13. 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

> M. Shaw and D. Garlan, *Software Architecture: Perspectives on an Emerging Discipline*, Prentice-Hall, 1996.

> F. Buschmann, et al., *Pattern-Oriented Software Architecture — A System of Patterns*, John Wiley, 1996.

> D. Lea, *Concurrent Programming in Java — Design principles and Patterns*, The Java Series, Addison-Wesley, 1996.

> N. Carriero and D. Gelernter, *How to Write Parallel Programs: a First Course*, MIT Press, Cambridge, 1990.

Roadmap

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> Three-layered application architecture
> Flow architectures
  —Active Prime Sieve
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Software Architecture

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 style

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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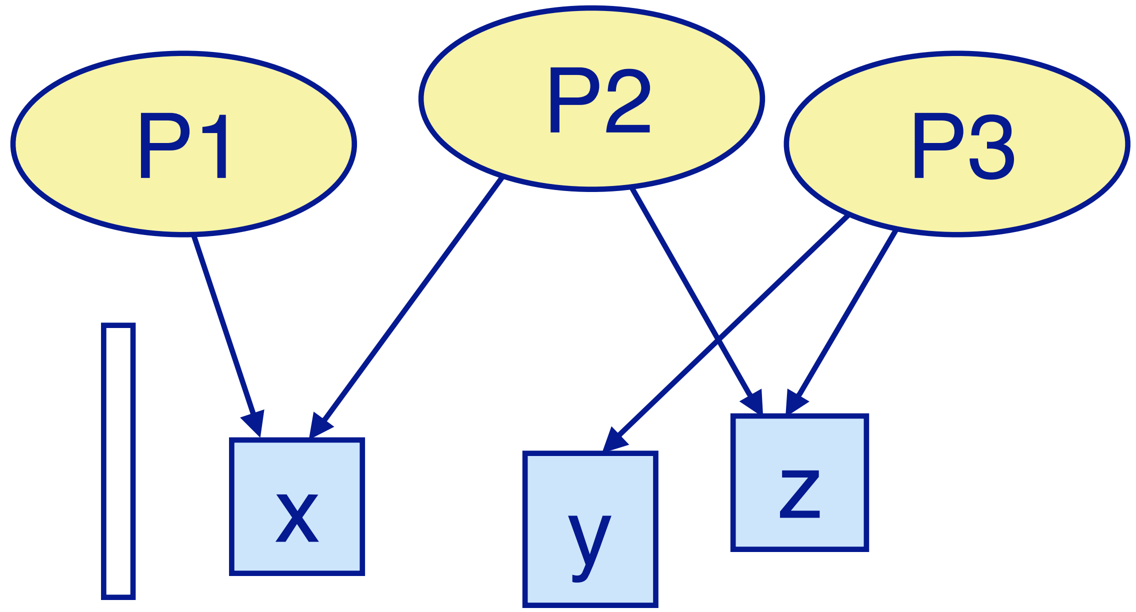
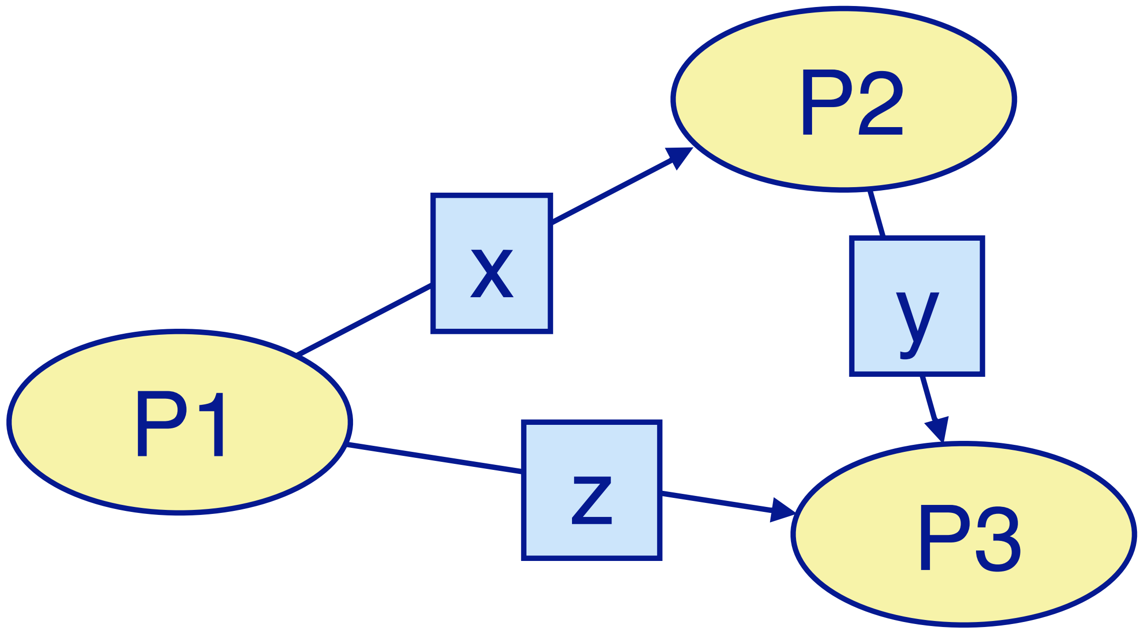
Communication Styles

Shared Variables

Processes communicate indirectly.

Explicit synchronization mechanisms are needed.





Message-Passing

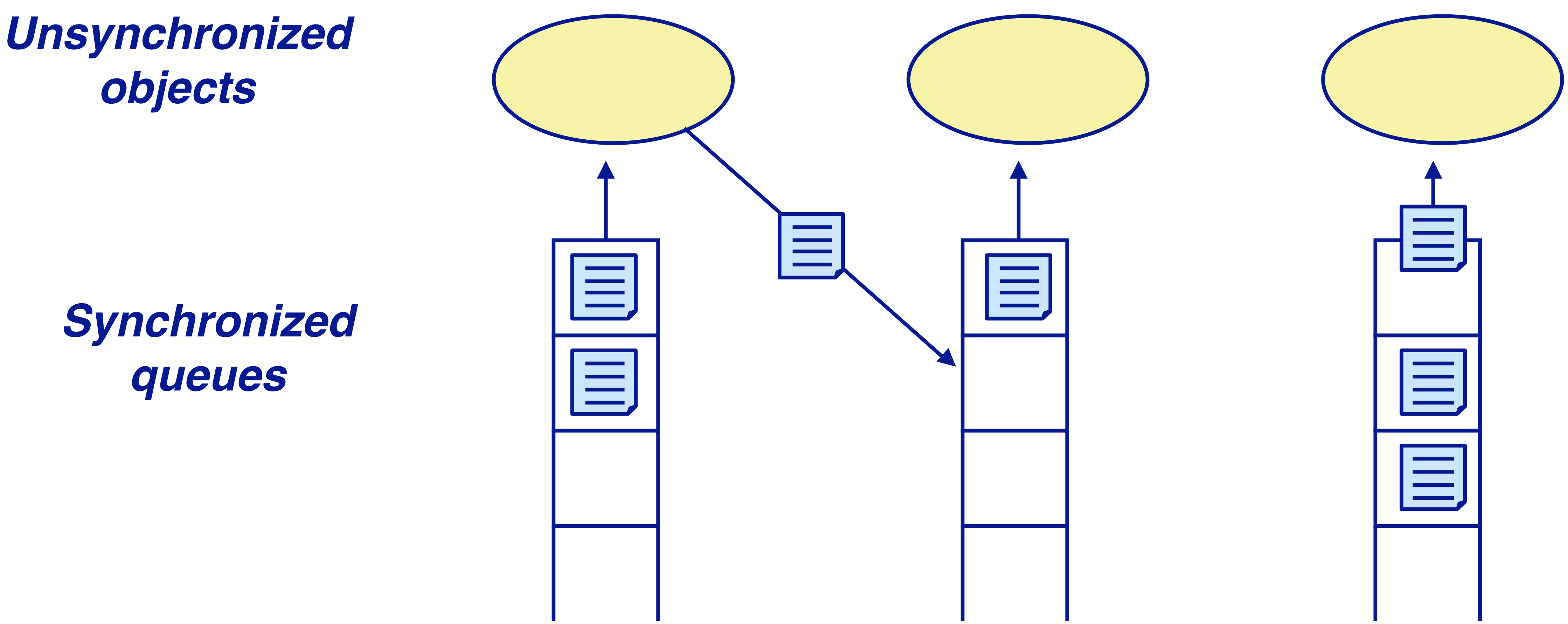
Communication and synchronization are combined.

Communication may be either *synchronous or asynchronous*.

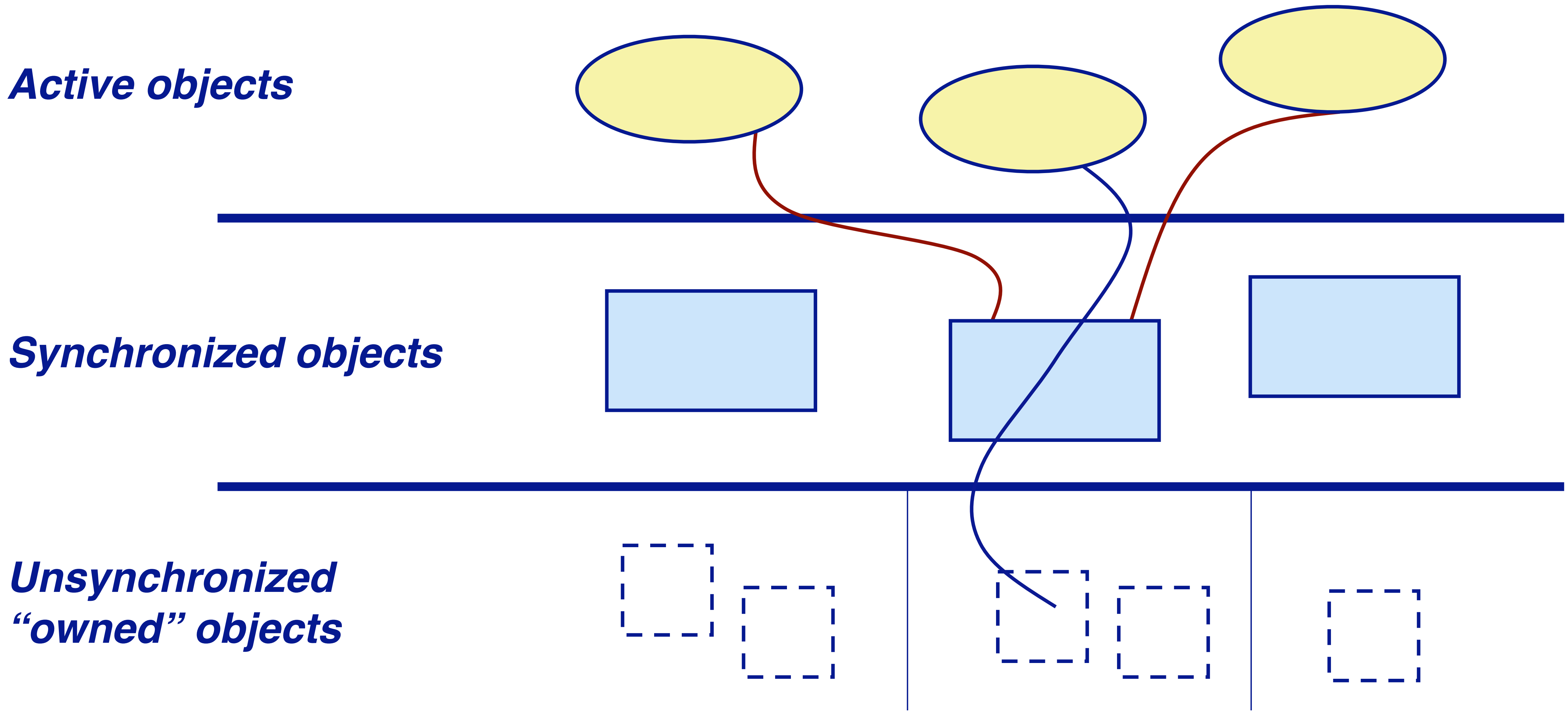
Simulated Message-Passing

Most concurrency and communication styles can be simulated by one another:

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



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:

> 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
```

Unix Pipes

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

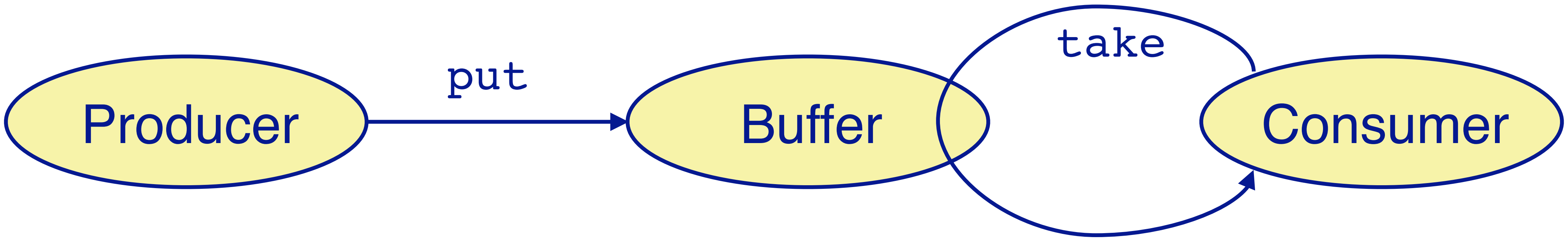
Flow can be *pull-based*, *push-based*, or a mixture:

> 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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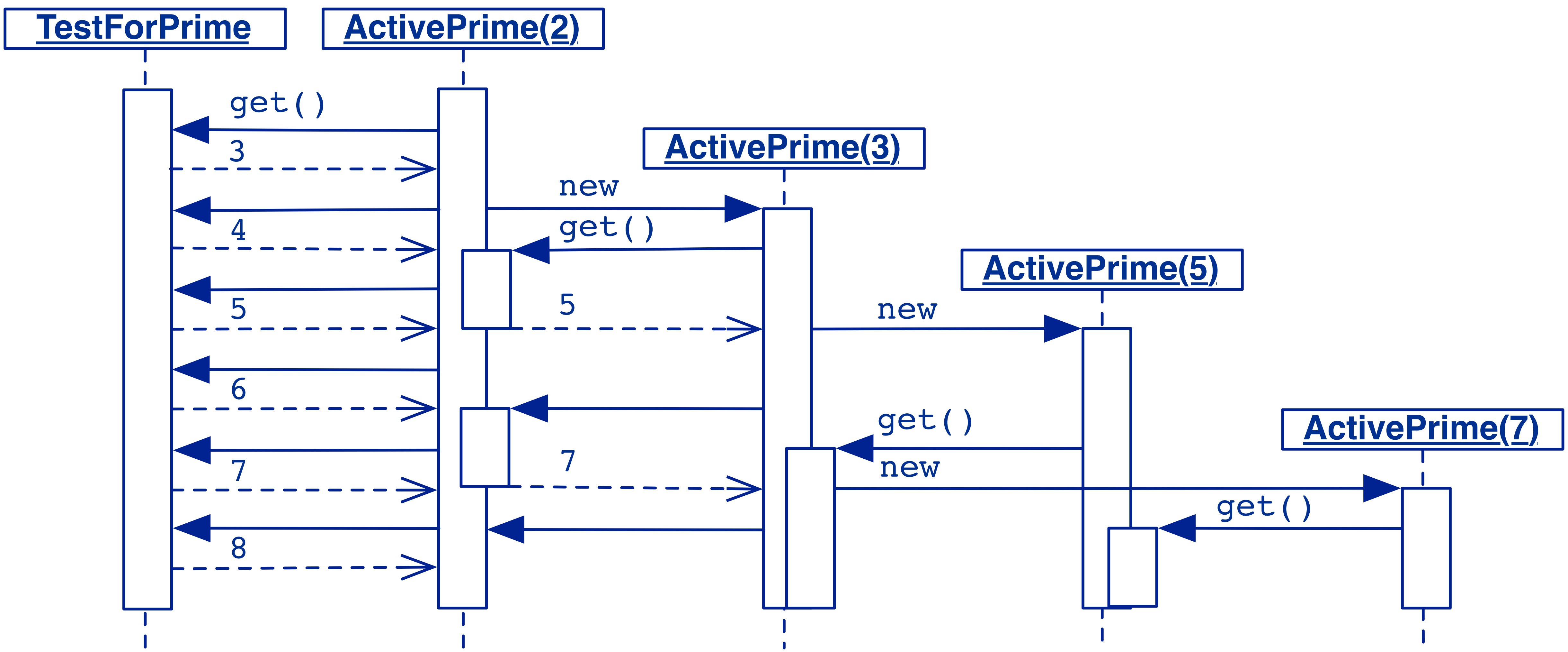
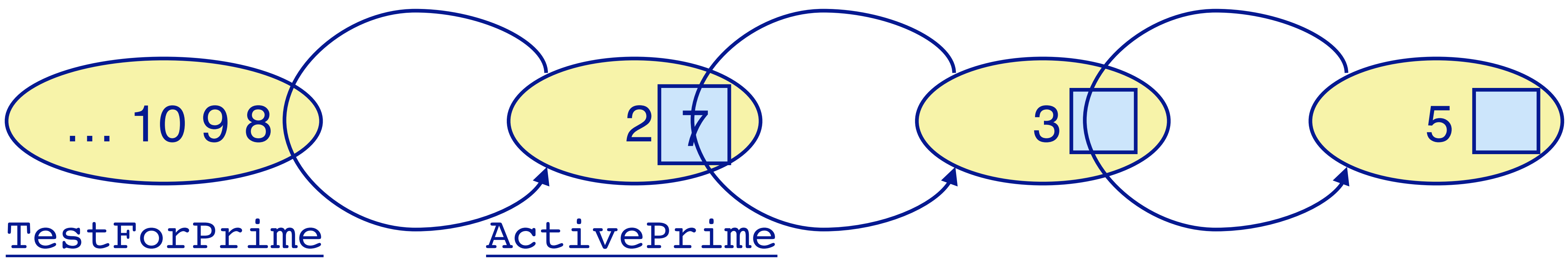
Example: a Pull-based Prime Sieve

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.

The PrimeSieve

The main PrimeSieve class creates the initial configuration

```
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`:

```
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();
   }
```

```java
    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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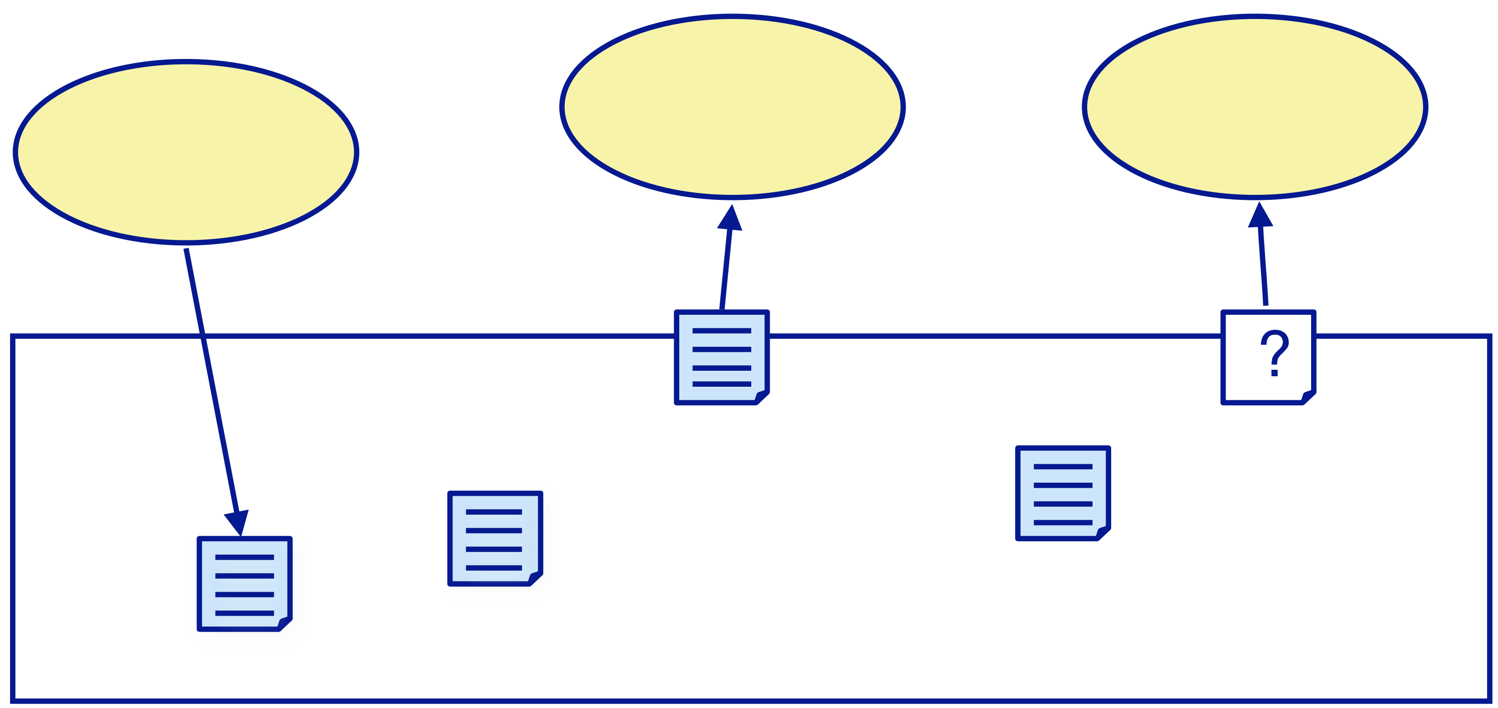
Blackboard Architectures

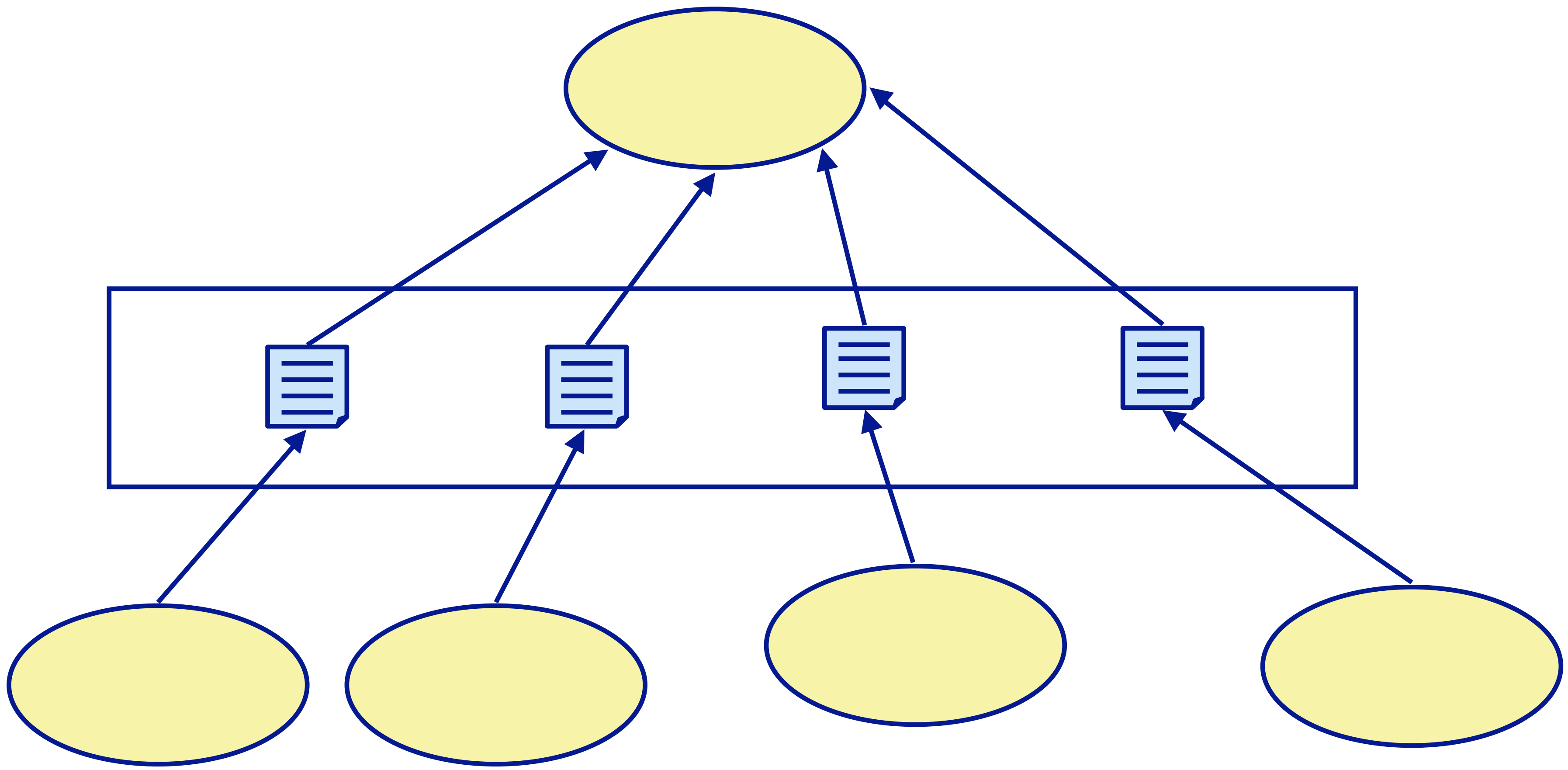
Blackboard architectures put all synchronization in a "coordination medium" where agents can exchange messages.



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

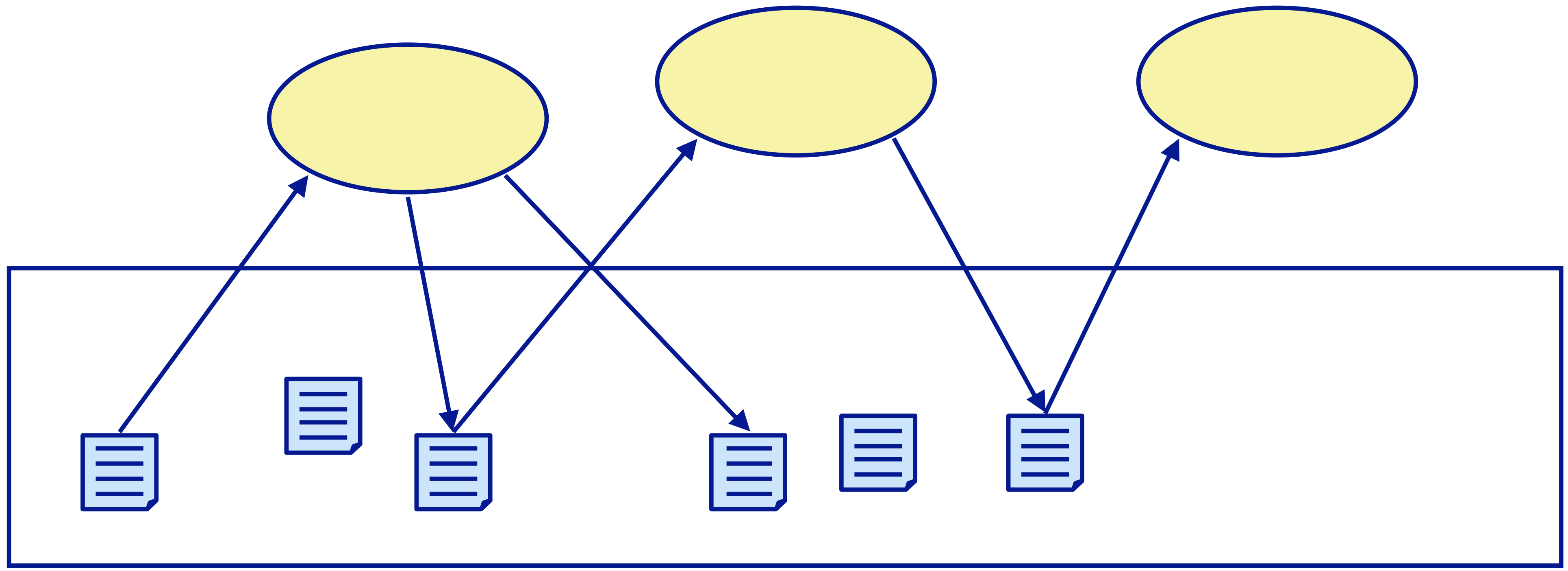
Result parallelism is a blackboard architectural style in which workers *produce parts of a more complex whole*.



Workers may be arranged hierarchically ...

Agenda Parallelism

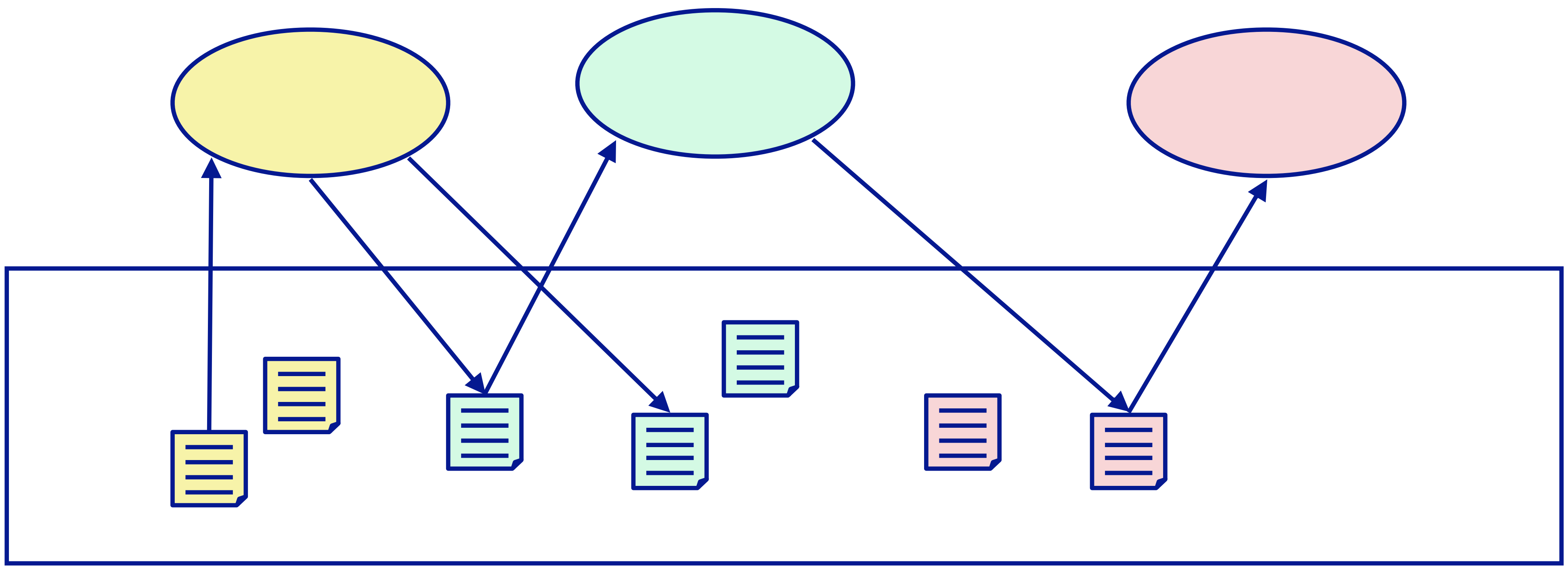
Agenda parallelism is a blackboard style in which workers *retrieve tasks to perform from a blackboard*, and may generate new tasks to perform.



Workers repeatedly retrieve tasks until everything is done.
Workers are typically able to perform arbitrary tasks.

Specialist Parallelism

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

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

`out(T)`	*output* a tuple T to the medium (non-blocking) e.g., out(“employee”, “pingu”, 35000)
`in(S)`	*(destructively) input* a tuple matching S (blocking) e.g., in(“employee”, “pingu”, ?salary)
`rd(S)`	*(non-destructively) read* a tuple (blocking)
`inp(S)`	*try to input* a tuple report success or failure (non-blocking)
`rdp(S)`	*try to read* a tuple report success or failure (non-blocking)
`eval(E)`	evaluate E in a *new process* leave the result in the tuple space

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Example: Fibonacci with JavaSpaces

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

JavaSpaces

Accessing the tuple space

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

```
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();
}
```

We wrap a JavaSpaces implementation to resemble Linda more closely.

```
Computing fib(5)
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]
rdp(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: fib(5) = 8
```

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?*