CCSTM: A Library-Based Software Transactional Memory for Scala

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Software Transactional Memory*

Atomic execution of multiple loads and stores

- Declarative syntax
- Accesses needn't be known ahead of time
- Parallel execution whenever possible

```
// Thread A - push x
atomic begin
  val n ← new Node(x)
  n.next ← head
  head ← n
end
```

```
// Thread B - push y
atomic begin
  val n ← new Node(y)
  n.next ← head
  head ← n
end
```

** - The ideal*

Wikipedia: Atomicity (programming)

> In concurrent programming, an operation is linearizable, **atomic**, indivisible or uninterruptible if it appears to take effect instantan-eously.

So Far

Atomic blocks are like a magic replacement for locks

- No serialization on coarse-grained locks
- No complicated fine-grained locking schemes
- No worrying about deadlock

Parallel Execution of Transactions

Q: How can TM execute atomic blocks in parallel if their read and write sets are not known in advance?

```
// Thread A
atomic begin
  ... // lots of work
  x = 1
end
```

← conflict →

```
// Thread B
atomic begin
  ... // lots of work
  x = 2
undo stores, retry txn
atomic begin
  ... // lots of work
  x = 2
end
```

A: Speculatively, fixing with rollback+retry

Supporting Speculative Execution

Transactional reads

- Loads must be remembered, to check for conflicts

Transactional writes

- Both original and speculatively-modified versions of data must be retained
  - *Undo log: original version on the side*
  - *Write buffer: speculative version on the side*

Control flow

- Non-local control transfer is possible from any memory access to the beginning of the transaction

Ideal STM (Graded by the User)

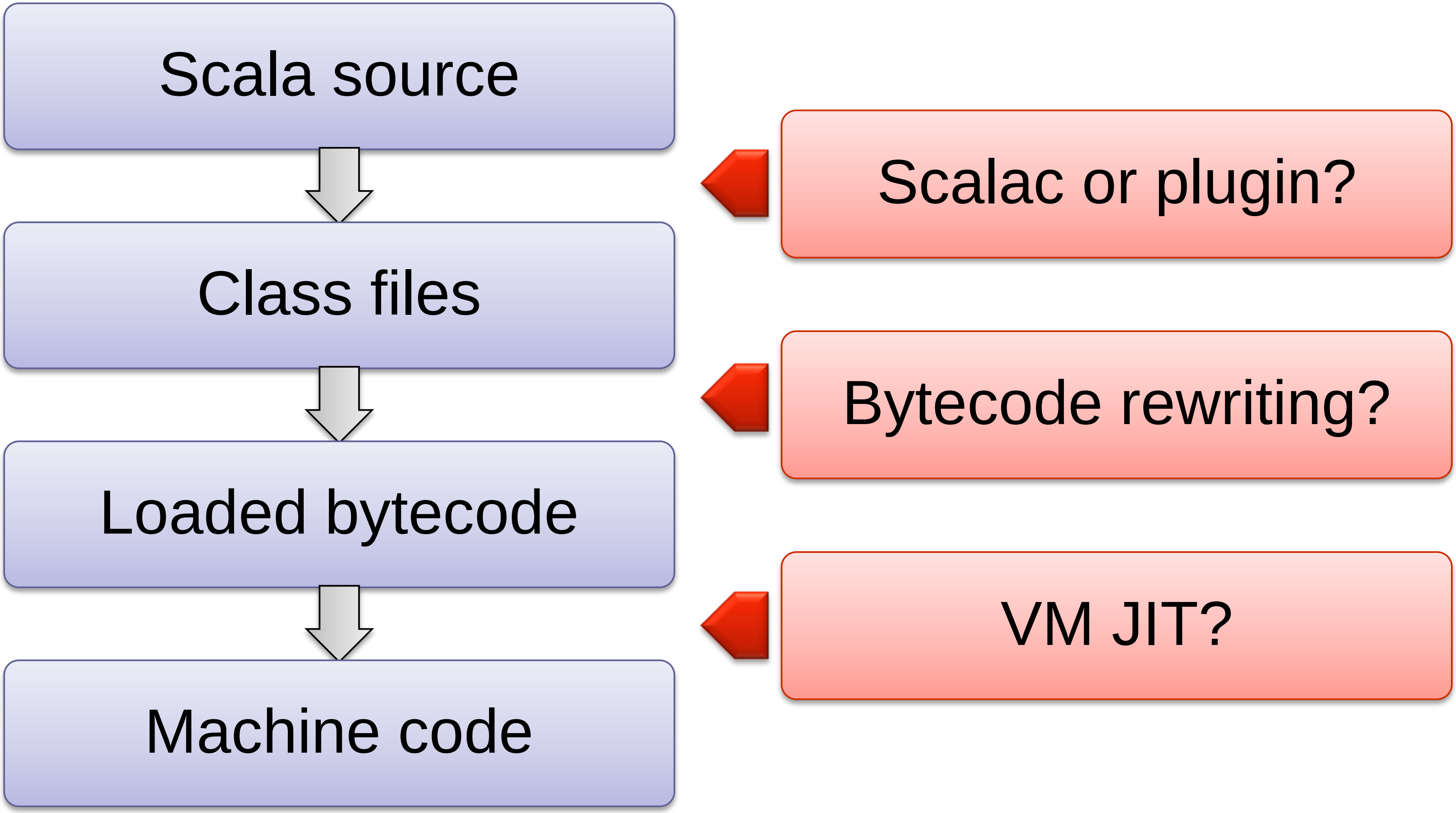
Ease of use + Simple mental model … – … so long as you avoid I/O (hard to roll back)	A-
Composability of code using transactions + Nesting has expected semantics, no deadlocks	A
Testability + Invariants are preserved throughout a transaction, even if other code doesn't synchronize properly	A+
Performance – Single-thread overheads are higher than locks	B
Scalability + Reads often scale better than locks + Writes often scale like the best fine-grained locking	A

Compiling an Atomic Block for STM

```
atomic begin



  val n ← new Node(x)

  n.next ← head



  head ← n

end
```

```
val txn = new Txn()
do {
  try {
    txn.begin()

    val n = new Node(x)(txn)

    val tmp = txn.readAnyRef[Node](
      this, HeadOffset)
    txn.write(n, NextOffset, tmp)

    txn.write(this, HeadOffset, n)

  } catch {
    case RollbackError => {}
    case ex => txn.userException(ex)
  }
} while (!txn.attemptCommit())
```

Who Instruments the Code?



How Do We Compile Atomic Blocks?

Loads and stores inside **`atomic`** are redirected to STM

"Inside" is a dynamic scope

Two copies of every method are needed

How Do We Compile Atomic Blocks?

STM creates illusion of atomicity and isolation

Too slow to send all non-txn accesses to STM

Type system extended to segregate txn and non-txn data

or

User error → loss of atomicity, values from thin air, “catch fire”

Ideal STM (Graded by Martin)

Ease of language integration
- Strong atomicity and isolation require extensions to the type system

Composability of implementations
- Only one STM can be used in a VM

Testability
- Tight integration requires a large up-front design before users can provide feedback

Performance
- Code that doesn't use transactions may have reduced performance, especially during startup

Scalability
- If any part of a system uses STM, all of the classes must be instrumented

needs improvement

Can We Pass Both Classes?

Transactional memory is a nice abstraction for the user

Can we provide most of the benefit without intrusive language modifications?

CCSTM: Library-Based STM

No instrumentation, so STM must be called explicitly

Managed data encapsulated by **`Ref[A]`**

	Deeply-Integrated	CCSTM
Mutable shared state	`var x = □`	`val x = Ref(□)`
Read	`□ = x`	`□ = x()`
Write	`x = □`	`x := □`
Atomic block	`atomic { □ }`	`STM.atomic { implicit t => □ }`

`trait Ref[A]` – Implementations

Decomposed into **`Source[+A]`** and **`Sink[-A]`**

- From Daniel Spiewak's Scala STM

Storage **`Ref`**-s store a mutable value directly

- **`TBooleanRef`**, **`TByteRef`**, … **`TAnyRef[A]`**
- **`object Ref`**'s **`apply(v)`** picks the right implementation
- Internal representation is flexible
  - *`TPairRef[A,B]` deconstructs and reconstructs its value*
  - *`StripedIntRef`, `LazyConflictIntRef` reduce conflicts*

Proxy **`Ref`**-s are constructed on demand

- **`TArray[A]`** avoids long-term boxing
- **`TxnFieldUpdater`** instances create **`Ref`**-s for any property with volatile semantics

`trait Ref[A]` – More Operations

`def get: A` – non-operator read

`def map[Z](f: A => Z): Z` – no rollback if `f(get)` doesn't change

`def unrecordedRead: UnrecordedRead[A]` – no conflict checking

`def await(pred: A => Boolean)` – retries txn if `!pred(get)`

`def set(v: A)` – non-operator write

`def transform(f: A => A)` – equivalent to `set(f(get))`

`def transformIfDefined(pf: PartialFunction[A,A]): Boolean` – generalizes `compareAndSet`

`def tryWrite(v: A): Boolean` – fails instead of blocking

`def getAndSet(v: A): A` – returns the previous value

…

Scoping of the Current Txn

How is the active **`Txn`** found by **`Ref`**'s methods?

- STM participates in the compilation of all code
  - Option 1: Add a **`Txn`** parameter during translation
  - Option 2: Add a **`currentTxn`** field to **`Thread`**
  - *Unavailable to a library-based STM*
- Dynamic lookup
  - Option 3: **`ThreadLocal`**
  - *Undesirable performance overhead*
- Static lookup
  - Option 4: **`Ref`**'s methods take an implicit **`Txn`**
  - *Hinders composability*

Our Solution: Hybrid Scoping

Dynamic scoping for atomic blocks

- Using `ThreadLocal`

Static scoping for `Ref`'s methods

- Using an implicit `Txn` parameter
  (Omitted from the method list two slides ago)

Don't have an implicit `Txn` available?
Just declare a new atomic block

- If no txn was active, you probably needed one anyway
- If a txn is in the dynamic scope, the new block nests

Single-Operation Transactions

What happens if a **`Ref`** method is called outside an atomic block?

1. Compile time error?

   Makes it harder to accidentally omit atomic blocks

2. Execute as if in its own transaction?

   Convenient, especially with `Ref`'s powerful methods

3. Both of the above

   Add an alternate syntax for single-operation txns

`Ref.single`** returns a view with methods that mirror **`Ref`**'s, but that need no implicit **`Txn`

```
STM.atomic { implicit t =>
  x := x() + 1
}
```

is equivalent to

```
x.single.transform { _ + 1 }
```

CCSTM (Graded by the User)

Ease of use + Clean and concise for new code – Existing code must be modified	(A-)	B+
Composability + Just as good as deeply-integrated STM	(A)	A
Testability + Local reasoning still possible – No checking that shared mutable state is in `Ref`	(A+)	A
Performance – Still has a single-thread performance penalty + Single-operation transactions are optimized	(B)	B+
Scalability + Easier to provide advanced conflict-avoidance strategies	(A)	A+

CCSTM (Graded by Martin)

Ease of language integration + None needed	★
Composability of implementations + Coexistence of STMs is fine – Atomic blocks from different STMs don't nest	★
Testability + CCSTM can be used independently	★
Performance + Components only pay for what they use	★
Scalability + Only components using CCSTM are aware of it	★

Scala Features We Enjoyed

- **Operator overloading** – concise reads and writes
- **Anonymous methods** – concise atomic blocks
- **Type inference** – less clutter when declaring `Ref`-s
- **Mixins** – reduced code duplication
- **Implicit parameters** – improves performance, allows static checking of `Ref` usage
- **Companion object factory methods, class manifests** – storage optimizations for `Ref[A]` and `TArray[A]`
- **Abstract type constructors** – lets `TxnFieldUpdater` handle fields of generic classes
- **JVM integration** – allowed use of advanced features from `java.util.concurrent.atomic`
- `@specialized` – future performance enhancements?

Questions?

http://ppl.stanford.edu/ccstm

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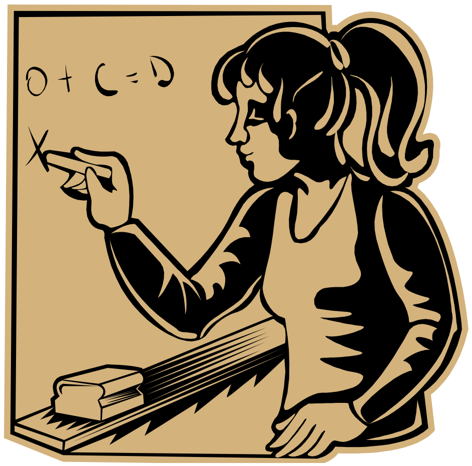
Dealing with Shared Mutable State



Solution #1 – Avoid mutable state entirely

- Programs are functions from input to output
- No variables, just values

Problem: User must (re)create their own abstractions to model identity

*Identity: a stable logical entity associated with a series of different values over time**

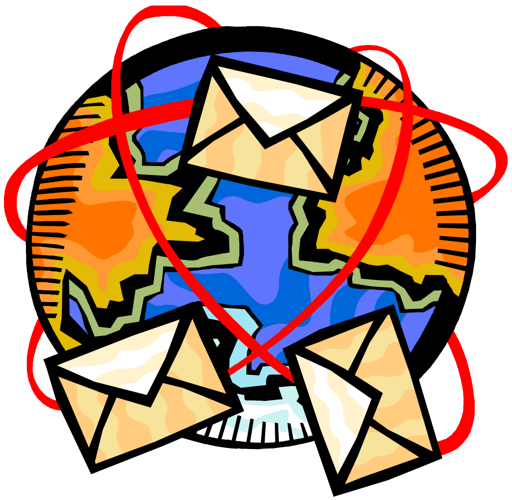
* - from Rich Hickey, http://clojure.org/state

Dealing with Shared Mutable State

Solution #1 – Avoid mutable state entirely

Solution #2 – Avoid *shared* mutable state

- Use explicit inter-thread (inter-actor) communication
- Mutable state is directly accessed only by its owning context



Problem: Coordination between multiple actors can be complicated

Problem: Best data-to-actor binding might be contrived or dynamic

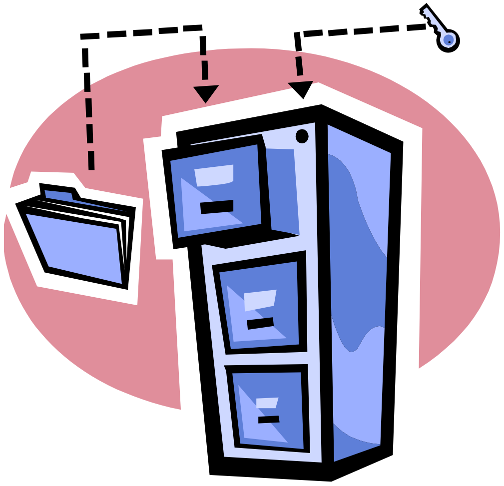
Dealing with Shared Mutable State

Solution #1 – Avoid mutable state entirely

Solution #2 – Avoid *shared* mutable state

Solution #3 – Prevent conflicting accesses

- Protect accesses using locks



Problem: Not declarative

- Code shows one synchronization strategy, not a desired property of the program

Problem: Simplicity ↔ scalability tradeoff

- Coarse-grained locks → simple, doesn't scale
- Fine-grained locks → tricky, might scale

Problem: Not composable

- Correctness is a whole-program property

Dealing with Shared Mutable State

Solution #1 – Avoid mutable state entirely

Solution #2 – Avoid *shared* mutable state

Solution #3 – Prevent conflicting accesses

Solution #4 – Back up and retry after a conflict

- Software transactional memory

```
// Thread 1
atomic {
  x.bal = x.bal - 20
  y.bal = y.bal + 20
}
```

```
// Thread 2
atomic {
  y.bal = y.bal - 20
  x.bal = x.bal + 20
}
```