Haskell for the Cloud

Andrew P. Black

Joint work with Jeff Epstein & Simon Peyton Jones

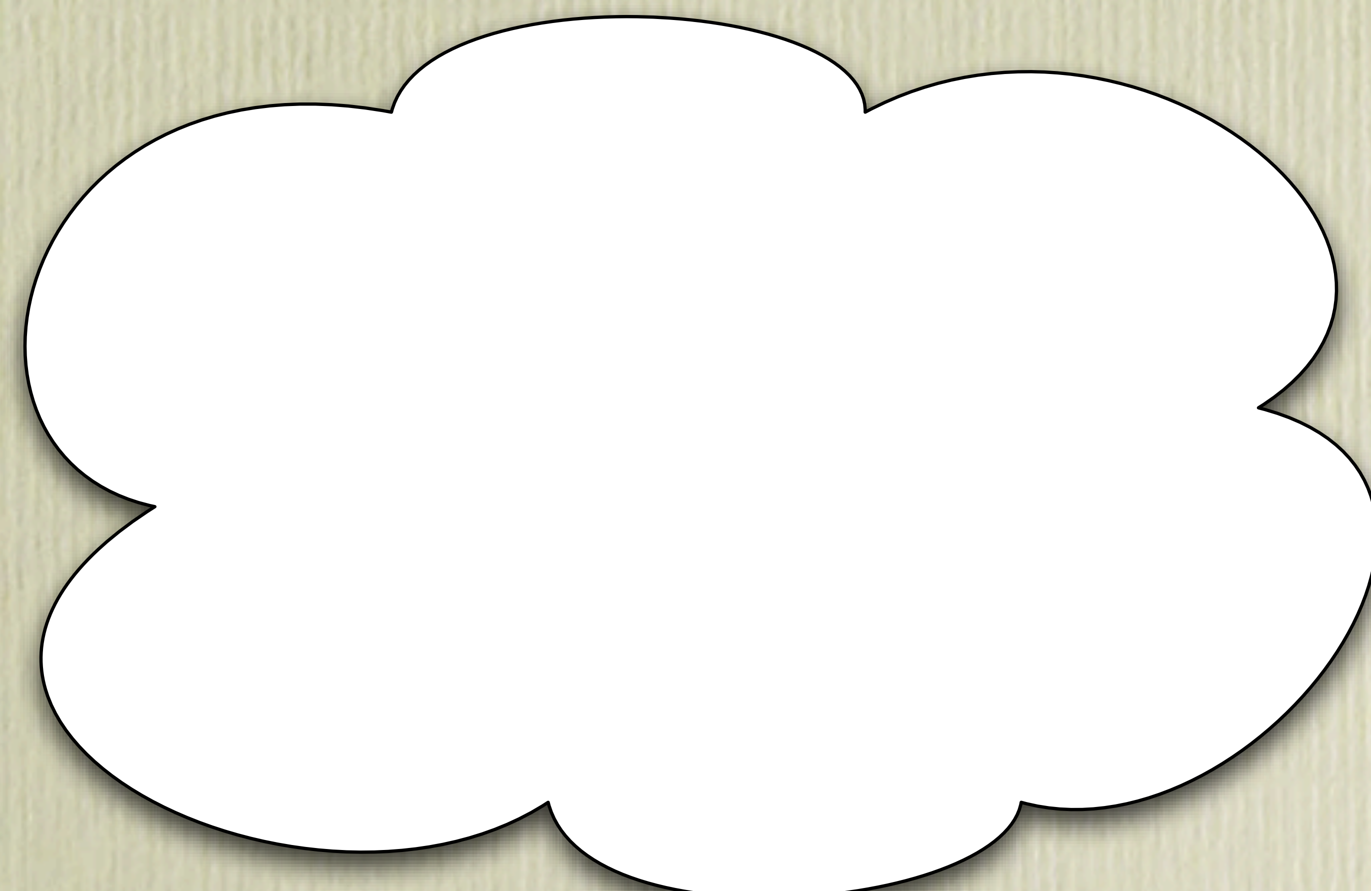
Portland State University

Cloud Haskell in a Nutshell

- A DSL for Cloud Computing implemented as a Haskell library
  - From Erlang:
    - Processes with message-passing parallelism
    - Failure and recovery model
  - From Haskell:
    - Types: purity and monads
    - Typed Channels
    - Shared-memory concurrency *within* a process

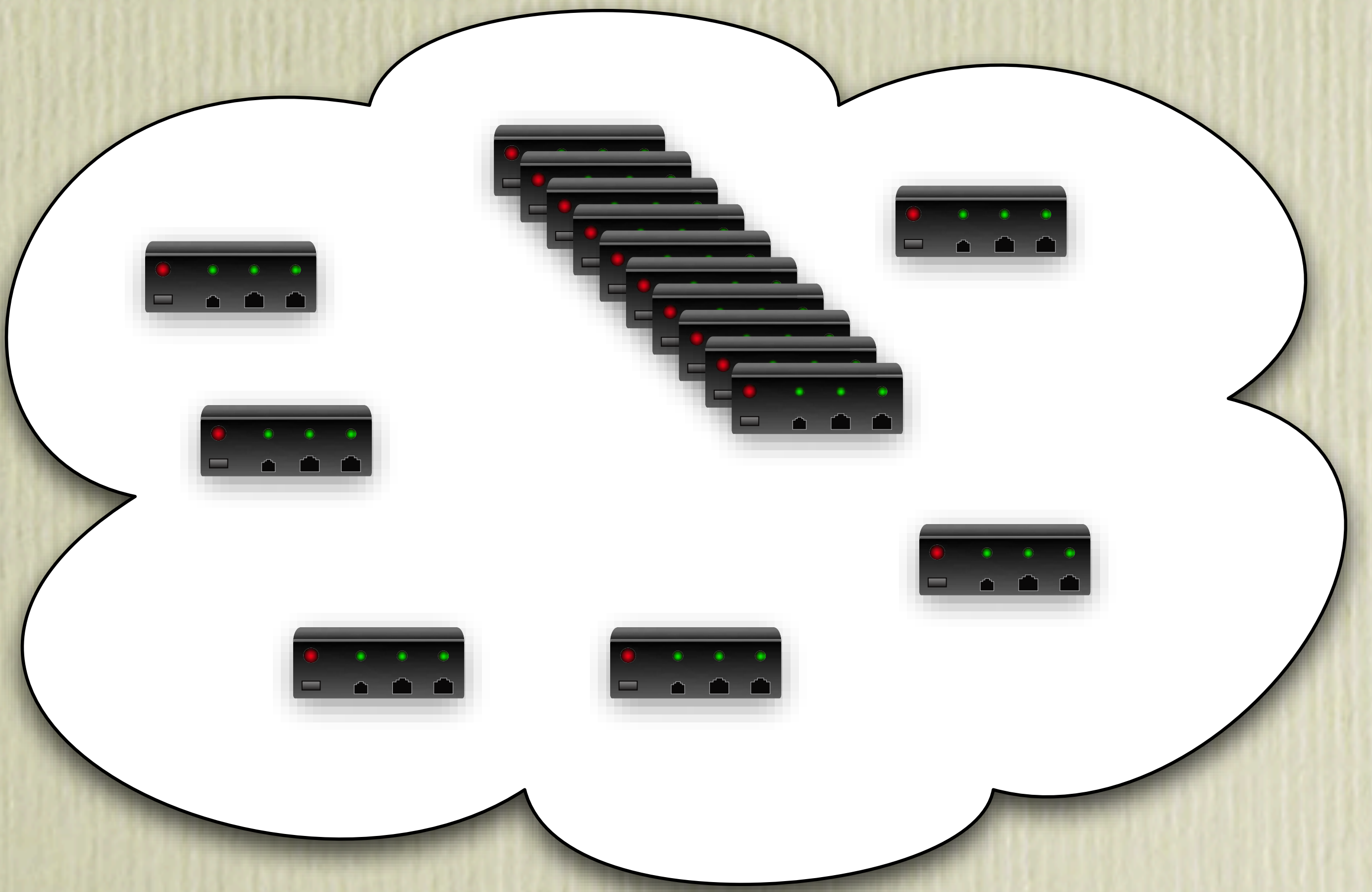
What's a Cloud?

What's a Cloud?



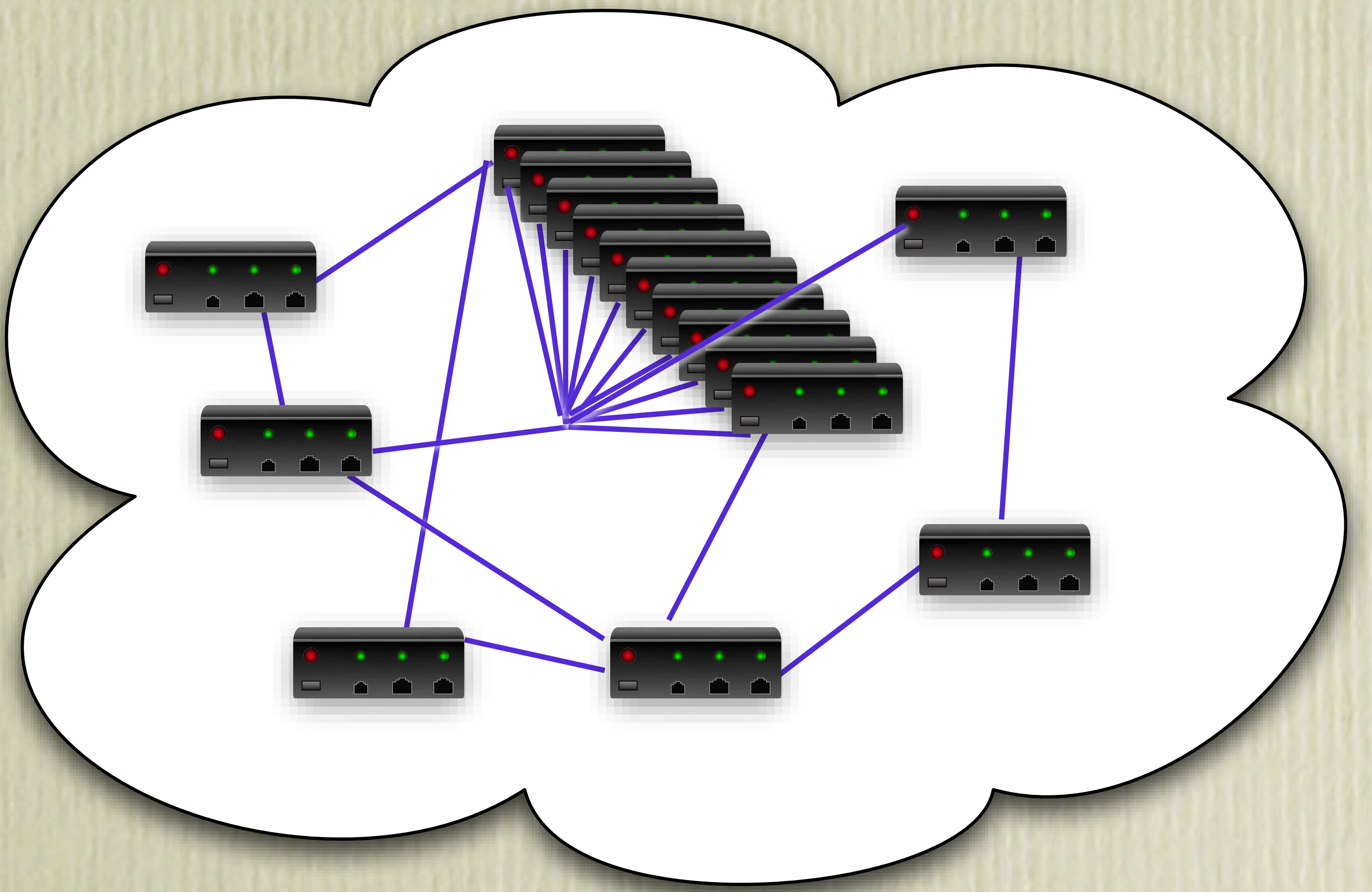
What's a Cloud?

many separate processors



What's a Cloud?

many separate processors connected by a network

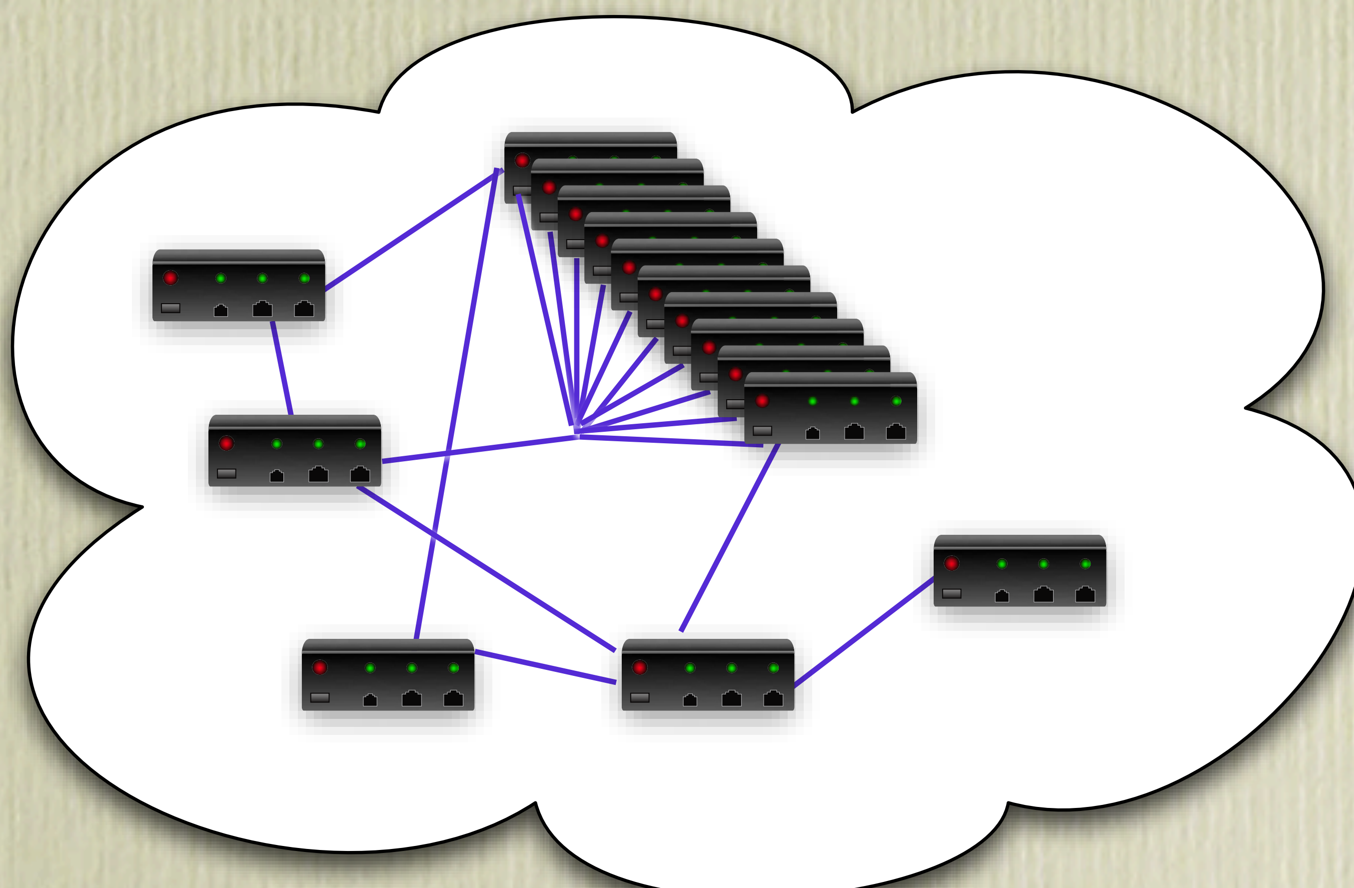


What's a Cloud?

many separate processors

connected by a network

independent failure modes



This Talk:

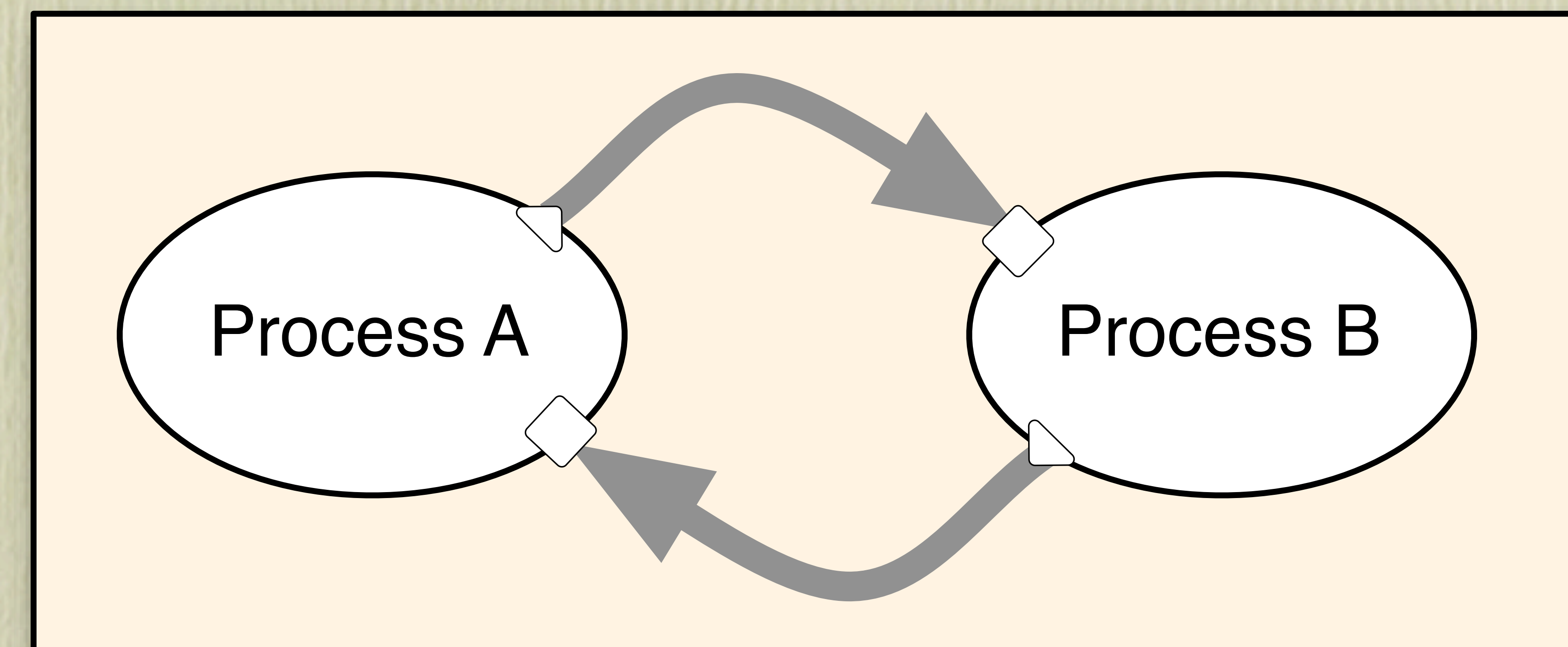
1. Erlang-style concurrency in Haskell
   - Processes, messages & failures
2. Typed Channels
3. Serialization of function closures
4. Assessment
   - Example applications

Erlang in Haskell

- Processes & Messages
- Linking Processes
- Selective Receive of Messages

Processes & Messages

- Process: a concurrent activity that has the ability to send and receive messages



- Processes *cannot* share memory

```
instance Monad ProcessM
instance MonadIO ProcessM
send  :: Serializable a ⇒ ProcessId → a →ProcessM ()
expect :: Serializable a ⇒ ProcessM a
```

Portland State University

```
instance Monad ProcessM
instance MonadIO ProcessM
send   :: Serializable a ⇒ ProcessId → a →ProcessM ()
expect    :: Serializable a ⇒ ProcessM a
```

- Ping pong:

```
data Ping = Ping ProcessId
data Pong = Pong ProcessId
— omitted: Serializable instance for Ping and Pong

ping :: ProcessM ()
ping = do { self ← getSelfPid
          ; Pong partner ← expect
          ; send partner (Ping self)
          ; ping }
```

```
instance Monad ProcessM
instance MonadIO ProcessM
send   :: Serializable a ⇒ ProcessId → a →ProcessM ()
expect    :: Serializable a ⇒ ProcessM a
```

- Compare with the Erlang version:

```
ping() → receive
           {pong, Partner} → Partner ! {ping, self()}
         end,
         ping().
```

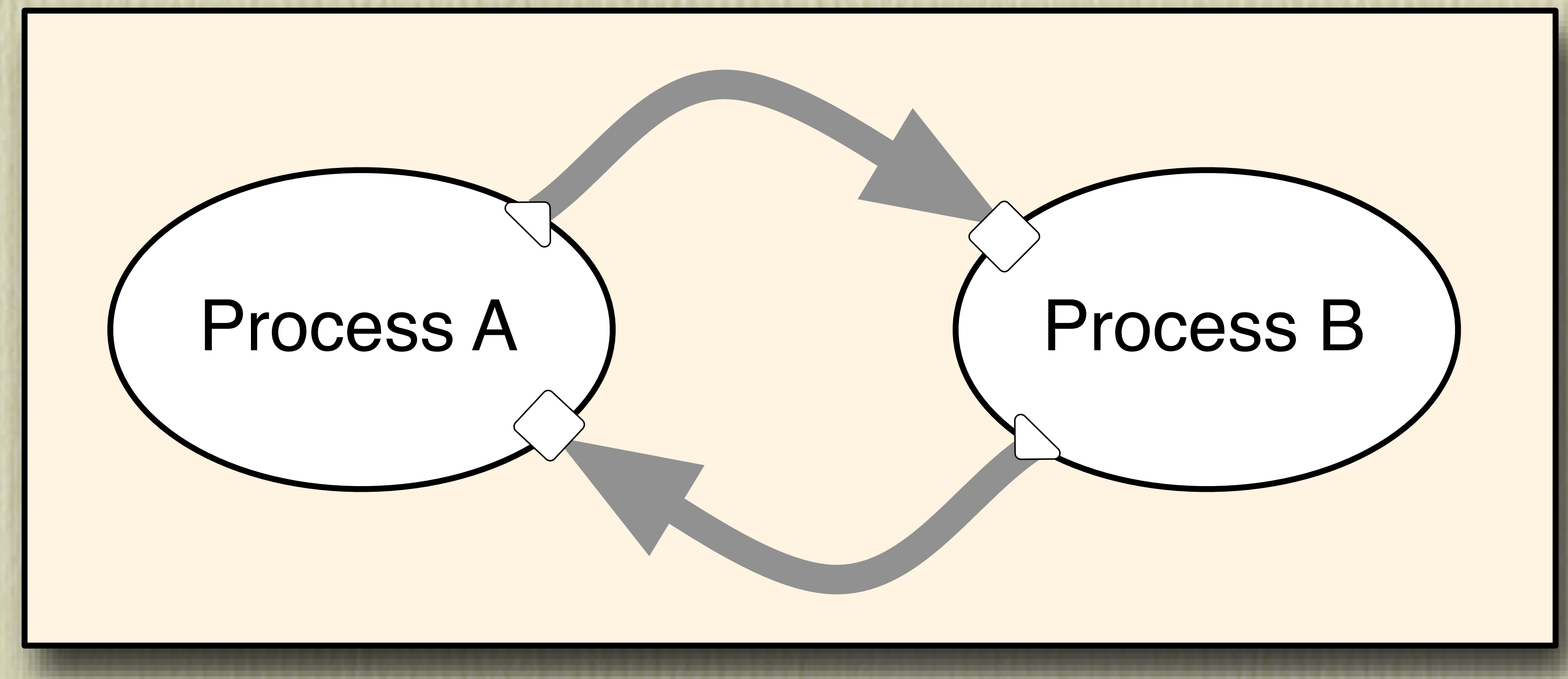
```
data Ping = Ping ProcessId
data Pong = Pong ProcessId
— omitted: Serializable instance for Ping and Pong

ping :: ProcessM ()
ping = do { self ← getSelfPid
          ; Pong partner ← expect
          ; send partner (Ping self)
          ; ping }
```

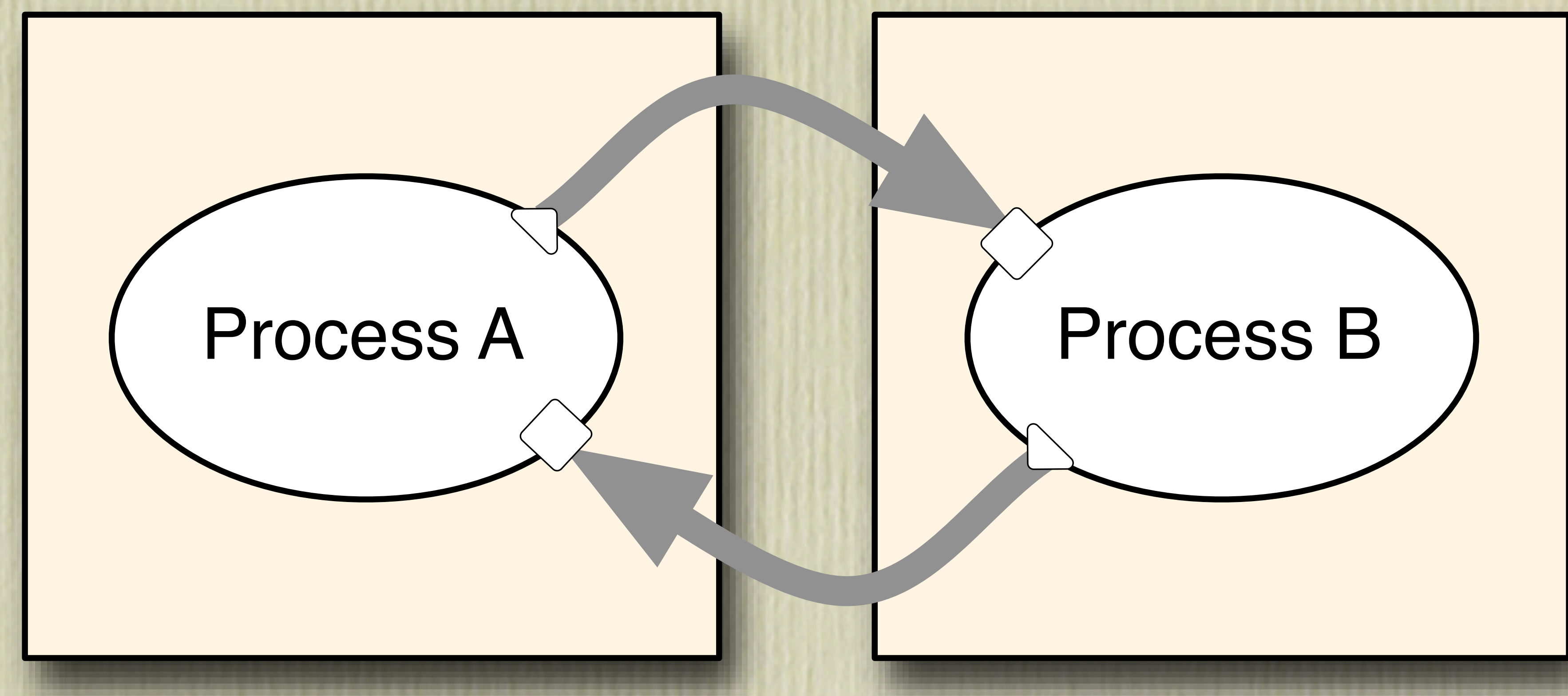
```
instance Monad ProcessM
instance MonadIO ProcessM
send  :: Serializable a ⇒ ProcessId → a →ProcessM ()
expect :: Serializable a ⇒ ProcessM a
```

- Key idea: only Serializable values can be sent in messages.
- Certain values are *deliberately* not serializable
  - MVars, IVars and TVars, in particular

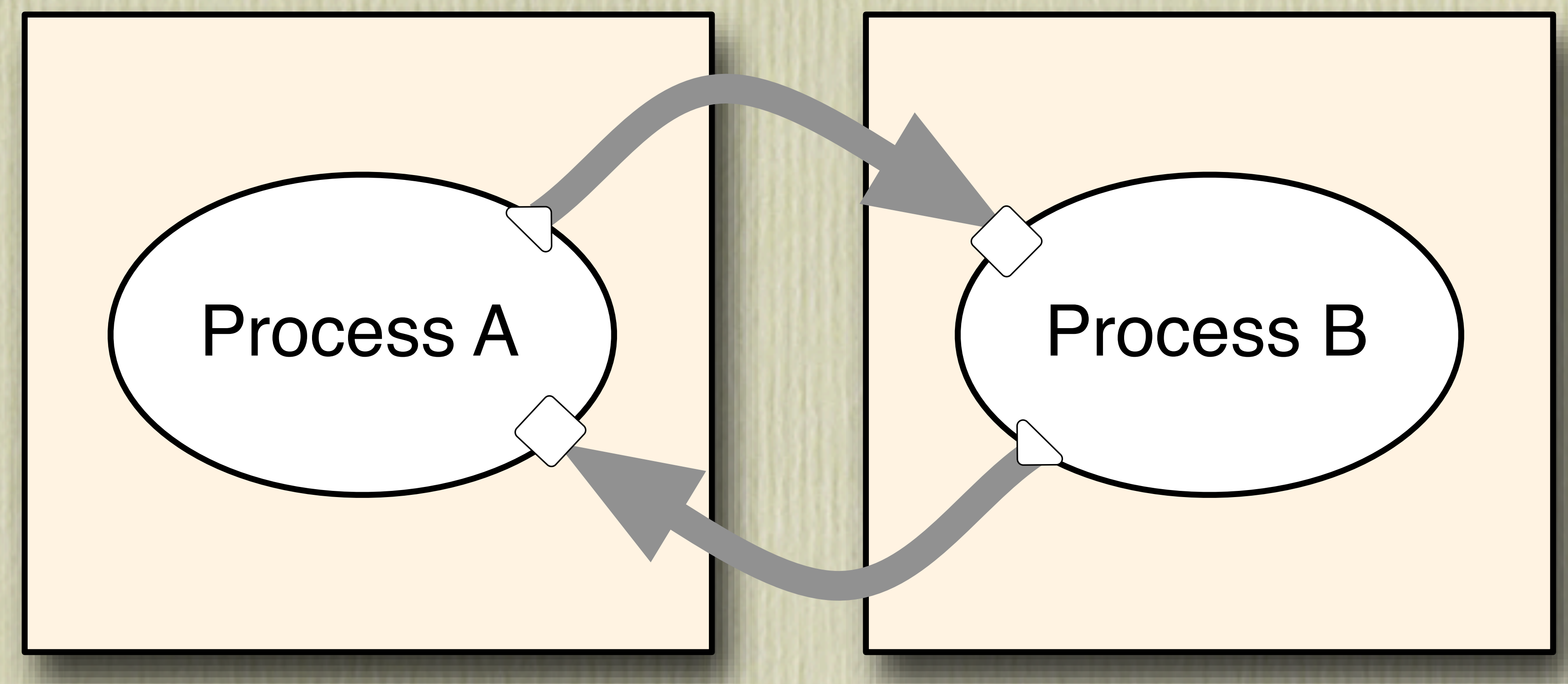
- Consequently:



Consequently:

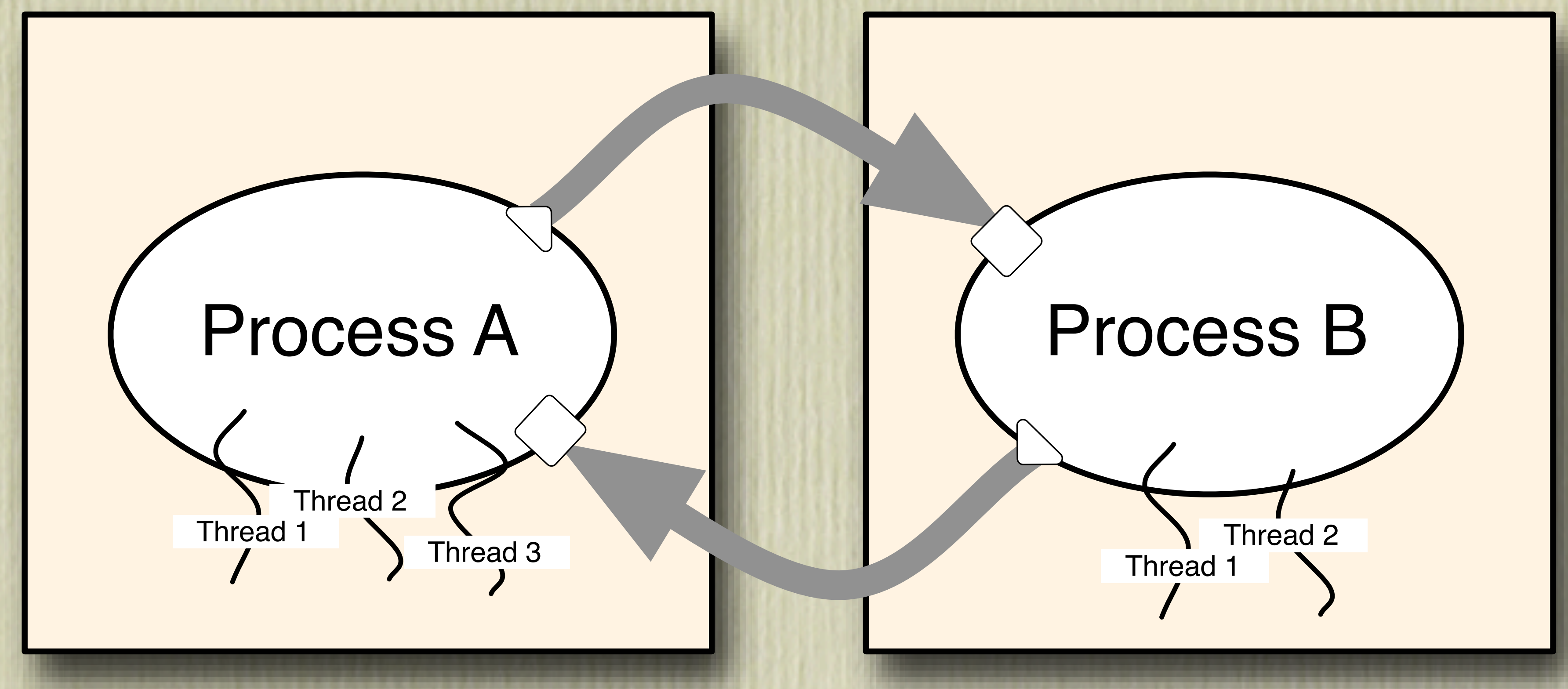


Consequently:

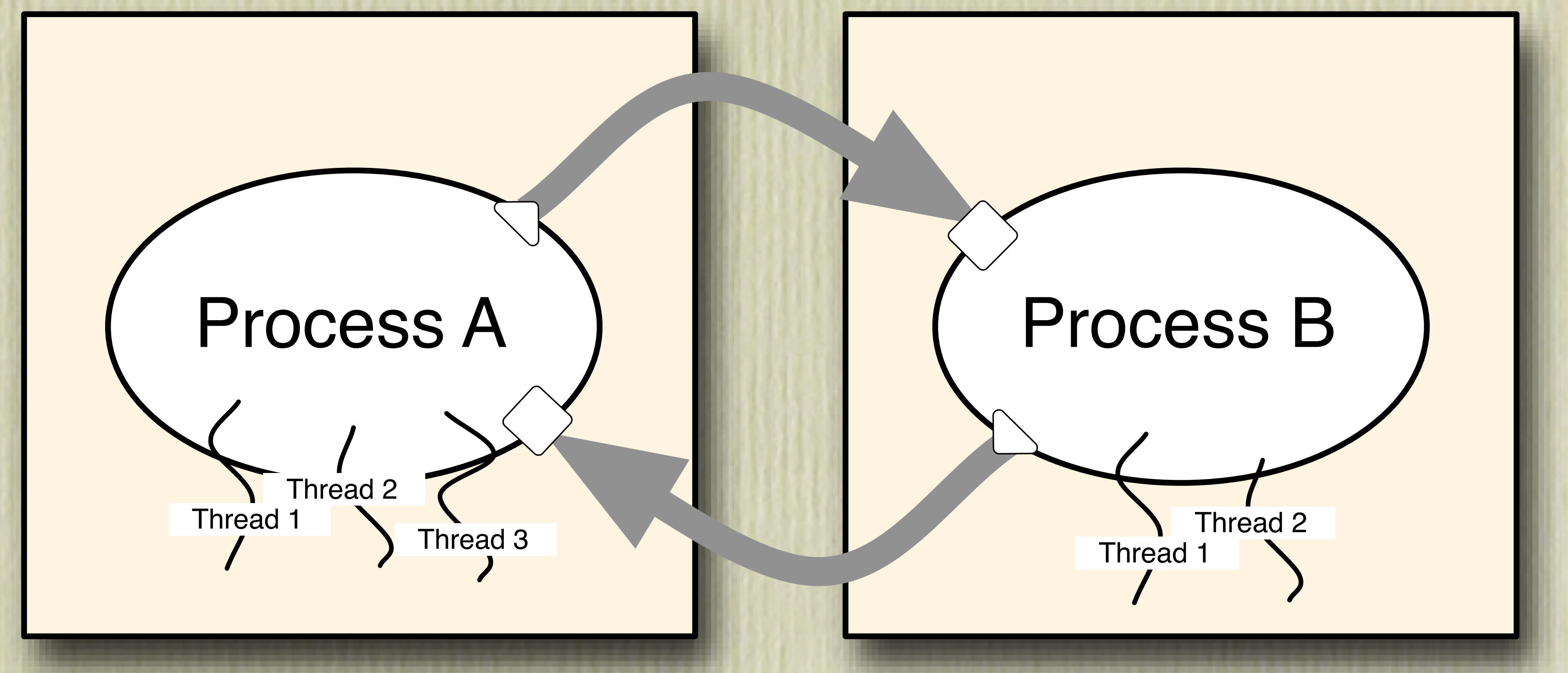


Processes can be moved from one computer to another without invalidating the programming model

Consequently:



Consequently:



Concurrent Haskell's threads, MVars, STM, etc., can all be used *inside* a single Process

Why?

Why?

- Would it be possible to serialize MVars?

Why?

- Would it be possible to serialize MVars?
  - = Is it possible to simulate shared memory in a distributed memory environment?

Why?

- Would it be possible to serialize MVars?
  = Is it possible to simulate shared memory in a distributed memory environment?
  - Yes!

Portland State UNIVERSITY

Why?

- Would it be possible to serialize MVars?
  = Is it possible to simulate shared memory in a distributed memory environment?
  - Yes!
- Would it be a good idea to serialize MVars?

Why?

- Would it be possible to serialize MVars?
  = Is it possible to simulate shared memory in a distributed memory environment?
  - Yes!
- Would it be a good idea to serialize MVars?
  - We don't think so.

Why?

- Would it be possible to serialize MVars?
  - = Is it possible to simulate shared memory in a distributed memory environment?
  - Yes!
- Would it be a good idea to serialize MVars?
  - We don't think so.
  - Glasgow Distributed Haskell disagrees!

Starting & Positioning Processes

- A Node (address space, or virtual computer) is identified by a `NodeId`
- Processes are created by `spawn`
  - First try:

```
— wrong
spawn :: NodeId → ProcessM () → ProcessM ProcessId
do   { pingProc ← spawn someNode ping
     ; pongProc ← spawn otherNode pong
     ; send pingProc (Pong pongProc) }
```

Portland State University

Actual type of Spawn

```
— wrong
spawn :: NodeId → ProcessM () → ProcessM ProcessId
do   { pingProc ← spawn someNode ping
     ; pongProc ← spawn otherNode pong
     ; send pingProc (Pong pongProc) }
```

```
— right
spawn :: NodeId → Closure (ProcessM ())
                          → ProcessM ProcessId
```

Actual type of Spawn

```
— wrong
spawn :: NodeId → ProcessM () → ProcessM ProcessId
```

```
— right
spawn :: NodeId → Closure (ProcessM ())
                          → ProcessM ProcessId
```

Actual type of Spawn

```
— wrong
spawn :: NodeId → ProcessM () → ProcessM ProcessId
```

```
— right
spawn :: NodeId → Closure (ProcessM ())
                                   → ProcessM ProcessId
```

More about Closures later

Selective Receive

- Erlang provides selective receive by pattern-matching on atoms.

```
math() →
  receive
    {add, Pid, Num1, Num2} →
        Pid ! Num1 + Num2;
    {divide, Pid, Num1, Num2} when Num2 ≠ 0 →
        Pid ! Num1 / Num2;
    {divide, Pid, _, _} →
        Pid ! div_by_zero
  end,
  math().
```

- Haskell programmers would use type constructors instead of atoms:

```
data MathOp   =   Add ProcessId Double Double
              |   Divide ProcessId Double double
              |   Answer Double
              |   DivByZero
```

- However, this breaks modularity, e.g, it forces servers to respond to Answer and clients to respond to Add.

- It's better to use several independent types:

```
data Add       = Add ProcessId Double Double
data Divide    = Divide ProcessId Double Double
data DivByZero = DivByZero
```

- However, now we need something more than expect, because we don't know which message will arrive first.

Portland State UNIVERSITY

match & receiveWait

```
math :: ProcessM ()
math =
    receiveWait
    [     match   (λ(Add pid num1 num2) →
                          send pid (num1 + num2)),
          matchIf (λ(Divide _ _ num2) → num2 ≠ 0)
                  (λ(Divide pid num1 num2) →
                          send pid (num1 / num2)),
          match   (λ(Divide pid _ _) →
                          send pid DivByZero) ]
      ≫ math
```

match & receiveWait

```
math :: ProcessM ()
math =
    receiveWait
    [     match   (λ(Add pid num1 num2) →
                          send pid (num1 + num2)),
          matchIf (λ(Divide _ _ num2) → num2 ≠ 0)
                  (λ(Divide pid num1 num2) →
                          send pid (num1 / num2)),
          match   (λ(Divide pid _ _) →
                          send pid DivByZero) ]
      ≫ math
```

```
match :: Serializable a ⇒
(a → ProcessM q) → MatchM q ()
```

match & receiveWait

```
math :: ProcessM ()
math =
  receiveWait
  [   match   (λ(Add pid num1 num2) →
                       send pid (num1 + num2)),
      matchIf (λ(Divide _ _ num2) → num2 ≠ 0)
              (λ(Divide pid num1 num2) →
                       send pid (num1 / num2)),
      match   (λ(Divide pid _ _) →
                       send pid DivByZero) ]
    ≫ math
```

```
receiveWait ::
    [MatchM q ()] → ProcessM q
```

```
match :: Serializable a ⇒
(a → ProcessM q) → MatchM q ()
```

match & receiveWait

```
math :: ProcessM ()
math =
    receiveWait
    [     match   (λ(Add pid num1 num2) →
                        send pid (num1 + num2)),
          matchIf (λ(Divide _ _ num2) → num2 ≠ 0)
                  (λ(Divide pid num1 num2) →
                        send pid (num1 / num2)),
          match   (λ(Divide pid _ _) →
                        send pid DivByZe
      ≫ math
```

receiveWait ::
    [MatchM q ()] → ProcessM q

matchIf :: Serializable a ⇒
(a → Bool) → (a →
ProcessM q) → MatchM q ()

match :: Serializable a ⇒
(a → ProcessM q) → MatchM q ()

Also: receiveTimeout and matchUnkown

```
instance Monad MatchM
receiveWait    :: [MatchM q ()] → ProcessM q
receiveTimeout :: Int → [MatchM q ()]
                                   → ProcessM (Maybe q)
match   :: Serializable a ⇒ (a → ProcessM q)
                                   → MatchM q ()
matchIf :: Serializable a ⇒ (a → Bool)
                         → (a → ProcessM q) → MatchM q ()
matchUnknown :: ProcessM q → MatchM q ()
```

Typed Channels

- We can use types to ensure that processes are prepared to accept the messages that are sent to them
- Instead of sending a message to a process, we send it on a channel, specialized for a single type
    - A channel is a pair of ports: a send port and a receive port

Channel Interface

```
newChan  :: Serializable a ⇒
                ProcessM (SendPort a, ReceivePort a)
sendChan :: Serializable a ⇒
                SendPort a → a → ProcessM ()
receiveChan :: Serializable a ⇒
                ReceivePort a → ProcessM a
mergePortsBiased :: Serializable a ⇒
                [ReceivePort a]→ ProcessM (ReceivePort a)
mergePortsRR :: Serializable a ⇒
                [ReceivePort a] → ProcessM (ReceivePort a)
```

SendPort a is serializable; ReceivePort a is *not* serializable

Ping-Pong: once more, with Channels

```
ping2 :: SendPort Ping → ReceivePort Pong →
                                          ProcessM ()
ping2 pingout pongin =
  do   { (Pong partnersPort) ← receiveChan pongin
       ; sendChan partnersPort (Ping pongin)
       ; ping2 pingout pongin }
```

Combing Ports

- Suppose that we have several communication partners,
  - e.g., messages arrive from the hardware that we are monitoring, and from other control processes in the network.
- We want to receive from one of several ports.

MergePortsBiased	CombinePortsBiased
MergePortsRR	CombinePortsRR

Serializing function closures

- Sending a function to a remote address space involves serializing not only its code, but also its free variables:

```
— wrong
sendFunc :: SendPort (Int→Int) → Int → ProcessM ()
sendFunc p x = sendChan p (λy → x + y + 1)
```

- The function being sent is `(λy → x + y + 1)`, which captures the variable `x`.

Key insight

- Whether a function is serializable or not has nothing to do with its *type*.
  - It depends on whether it has free variables,
  - whether those free variables are serializable

  which are *not* extensional properties of the function

Prior Solutions

- Make the runtime responsible for serializing anything and everything
  - But some things should be serialized specially
  - And others should not be serialized at all
- Java does essentially this
- Yet: *de*-serialization must still be built-in
  - this requires runtime reflection

Portland State University

More modest magic

- Some functions are easy to serialize
  - those with no free variables
  - How? Serialize the code address
    - assuming the same code is running at both ends
- We need a way of charactering such definitions as a *type:*

```
instance Serializable (Static a)
```

- Intuition: values of type (Static a) are always serializable, regardless what a is!

Static and non-Static types

- Two new terms: static exp and unstatic exp
  - intuition: static exp is well-typed iff exp can be serialized.
- Top-level bindings are tagged S; all others are tagged D
- A term static exp has type τ iff exp :: τ and all the free variables in exp are S-bound

$$\begin{array}{rcl} \Gamma & ::= & \overline{x :_\delta \sigma} \\ \delta & ::= & \mathsf{S} \mid \mathsf{D} \end{array}$$

$$\Gamma\!\downarrow \; = \; \{x :_{\mathsf{s}} \sigma \mid x :_{\mathsf{s}} \sigma \in \Gamma\}$$

$$\frac{\Gamma\!\downarrow \;\vdash e : \tau}{\Gamma \vdash \mathsf{static}\ e : \mathsf{Static}\ \tau} \quad \text{(Static intro)}$$

$$\frac{\Gamma \vdash e : \mathsf{Static}\ \tau}{\Gamma \vdash \mathsf{unstatic}\ e : \tau} \quad \text{(Static elim)}$$

Examples:

Examples:

id :: a → a

id x = x

id is S-bound, but has a non-static type.

id $:_S$ a → a

Examples:

id :: a → a id x = x	id is S-bound, but has a non-static type. id $:_S$ a → a
f :: Static a → (Static a, Int) f x = (x, 3)	x is D-bound, but has a static type x $:_D$ Static a

Examples:

id :: a → a id x = x	id is S-bound, but has a non-static type. id $:_S$ a → a
f :: Static a → (Static a, Int) f x = (x, 3)	x is D-bound, but has a static type x $:_D$ Static a
static (length ∘ filter id)	Free variables of a static term need not have static types

- So what? We need to serialize functions that *do* have free variables.
- Static values make it possible to do closure conversion
- Let's try:

```
— wrong
data Closure a where
   MkClosure :: Static (env → a) → env → Closure a
```

- This makes the environment explicit:
  - env is the (existentially quantified) type of the environment of our function

- Slight snag: `env` is not serializable
- OK: let's make it so!

```
— still wrong
data Closure a where
   MkClosure :: Serialzable env ⇒
                           Static (env → a) → env → Closure a
   deriving Typeable
```

- Now serialization is easy:

```
instance Binary (Closure a) where
   put (MkClosure f env) = put f ≫ put env
```

- But what about *de*-serialization?

- Deserialization is a problem because, at the receiving end, we don't know what env is.
  - Can we send a representation of its type?
  - And then what?
    - Do a run-time type-class lookup?
  - Send a representation of the de-serialization function?
    - This would require us to serialize closures …
- Simple and (in hindsight!) obvious solution:
  - get rid of the existential!

The solution

```
— finally right
data Closure a where
    MkClosure :: Static (ByteString → a) → ByteString →
                                                      Closure a
```

- Isn't this awfully restrictive?

    No! *Any* env that is serializable is equipped with encode and decode functions that convert it to and from a ByteString!

- The (de)-serialization is now done at closure-construction time

Examples

```
sendFunc :: SendPort (Closure (Int → Int)) → Int → ProcessM ()
sendFunc p x = sendChan p clo
  where clo = MkClosure (static sfun) (encode x)

sfun :: ByteString → Int → Int
sfun = λbs → let x = decode bs
             in λy → x + y + 1
```

Add newWorker example

Portland State UNIVERSITY

Examp

p is a SendPort that expects a (Closure (Int→Int))

```
sendFunc :: SendPort (Closure (Int → Int)) → Int → ProcessM ()
sendFunc p x = sendChan p clo
   where clo = MkClosure (static sfun) (encode x)

sfun :: ByteString → Int → Int
sfun = λbs → let x = decode bs
             in λy → x + y + 1
```

Add newWorker example

Examp

p is a SendPort that expects a (Closure (Int→Int))

```
sendFunc :: SendPort (Closure (Int → Int)) → Int → ProcessM ()
sendFunc p x = sendChan p clo
   where clo = MkClosure (static sfun) (encode x)

sfun :: ByteString → Int → Int
sfun = λbs → let x = decode bs
             in λy → x + y + 1
```

In the Closure we put a *pre-serialized* version of the free variable x

Add newWorker example

Examp

p is a SendPort that expects a (Closure (Int→Int))

```
sendFunc :: SendPort (Closure (Int → Int)) → Int → ProcessM ()
sendFunc p x = sendChan p clo
  where clo = MkClosure (static sfun) (encode x)

sfun :: ByteString → Int → Int
sfun = λbs → let x = decode bs
             in λy → x + y + 1
```

In the Closure we put a *pre-serialized* version of the free variable x

sfun *de-serializes* its own argument

Add newWorker example

Summary

- New type constructor `Static`, with built-in serialization.
- A new term form `(static e)`
- A new primitive function `unstatic :: Static a → a`
- These primitives let us construct closures manually and control when and how they are serialized.
  - This looks tiresome, and programmers will probably want some syntactic support: future work

Faking it

- Static is not yet implemented in GHC
- We use Template Haskel workarounds

```
sendFunc :: SendPort (Closure (Int → Int)) → Int → ProcessM ()
sendFunc p x = sendChan p ($( mkClosure 'add1) x)
add1 :: Int → Int → Int
add1 x y = x + y + 1

$(remotable ['add1])
```

- Programmer is still doing closure-conversion
  - by defining add1 as a top-level function whose first argument is an explicit environment (Int)
  - mkClosure operates on the *names* of functions:
    - mkClosure :: Name → Q Exp

Assessment

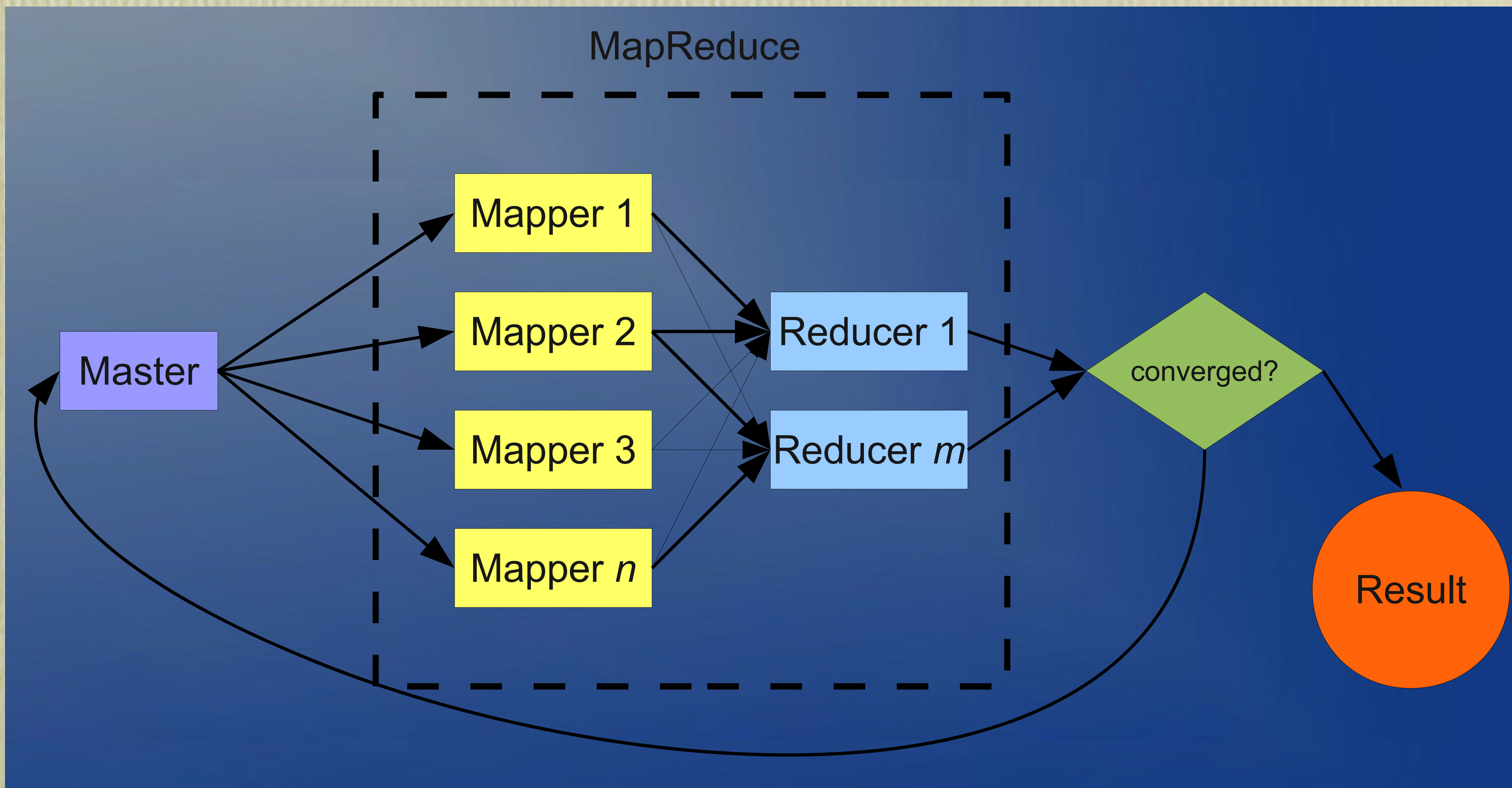
- Limited experience so far
- Small examples on local networks, and *k*-means on an Amazon EC2 cluster.

k-means

Data clustering algorithm:

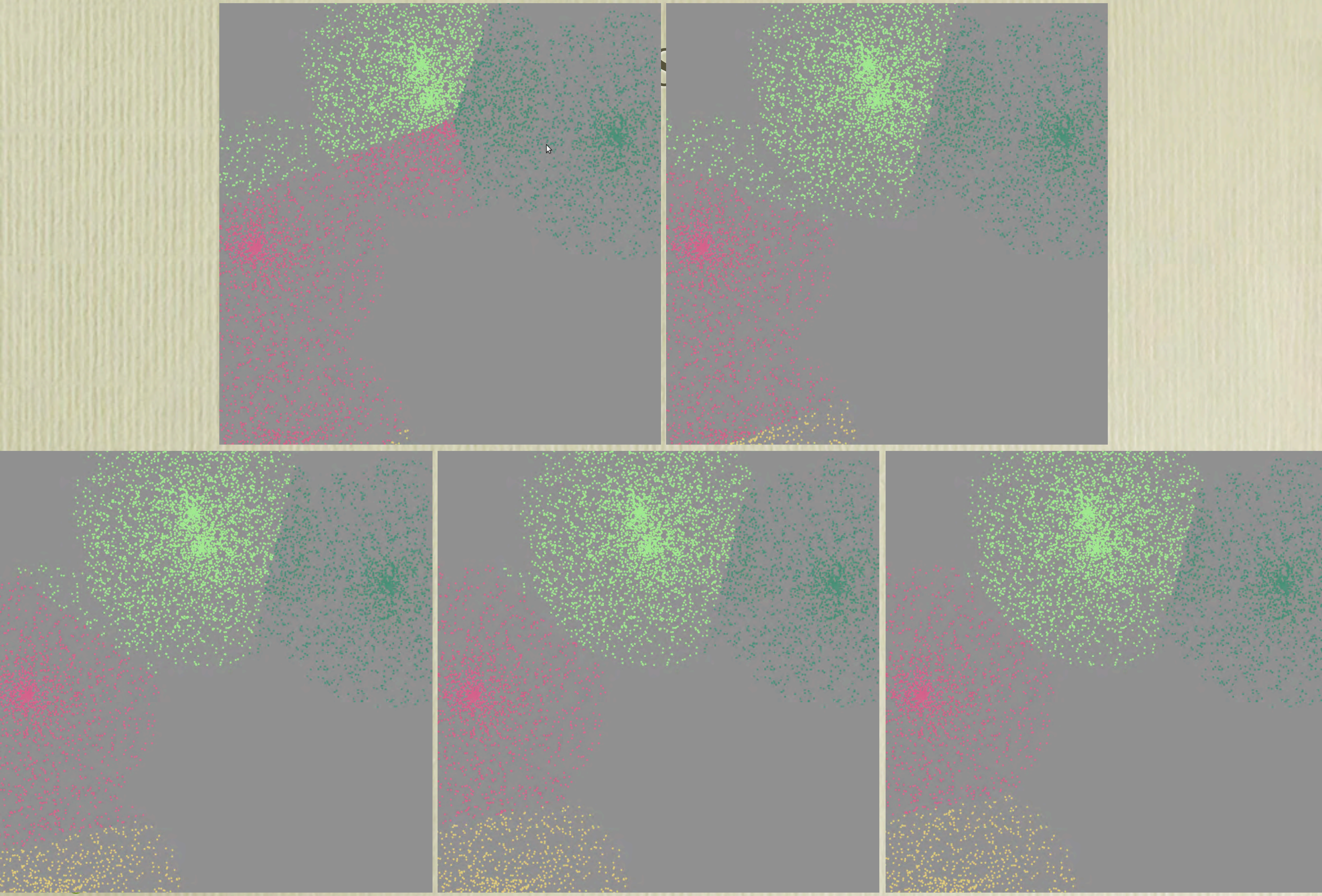
1. Guess at centroids of *k* clusters
2. Put each point in nearest cluster
3. Compute the centroids of these cluster of points
4. Use the computed centroids as the next guess
5. Continue until convergence

k-means

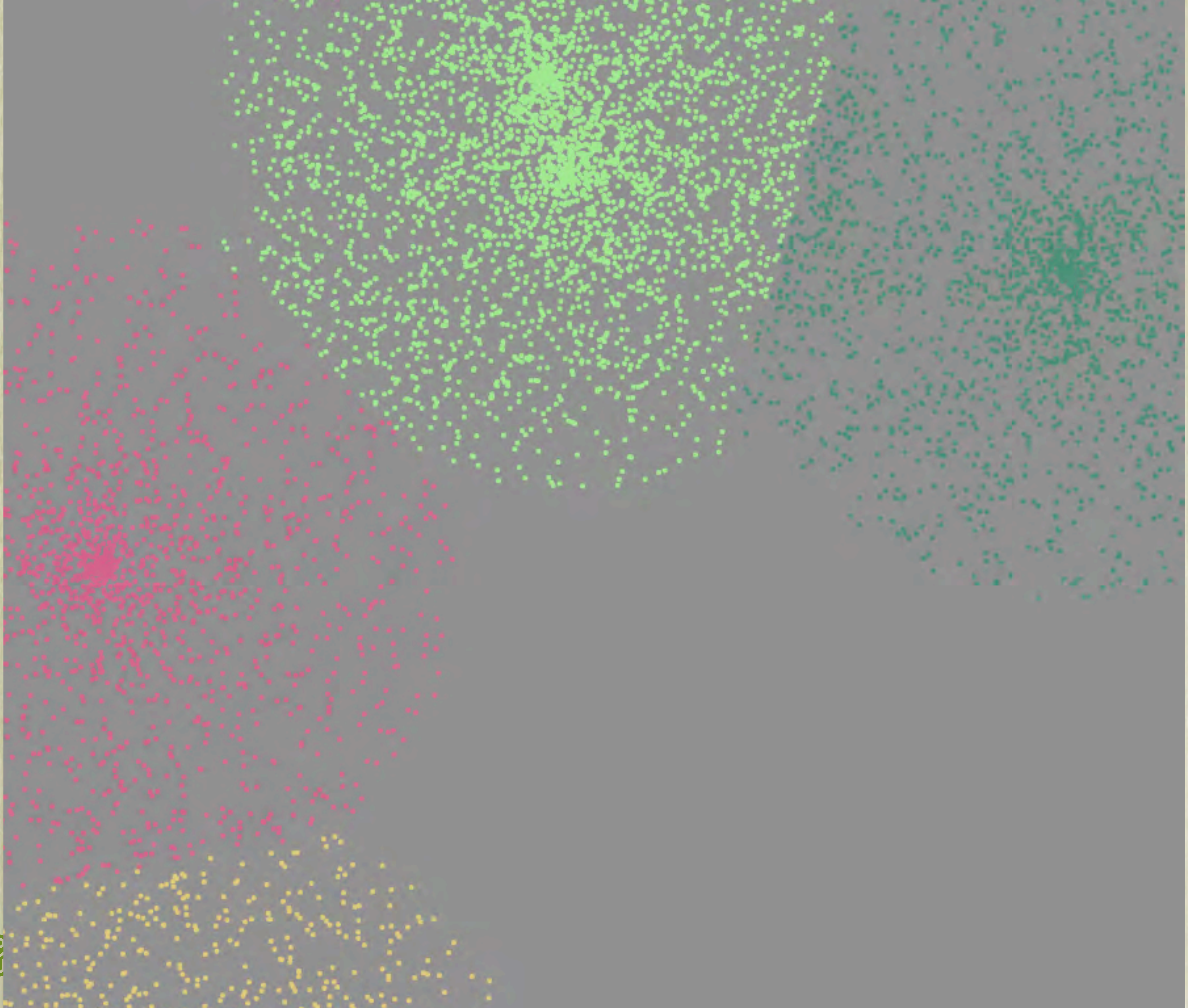


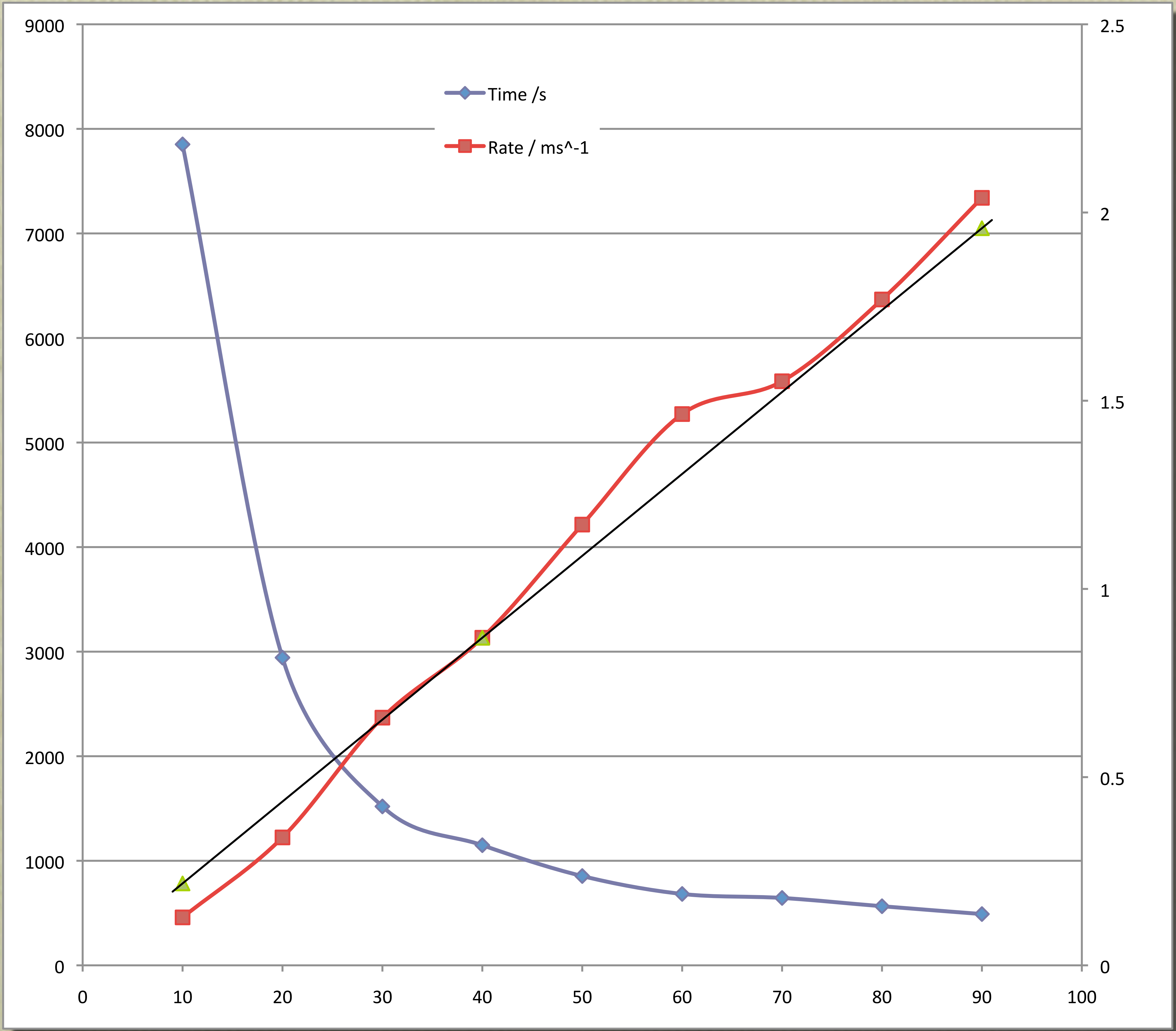
MapReduce
Master
Mapper 1
Mapper 2
Mapper 3
Mapper *n*
Reducer 1
Reducer *m*
converged?
Result

k-means results



k-means results





k-means results

nodes: m1.small (1 core, 1.7 GB)

1 million 100-D points

one reducer

5 iterations

Portland State UNIVERSITY

Related Work

- Inspired by Erlang
  - Also by Ciel execution engine and the Skywriting language [Murray *et al*]
- MPI from the HPC community
  - language independent
- RPC and RMI mechanisms
  - Birrell & Nelson, Emerald, CORBA, Java RMI, SOAP, ...

- Distributed functional languages: GDH (distributed shared memory), Concurrent ML, paraML
  - Acute [Sewell *et al.*]: uses runtime representations of datatypes
  - HashCaml: does support serialization of function values, also with explicit type-passing
  - Alice [Rossberg's Thesis]
  - Clean: type-safe pickling, including function closures
- Our design point: serialization of closures is *not* built-in

Future Work

- Low level: implement Static in GHC
- Restartable task level
  - inspired by Skywriting project
  - tasks: idempotent, restartable computations
  - system tracks data dependencies between tasks
  - allocates tasks to processors
  - recovers from failure

Summary

- Cloud Haskell: a *starting point* for building distributed applications
- Contributions:
  - Typed version of Erlang's process & messaging interfaces
  - Typed channels; receive port is not Serializable
  - Serialization of function closures
  - It works (on 90 Amazon EC2 nodes)

Portland State UNIVERSITY