12. Architectural Styles for Concurrency

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Roadmap

> What is Software Architecture?
> Three-layered application architecture
> Flow architectures
  — Active Prime Sieve
> Blackboard architectures
  — Fibonacci with Linda
Sources


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> What is Software Architecture?
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A **Software Architecture** defines a system in terms of computational components and interactions amongst those components.

An **Architectural Style** defines a family of systems in terms of a pattern of structural organization.

— cf. Shaw & Garlan, Software Architecture, pp. 3, 19
Architectural styles typically entail four kinds of properties:

> A **vocabulary** of design elements  
  — e.g., “pipes”, “filters”, “sources”, and “sinks”

> A set of **configuration rules** that constrain compositions  
  — e.g., pipes and filters must alternate in a linear sequence

> A **semantic interpretation**  
  — e.g., each filter reads bytes from its input stream and writes bytes to its output stream

> A set of **analyses** that can be performed  
  — e.g., if filters are “well-behaved”, no deadlock can occur, and all filters can progress in tandem
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**Communication Styles**

**Shared Variables**
*Processes communicate indirectly.*
Explicit synchronization mechanisms are needed.

**Message-Passing**
*Communication and synchronization are combined.*
Communication may be either synchronous or asynchronous.
Most concurrency and communication styles can be simulated by one another:

*Message-passing can be modeled by associating message queues to each process.*

*Unsynchronized objects*

*Synchronized queues*
Three-layered Application Architectures

This kind of architecture avoids nested monitor problems by restricting concurrency control to a single layer.
Problems with Layered Designs

**Hard to extend beyond three layers because:**

> Control may depend on unavailable information
  
  — Because it is not safely accessible
  
  — Because it is not represented (e.g., message history)

> Synchronization policies of different layers may conflict
  
  — E.g., nested monitor lockouts

> Ground actions may need to know current policy
  
  — E.g., blocking vs. failing
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Flow Architectures

Many synchronization problems can be avoided by arranging things so that information only flows in one direction from sources to filters to sinks.

*Unix “pipes and filters”:*
> Processes are connected in a linear sequence.

*Control systems:*
> events are picked up by sensors, processed, and generate new events.

*Workflow systems:*
> Electronic documents flow through workflow procedures.
Unix Pipes

Unix pipes are *bounded buffers* that connect producer and consumer processes (*sources, sinks and filters*):

```
cat file  # send file contents to output stream
| tr -c ’a-zA-Z’ ’\012’  # put each word on one line
| sort     # sort the words
| uniq -c  # count occurrences of each word
| sort -rn # sort in reverse numerical order
| more     # and display the result
```
Processes should *read from standard input and write to standard output* streams:

— Misbehaving processes give rise to “broken pipes”!

*Process creation* and *scheduling* are handled by the O/S. *Synchronization* is handled implicitly by the I/O system (through buffering).
Flow Stages

Every flow stage is a *producer or consumer* or both:

> **Splitters** (Multiplexers) have *multiple successors*
  > Multicasters *clone results* to multiple consumers
  > Routers *distribute results* amongst consumers

> **Mergers** (Demultiplexers) have *multiple predecessors*
  > Collectors *interleave inputs* to a single consumer
  > Combiners *process multiple input* to produce a single result

> **Conduits** have both multiple predecessors and consumers
Flow Policies

Flow can be *pull-based*, *push-based*, or a mixture:

> **Pull-based flow**: Consumers *take results* from Producers
> **Push-based flow**: Producers *put results* to Consumers
> **Buffers**:
  > — **Put-only buffers** (relays) *connect push-based stages*
  > — **Take-only buffers** (pre-fetch buffers) *connect pull-based stages*
  > — **Put-Take buffers** connect (adapt) push-based stages to pull-based stages
Limiting Flow

**Unbounded buffers:**
> If producers are faster than consumers, buffers may *exhaust available memory*

**Unbounded threads:**
> Having too many threads can *exhaust system resources* more quickly than unbounded buffers

**Bounded buffers:**
> Tend to be either *always full or always empty*, depending on relative speed of producers and consumers

**Bounded thread pools:**
> *Harder to manage* than bounded buffers
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Example: a Pull-based Prime Sieve

Primes are agents that reject non-primes, pass on candidates, or instantiate new prime agents:
Using Put-Take Buffers

*Each ActivePrime uses a one-slot buffer to feed values to the next ActivePrime.*

The first ActivePrime holds the seed value 2, gets values from a TestForPrime, and creates new ActivePrime instances whenever it detects a prime value.
Architectural Styles for Concurrency

The PrimeSieve

The main PrimeSieve class creates the initial configuration

```java
public class PrimeSieve {
    public static void main(String args[]) {
        genPrimes(1000);
    }
    public static void genPrimes(int n) {
        try {
            ActivePrime firstPrime = new ActivePrime(2, new TestForPrime(n));
        } catch (Exception e) { }
    }
}
ActivePrimes
```
Pull-based integer sources

Active primes get values to test from an IntSource:

```java
public interface Source<Value> { Value get(); }

class TestForPrime implements Source<Integer> {
    private int nextValue;
    private int maxValue;
    public TestForPrime(int max) {
        this.nextValue = 3;
        this.maxValue = max;
    }
    public Integer get() {
        if (nextValue < maxValue) { return nextValue++; }
        else { return 0; }
    }
}
```
The ActivePrime Class

ActivePrimes themselves implement IntSource

class ActivePrime extends Thread implements Source<Integer> {
    private static Source<Integer> lastPrime; // shared
    private int value; // value of this prime
    private int square; // square of this prime
    private Source<Integer> intSrc; // source of ints to test
    private OneSlotBuffer<Integer> slot; // pass on test value
    public ActivePrime(int value, Source<Integer> intSrc)
        throws ActivePrimeFailure
    {
        this.value = value;
        ...
        slot = new OneSlotBuffer<Integer>();
        lastPrime = this; // NB: set class variable
        this.start();
    }
}
public int value() { return this.value; }
public void run() {
    int testValue = intSrc.get(); // may block
    while (testValue != 0) {
        if (testValue < this.square) {
            try {
                new ActivePrime(testValue, lastPrime);
            } catch (Exception e) {
                testValue = 0; // stop the thread
            }
        } else if ((testValue % this.value) > 0) {
            this.put(testValue);
        }
        testValue = intSrc.get(); // may block
    }
    put(0); // stop condition
}
private void put(Integer val) { slot.put(val); }
public Integer get() { return slot.get(); }
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Blackboard architectures put all synchronization in a “coordination medium” where agents can exchange messages.

Agents do not exchange messages directly, but post messages to the blackboard, and retrieve messages either by reading from a specific location (i.e., a channel), or by posing a query (i.e., a pattern to match).
Result parallelism is a blackboard architectural style in which workers produce parts of a more complex whole.
Agenda Parallelism

Agenda parallelism is a blackboard style in which workers *retrieve tasks to perform from a blackboard*, and may generate new tasks to perform.

Workers repeatedly retrieve tasks until everything is done. Workers are typically able to perform arbitrary tasks.
Specialist parallelism is a style in which each worker is specialized to perform a particular task.

Specialist designs are equivalent to message-passing, and are often organized as flow architectures, with each specialist producing results for the next specialist to consume.
**Linda** is a *coordination medium*, with associated primitives for coordinating concurrent processes, that *can be added to an existing programming language*.

The coordination medium is a *tuple-space*, which can contain:

— *data tuples* — tuples of primitives vales (numbers, strings ...)
— *active tuples* — expressions which are evaluated and eventually turn into data tuples
# Linda primitives

<table>
<thead>
<tr>
<th>Function</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><code>out(T)</code></td>
<td>Output a tuple <code>T</code> to the medium (non-blocking) e.g., <code>out(&quot;employee&quot;, &quot;pingu&quot;, 35000)</code></td>
</tr>
<tr>
<td><code>in(S)</code></td>
<td>(destructively) Input a tuple matching <code>S</code> (blocking) e.g., <code>in(&quot;employee&quot;, &quot;pingu&quot;, ?salary)</code></td>
</tr>
<tr>
<td><code>rd(S)</code></td>
<td>(non-destructively) Read a tuple (blocking)</td>
</tr>
<tr>
<td><code>inp(S)</code></td>
<td>Try to input a tuple, report success or failure (non-blocking)</td>
</tr>
<tr>
<td><code>rdp(S)</code></td>
<td>Try to read a tuple, report success or failure (non-blocking)</td>
</tr>
<tr>
<td><code>eval(E)</code></td>
<td>Evaluate <code>E</code> in a new process, leave the result in the tuple space</td>
</tr>
</tbody>
</table>
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Example: Fibonacci with JavaSpaces

```java
int fib(final int n) {
    Tuple tuple;
    tuple = rdp(new Tuple("Fib", n, null)); // non-blocking
    if (tuple != null) {
        return tuple.result;
    }
    if (n<2) {
        out(new Tuple("Fib", n, 1)); // non-blocking
        return 1;
    }
    eval("Fib", n, new Eval("fib(" + (n-1) + ")+fib(" + (n-2) + ")") { 
        public int expr() { return fib(n-1)+fib(n-2); }
    });
    tuple = rd(new Tuple("Fib", n, null)); // blocking
    return tuple.result;
} // Post-condition: rdp("Fib",n,null) != null
```

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private Tuple rdp(Tuple template) {
    return tupleSpace.read(template, ZeroWaitTime);
}
private Tuple rd(Tuple template) {
    return tupleSpace.read(template, WaitTime);
}
private Tuple inp(Tuple template) {
    return tupleSpace.take(template, ZeroWaitTime);
}
private void out(Tuple template) {
    tupleSpace.write(template, LeaseTime);
}
private void eval(String fn, final Integer arg, final Eval eval) {
    new Thread() {
        public void run() {
            out(new Tuple("Fib", arg, eval.expr()));
        }
    }.start();
}

public class Tuple {
    public String functionName;
    public Integer argument;
    public Integer result;
    ...
}

We wrap a JavaSpaces implementation to resemble Linda more closely.
Computing \text{fib}(5)

\begin{verbatim}
  rdp(Tuple("Fib", 5, null)) = null
  eval("Fib", 5, fib(4)+fib(3))
  rd(Tuple("Fib", 5, null)) [blocks]
  rdp(Tuple("Fib", 4, null)) = null
  eval("Fib", 4, fib(3)+fib(2))
  rd(Tuple("Fib", 4, null)) [blocks]
  rdp(Tuple("Fib", 3, null)) = null
  eval("Fib", 3, fib(2)+fib(1))
  rd(Tuple("Fib", 3, null)) [blocks]
  rdp(Tuple("Fib", 2, null)) = null
  eval("Fib", 2, fib(1)+fib(0))
  rd(Tuple("Fib", 2, null)) [blocks]
  rd(Tuple("Fib", 1, null)) = null
  out(Tuple("Fib", 1, 1))
  rdp(Tuple("Fib", 0, null)) = null
  out(Tuple("Fib", 0, 1))
  out(Tuple("Fib", 2, 2))
  rd(Tuple("Fib", 2, 2)) [returns]
  rdp(Tuple("Fib", 1, null)) = Tuple("Fib", 1, 1)
  out(Tuple("Fib", 3, 3))
  rd(Tuple("Fib", 3, 3)) [returns]
  rdp(Tuple("Fib", 2, null)) = Tuple("Fib", 2, 2)
  out(Tuple("Fib", 4, 5))
  rd(Tuple("Fib", 4, 5)) [returns]
  rdp(Tuple("Fib", 3, null)) = Tuple("Fib", 3, 3)
  out(Tuple("Fib", 5, 8))
  rd(Tuple("Fib", 5, 8)) [returns]
DONE: \text{fib}(5) = 8
\end{verbatim}
What you should know!

- What is a Software Architecture?
- What are advantages and disadvantages of Layered Architectures?
- What is a Flow Architecture? What are the options and tradeoffs?
- What are Blackboard Architectures? What are the options and tradeoffs?
- How does result parallelism differ from agenda parallelism?
- How does Linda support coordination of concurrent agents?
Can you answer these questions?

> How would you model message-passing agents in Java?
> How would you classify Client/Server architectures?
> Are there other useful styles we haven’t yet discussed?
> How can we prove that the Active Prime Sieve is correct? Are you sure that new Active Primes will join the chain in the correct order?
> Which Blackboard styles are better when we have multiple processors?
> Which are better when we just have threads on a monoprocessor?
> What will happen if you start two concurrent Fibonacci computations?
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