Learn RISC-V CPU Implementation and **BSV**
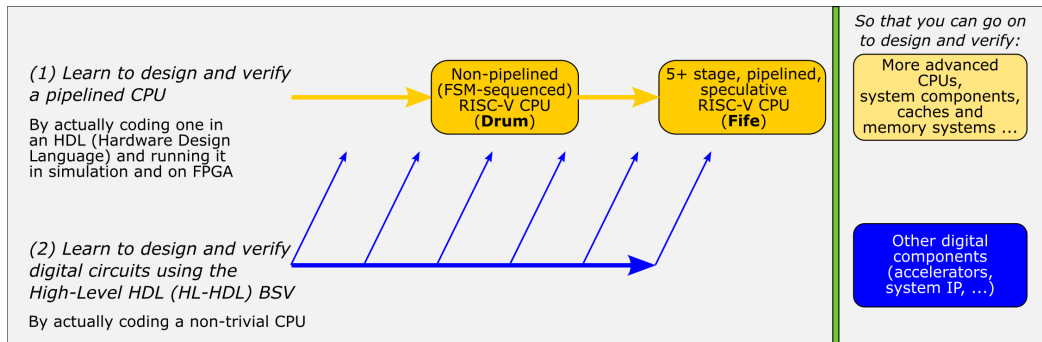(**BSV**: a High-Level Hardware Design Language)

Rishiyur S. Nikhil

L1: Introduction

bluespec

# Goals for this book/course

These goals are complementary:

- One cannot really learn CPU design without actually doing it, for which we need an HDL.
- One cannot really learn an HDL without actually doing it, for which we need interesting examples.

Learn **BSV** to design the CPUs

- **BSV** is a high-level hardware design language (HL-HDL).
- Modern (features on par with modern software programming languages).
- Industrial strength; stable language and tools.
  More than 20 years usage in industry and academia for major hardware designs.

Topics we will cover (in red text)
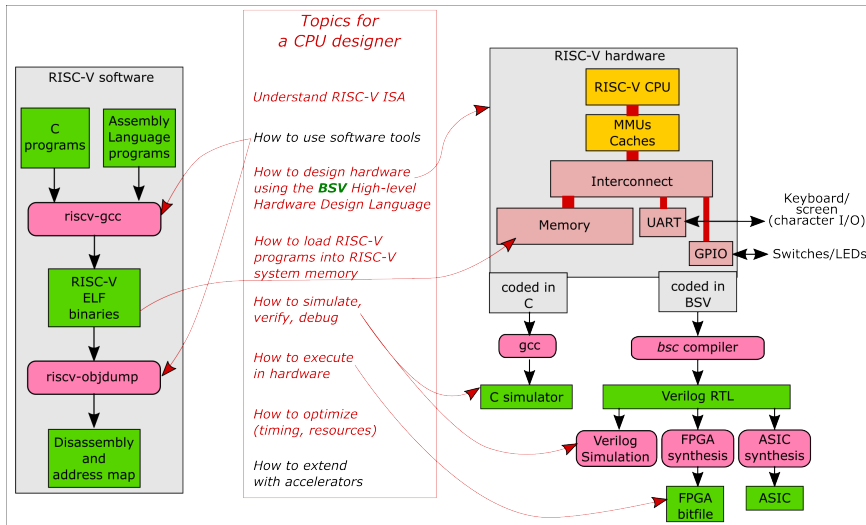
Two CPU implementations (microarchitectures): Drum and Fife
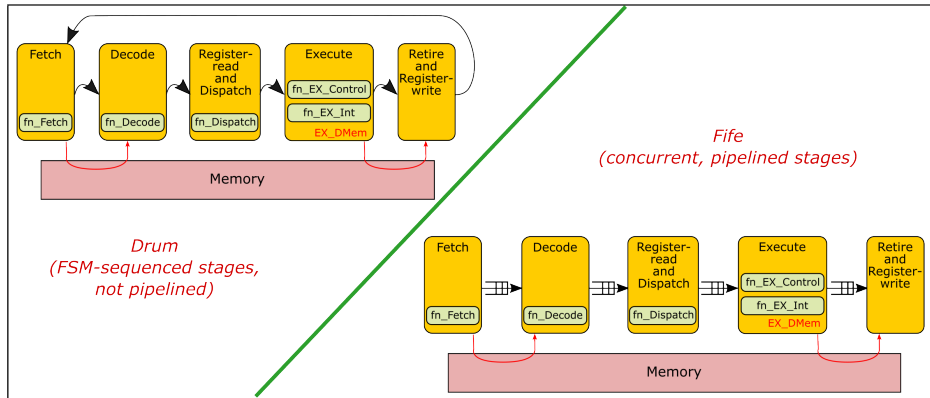
The two implementations share much code capturing RISC-V functionality

Why two microarchitectures?

- *Incremental learning:* we can master all the *functional* aspects of RISC-V with Drum, and focus entirely on pipelining aspects with Fife.

- *Functional debugging:* Bugs may be due to:

  (A) wrong implementation of RISC-V functionality (*e.g.,* address calculation)
  (B) wrong implementation of pipelining (*e.g.,* register read/write hazard)

  Drum allows us to debug all aspects of (A) in a simpler system (no complications due to pipelining).

  All this carries over directly into Fife, so when debugging Fife, we can focus on (B).

  Drum can be viewed as a *synthesizable reference model* for Fife or other RISC-V CPUs.

- *Both implementations are useful in different applications:*
  - Drum uses smaller circuits (microcontrollers, embedded, IoT, ...)
  - Fife is faster, larger, for more demanding applications

Book and full source code; ready to build and execute

This course is based on:

- a free PDF textbook

- full source code for Drum and Fife

    - Free and open-source
    - Drum and Fife CPU sources are written in **BSV**. Parts of the testbench are written in C.

Use free and open-source tools to build Drum and Fife into simulation executables, and have them execute RISC-V binaries (ELF files, output of *gcc*).

- **BSV** code needs the *bsc* compiler.

- Two ways to simulate:

    - Bluesim (standalone; just need *bsc*)
    - Standard Verilog simulation
      We will demostrate using Verilator, but you can use any Verilog simulator.

We will also demonstrate synthesis of Drum and Fife, and running on an FPGA.
(we will use an Amazon AWS "F1 instance", but you can use any FPGA).

Teaching methodology

Learn RISC-V CPU design and **BSV** together:

- We will interleave RISC-V and **BSV** topics, to learn them together.
- We will learn a little **BSV**, then apply that to some part of the RISC-V CPU design.
- We will repeat this process until we have the full CPU designs.
- Every example will involve actual **BSV** code for Drum and/or Fife.

Learn Drum first, then Fife:

- We will learn all of Drum first, and have Drum execute RISC-V programs.
- Then we will learn pipelining principles, and how we code them for Fife.
- Fife executes the same RISC-V programs as Drum.

Debugging and optimization:

- Along the way we will develop testbenches for components and demonstrate debugging the **BSV** code.
- After Fife is running, we will discuss deeper optimizations for Drum and Fife.

Teaching methodology: an unconventional approach

Most courses on hardware design spend a lot of time on circuit diagrams and schematics, boolean logic gates (AND, OR, NOT, XOR, ...), combinational circuits, logic minimization, flip flops, registers, binary number representations (twos complement), FSMs (Finite State Machines), and so on.

However, most modern digital hardware design is done at a higher level of abstraction. Designs are described using languages like Verilog, SystemVerilog and VHDL, and we rely on *compilers* to produce gates, wires, registers, *etc.*. Accordingly, we will focus on language-based hardware design, and not so much on the detailed underlying circuits.

With **BSV**, because of its rule-based execution model, we can take it even further; we will not even have to talk about clocks and clock timing until late in the course.

Analogy

Most modern programs are written in high-level languages, which are compiled into machine code using compilers. It is not necessary to understand machine code in order to write programs (unless you are trying to optimize at the bleeding edge of high performance).

Reminders

Please git clone: https://github.com/rsnikhil/Learn_Bluespec_and_RISCV_Design
(git pull for latest version). Repsitory structure:
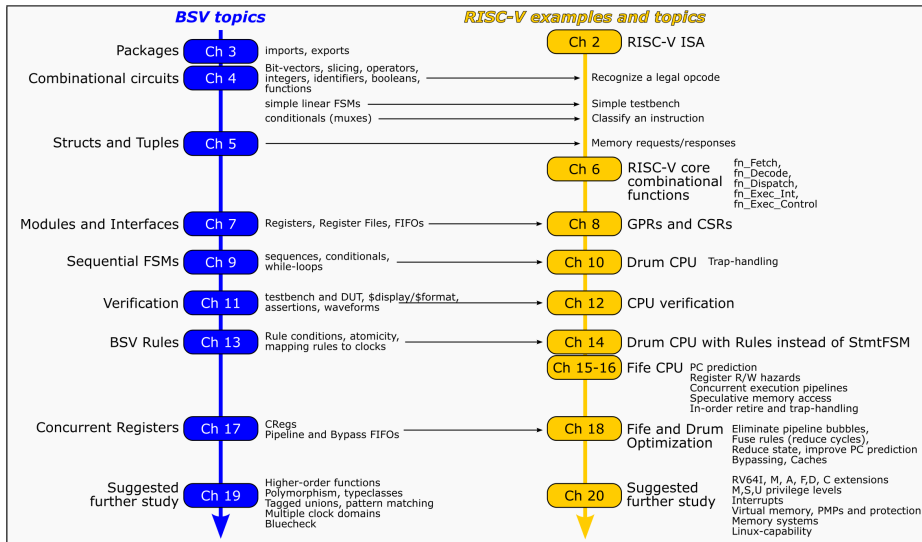
```
./Book_BLang_RISCV.pdf
  Slides/
      Slides_01_Intro.pdf
      Slides_02_ISA.pdf
      ...
  Exercises/
      Ex-03-A-Hello-World/
      Ex-03-B-Top-and-DUT/
      ...
  Code/
      src_Top/
      src_Drum/
      src_Fife/
      src_Common/
      ...
  Doc/Installing_bsc_Verilator_etc.{adoc,html}
```

- Slides and Exercise are numbered in sync with book Chapter numbers.
- For Exercises, please see Appendix E of the book. Some (not all) exercises have associated code in the Exercises/ directory.

To compile and run the code for exercises, Drum and Fife, please make sure you have installed:

- *bsc* compiler (see https://github.com/B-Lang-org/bsc)
- Verilator compiler (see https://www.verilator.org/)

Chapter Roadmap

BSV topics

RISC-V examples and topics

| BSV topics			RISC-V examples and topics
Packages	Ch 3	imports, exports	Ch 2 — RISC-V ISA
Combinational circuits	Ch 4	Bit-vectors, slicing, operators, integers, identifiers, booleans, functions	Recognize a legal opcode
		simple linear FSMs	Simple testbench
		conditionals (muxes)	Classify an instruction
Structs and Tuples	Ch 5		Memory requests/responses
			Ch 6 — RISC-V core combinational functions — fn_Fetch, fn_Decode, fn_Dispatch, fn_Exec_Int, fn_Exec_Control
Modules and Interfaces	Ch 7	Registers, Register Files, FIFOs	Ch 8 — GPRs and CSRs
Sequential FSMs	Ch 9	sequences, conditionals, while-loops	Ch 10 — Drum CPU — Trap-handling
Verification	Ch 11	testbench and DUT, $display/$format, assertions, waveforms	Ch 12 — CPU verification
BSV Rules	Ch 13	Rule conditions, atomicity, mapping rules to clocks	Ch 14 — Drum CPU with Rules instead of StmtFSM
			Ch 15-16 — Fife CPU — PC prediction, Register R/W hazards, Concurrent execution pipelines, Speculative memory access, In-order retire and trap-handling
Concurrent Registers	Ch 17	CRegs, Pipeline and Bypass FIFOs	Ch 18 — Fife and Drum Optimization — Eliminate pipeline bubbles, Fuse rules (reduce cycles), Reduce state, improve PC prediction, Bypassing, Caches
Suggested further study	Ch 19	Higher-order functions, Polymorphism, typeclasses, Tagged unions, pattern matching, Multiple clock domains, Bluecheck	Ch 20 — Suggested further study — RV64I, M, A, F,D, C extensions, M,S,U privilege levels, Interrupts, Virtual memory, PMPs and protection, Memory systems, Linux-capability

# General operation of digital circuits

We now provide just enough intuition about digital circuits to allow us to proceed with **BSV** design.

Digital hardware is driven by a *clock*, an electrical signal that oscillates between a low voltage and a high voltage, with sharp transitions between the two, at regular intervals (it is therefore sometimes called a "square" wave).
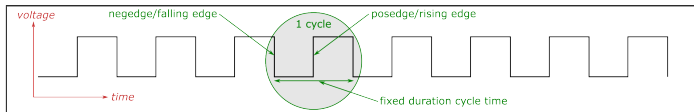
Any value that must be visible from one clock to the next must be stored in a *state element* (a component that can "remember" values, *i.e.*, has *state*, like a register, FIFOF, buffer, memory, ...).

General structure and operation of digital circuits
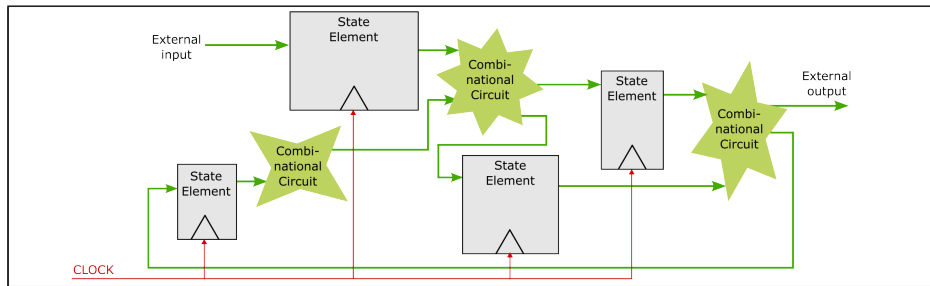
Digital circuits are composed of *state elements* and *combinational circuits* connecting outputs of state elements to inputs of state elements. State elements are *storage* elements. Combinational circuits are *acyclic* networks of *logic gates* (AND, OR, NOT, ...). Any digital circuit repeatedly performs the following:

- After each "posedge" (positive edge of a clock), the combinational circuits compute new inputs for all state elements, based on the current values in state elements
- At the next posedge, these new input values are stored into the state elements.

General operation of digital circuits; notes and caveats

- Nowadays, clock cycle times/periods are typically measured in nanoseconds.
  For example, a 100 MHz clock has a 10ns cycle time.

- Physics and circuit silicon technology dictates how long an electrical signal takes to propagate from the output of a state element and through a combinational circuit before it arrives at the input of a state element. The clock period needs to be greater than this.

  In the *digital abstraction* we assume this condition is met, and we "idealize" wire and combinational circuit delays as taking zero time.

- Advanced digital ciruits may have multiple clocks driving different parts of the circuit.

- Advanced digital ciruits may vary the clock speed dynamically, to match power consumption to current performance demands (higher speeds ⇒ more power consumption).

- Some digital ciruits use the negative edge ("negedge") of the clock insted of the posedge.

- Advanced digital ciruits may use both the posedge and the negedge of the clock.
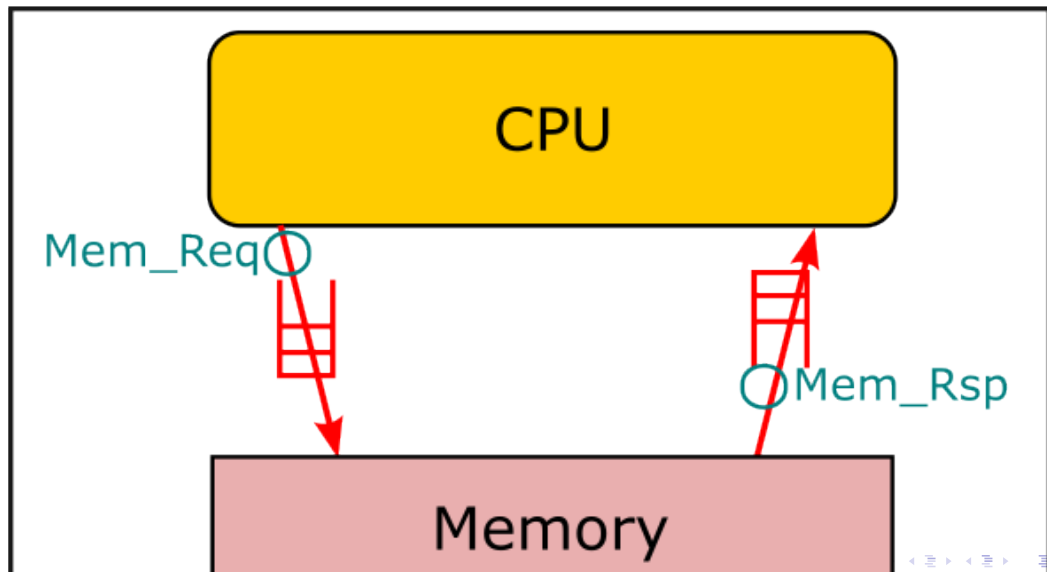
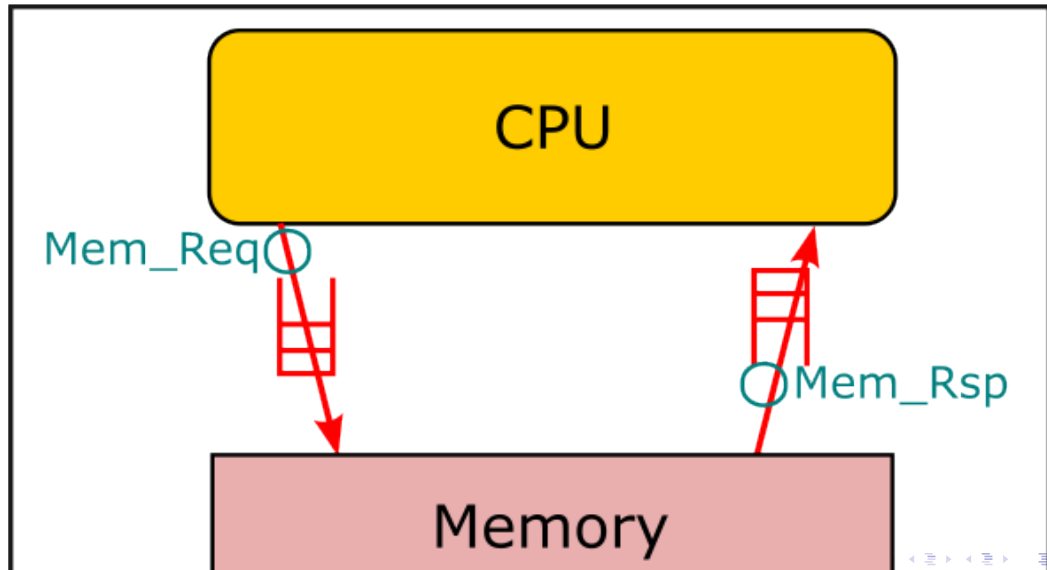# Computer Memories
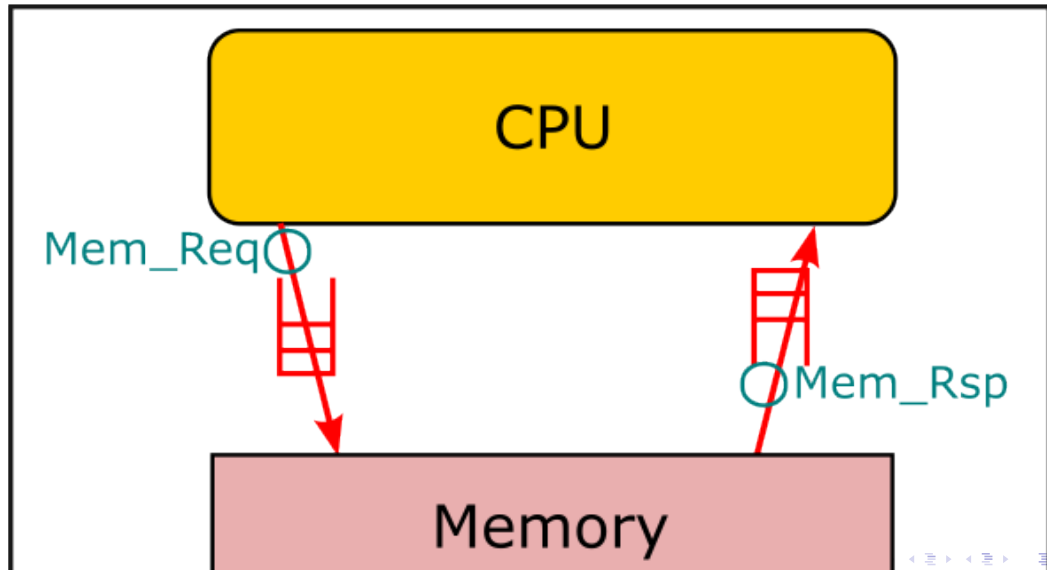
Memory Hierarchies

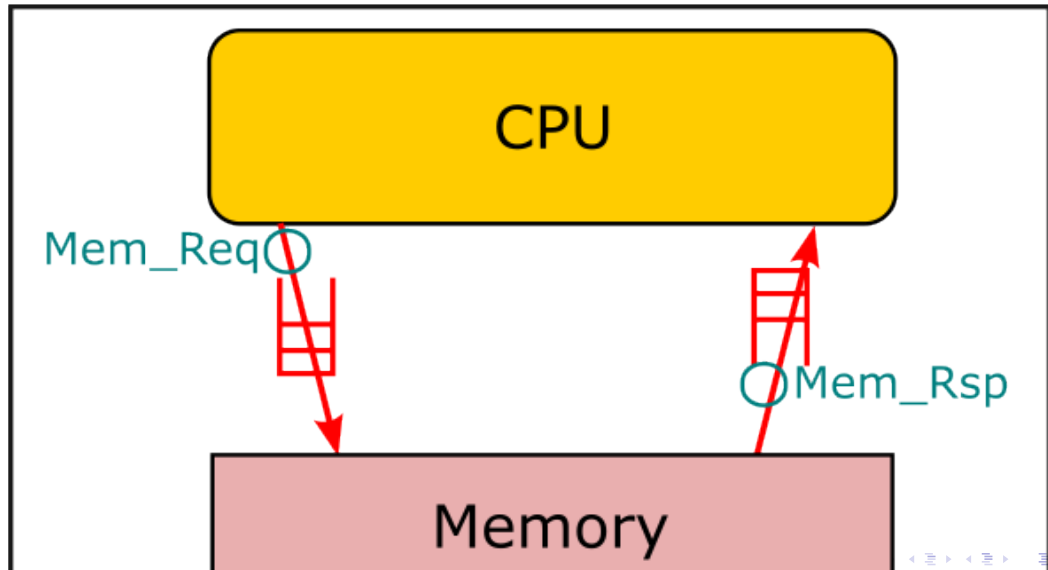Most modern computers have one or more levels of *cache* memories between the CPU and main memory.

Faster
Smaller
More power consumption
More expensive
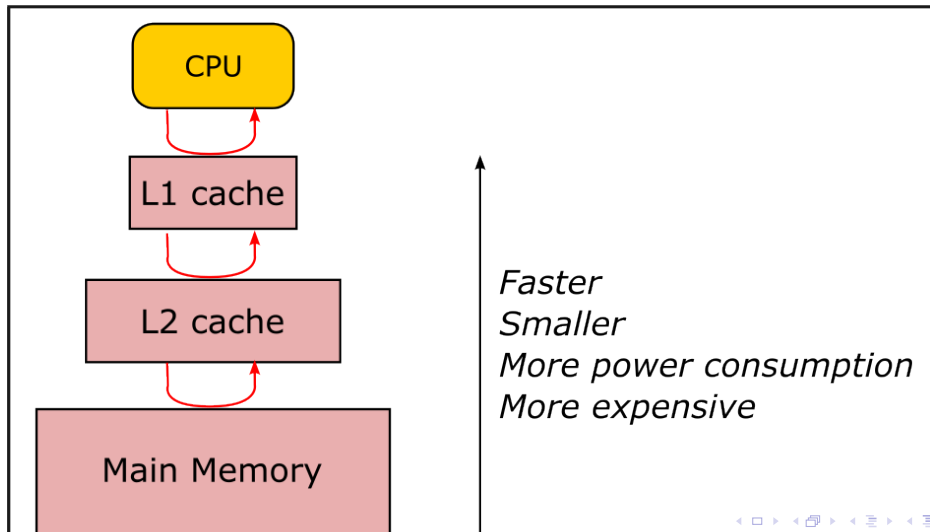
Split-phase Memory Access

Pipelined Memory Access

End