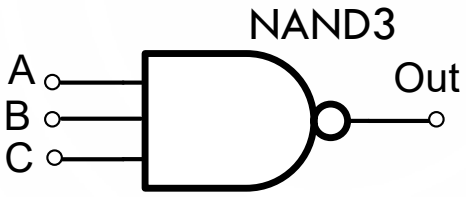
- XOR and XNOR are both inverting and non-inverting

Multi-Input Gates

3-Input NAND

NAND3 Boolean equation

$$\text{Out} = \overline{A \cdot B \cdot C}$$

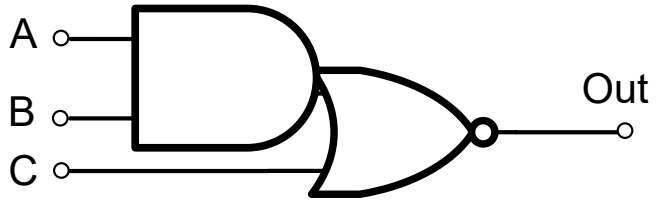


A	B	C	Out
0	0	0	1
0	0	1	1
0	1	0	1
0	1	1	1
1	0	0	1
1	0	1	1
1	1	0	1
1	1	1	0

And-Or-Invert

AOI21 Boolean equation

$$\text{Out} = \overline{A \cdot B + C}$$

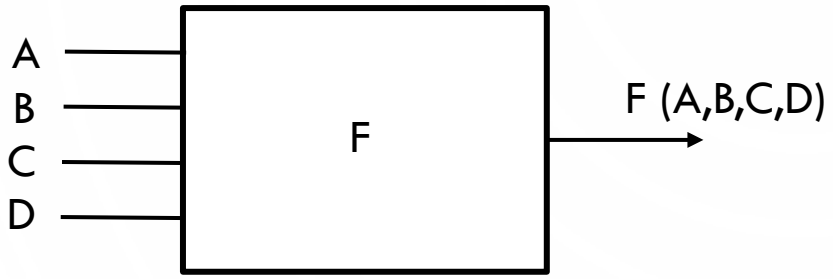


A	B	C	Out
0	0	0	1
0	0	1	0
0	1	0	1
0	1	1	0
1	0	0	1
1	0	1	0
1	1	0	0
1	1	1	0

- Single gate in modern CMOS usually doesn't have more than 3-4 inputs

Combinational Logic (CL) Blocks

Example four-input function:



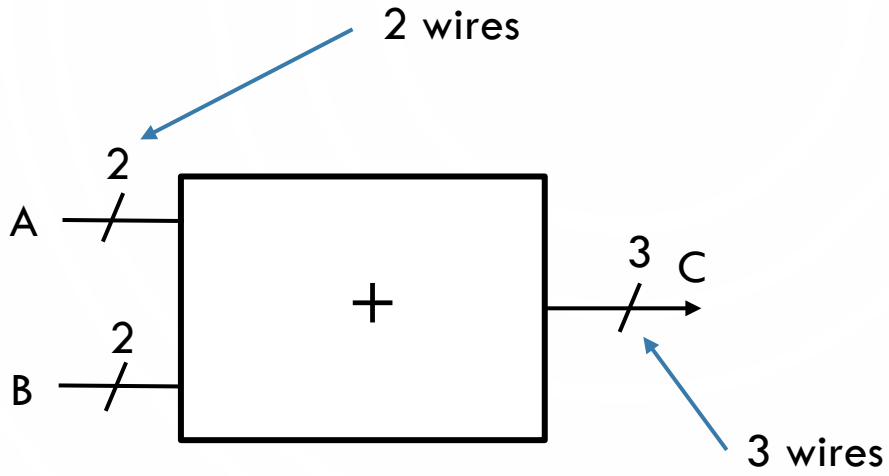
- Output a function only of the current inputs (no history).
- Truth-table representation of function. Output is explicitly specified for each input combination.
- In general, CL blocks have more than one output signal, in which case, the truth-table will have multiple output columns.

Truth Table

A	B	C	D	Out
0	0	0	0	F(0,0,0,0)
0	0	0	1	F(0,0,0,1)
0	0	1	0	F(0,0,1,0)
0	0	1	1	F(0,0,1,1)
0	1	0	0	F(0,1,0,0)
0	1	0	1	F(0,1,0,1)
0	1	1	0	F(0,1,1,0)
0	1	1	1	F(0,1,1,1)
1	0	0	0	F(1,0,0,0)
1	0	0	1	F(1,0,0,1)
1	0	1	0	F(1,0,1,0)
1	0	1	1	F(1,0,1,1)
1	1	0	0	F(1,1,0,0)
1	1	0	1	F(1,1,0,1)
1	1	1	0	F(1,1,1,0)
1	1	1	1	F(1,1,1,1)

Example CL Block

- 2-bit adder. Takes two 2-bit integers and produces 3-bit result.



A1	A0	B1	B0	C2 C1 C0
0	0	0	0	0 0 0
0	0	0	1	0 0 1
0	0	1	0	0 1 0
0	0	1	1	0 1 1
0	1	0	0	0 0 1
0	1	0	1	0 1 0
0	1	1	0	0 1 1
0	1	1	1	1 0 0
1	0	0	0	0 1 0
1	0	0	1	0 1 1
1	0	1	0	1 0 0
1	0	1	1	1 0 1
1	1	0	0	0 1 1
1	1	0	1	1 0 0
1	1	1	0	1 0 1
1	1	1	1	1 1 0

- Think about truth table for 32-bit adder. It's possible to write out, but it might take a while!

Theorem:
Any combinational logic function can be implemented as a network of simple logic gates.

Quiz

Total number of possible truth tables with 4 inputs is:

a) 4

b) 16

c) 256

d) 16,384

e) 65,536

f) None of the above

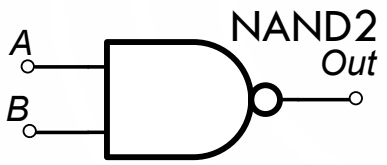
www.yellkey.com/notice

Logic Circuit

- A logic gate can be implemented in different ways

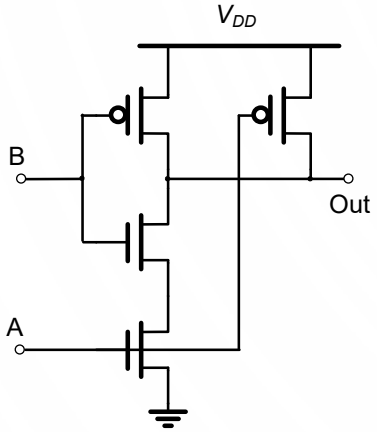
NAND

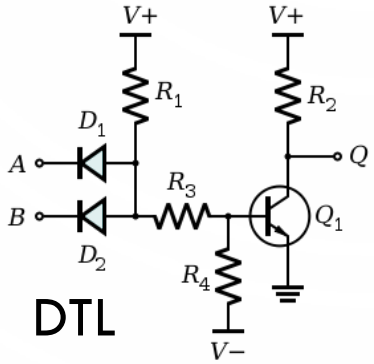
$$\text{Out} = \overline{A \cdot B}$$



A	B	Out
0	0	1
0	1	1
1	0	1
1	1	0

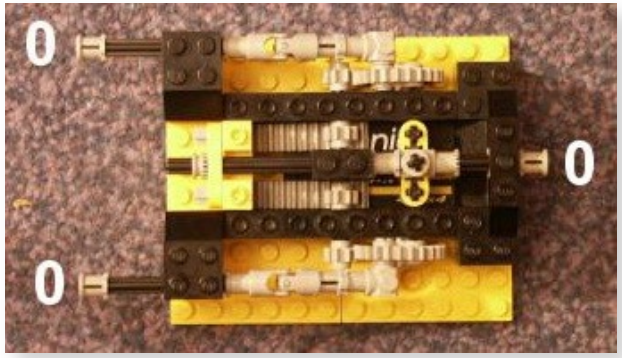
CMOS





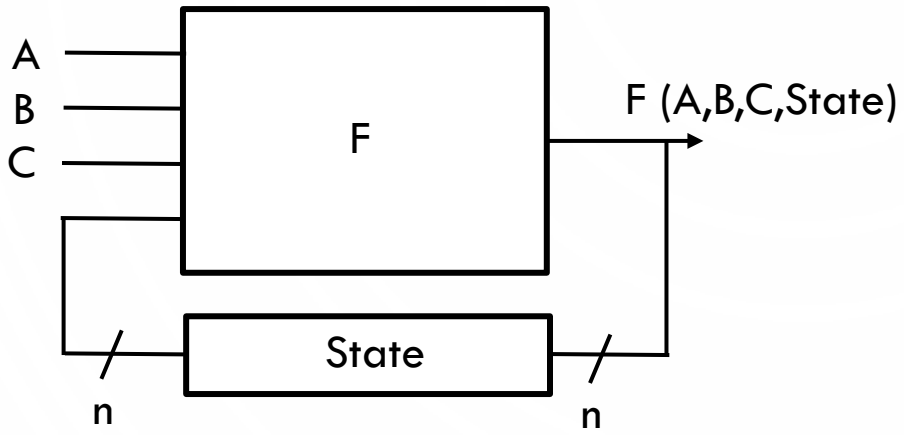
DTL

Sizing of transistors (W/L) in CMOS changes properties (delay, power, size) of a logic gate



Mechanical LEGO logic gates. A clockwise rotation represents a binary "one" while a counter-clockwise rotation represents a binary "zero."

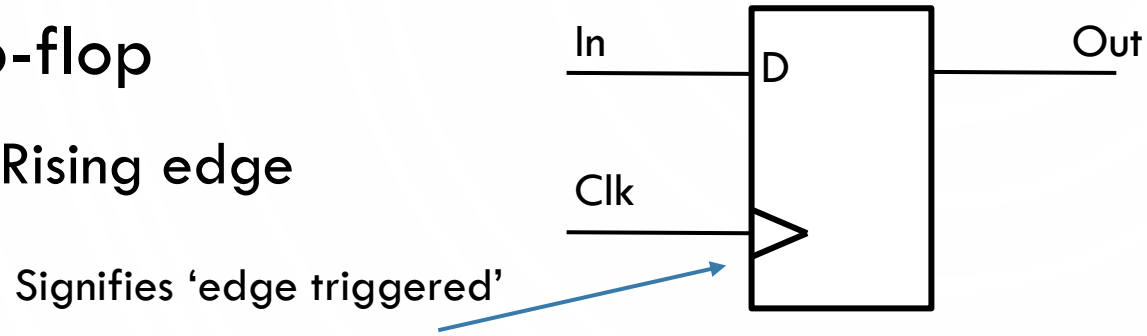
Sequential Logic Blocks



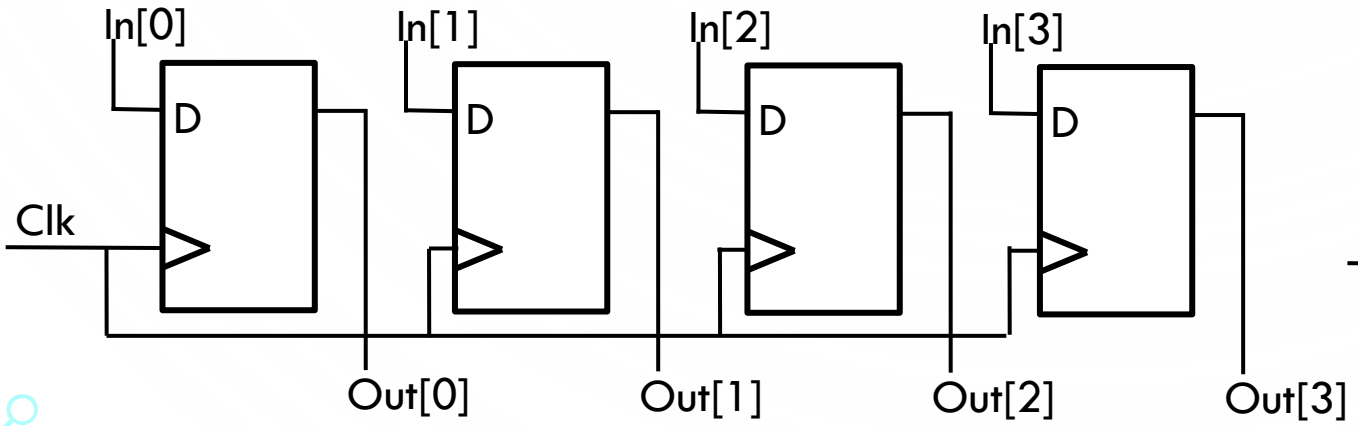
- Output is a function of both the current inputs and the state.
- State represents the memory.
- State is a function of previous inputs.
- In synchronous digital systems, state is updated on each clock tick.

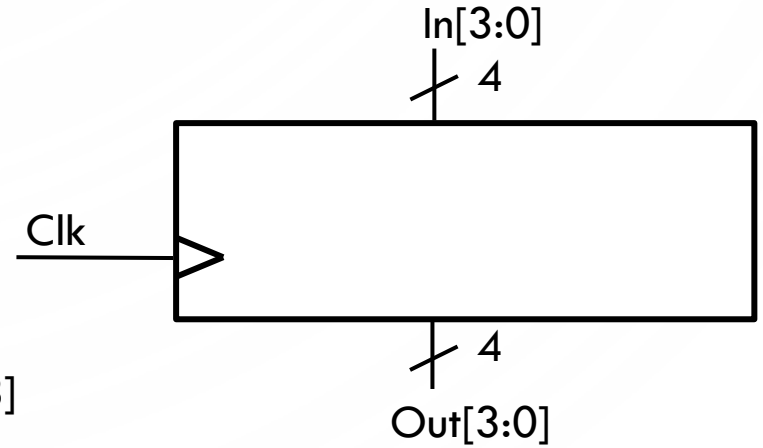
Flip-Flop as A Sequential Circuit

- Synchronous state element transfers its input to the output on a rising (or, rarely, falling) clock edge
- Flip-flop
  - Rising edge



- 4-bit register

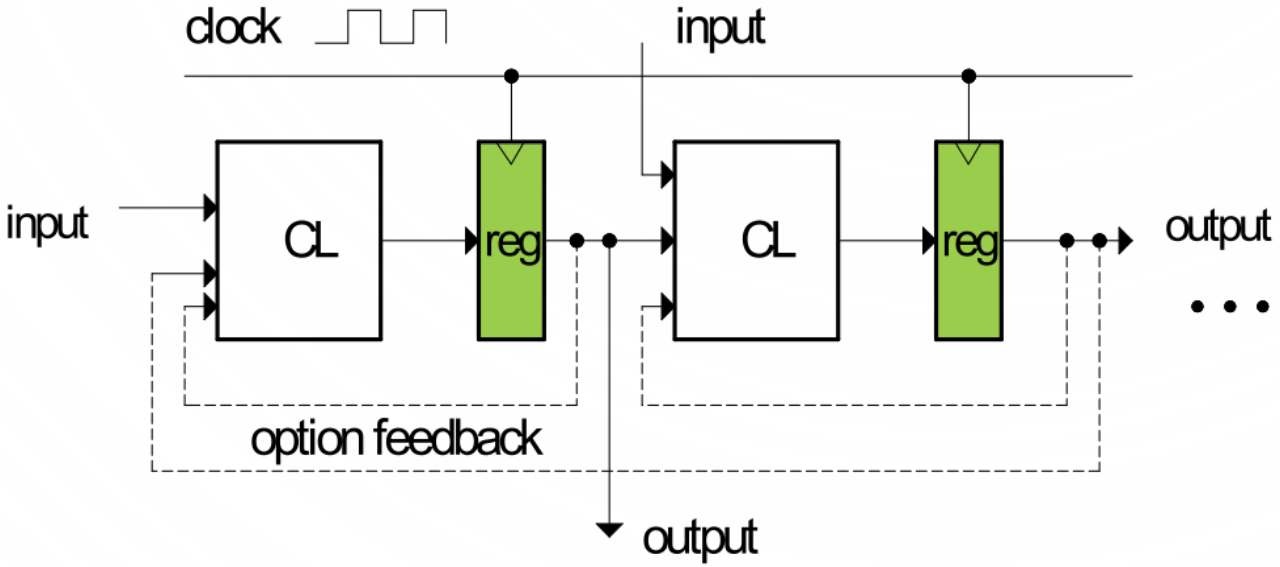




Register Transfer Level Abstraction (RTL)

Any synchronous digital circuit can be represented with:

- Combinational Logic (CL) blocks, plus
- State elements (registers or memories)
- Clock orchestrates *sequencing* of CL operations



- State elements are combined with CL blocks to control the flow of data.

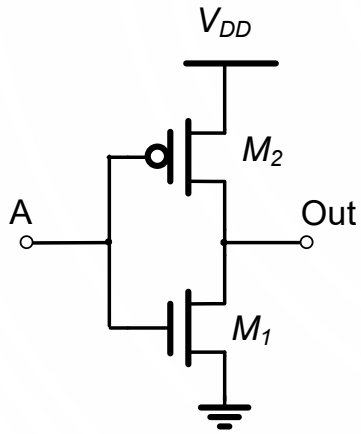
Administrivia

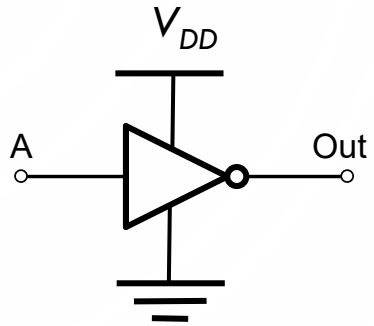
- Labs and discussions start this week
- Lab 1 posted, please start it before coming to the lab session
- Lab 2 is more involved
  - Be prepared
  - Verilog primer
- Homework 1 posted this week, due next Friday
  - Start early
- Apple NSI event: Wednesday, August 30, 11:45am, Banatao Auditorium
  - Burritos + bobba

Design Metrics: Robustness

What Makes Circuits Digital?

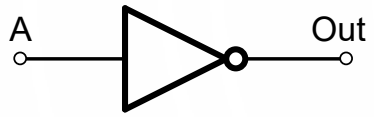
- Chips are noisy
- Supply noise will appear at the output of the logic gate

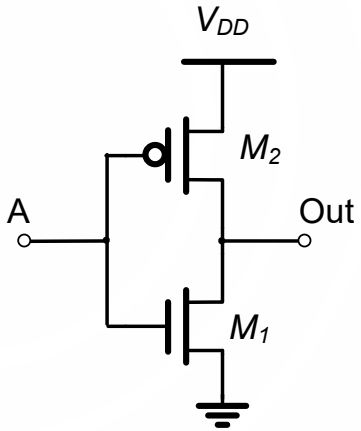




- The following logic gate should still interpret its inputs as 0s and 1s
- This necessary property is called "Restoration" or "Regeneration"
- A lot of money was spent in the past to unsuccessfully make logic out of non-regererative gates
  - Some of emerging CMOS replacements don't have gain…

Beneath the Digital Abstraction

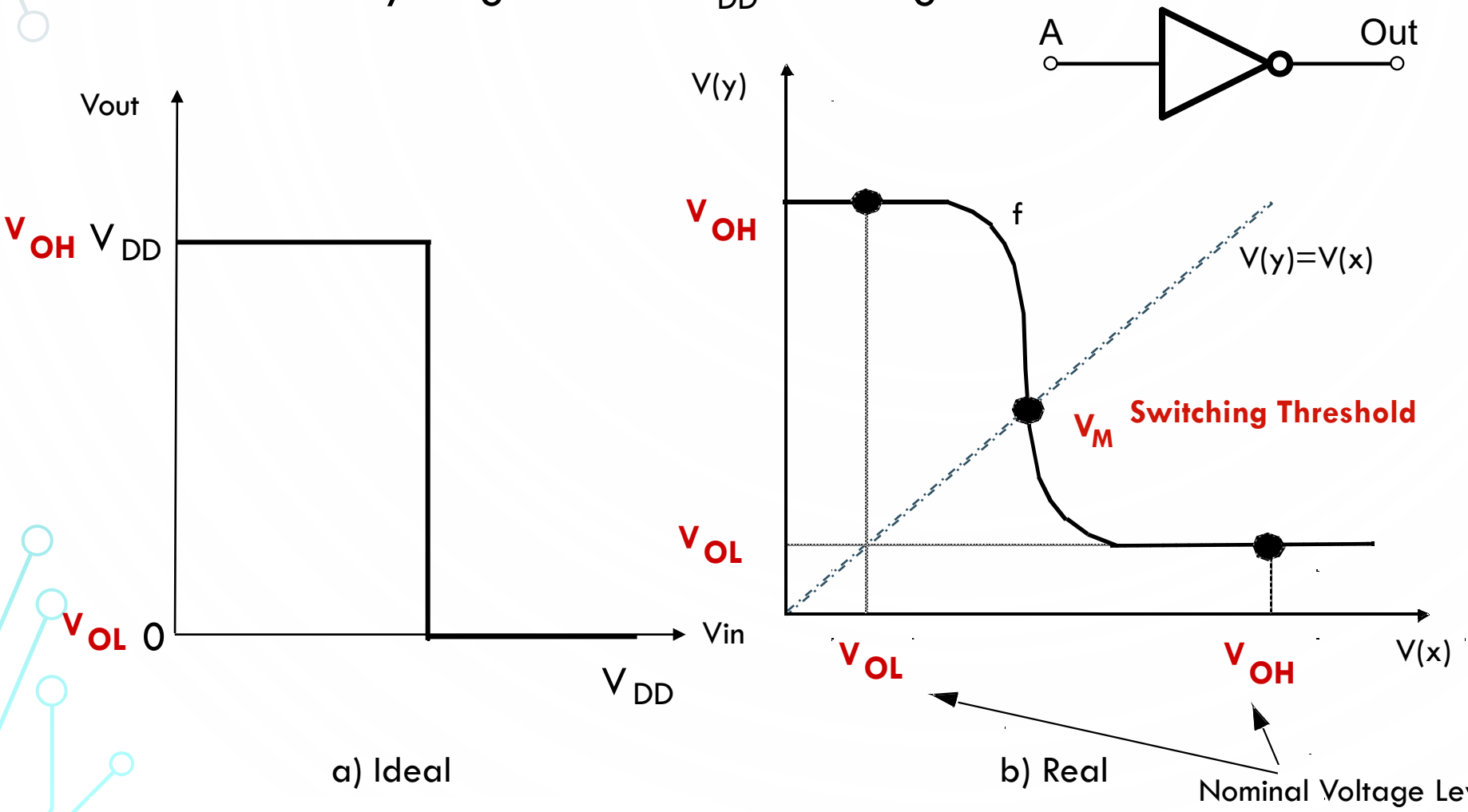




- Logic levels:
  - Mapping a continuous voltage onto a discrete binary logic variable
  - Low (0): $[0, V_L]$
  - High (1): $[V_H, V_{DD}]$
  - V_L V_H: nominal voltage levels

Voltage Transfer Characteristic

- A gate should interpret everything that is close to 0V as a logic 0
  - And everything close to V_{DD} as a logic 1

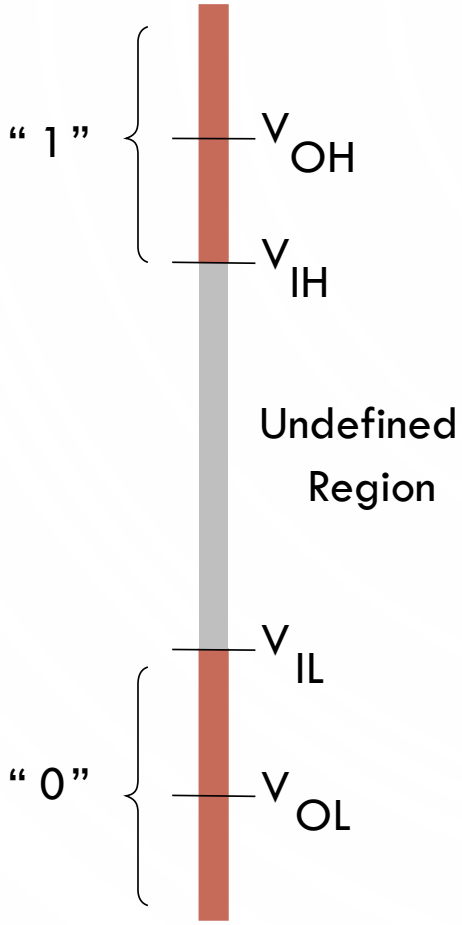


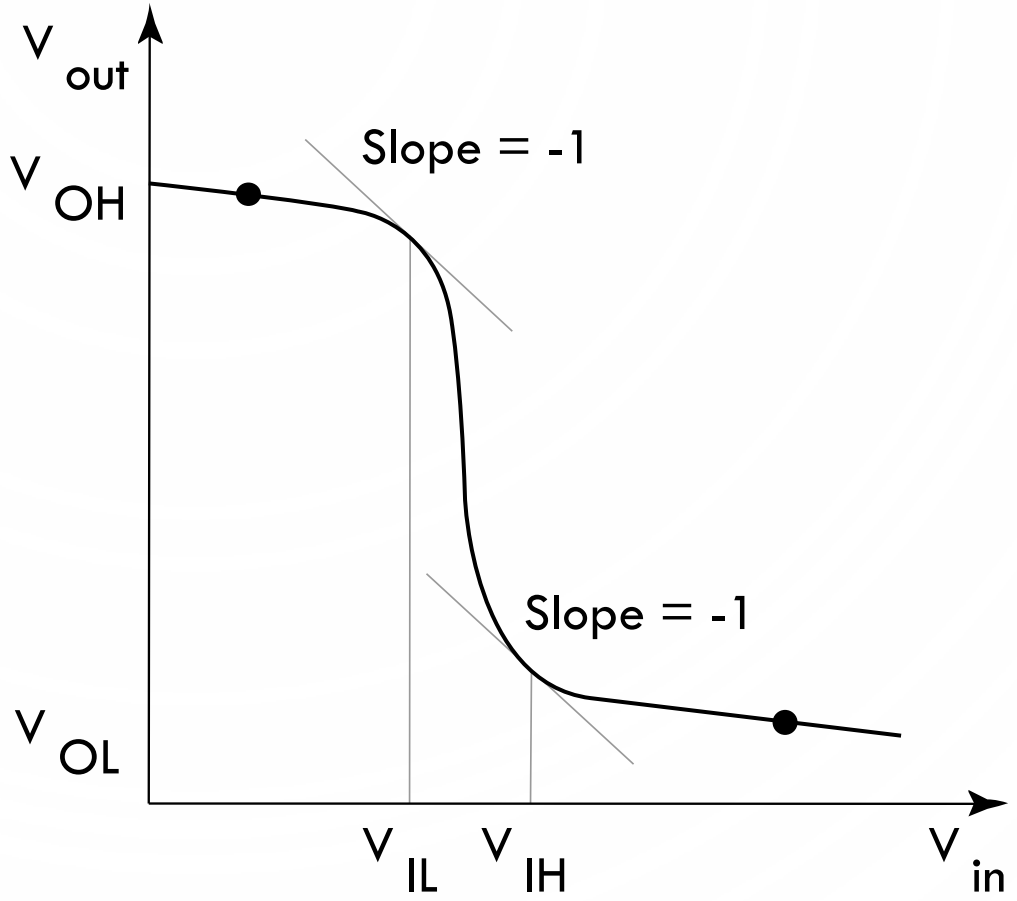
$V_{OH} = f(V_{OL})$
$V_{OL} = f(V_{OH})$
$V_M = f(V_M)$

In CMOS:

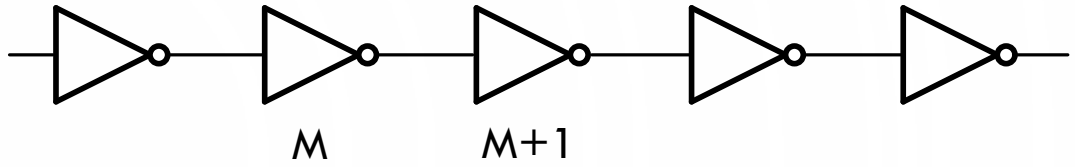
$V_{OH} = V_{DD}$
$V_{OL} = 0$
$V_M \sim V_{DD}/2$

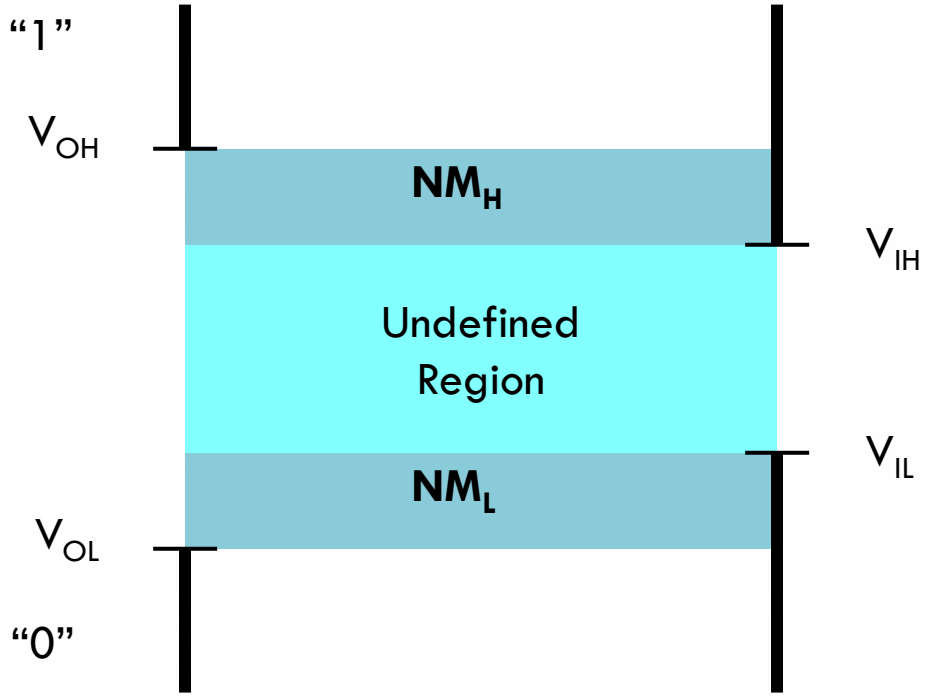
Mapping Between Analog Voltages and Digital Signals





Definition of Noise Margins





Noise margin high:
$NM_H = V_{OH} - V_{IH}$

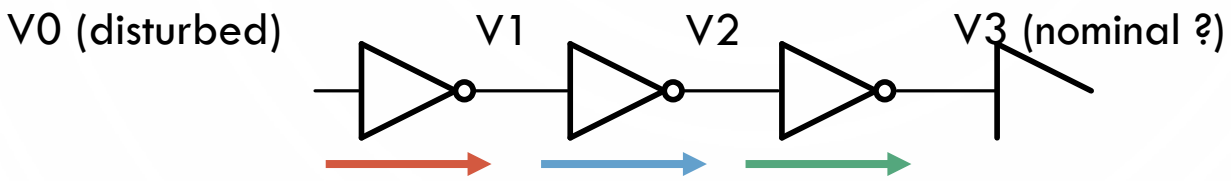
Noise margin low:
$NM_L = V_{IL} - V_{OL}$

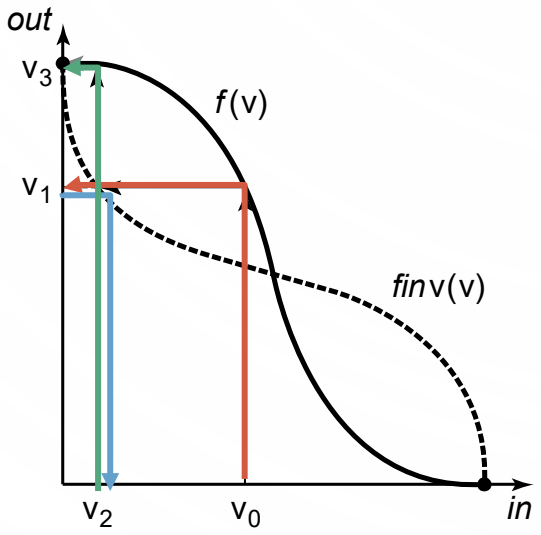
Gate Output (Stage M) → Gate Input (Stage M+1)

The amount of **noise** that could be added to **a worst-case output** so that the signal can still be interpreted correctly as **a valid input** to the next gate.

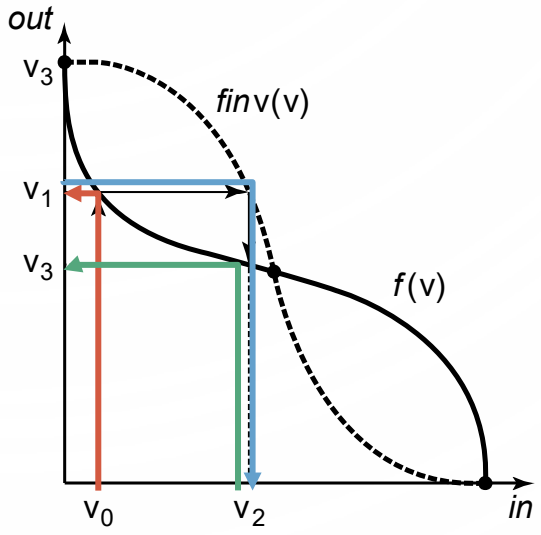
Regenerative Property

- Ensures that a **disturbed** signal gradually **regenerates** one of the **nominal voltage levels** after passing through a few logical stages.
  - Look for a sharp transition in voltage transfer characteristics.





Regenerative gate

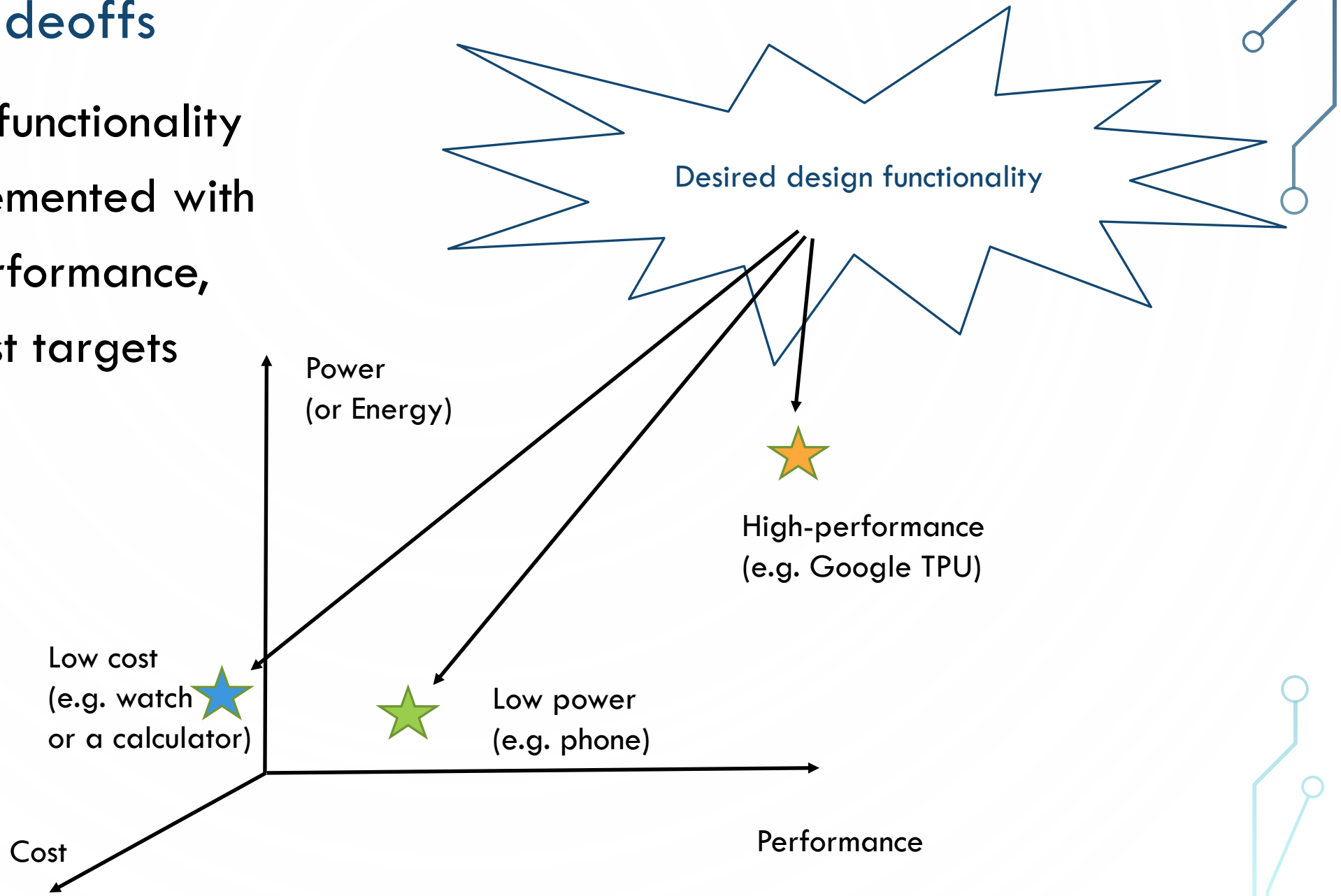


Non-regenerative gate

Design Metrics: Performance

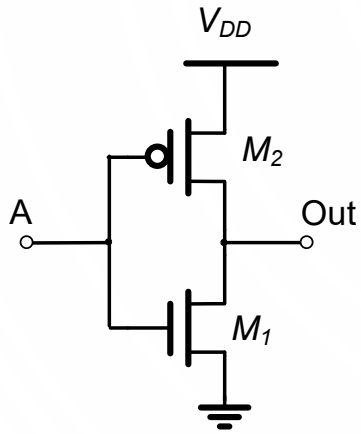
Design Tradeoffs

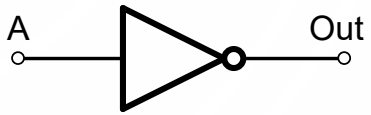
- The desired functionality can be implemented with different performance, power or cost targets



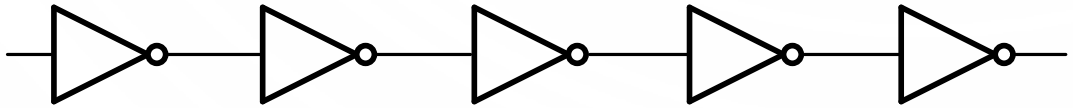
Digital Logic Delay

- Changes at the inputs do not instantaneously appear at the outputs
  - There are finite resistances and capacitances in each gate…

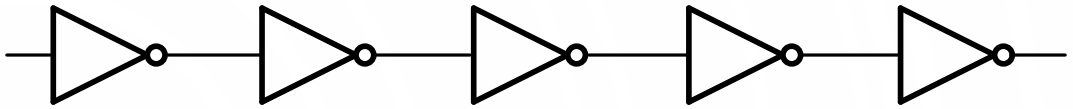




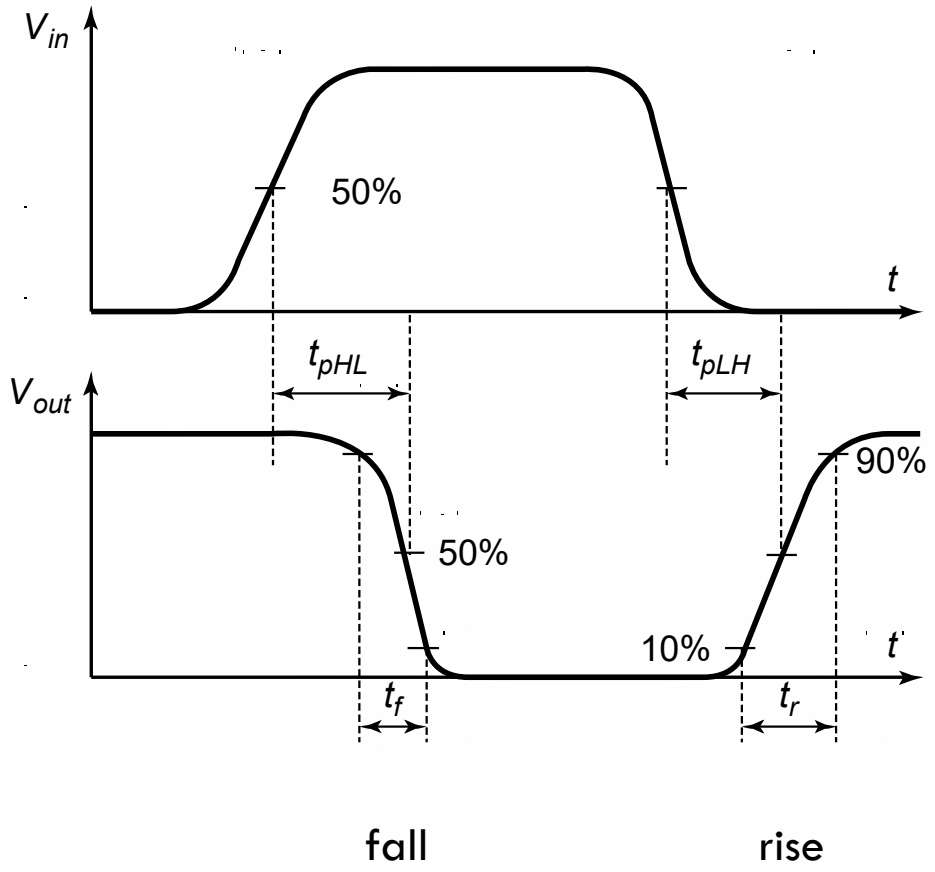
- Propagation through a chain of gates



Delay Definitions

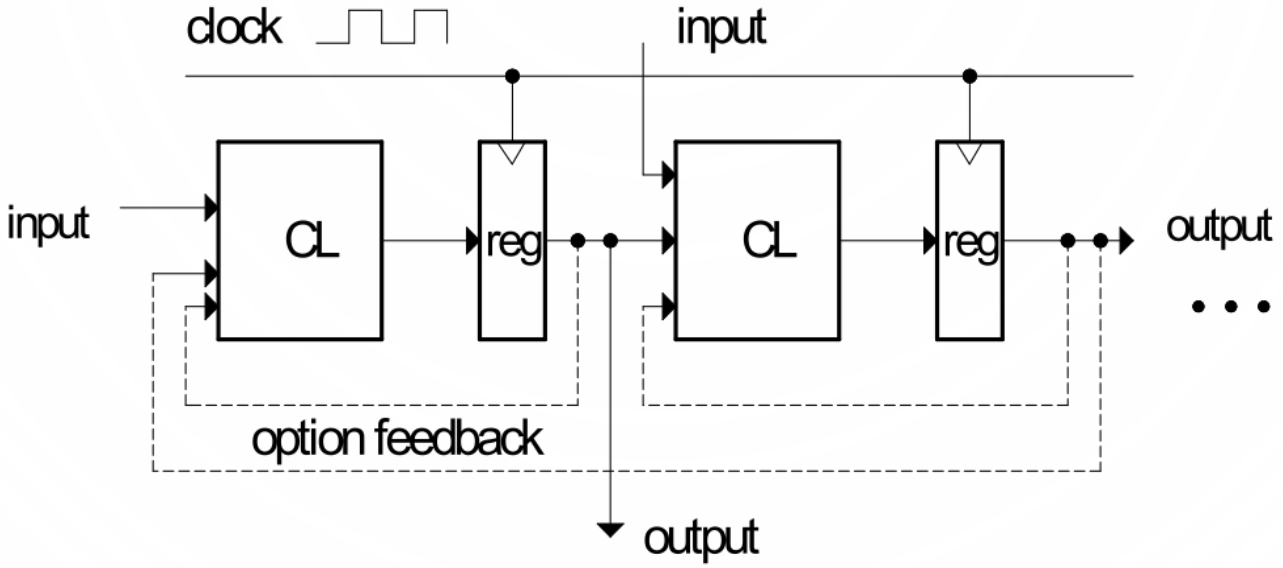


- Delay calculations need to be additive
  - Calculate the delay from the same point in the waveform



Digital Logic Timing

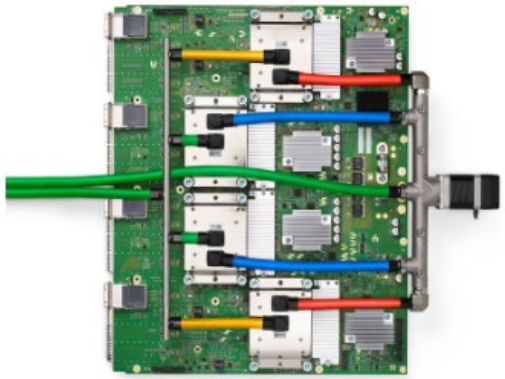
- The longest propagation delay through CL blocks sets the maximum clock frequency



- To increase clock rate:
  - Find the longest path
  - Make it faster

Performance

- Throughput
  - Number of tasks performed in a unit of time (operations per second)
  - E.g. Google TPUv4 chip performs 275 TFLOPS (10^{12} floating-point operations per second, where a floating point operation is BFLOAT16)
  - Watch out for 'op' definitions – can be a 1-b ADD or a double-precision FP add (or more complex task)
  - Peak vs. average throughput
- Latency
  - How long does a task take from start to finish
  - E.g. facial recognition on a phone takes 10's of ms
  - Sometime expressed in terms of clock cycles
  - Average vs. 'tail' latency

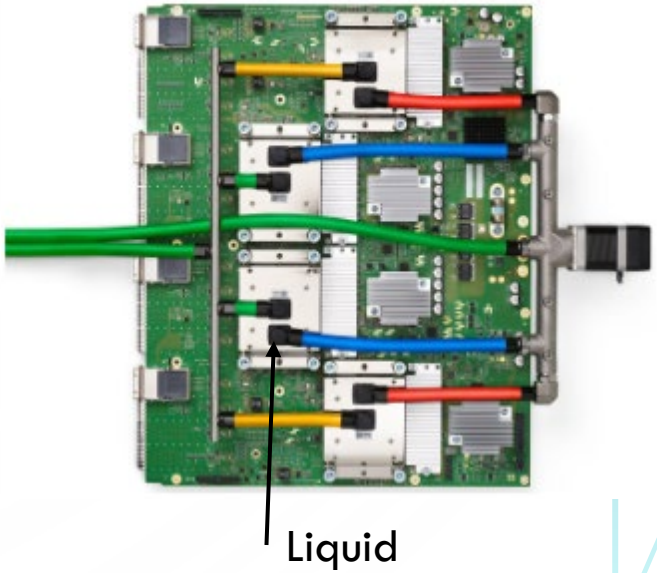


Design Metrics: Energy and Power

Energy and Power

- Energy (in joules (J))
  - Needed to perform a task
  - Add two numbers or fetch a datum from memory
    - (or fetch two numbers, add them and store in memory)
  - Active and standby
  - Battery stores certain amount of energy (in Ws = J or Wh)
  - That is what utility charges for (in kWh)
  - Energy footprint matters for the environment!
- Power (in watts (W))
  - Energy dissipated in time (W = J/s)
  - Sets cooling requirements
    - Heat spreader, size of a heat sink, forced air, liquid, …

TPU v4. ~200W



Design Metrics: Cost

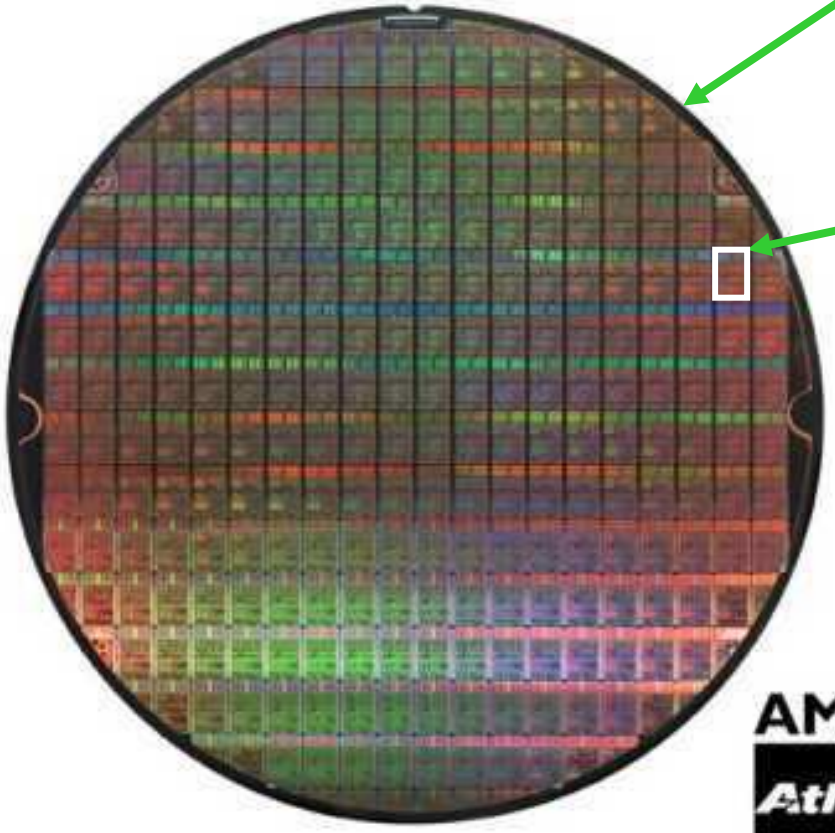
Cost

- Non-recurring engineering (NRE) costs
- Cost to develop a design (product)
  - Amortized over all units shipped
  - E.g. $20M in development adds $.20 to each of 100M units
- Recurring costs
  - Cost to manufacture, test and package a unit
  - Processed wafer cost is ~10k (around 16nm node) which yields:
    - 1 Cerebras wafer-scale chip
    - 50-100 large FPGAs or GPUs
    - 500 laptop CPUs
    - >1000 cell phone SoCs

$$\text{cost per IC} = \text{variable cost per IC} + \frac{\text{fixed cost}}{\text{volume}}$$

$$\text{variable cost} = \frac{\text{cost of die} + \text{cost of die test} + \text{cost of packaging}}{\text{final test yield}}$$

Die Cost



$$\text{cost of die} = \frac{\text{cost of wafer}}{\text{dies per wafer} * \text{die yield}}$$

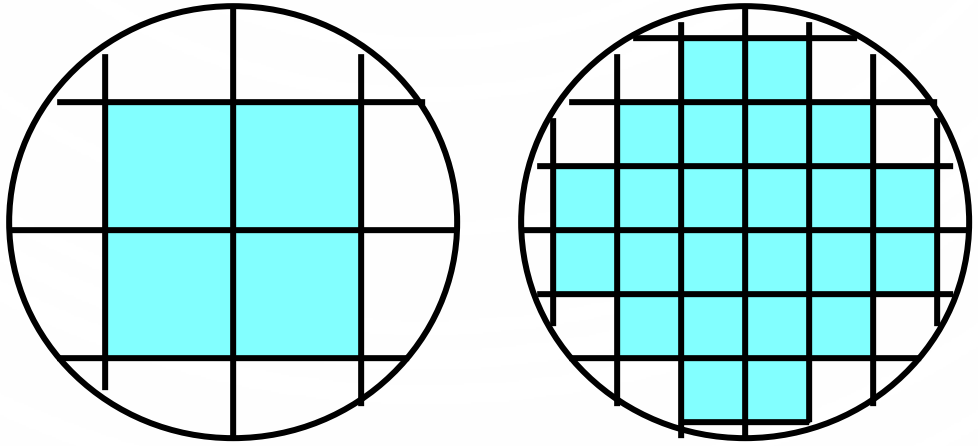
From: http://www.amd.com

Yield

$$Y = \frac{\text{No. of good chips per wafer}}{\text{Total number of chips per wafer}} \times 100\%$$

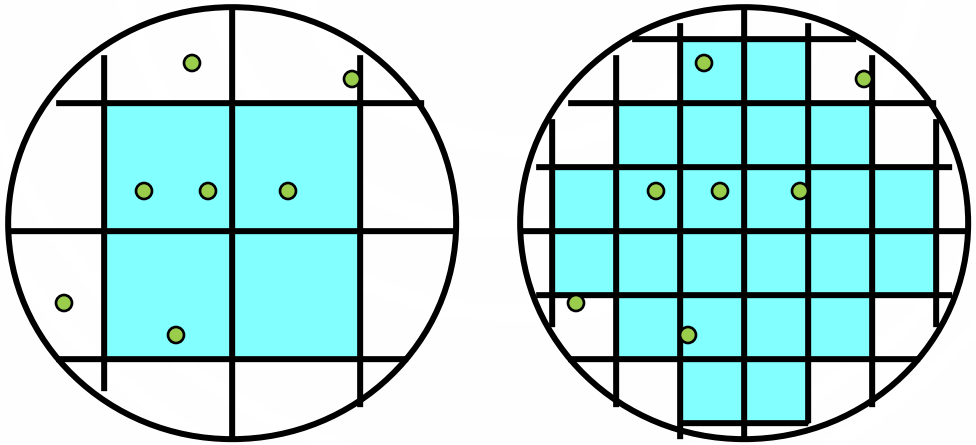
$$\text{Die cost} = \frac{\text{Wafer cost}}{\text{Dies per wafer} \times \text{Die yield}}$$

$$\text{Dies per wafer} = \frac{\pi \times (\text{wafer diameter}/2)^2}{\text{die area}} - \frac{\pi \times \text{wafer diameter}}{\sqrt{2 \times \text{die area}}}$$



Defects

Yield = 0.25



Yield = 0.76

$$\text{die yield} = \left(1 + \frac{\text{defects per unit area} \times \text{die area}}{\alpha}\right)^{-\alpha}$$

α is approximately in the range 0.5-5

If α =3, die cost $= f(\text{die area})^4$

Summary

- The design process involves traversing the abstraction layers of specification, modeling, architecture, RTL design and physical implementation
- Tests follow the design refinements
- Targets are processors, FPGAs or ASICs
- Automated design flows help manage the complexity
- Optimize for performance, energy and cost