Declarative distributed concurrency in Scala

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Scale by the Bay 2018

November 16, 2018

Talk summary

How I learned to forget semaphores and to love concurrency

`Chymyst` = an implementation of the Chemical Machine (CM) paradigm

- CM $\approx$ Actors made purely functional and auto-parallelized
- Intuitions about why CM works better than other concurrency models
  - Comparison with related work: ING Baker, BPMN (workflow)
- New extension for distributed programming: DCM
- Code examples and demos

Not in this talk: academic theory

- Petri nets, π-calculus, join calculus, joinads, mobile agent calculus...
- DCM formulated within a theory of distributed programming?

Concurrent & parallel programming: How we cope

Imperative concurrency & parallelism is difficult to reason about:

- low-level API: callbacks, threads, semaphores, mutex locks
- hard to reason about mutable state and running processes
- hard to test – non-deterministic runtime behavior!
  - race conditions, deadlocks, livelocks

Known declarative approaches to avoid these problems:

Kind of concurrency	**Typeclass**	**Scala implementation**
synchronous parallelism	applicative functor	Spark, `.par.map()`
asynchronous streaming DAG	monadic functor	`Future`, `async`/`await`, `RxJava`, Akka Streams
unrestricted streaming	recursive monad+	Flink, fs2, ZIO
unrestricted concurrency	?	Akka, `Chymyst`

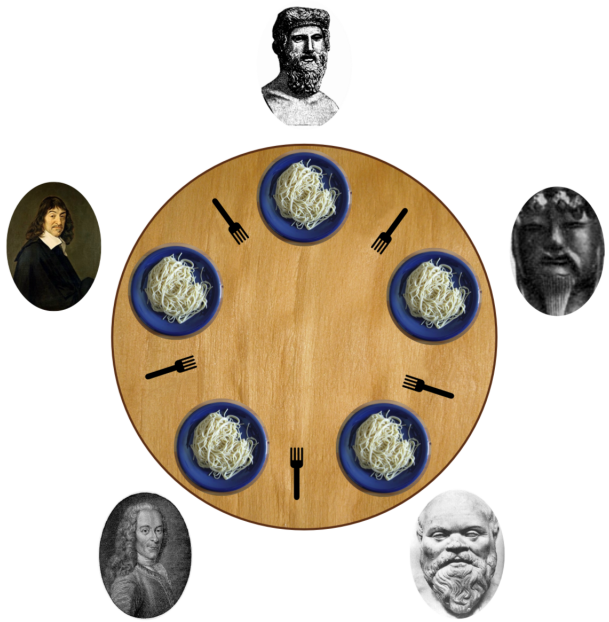
For distributed computing: challenges remain

- coordination and consensus, persistence and fault tolerance
- cluster configuration and discovery
  - distributed coordination as a service: Apache ZooKeeper, `etcd`

"Dining philosophers"

The paradigmatic problem of concurrency, parallelism and resource contention

Five philosophers sit at a round table, taking turns eating and thinking for random time intervals



Problem: simulate the process, avoiding deadlock and starvation

Solutions in various programming languages: see Rosetta Code

- Can this be implemented via (effectful) streams? (I think not.)
- The Chemical Machine code is purely declarative

What is the Chemical Machine

The Chemical Machine paradigm:

- A *declarative language* for concurrent and parallel computations
  - largely unknown and unused by the software engineering community
  - `Chymyst` – an open-source library & embedded DSL for Scala
  - presented in my SBTB talks in 2016 and 2017

Implement anything in 10 lines of code

Chemical Machine vs. Amazon's AWS Lambda

How does AWSλ work:

- wait for an event that signals arrival of input data
- run a computation whenever input data becomes available
- the computation is automatically parallelized, data-driven
- writing the output data will create a new event

Modify the AWSλ execution model by adding new requirements:

- a Lambda should be able to wait for several *unrelated* events
- several Lambdas may contend *atomically* on shared input events

With these new requirements, AWSλ becomes "AWSπ" – a purely functional *unrestricted concurrency* model

- (Implementation on AWS will be tricky)

The Chemical Machine vs. the Actor model

Modify the Actor execution model by adding new requirements:

- when messages arrive, actors are auto-created, maybe *in parallel*
- actors may wait atomically for messages in *several* different mailboxes

It follows from these requirements that...

- Auto-created actor instances are *stateless* and invisible to user
- User code defines *mailboxes* and *computations* that consume messages
- Repeated messages may be consumed in parallel
- Messages are sent to mailboxes, not to specific actor instances:

```
// Akka
val a: ActorRef = ... receive(x) ⇒...
val b: ActorRef = ... receive(y) ⇒...
a ! 100
b ! 1;   b ! 2;   b ! 3
```

```
// Chymyst
... go { case a(x) ⇒ ... }
... go { case b(y) + c(z) ⇒ ... }
a(100)
b(1);  b(2);  b(3); c("hello");
```

- All data resides on messages in mailboxes, is consumed automatically
- Mailboxes and computations are *values*, can be sent on messages

Any Actor program can be straightforwardly translated into CM

Understanding the CM via the chemical metaphor

From real to abstract chemistry

Real chemistry is "asynchronous", "concurrent", and "distributed"

$$HCl + NaOH \rightarrow NaCl + H_2O$$

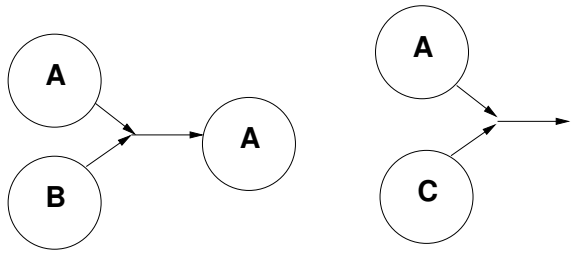
Use as inspiration for the execution model of "abstract chemistry":

- Abstract "molecules" float around in a "chemical reaction site"
- Certain sorts of molecules may combine to start a "reaction":

Abstract chemical laws:

`a + b` $\rightarrow$ `a`

`a + c` $\rightarrow \emptyset$



- Program code defines molecules `a`, `b`, `c`, ... and chemical laws
- At initial time, the code emits some molecules into the site
- The runtime system evolves the molecules *concurrently* and *in parallel*

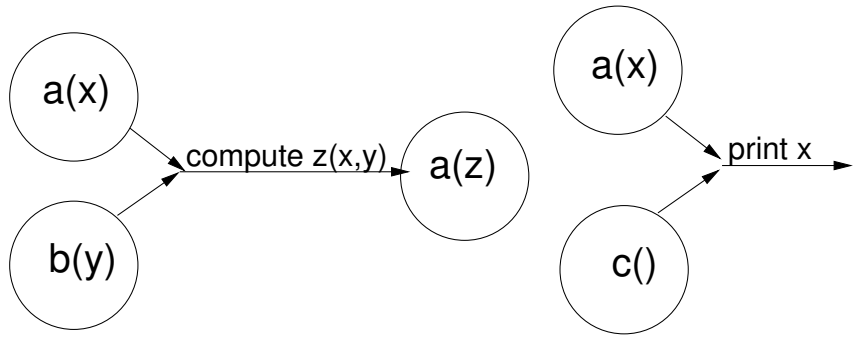
Want to run *computations* similarly to how chemical reactions run!

Chemical Machine in a nutshell

"Better concurrency through chemistry"

Translating the chemical metaphor into a model of computation:

- Each molecule carries a **value** ("concurrent data")
- Each reaction computes new values from its input values
- Some molecules with new values may be emitted back into the reaction site




```
site(
  go { case a(x) + b(y) ⇒
   val z = f(x, y); a(z) },
  go { case a(x) + c(_) ⇒
      println(x) }
)
```

When a reaction starts: input molecules disappear, new values are computed, output molecules are emitted

Reactions are *functions* from input values to output values

- Need to learn how to "think in molecules"

Chemical Machine vs. Actor model

- reaction $\approx$ template for an (auto-started) actor
- emitted molecule with value $\approx$ message with value, in a mailbox
- molecule emitters $\approx$ mailbox references

Programming with actors:

- user code creates and manages explicit actor instances
- actors typically hold mutable state and/or mutate "behavior"
  - reasoning is about running processes *and* the data sent on messages

Programming with the Chemical Machine:

- processes auto-start when the needed input molecules are available
- many reactions may start at once, automatically parallel
  - user code does not manipulate references to processes
    - ★ no state, no supervision, no lifecycle, no "dead letters", no routers
  - reasoning is *only* about the *data* currently available on molecules
    - ★ no reasoning about running processes having state

`Chymyst` code is typically 2x – 3x shorter than equivalent Akka code

Example: throttling

Throttle emitting molecules `s(x)` with minimum allowed delay of `delta` ms

```
def throttle[X](s: M[X], delta: Long): M[X] = {
 val r = m[X]
 val enable = m[Unit]
// This molecule is confined to the local scope.
 site(
  go { case r(x) + enable(_) ⇒
         s(x)
         Thread.sleep(delta)
         enable()
     }
 )
 enable() // Enable emitting ‘s‘ initially.
 r // Outside scope will be able to emit ‘r‘.
}
```

- No threads/semaphores/locks, no mutable state
- External code may emit `r(x)` at will, and `s(x)` is then throttled

Implementations in Akka, in Monix, and ZIO: > 50 LOC each

Example: map/reduce

A simple map/reduce implementation:

```
val c = m[A] // Initial values have type ‘A‘.
val d = m[(Int, B)] // ‘B‘ is a commutative monoid.
val res = m[B] // Final result of type ‘B‘.
val fetch = b[Unit, B] // Blocking emitter.
site(
  // ‘‘map’’
  go { case c(x) ⇒ d((1, long_computation(x))) },
  // ‘‘reduce’’
  go { case d((n1, b1)) + d((n2, b2)) ⇒
   val (newN, newB) = (n1 + n2, b1 |+| b2)
   if (newN == total) res(newB) else d((newN, newB))
  },
  go { case fetch(_, reply) + res(b) ⇒ reply(b) }
)
(1 to 100).foreach(x ⇒ c(x))
fetch() // Blocking call will return the final result.
```

Compare with the Akka implementation here (100+ LOC)

Example: parallel merge-sort

Chymyst code: MergeSortSpec.scala

```
val mergesort = m[(Array[T], M[Array[T]])]
site(
  go { case mergesort((arr, sortedResult)) ⇒
    if (arr.length <= 1) sortedResult(arr)
      else {
        val sorted1 = m[Array[T]]
        val sorted2 = m[Array[T]]
        site(
          go { case sorted1(x) + sorted2(y) ⇒
             sortedResult(arrayMerge(x,y))
             }
        )
        val (part1, part2) = arr.splitAt(arr.length/2)
        // Emit lower-level mergesort molecules:
        mergesort(part1, sorted1) + mergesort(part2, sorted2)
    }
})
```

Implementation in Akka: 30 LOC for the same functionality

Example: Dining philosophers

Five Dining Philosophers

Philosophers `1, 2, 3, 4, 5` and forks `f12, f23, f34, f45, f51`

```
// ... definitions of emitters, think(), eat() omitted for brevity
site (
  go { case t1(_) ⇒ think(1); h1() },
  go { case t2(_) ⇒ think(2); h2() },
  go { case t3(_) ⇒ think(3); h3() },
  go { case t4(_) ⇒ think(4); h4() },
  go { case t5(_) ⇒ think(5); h5() },

  go { case h1(_) + f12(_) + f51(_) ⇒ eat(1); t1() + f12() + f51() },
  go { case h2(_) + f23(_) + f12(_) ⇒ eat(2); t2() + f23() + f12() },
  go { case h3(_) + f34(_) + f23(_) ⇒ eat(3); t3() + f34() + f23() },
  go { case h4(_) + f45(_) + f34(_) ⇒ eat(4); t4() + f45() + f34() },
  go { case h5(_) + f51(_) + f45(_) ⇒ eat(5); t5() + f51() + f45() }
)
t1() + t2() + t3() + t4() + t5()

f12() + f23() + f34() + f45() + f51()
```

Source code: DiningPhilosophers.scala

For more examples, see the code repository (first-of, barriers, rendezvous, critical sections, readers/writers, Game of Life, elevators, etc.)

Reasoning about code in the Chemical Machine paradigm

Reasoning about concurrent data:

- Emit molecule with value $\approx$ lift data into the "concurrent world"
- Define reaction $\approx$ lift a function into the "concurrent world"
- Reaction site $\approx$ container for concurrent functions and data
- Reaction consumes molecules $\approx$ function consumes input values
- Reaction emits molecules $\approx$ function returns result values

Reasoning about code:

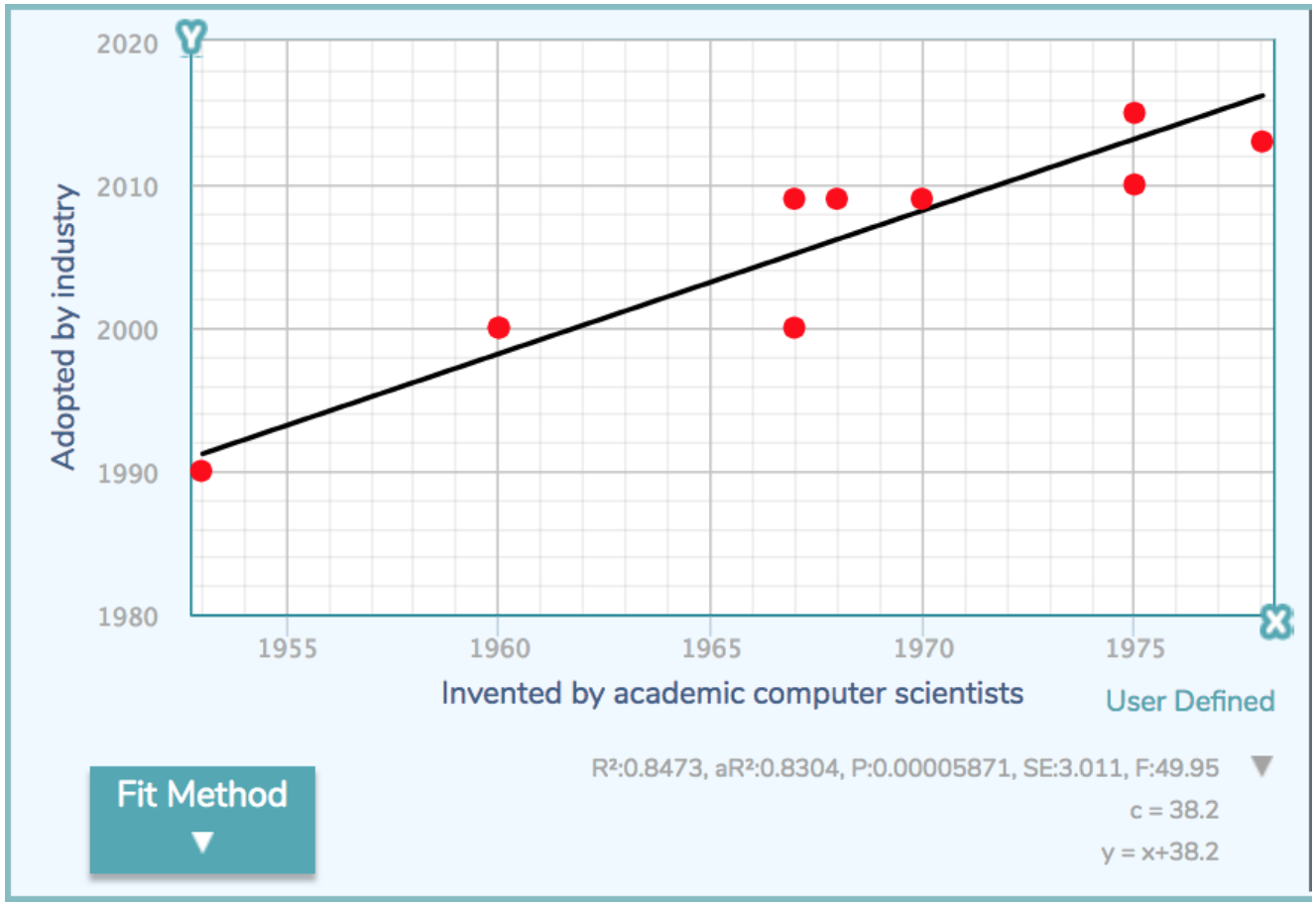
- What data do we need to handle concurrently? (Put it on molecules.)
- What computations consume this data? (Define reactions.)

Guarantees:

- Molecule emitters and reactions are immutable values in local scopes
- Reaction sites are immutable once activated; can refactor to libraries
- Multiple input molecules are consumed atomically by reactions

Chemical Machine paradigm to become mainstream in 2033

- The Chemical Machine paradigm was invented in 1995
- The gap from academic invention to industry adoption is 38.2 years (declarative math, map/reduce, continuations, OOP, CSP, Actors, constraint programming, DAG dataflow, λ-functions, Hindley-Milner)



Current features of Chymyst

- Blocking molecules with timeouts and back-signalling
- Automatic pipelining of molecules (ordered mailboxes)
- "Static" molecules with read-only access (similar to Akka "agents")
- Compile-time and early run-time DSL error reporting
- Logging, debugging, unit-testing facilities
- Thread pools with thread priority control

Related frameworks: Petri nets

Workflow management: an approach based on Petri nets

- ING Baker – a DSL for workflow management
- Process modeling and control ("elevator system" etc.)
- Business process management (BPM) systems

`Chymyst` implements a rich version of Petri nets:

- Transitions admit arbitrary guard conditions and error recovery
- Transitions carry values, reactions are values, can be nested
- Nondeterministic, asynchronous, parallel execution

A Petri net model is straightforwardly translated into a CM program

Distributed Chemical Machine

Run concurrent code on a cluster with no code changes

- Some molecules are declared as "distributed", of type `DM[T]`
- No other new language constructions are necessary!
  - early prototype in progress

A simple implementation of map/reduce in DCM:

```
implicit val cluster = ClusterConfig(???)
val c = dm[Int] ; val d = dm[Int] // distributed
val res = m[(Int, List[Int])]
val fetch = b[Unit, List[Int]]
site(
  go { case c(x) ⇒ d(x * 2) },  // "map" on cluster,
 // "reduce" on the driver node only
  go { case res((n, list)) + d(x) ⇒ res((n-1, s::list)) },
 // fetch results
  go { case fetch(_, reply) + res((0, list)) ⇒ reply(list) }
)
if (isDriver) { // `true` only on the driver node
  Seq(1, 2, 3).foreach(x ⇒ c(x))
  res((3, Nil)) ; fetch() // Returns the result.
}
```

Comparison: Akka implementation of distributed map/reduce (400+ LOC)

Distributed cache in 10 lines of code

- Mutable `Map[String, String]` with operations: `put`, `get`, `delete`

```
val data = dm[mutable.Map[String, String]]
val put = dm[(String, String)]
val get = dm[(String, M[Option[String]]]
val delete = dm[String]
site(
 go { case data(dict) + put((k, v)) ⇒ data(dict.updated(k, v)) },
 go { case data(dict) + get((k, r)) ⇒ data(dict); r(dict.get(k)) },
 go { case data(dict) + delete(k) ⇒ dict.remove(k); data(dict) }
)
if (isDriver) data(mutable.Map[String, String]())
```

- Comparison: Distributed cache in 100 lines of Akka

Reasoning in the Distributed Chemical Machine

Distributed computing is made declarative

- Determine which data needs to be distributed and/or concurrent
- Determine which computations will need to consume that data
- Emit initial molecules and let the DCM run

Peer-to-peer architecture

- All DCM peers operate in the same way (no master/worker)
- All DCM peers need to define the same distributed reaction sites
  - To designate a DCM peer as a "driver", use config files
- Distributed molecules may be consumed by *any* DCM peer

Examples (see documentation)

- Broadcast (DCM peers see it exactly once upon connecting)
- Distributed peer-to-peer chat

Chemical Machine: implementation details

- Each reaction site has a scheduler thread and a worker thread pool
- Each molecule is "bound" to a unique reaction site
- Each emitted molecule is stored in a multi-set at its reaction site
- Each emitted molecule triggers a search for possible reactions
  - Reaction search proceeds concurrently for different reaction sites
- Reactions are scheduled on the worker thread pool
  - The thread pool can be configured per-reaction or per-site
- Scala macros are used for static analysis and optimizations
  - Automatically pipelined molecules
  - Simplify and analyze Boolean conditions
- Error analysis is also performed at early run time
  - Reaction site with errors remain inactive

Distributed Chemical Machine: implementation details

- Each distributed molecule (DM) is bound to a unique reaction site
- Emitted DM data goes into the ZK instance
- Each DCM peer listens to ZK messages and checks for its DMs
  - Once a DM is found, its data is downloaded and deserialized
- On a DCM peer, each DM is identified with a unique local RS
  - Downloaded molecules are emitted into the local RS to run reactions
  - All DCM peers must run identical reaction code for DMs
- Each DCM peer acquires a distributed lock on its DMs
  - Lock is released once reaction scheduling is complete
- If a node goes down or network fails, molecules will be *unconsumed*
  - Another DCM peer will pick up these molecules later

Conclusions and outlook

- Chemical Machine = declarative, purely functional concurrency
  - Similar to "Actors", but easier to use and "more purely functional"
  - Significantly shorter code, easier to reason about
- An open-source Scala implementation: `Chymyst`
  - Static DSL code analysis (with Scala macros)
  - Industry-strength features (thread priority control, pipelining, fault tolerance, unit testing and debugging APIs)
  - Extensive documentation: tutorial book
- Promising applications:
  - Workflow management
  - Distributed peer-to-peer systems
  - Process modeling, GUIs, BPM
- Distributed Chemical Machine in the works