Testing and Continuous Integration

Emad Jacob Maroun

Technical University of Denmark
Embedded Systems Engineering

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Agile Manifesto Focus

Individuals and interactions over processes and tools

Working software over comprehensive documentation

Customer collaboration over contract negotiation

Responding to change over following a plan [1]

[1] https://agilemanifesto.org/

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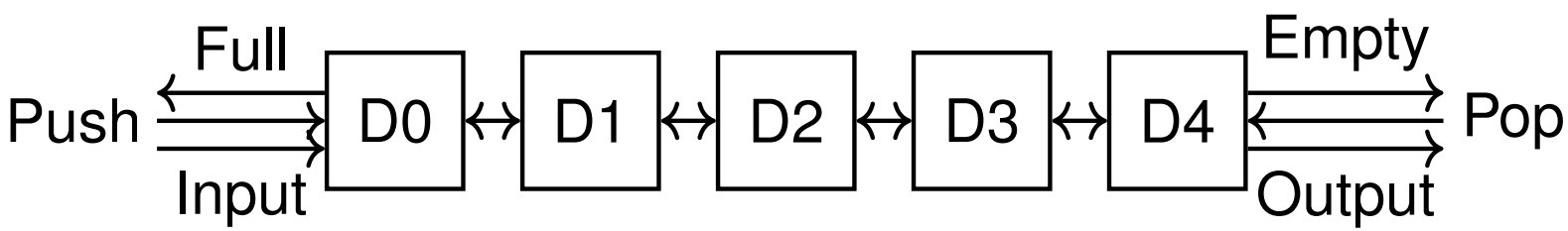
  - Catch errors & bugs
  - Document requirements
  - Catch regressions
  - Improve collaboration through iteration
- Continuous integration:
  - Centralized server as single source of truth
  - Runs all tests on every merge/pull request (PR)
  - Ensures project is always in a working state
  - Maybe: Manage deployments (continuous deployment)

Running Example: FIFO Queue

What is a FIFO Queue?

- First-In, First-Out
- First element added is the first one removed
- Commonly used for buffering and data flow control



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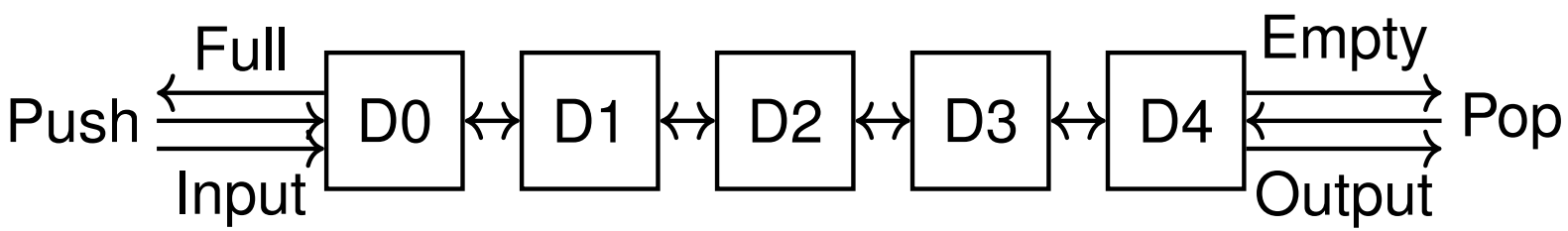
Applications

- Temporary storage between producer and consumer
- Clock domain crossing
- Managing data streams in communication



Testing Levels

1. **Unit Tests**
   - Testing individual components in isolation
   - Exercise basic units of functionality
2. **Integration Tests**
   - Testing component interaction
   - Compound units of functionality
3. **System Tests**
   - Testing the complete system
   - Use-case/user story tests
4. **Acceptance Tests**
   - Testing by the client
5. Non-functional tests: Speed, size, documentation

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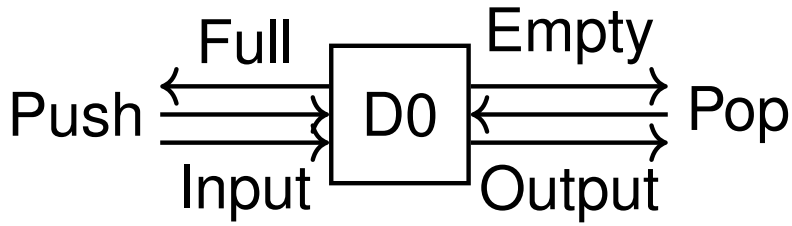

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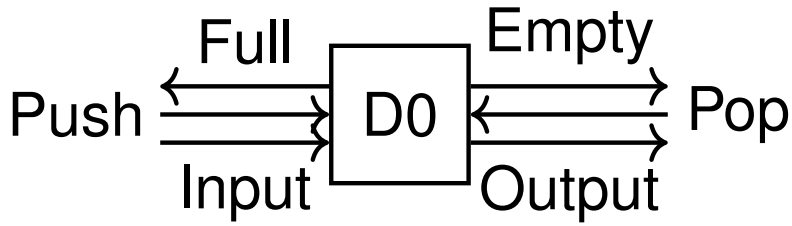

FIFO Unit Tests (10): Exercise: 3 mins

- Initialized to empty
- On push becomes full & !empty
- On pop becomes !full & empty
- If empty, pop does nothing (pops zero?)
- If empty, push updates next pop
- If full, can pop
- If full, push doesn't change next pop
- Values pushed will be popped next cycle
- Can store indefinitely
- Can push and pop in simultaneously (forwarding?)

Testing Levels - Integration Tests

- Identify common module interactions
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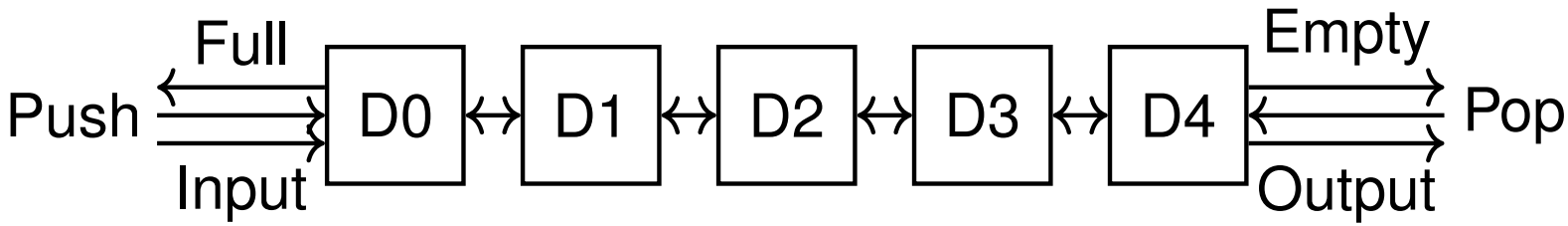

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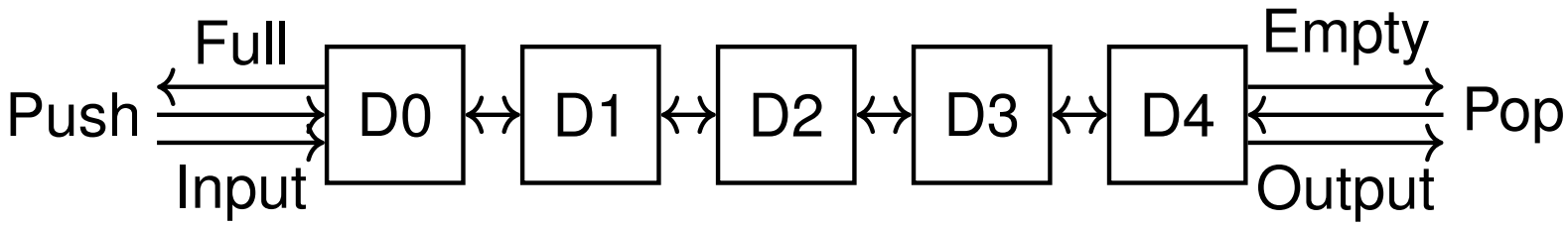
FIFO Tests (9): Exercise: 5 mins

- Initialized to empty
- On push becomes !empty
- On pop becomes !full
- Pushed item will pop eventually
- List of items will pop in pushed order
- If full, can pop and push simultaneously
- Can store indefinitely
- Items get to the front without popping
- Two lists pushed eventually become one list



Test-Driven Development (TDD)

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- A software development approach where tests are written **before** the code
- Follows a short cycle: **Red** $\rightarrow$ **Green** $\rightarrow$ **Refactor**

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Benefits in Agile Design

- Encourages modular, testable design
- Provides immediate feedback and confidence in changes
- Supports continuous integration and rapid iteration

Importance of Testable Design

Why Design for Testability?

- **Early Bug Detection:** Easier to identify and fix issues during development
- **Supports Automation:** Enables integration with CI
- **Improves Maintainability:** Modular and testable components are easier to update and refactor
- **Enables Agile Practices:** Prerequisite for iterative, feedback-driven development

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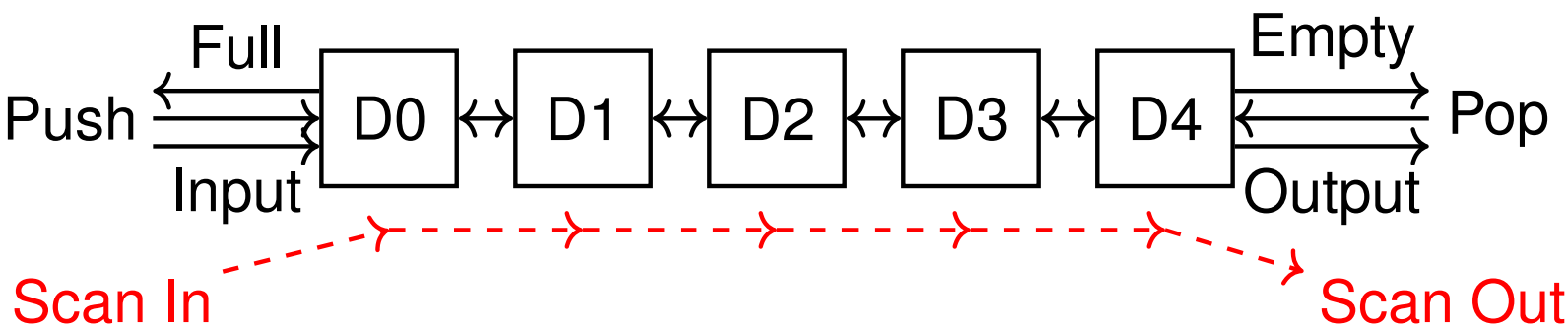
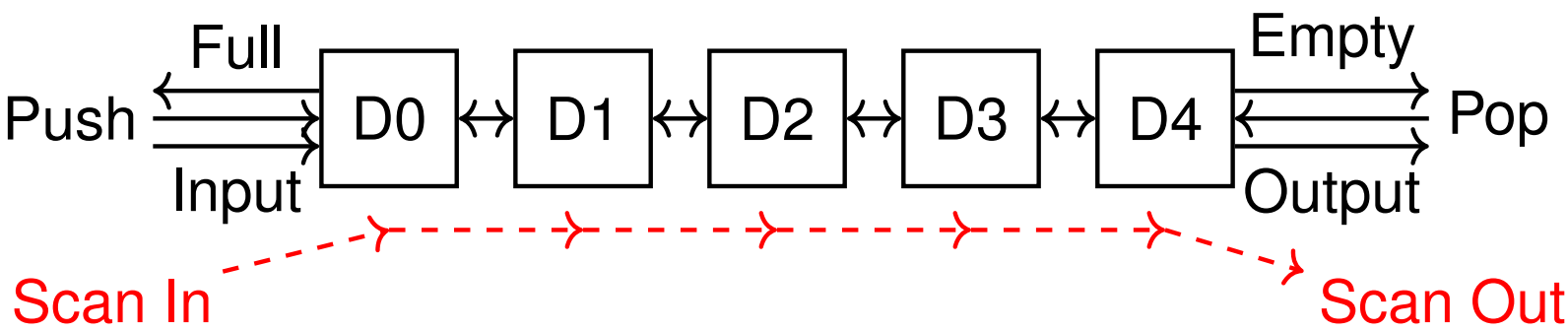
In Digital Design Context:

- Use of simulation testbenches for modules like FIFOs
- Design-for-Testability (DFT) features:
  - Scan chains for test setup and verification
  - Built-in self-test (BIST)
- Clear separation of control and data paths for easier verification

Scan Chain - FIFO



Scan Chain - FIFO



How does the scan chain change testing?

Property-Based Testing (PBT)

Why Property-Based Testing?

- Many systems have an **infinite input space** — it's impractical to test all possible cases manually
- PBT helps uncover **classes of bugs** by generating a wide range of random, valid inputs

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Core Strategy:

1. **Identify a property** that should always hold (e.g., "push followed by pop returns the same value")
2. **Define an input generator** that produces only valid inputs
3. **Implement a reference (golden) model** to compare expected behavior
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When a bug is found:

- The failing input is **shrunk** to a minimal counterexample
- A new **unit or integration test** is created to capture and prevent regression

Property-Based Testing in Chisel

- Use of ScalaCheck for PBT
- Verifying hardware modules with randomized inputs

Example:

```
property("Push then pop") =
forAll { (in: UInt) =>
 test(new FifoBlock()) { c =>
  c.io.push.poke(true.B)
  c.io.inputs.poke(in)
  c.clock.step()
  c.io.push.valid.poke(false.B)
  c.io.pop.poke(true.B)
  c.io.output.expect(in)
  c.clock.step()
  c.io.output.expect(0)
 }
}
```

Key Points:

- `forAll` generates random valid inputs
- The property asserts that pop returns the pushed value
- Failing cases are minimized and can be turned into regression tests

Example: Push/pop list

```
property("FIFO preserves order of items") =
forAll { (depth: Int, inputs: List[Int]) =>
 whenever(depth > 0 && depth <= 32 && inputs.length <= depth) {
  test(new MyFifo(depth)) { c =>
   // Enqueue all elements
   for (in <- inputs) {
    c.io.push.poke(true.B)
    c.io.input.poke(in.U)
    c.clock.step()
   }
   while (c.io.empty.peek().litToBoolean) {
    c.clock.step()
   }

   // Dequeue and check order
   for (expected <- inputs) {
    c.io.pop.poke(true.B)
    c.io.output.expect(expected.U)
    c.clock.step()
   }
  }
 }
}
```

`Arbitrary` and Shrinking

Arbitrary

- A type class used to define how to generate random values
- Default `Arbitrary` instances for common types (e.g., `Int`, `List[Int]`)
- Define custom generators by creating your own `Arbitrary` instances

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Example: Custom `Arbitrary` for Bounded Lists

```
implicit val smallListArb: Arbitrary[List[Int]] =
Arbitrary {
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Shrinking

- Tries to find the **smallest failing input**
- Helps identify minimal failures

Tip: Override default shrinking using `Shrink`

Getting Started with ScalaCheck in Chisel

1. **Add ScalaCheck to `build.sbt`:**

```
libraryDependencies += "org.scalacheck" %% "scalacheck" % "1.19.0" % Test
```

2. **Import Required Packages:**

```
import org.scalacheck._
import org.scalacheck.Prop.forAll
```

3. **Create a ScalaCheck Property Class:**

```
class FifoProps extends Properties("FIFO") with ChiselScalatestTester {
 property("basic enqueue/dequeue") = forAll { (in: Int) =>
  test(new MyFifo(depth = 4)) { c =>
   ...
  }
 }
}
```

4. **Run with `sbt test`**

Continuous Integration (CI): Motivation

Tests are only useful if they are run!

The Problem:

- Developers may forget to run tests
- Different machines = inconsistent environments
- Tests can be time-consuming or complex
- As teams grow, ensuring everyone runs all tests becomes impractical

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The Solution:

- Use a CI server to automatically run tests on every change
- Integrate with version control (e.g., GitHub Actions, GitLab CI)
- Enforce test success before merging pull requests

Continuous Integration (CI): Benefits and Extras

Key Benefits:

- Developers don't need to run all tests locally
- Tests run in a clean, consistent environment
- Regressions are caught **before** merging
- Ensures the `master` branch is always in a working state

Additional Advantages:

- Run performance or stress tests regularly
- Automate builds, documentation, and deployments
- Even useful for solo developers to avoid regressions

CI Tools:

- GitHub Actions, GitLab CI/CD, Jenkins, CircleCI, Travis CI

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2. Example `ci.yml` for Chisel Project:

```
name: CI
  on:
    pull_request:
    push:
  jobs:
    test:
    runs-on: ubuntu-latest
    steps:
      - name: Checkout
        uses: actions/checkout@v4
      - name: Setup JDK
        uses: actions/setup-java@v4
        with:
          distribution: temurin
          java-version: 11
      - name: Setup sbt launcher
        uses: sbt/setup-sbt@v1
      - name: Build and Test
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        run: sbt test
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3. Commit and Push:

- Automatically run on each push or PR
- Check the `Actions` tab for results

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- **Push:** Insert a new key and payload at the front of the array
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- **Applications:** Used in high-speed systems like **network routers**
- **Trade-offs:**
  - Very low latency
  - High hardware cost (area and power)
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- **Configurable:** Key size, payload size, and array length

Commands and Configuration

Supported Commands:

- `IDLE` – Do nothing
- `PUSH` – Insert a key/payload pair into the front of the array
- `POP` – Remove the smallest key/payload pair from the end
- `PUSH/POP` – Simultaneously insert a new pair and remove the smallest

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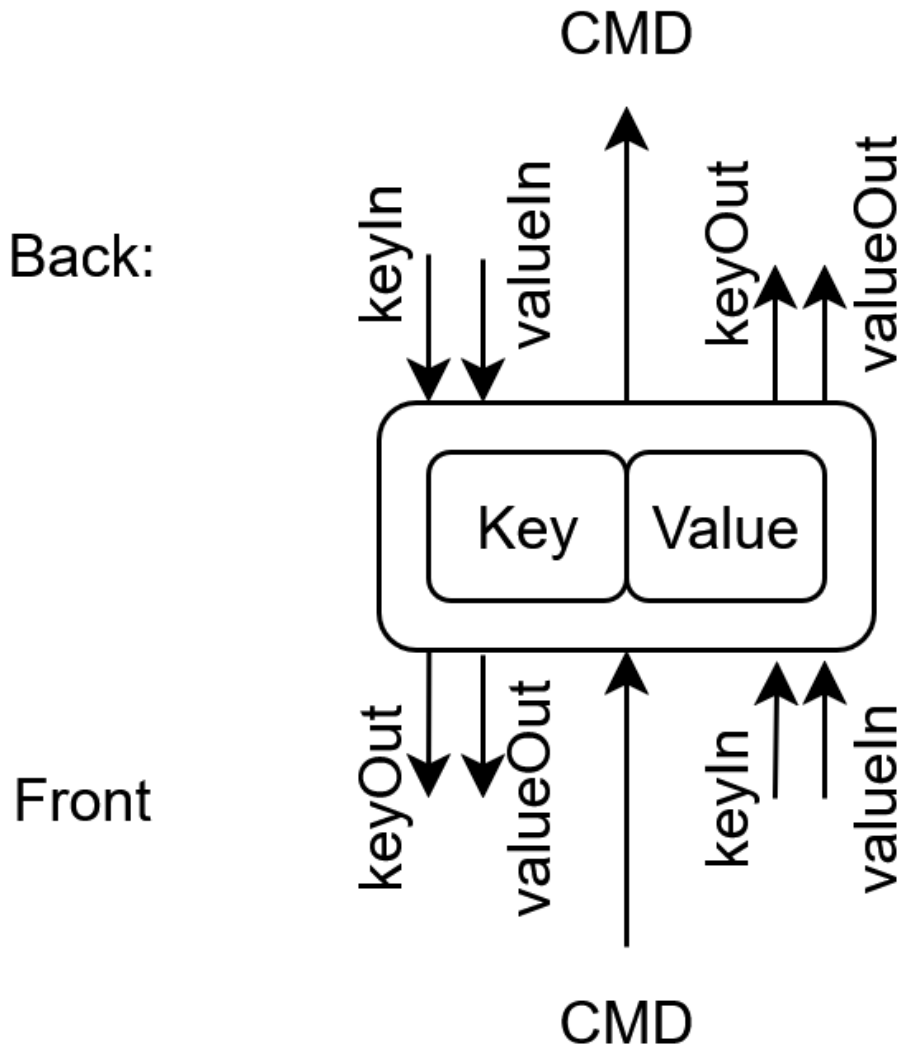
Design Requirements:

- **Configurable parameters:**
  - `keyWidth` – Bit width of the key (used for sorting)
  - `valueWidth` – Bit width of the payload
  - `depth` – Number of stages in the systolic array
- **Modular design:** Each stage compares and forwards data
- **Testable:** Design should support unit and integration testing

Systolic Array Priority List: Node



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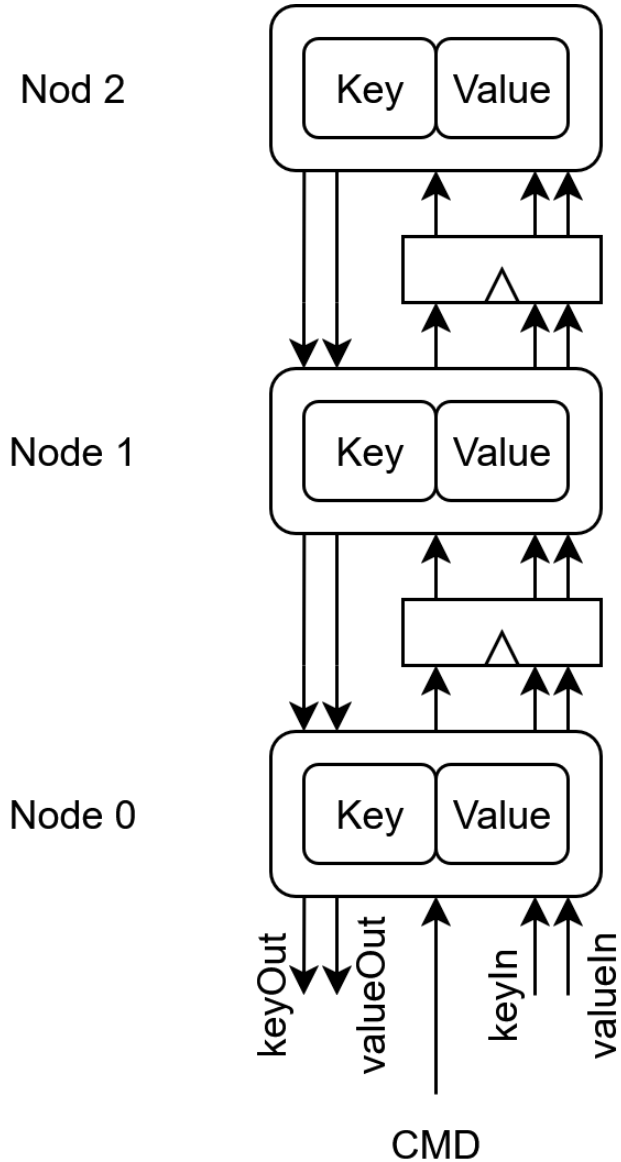

Testing the Priority List

How should this be tested?

Testing the Priority List

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- **Unit Tests:**
  - Test individual array elements (stages) for correct compare-and-forward behavior
- **Integration Tests:**
  - Validate full array behavior across PUSH/POP operations
  - Ensure keys bubble correctly and throughput matches expectations
- **Property-Based Tests:**
  - **Push-Pop Consistency:** Every pushed value should eventually be popped
  - **Sorted Output:** Popped values should be in ascending key order
  - **Idle Preservation:** IDLE cycles should not lose or corrupt data
  - **Stable Sorting:** Equal keys should preserve insertion order

Extension: Grouped Value Support

New Requirements:

- Values must be tracked in **groups**—each key may have multiple associated values
- Each `PUSH` command may insert a **variable number of values**
- Newly pushed values must **merge** with existing values for the same key
- System should be **configurable** in terms of maximum pair lengths

Extended Commands:

- `Push(0)` – No operation
- `Pop(0)` – Pop lowest key and its value group
- `Push(x)` – Push `x` values with a given key
- `Pop(x)` – Pop lowest key group, then push `x` values with a new key

Summary

- Testing is an integral part of agile development
- Test-driven development aids fast iteration and cooperation
- Property-based testing increases test quality
- Continuous integration ensures code quality is maintained
- Lab session: Priority List