Tackling Concurrency With STM

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Two Flavors of Concurrency

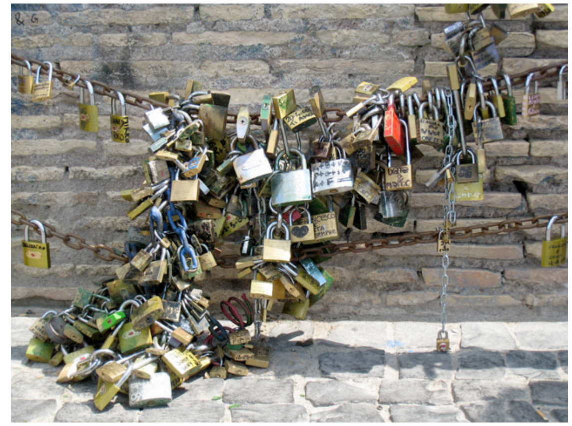
- Divide and conquer
  - divide data into subsets and process it by running the same code on each subset concurrently
  - MapReduce solutions focus on this flavor
- Coexist
  - execute different code concurrently and allow it to safely access the same data
  - Transactional Memory (TM) focuses on this flavor

Concurrency Options

- Locks
  - popular in C, C++ and Java

- Actors
  - popular in Erlang, Haskell and Scala
- Transactional Memory
  - popular in Clojure and Haskell
  - can be implemented in hardware or software

Locks



- Pros
  - explicit control over when locks are acquired and released
    allows optimal solutions
  - developer familiarity
  - supported by many programming languages
- Cons
  - which locks need to be acquired?
  - what order to prevent deadlock?
  - variables for which locks should be acquired can be accessed even when no locks or the wrong locks are acquired
  - must remember to release locks in error recovery code
  - correctly synchronized methods don't compose
  - pessimistic approach reduces concurrency

Actors ...

- Software entities that execute as separate processes or threads
- Only use data passed to them via asynchronous messages

  - can retain data for use in subsequent processing
- When a message is received by an actor it can
  - create new actors
  - send messages to other actors
  - decide how it will handle subsequent messages

... Actors

- Pros
    - since no memory is shared between actors,
      data access doesn't need synchronization
- Cons
    - some messages may be large since they are the only way to share data
    - no general mechanism for coordinating activities of multiple actors
      (i.e. transactions)
        - may want to send messages to multiple actors within a txn
          and guarantee that either all messages are processed successfully
          or all the actors involved rollback changes to their retained state

TM

- Provides ACID txn characteristics for memory
  - **atomic** - all changes commit or all changes roll back; changes appear to happen at a single moment in time
  - **consistent** - operate on a snapshot of memory using newest values at beginning of txn
  - **isolated** - changes are only visible to other threads after commit
  - **not durable** - changes are lost if software crashes or hardware fails
- Demarcating txns
  - **`atomic {...}`** in literature, **`(dosync ...)`** in Clojure, **`atomically`** in Haskell
- Nested txns join the outermost txn - txns compose

TM Retries

- If two txns overlap in time
  and they attempt to write the same memory
  then one of them will discard their changes
  and retry from their beginning
  - in some implementations, reads can also trigger retries
    - could retry txn A if txn B modifies memory that was read by txn A since it may have made decisions based on the value it read
    - reads only trigger a retry in Clojure when the history list of a Ref doesn't contain a value committed before the txn began (a fault) ... will make sense when history lists are described later

TM Pros

- Familiar concept from database world
- Optimistic, not pessimistic
  - provides more opportunities for concurrency,
    especially for txns that only read data
- Easier to write correct code than using locks
  - don't have to determine which locks need to be acquired and order
  - only have to identify sections of code that require
    a consistent view of the data it reads and writes
- Implementations can guarantee ...
  - no deadlocks, livelocks or race conditions (see next slide)

Concurrency Issues

- Deadlock
  - concurrent threads cannot proceed because they are each waiting on a resource for which another has acquired exclusive access
- Livelock
  - concurrent threads are performing work (not blocked), but cannot complete due to something other threads have done or not done
- Race condition
  - the outcome of a thread may be wrong due to the timing of changes to shared state made by other concurrent threads
- None of these can occur in Clojure STM

TM Cons

- Potential for many retries resulting in wasted work
- Overhead imposed by txn bookkeeping
  - more detail on this later

- Need to avoid side-effects
  - such as I/O
  - since txns may retry any number of times

Clojure provides a solution using Agents.

- Tool support is currently lacking
  - for learning which memory locations experienced write conflicts
  - for learning how often each txn retried and why

On Your Honor

- TM works best in programming languages that provide a special kind of mutable variable that can only be modified in a txn
  - Ref in Clojure
  - TVar in Haskell
- Otherwise developers are on their honor to use TM correctly
  - similar to developers being on their honor to use locks correctly

Garbage Collection Analogy

- From Dan Grossman
  - associate professor at University of Washington
  - see paper "The Transactional Memory / Garbage Collection Analogy"
  - listen to Software Engineering Radio podcast #68
- Can GC be replaced by TM in these statements?
  - "Many used to think GC was too slow without hardware."
  - "Many used to think GC was about to take over, decades before it did."
  - "Many used to think we needed a back door
    for when GC was too approximate."

More on Concurrency Options

- Shared state
  - locks provide manual management of shared state
  - TM provides semi-automated management of shared state
  - actors avoid shared state; Can it be avoided? Are transactions needed?
- Baseball analogy
  - locks never attempt to steal a base since they might get caught - pessimistic
  - TM does and just returns to the previous base and retries if caught - optimistic
  - actors utilize a coach actor to send a message to the runner actor
    to request a steal attempt;
    the umpire actor sends a message to runner actor
    to indicate whether they are safe

Persistent Data Structures

- Immutable data structures such as lists, vectors, sets and hash maps
- Can efficiently create new ones from existing ones
- New ones share memory with old ones
  - okay since they can't be modified
- Safe for concurrent access
- An opinion
  - saying a language is functional, but doesn't have persistent data structures is like saying a language is OO, but doesn't support polymorphism

STM Implementations

- Part of language
  - Clojure, Haskell, Perl 6
- As a library
  - C, C++, C#, Common Lisp, Java, MUMPS, OCaml, Python, Scheme, Smalltalk
- Implementations vary greatly
  - difficult to make general statements about STM characteristics such as memory usage and performance

Clojure STM Implementation

- The remaining slides describe the Clojure STM implementation, starting with concepts related to it
- Valuable even if you don't use Clojure
  - to understand how at least one STM implementation works under the covers
  - to enable reasoning about performance characteristics
  - to encourage implementations for other languages

Clojure

Transaction Creation

- (**dosync** *body*)
  - passed expressions that form the body of a txn

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Reference Types

- Mutable references to immutable objects
- Four kinds
  - Var
  - Atom
  - Agent
  - Ref
- Modification characteristics

"coordinated" here means managed by txns

	Uncoordinated	Coordinated
Synchronous	Var, Atom	Ref
Asynchronous	Agent	

Vars

- Can have a root value that is shared by all threads
  - `(def name value)`
- Can have thread-specific values
  - `(binding [name value ...] body)`
- Often used for constants and configuration variables such as `*out*`
- Reads (dereferences) are atomic - `@name`
- Writes are also atomic
  - with `binding`

"atomic" here means that multiple threads can access them without synchronization

Atoms

- Have a single value that is shared across threads
  - `(def name (atom value))`

  def isn't the only way to bind a reference type to a name; can pass as a function argument and use **let** and **binding**

- Reads (dereferences) are atomic - `@name`
- Writes are also atomic
  - `(reset! name value)`
  - `(compare-and-set! name current-value new-value)`
  - `(swap! name update-function arg*)`

  Function names that end with ! typically indicate that the function either modifies its arguments or has some other side effect.

Agents

- Have a single value that is shared across threads
  - `(def name (agent value))`
- Reads (dereferences) are atomic - `@name`
- Writes are asynchronous
  - by sending a function (called an "action" in this context) to the Agent that is executed in a different thread
  - action is passed the current value of the Agent and any additional, optional arguments
  - return value of action becomes new value of the Agent, atomically
  - only one action at a time is executed for a given Agent, which prevents concurrent updates to an Agent
  - actions sent to Agents inside an STM txn are held until the txn commits

`(send name action arg*)`
uses fixed size thread pool

`(send-off name action arg*)`
uses variable size thread pool

useful for causing side effects after a txn

Refs

- Have a single value that is shared across threads
  - `(def name (ref value))`
- Reads (dereferences) are atomic - `@name`
  - while reads are not required to be
    performed inside an STM txn,
    doing so provides access to a consistent snapshot
    of the set of Refs accessed inside the txn
- Writes must be performed inside an STM txn
- Refs are the only type managed by STM

In-Txn and Committed Values

- In-txn values of Refs
    - maintained by each txn
    - only visible to code running in the txn
    - committed at end of txn if successful
    - cleared after each txn try
- Committed values
    - maintained by each Ref in a circular linked-list (**`tvals`** field)
    - each has a commit "timestamp" (**`point`** field in **`TVal`** objects)
        - ordered long values obtained by calling **`incrementAndGet`** on an **`AtomicLong`**

in **`java.util.concurrent.atomic`** package

Changing a Ref ...

- Three ways
  - all must be performed inside an STM txn
- `(`**`ref-set`** *`ref new-value`*`)`
- `(`**`alter`** *`ref function arg*`*`)`
  - invokes the function, passing it the current Ref value and the arguments, changes the Ref to refer to the function return value, and returns the new value

For both **`ref-set`** and **`alter`**,
if another txn sets an in-txn value
for the same Ref, one of the txns will retry.
If another txn commits a change
to the same Ref, this txn will retry.

... Changing a Ref

- `(commute ref function arg*)`
  - similar to **`alter`**
  - use when the order of changes across concurrent txns doesn't matter and use of in-txn values won't produce incorrect results
  - the txn will not retry if another txn has modified the Ref since the current txn try began
  - during txn commit,
    all commute functions invoked in the txn
    are called again using latest committed Ref values
  - example uses
    - computing min, max and average of values in a collection
    - adding objects to a collection

Validators

- (**set-validator!** *ref function*)
- Function is invoked when the value of a given reference type is about to be modified
- Passed the proposed new value of the reference type
- Reject the change by returning false or throwing any kind of exception

Clojure

Watch Functions

- `(add-watch ref key function)`
- Function is invoked if
  the reference type may have changed
  - passed the key, the reference type, its old value and its new value
- A reference type can have
  any number of watch functions
  - each must be added with a unique key

Clojure

Watcher Agents

- (**add-watcher** *ref send-type agent function*)
- Function is "sent" to the Agent
  in a different thread
  if the reference type may have changed
  - passed current value of Agent and the reference type
- ***send-type*** determines the thread pool used
  to obtain the thread in which the function runs
  - **:send** for fixed or **:send-off** for variable size thread pool

Clojure STM Design and Implementation

- Design is based on
  - multi-version concurrency control
  - snapshot isolation
- Mostly implemented in Java now
  - but work to re-implement in Clojure is underway

Multi-Version Concurrency Control

- Uses timestamps or increasing txn ids
- Maintains multiple versions of objects with commit "timestamps"
- Txns read the most recent versions of objects that were committed before the txn start
- When attempting a write,
  if another txn has modified the object
  since the current txn started
  then the txn discards its changes and retries
- Reads are never blocked

> Clojure uses increasing ids for txn starts, try starts and commits. They are obtained by calling the **`incrementAndGet`** method on a Java **`AtomicLong`**. This uses a compare and swap (CAS) approach.

Snapshot Isolation

- Txns appear to
  operate on a snapshot of memory
  taken at the start of the txn
- At the end of the txn,
  changes are committed only if
  no other txns have committed changes
  to the values to be committed
  since the txn began

Write Skew

- Occurs when
  - concurrent txns read common sets of data, make changes to different data within that set, and there are constraints on the data

avoided by STM implementations that use "read tracking"; a performance tradeoff

- Example
  - data is the number of dogs and number of cats owned by a family
  - constraint is the sum of dogs and cats that can be owned by a family <= 3
  - John and his wife Mary own one dog and one cat
  - John adopts a new dog while Mary simultaneously adopts a new cat (2 txns)
  - both txns read the number of dogs and cats they own, but they modify different data
  - neither txn violates the constraint, so both succeed which results in a constraint violation

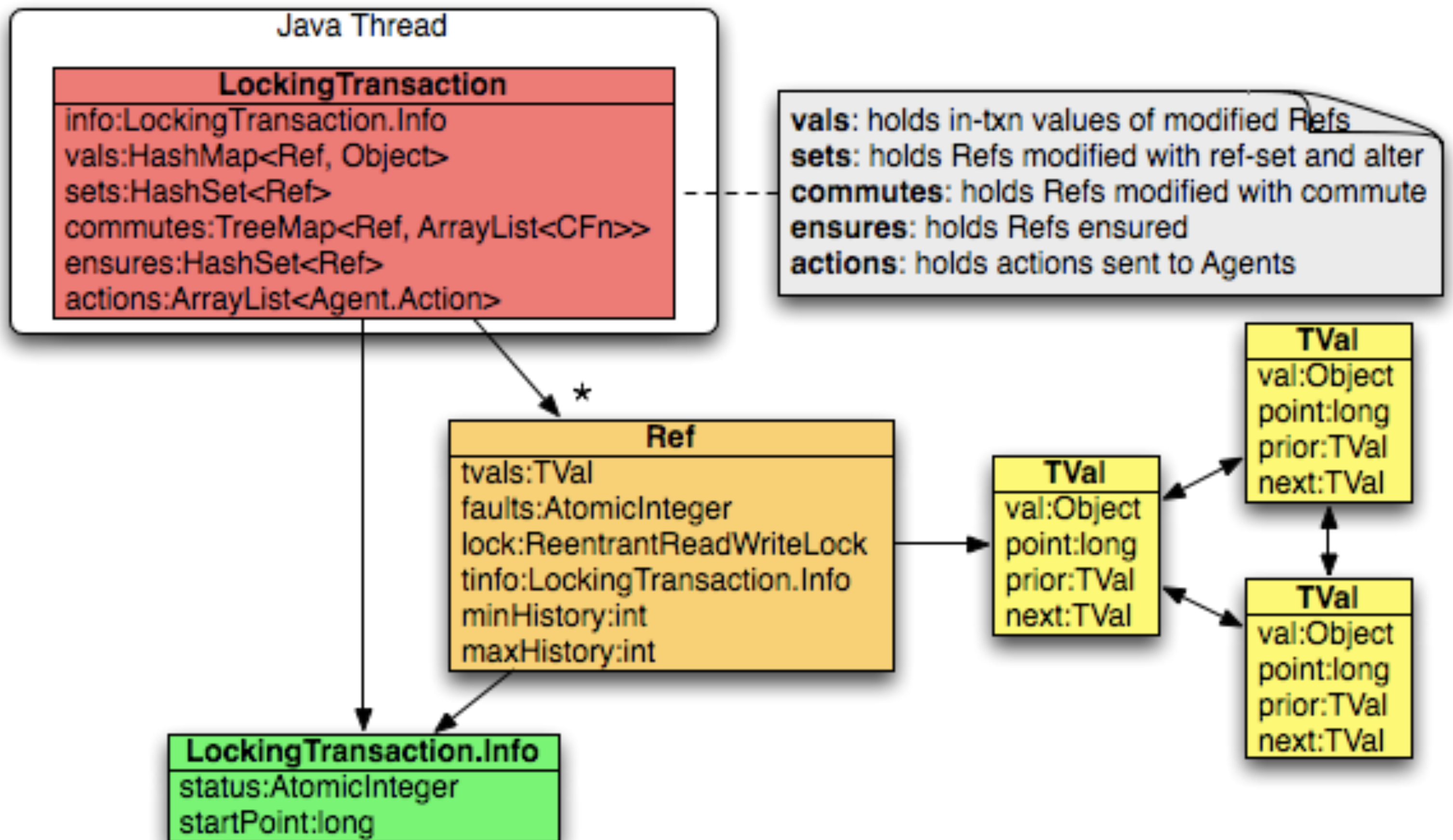
Clojure Solution To Write Skew

- (**ensure** *ref*)
- Prevents other txns from modifying the Ref
  - calling txn can modify the Ref unless another txn has also called **ensure** on it
- Must be called inside a txn
- For previous example
  - both txns should **ensure** the Ref they don't plan to modify since its value, together with that of the Ref being modified, is used in a constraint

Main STM Classes ...

- **`LockingTransaction`**
  - one of these objects per thread (**`ThreadLocal`**)
    - doesn't make sense to have more than one active txn per thread
    - avoids having to recreate bookkeeping collections
      referred to by **`LockingTransaction`** fields every time a new txn starts
  - **`dosync`** macro calls **`sync`** macro which calls
    `LockingTransaction runInTransaction` static method
- **`Ref`**
  - one of these objects per mutable reference to be managed by STM
- **`LockingTransaction.Info`**
  - part of lock-free strategy to mark Refs as having an uncommitted change

... Main STM Classes



Transaction Status

stored in `status` field of `LockingTransaction.Info` objects which are referred to from the `info` field of `LockingTransaction` objects and the `tinfo` field of `Ref` objects

- **`RUNNING`**
  - executing code in the body
- **`COMMITTING`**
  - finished executing code in the body; committing changes to Refs, if any
- **`RETRY`**
  - will attempt a retry, but hasn't started the next try yet
- **`KILLED`**
  - has been "barged" by another txn (explained later)
- **`COMMITTED`**
  - finished committing changes to Refs, if any; transaction completed (even if read-only)

Ref History List

- Each Ref maintains a list of recently committed values
  - using **`TVal`** objects
  - length is controlled by **`minHistory`** and **`maxHistory`**
    - default to 0 and 10, but can be customized for each Ref
- When a change to a Ref is committed
  - a new node is added to its history list if
    - history list length < **`minHistory`** OR
    - a fault (described on next slide) has occurred since the last commit of the Ref and history list length < **`maxHistory`**
  - otherwise the oldest node is modified to become the newest node

> With **`minHistory`** set to zero, the history list of each Ref grows according to how the Ref is actually used. If a Ref never has a fault, its history list never needs to grow.

Faults

- A fault occur when
  - there is an attempt to read a Ref in a txn AND
  - there is no in-txn value in the txn AND
  - all values in the history list for the Ref were committed after the txn started

means it hasn't been modified in the txn

- Faults cause
  - a txn to retry
  - the history chain for the Ref to grow, unless **`maxHistory`** has been reached

Clojure

Write Conflicts

- A write conflict occurs when
  - txn A attempts to modify a Ref
  - txn B has already modified the same Ref, but hasn't yet committed the change
    - it has an in-txn value
- When this occurs
  - txn A will attempt to barge txn B (see next slide)

Barging

- Determines whether txn A should be allowed to continue while txn B retries
- Three conditions must be met
  - txn A must have been running for at least 1/100th of a second (**BARGE_WAIT_NANOS**)
    - if it just started then it may as well be the one to retry
  - txn A started before txn B (favors older txns)
  - txn B has a status of RUNNING and can be changed to KILLED
    - won't interrupt a txn that is in the process of committing
- Otherwise txn A retries and txn B continues

What Causes a Retry?

- A Ref is read in a txn and one of the following is true
  - another txn barged the current one (status isn't RUNNING)
  - the Ref has no in-txn value and fault occurs

the next try will have a new start time, so will look for newer Ref values

- **`ref-set`** or **`alter`** is called on a Ref and one of the following is true
  - can't set the **`tinfo`** field of the Ref to indicate that it was modified by the current txn because a write lock cannot be obtained for the Ref because another thread holds a read or write lock for it
  - another txn changed the Ref, but hasn't committed yet and an attempt to barge it fails
- **`ref-set`**, **`alter`**, **`commute`** or **`ensure`** is called on a Ref and another txn barged the current one (status isn't RUNNING)
- During commit, a txn is preparing to rerun a commute function on a Ref, but another txn made an in-txn change to the same Ref and barging it fails

Retries

- When a txn retires
  - all read and write locks currently held are released
  - all in-txn values of modified Refs are discarded
  - many collections associated with the txn are cleared
    - **`ensures`**, **`notify`**, **`actions`**, **`vals`**, **`sets`** and **`commutes`**
  - the txn status is changed to RETRY
  - execution continues at the beginning of the txn body
- Limited number of retries
  - 10,000 (**`RETRY_LIMIT`**)
  - seems arbitrary and cannot be configured

Locks in STM ...

in `java.util.concurrent.locks` package

- **`ReentrantReadWriteLock`**
  - each instance manages the read and write locks for a single Ref
  - any number of concurrent txns can hold a read lock for a Ref
    OR one txn can hold the write lock for a Ref
  - locks are only held briefly, not for the duration of a txn
    - unless **`ensure`** is called on a Ref in which case a read lock is held until the Ref is modified in the txn or the txn ends

... Locks in STM ...

- Lock-free strategy
  - the **`tinfo`** field in **`Ref`** objects
    is set to a **`LockingTransaction.Info`** object
    to mark them as having an in-txn value for a given txn
  - alternative to having **`LockingTransaction`** objects
    lock **`Ref`** objects for the duration of a transaction

... Locks in STM

- Read locks are acquired to
  - read (dereference) a Ref in a txn that has no in-txn value - released when finished
  - ensure a Ref - not released until txn modifies the Ref or commits
  - commute a Ref - only held until newest value is copied into map of in-txn values; released before commute function is executed
- Write locks are acquired to
  - mark a Ref as having an in-txn value in a specific txn - released after marking
  - commit changes to Refs - released when commit completes

STM Overhead

- Despite overhead introduced by STM,
  it can still be faster than using locks
  because it is optimistic instead of pessimistic
  - more opportunities for concurrency instead of blocking
- Specific sources of overhead
  incurred during reads and writes of Refs
  are described next

STM Ref Read Overhead

- read = dereference
- Unless a Ref was modified in a txn, giving it an in-txn value, walk history list to find newest value before txn started
    - if no other txn committed a change to the Ref since the current one started, the first value in the chain is used and the lookup is fast

STM Ref Write Overhead ...

- Verify that a txn is running
  - if not, throw **`IllegalStateException`**
- Verify no commute
  - once **`commute`** has been called on a Ref,
    `ref-set` and **`alter`** cannot be called on it within the same txn
  - since **`commute`** functions are called a second time during the commit,
    calls to **`ref-set`** and **`alter`** after **`commute`**
    wouldn't have a lasting affect

... STM Ref Write Overhead ...

- On the first write of a Ref within the txn
  - add the Ref to the set of Refs modified by the txn
    - used during commit
  - mark the Ref as having an in-txn value for the txn
    - if **`ensure`** was called on the Ref earlier in the txn, release the read lock for the Ref
    - attempt to acquire a write lock for the Ref and retry if unsuccessful
    - if another txn has committed a change to the Ref since the current txn began, retry
    - if another txn made an in-txn change to the Ref since the current txn began, attempt to barge it and retry if unsuccessful
    - mark Ref as being "locked" by current txn (sets its **`tinfo`** field to refer to current txn)
    - release the write lock for the Ref

... STM Ref Write Overhead

- On each write of a Ref, including the first in a txn
  - add new value to the map of in-txn values for the txn
    - subsequent reads of the Ref inside the txn
      get the value from this map instead of the history chain

STM Commit Overhead ...

- Change txn status from **`RUNNING`** to **`COMMITTING`**
- Rerun **`commute`** functions called in txn
  - must acquire a write lock for each commuted Ref
- Acquire write locks for all Refs modified in txn so there can be no readers
- Validate
  - call all the validate functions registered on modified Refs and retry if any disapprove of a change
- Update history list for each modified Ref
  - add new node or modify an existing one (explained on slide 38)
- For each modified Ref that has at least one registered watcher, create a **`Notify`** object that describes the change

... STM Commit Overhead

- Change txn status from **`COMMITTING`** to **`COMMITTED`**
- Release all write locks acquired previously
- Release all read locks still held from calls to **`ensure`**
- Clear contents of several txn collection fields in preparation for next use
  - **`ensures`**, **`vals`**, **`sets`** and **`commutes`**
- If commit was successful,
  notify all registered Ref watchers using data in **`Notify`** objects
- Dispatch all actions sent to Agents in txn
- Clear contents of more txn collection fields (**`notify`** and **`actions`**)
- Return value of last expression in txn body

Conclusions

- STM makes writing correct concurrent code much easier than using locks!
- Clojure isn't the only programming language with STM support
- For more details on Clojure, see http://ociweb.com/mark/clojure/
- For more details on STM and the Clojure implementation, see http://ociweb.com/mark/stm/