Adventures in Clojure
Navigating the STM sea and exploring Worlds

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Part 1: Clojure in a 

Clojure in a nutshell

- A modern Lisp dialect (2007), designed by Rich Hickey
- JVM as runtime platform
- Promotes a Functional Programming style
- Designed for Concurrency

Functional Style

- Clojure is **not** a **pure** functional language (like Haskell), but...
- Emphasis on **immutable data structures**
- Lisp's lists generalized to abstract **sequences**: list, vector, set, map, ...
  - Used pervasively: all Clojure collections, all Java collections, Java arrays and Strings, regular expression matches, directory structures, I/O streams, XML trees, ...
  - Sequences are lazy and immutable

Clojure and Java

- Clojure compiles to JVM bytecode

- Easy for Clojure to reuse Java libraries

```
(new java.util.Random) ; Java: “new java.util.Random()”
=> java.util.Random@18a4f2

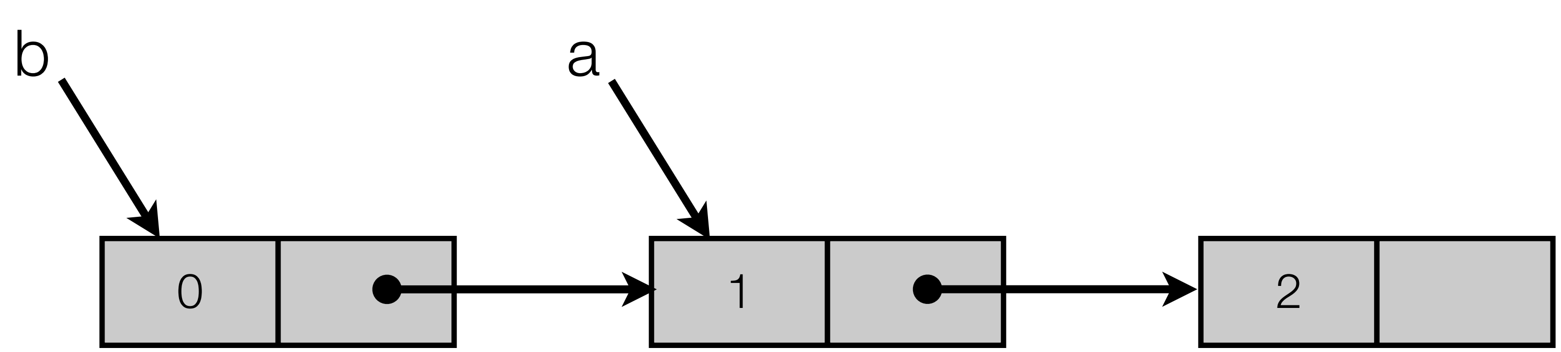
(. aRandom nextInt) ; Java: “aRandom.nextInt()”
=> 23494372
```

Part 2: Concurrency in Clojure

Persistent Data Structures

- The problem with immutable data structures: updates are costly (copy)
- Persistent data structures preserve old copies of themselves by efficiently *sharing structure* between older and newer versions.
- Simplest example: consing an element onto a linked list

```
(def a ‘(1 2))
(def b (cons 0 a))
```



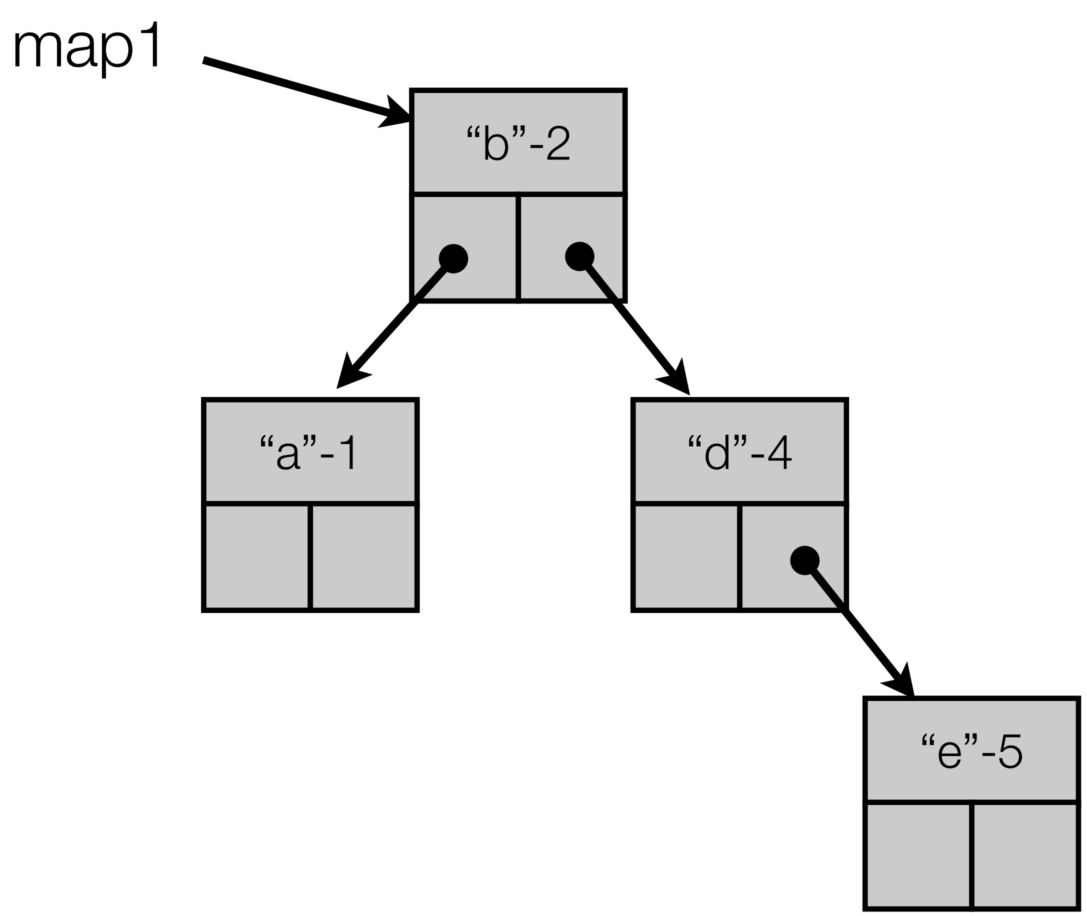
- b reuses all of a’s structure instead of having its own private copy

Persistent Data Structures

- Not only for linked lists, also for vectors, sets, maps, ...

- Example: binary tree insert

```
(def map1 {"a" 1, "b" 2, "d" 4, "e" 5})
(def map2 (assoc map1 "c" 3))
```



Persistent Data Structures

- Not only for linked lists, also for vectors, sets, maps, ...

- Example: binary tree insert

```
(def map1 {"a" 1, "b" 2, "d" 4, "e" 5})
(def map2 (assoc map1 "c" 3))
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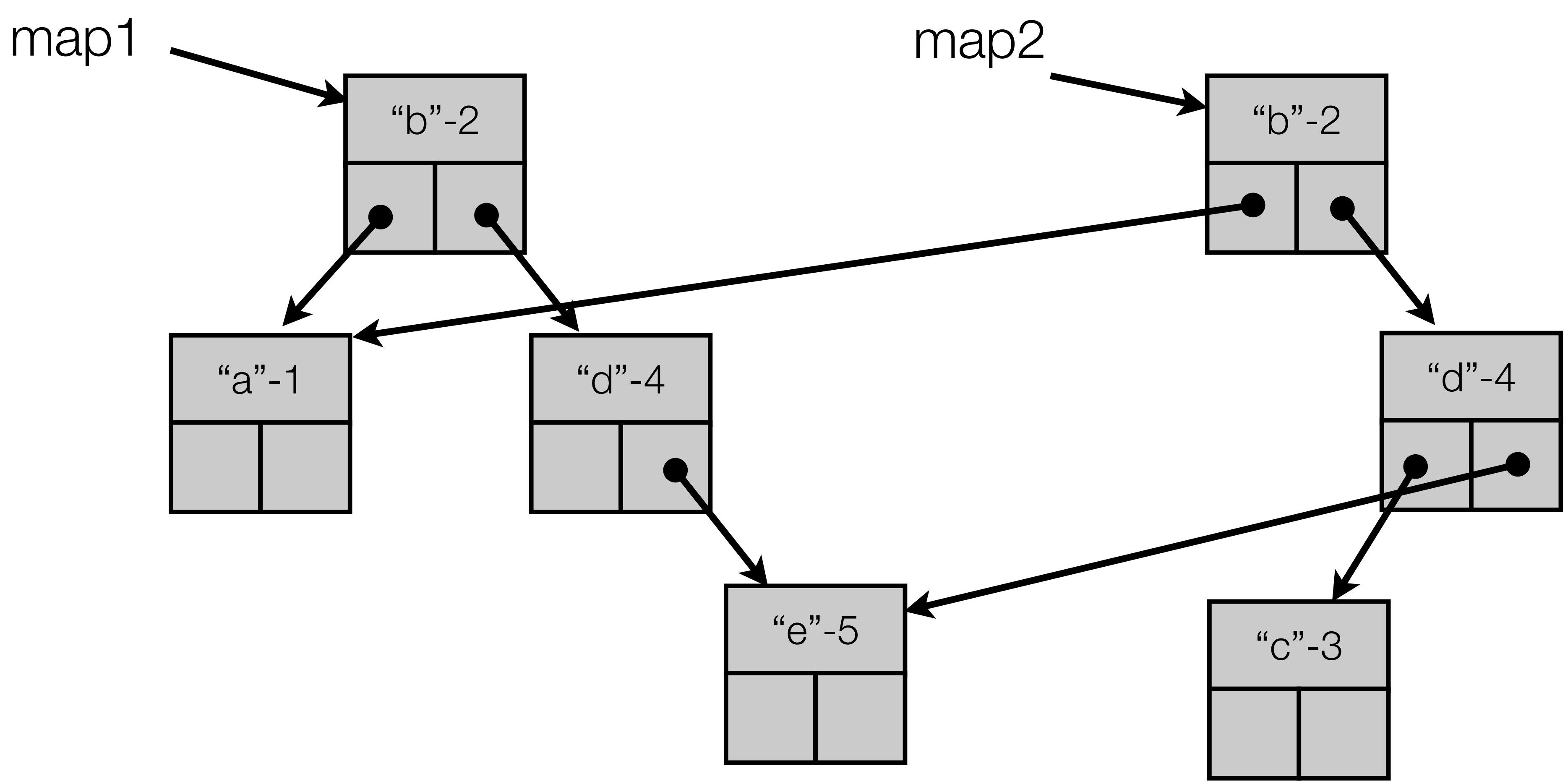


Threads

- Clojure reuses JVM threads as the unit of concurrency

```
(.start (Thread.
          (fn [] (println "Hello from new thread"))))
```

- Not as bad as it looks: Clojure does not combine threads with unbridled access to pervasive shared mutable state

Clojure Philosophy

- Immutable state is the default
- Where mutable state is required, programmer must explicitly select one of the following APIs:

state change is	**Asynchronous**	**Synchronous**
Coordinated	-	Refs
Independent	Agents	Atoms

Clojure’s concurrency primitives

state change is	**Asynchronous**	**Synchronous**
Coordinated	-	**Refs**
Independent	Agents	Atoms

Refs and Software Transactional Memory (STM)

- Ref: mutable *ref*erence to an immutable object

```
(def today (ref “Monday”))
```

- The ref wraps and protects its internal state. To read its contents, must explicitly dereference it:

```
(deref today)
=> “Monday”

@today
=> “Monday”
```

Refs and Software Transactional Memory (STM)

- To update a reference:

```
(ref-set today “Tuesday”)
```

- Updates can only occur in the context of a transaction:

```
(ref-set today “Tuesday”)
=> java.lang.IllegalStateException: No transaction running
```

Refs and Software Transactional Memory (STM)

- To start a transaction:

```
(dosync body)
```

- Example:

```
(dosync (ref-set today “Tuesday”))
=> “Tuesday”
```

Coordinated updates

- Changes to multiple refs within a transaction are **atomic** and **isolated**

```
(dosync
  (ref-set yesterday “Monday”)
  (ref-set today “Tuesday”))
```

- No other thread will be able to observe a state in which `yesterday` is already updated to “Monday”, while `today` is still set to “Monday”.

alter

- Often, the new state of a reference is dependent on the old state

```
(def weekdays ["mon","tue","wed","thu","fri","sat","sun"])

(def today-idx (ref 0))

(dosync
  (ref-set today-idx (mod (inc @today-idx) 7)))

; alternatively (preferred)
(defn next-day-idx [i] (mod (inc i) 7))
(dosync
  (alter today-idx next-day-idx))
```

Example: money transfer

- Transferring money atomically from one bank account to another

```
(defn make-account [sum]
  (ref sum))

(defn transfer [amount from to]
  (dosync
    (alter from (fn [bal] (- bal amount)))
    (alter to (fn [bal] (+ bal amount)))))

(def accountA (make-account 1500))
(def accountB (make-account 200))

(transfer 100 accountA accountB)
(println @accountA) ; 1400
(println @accountB) ; 300
```

How STM Works: MVCC

- Multiversion concurrency control (MVCC): each transaction starts with a **"snapshot" of the database** (i.e. the state of all refs).

- Instead of updating data directly, each transaction modifies its own **private copy** of the data.

  - Persistent data structures: private copy shares most of its structure with the original value

  - Changes made to private copies will not be seen by other transactions until the transaction commits.

MVCC: Example

```
(def today (ref “mon”))
(def yesterday (ref “sun”))
T1: (dosync
      (list (deref today)
            (deref yesterday)))
T2: (dosync
      (ref-set today “tue”)
      (ref-set yesterday “mon”))
```

global “ref” state

Ref	rev 0	rev 1
today	“mon”	
yesterday	“sun”	

MVCC: Example

```
(def today (ref "mon"))
(def yesterday (ref "sun"))
T1: (dosync
      (list (deref today)
            (deref yesterday)))
T2: (dosync
      (ref-set today "tue")
      (ref-set yesterday "mon"))
```

global "ref" state

Ref	rev 0	rev 1
today	"mon"	
yesterday	"sun"	

Both T1 and T2 start with read-point 0

in-transaction-values of T1

Ref	val	rev

in-transaction-values of T2

Ref	val	rev

```
>
 T2: (ref-set today "tue")
 T1: (deref today)
 T2: (ref-set yesterday "mon")
 T1: (deref yesterday)
 T2: commit
 T1: commit
```

MVCC: Example

```
(def today (ref "mon"))
(def yesterday (ref "sun"))
T1: (dosync
      (list (deref today)
            (deref yesterday)))
T2: (dosync
      (ref-set today "tue")
      (ref-set yesterday "mon"))
```

global "ref" state

Ref	rev 0	rev 1
today	"mon"	
yesterday	"sun"	

in-transaction-values of T1

Ref	val	rev

in-transaction-values of T2

Ref	val	rev
today	**"tue"**	**0**

```
>T2: (ref-set today "tue")
 T1: (deref today)
 T2: (ref-set yesterday "mon")
 T1: (deref yesterday)
 T2: commit
 T1: commit
```

MVCC: Example

```
(def today (ref "mon"))
(def yesterday (ref "sun"))
T1: (dosync
      (list (deref today)
            (deref yesterday)))
T2: (dosync
      (ref-set today "tue")
      (ref-set yesterday "mon"))
```

global "ref" state

Ref	rev 0	rev 1
today	"mon"	
yesterday	"sun"	

in-transaction-values of T1

Ref	val	rev
today	**"mon"**	**0**

in-transaction-values of T2

Ref	val	rev
today	"tue"	0

```
 T2: (ref-set today "tue")
>T1: (deref today)
 T2: (ref-set yesterday "mon")
 T1: (deref yesterday)
 T2: commit
 T1: commit
```

MVCC: Example

```
(def today (ref "mon"))
(def yesterday (ref "sun"))
T1: (dosync
      (list (deref today)
            (deref yesterday)))
T2: (dosync
      (ref-set today "tue")
      (ref-set yesterday "mon"))
```

global "ref" state

Ref	rev 0	rev 1
today	"mon"	
yesterday	"sun"	

in-transaction-values of T1

Ref	val	rev
today	"mon"	0

in-transaction-values of T2

Ref	val	rev
today	"tue"	0
yesterday	**"mon"**	**0**

```
 T2: (ref-set today "tue")
 T1: (deref today)
>T2: (ref-set yesterday "mon")
 T1: (deref yesterday)
 T2: commit
 T1: commit
```

MVCC: Example

```
(def today (ref "mon"))
(def yesterday (ref "sun"))
T1: (dosync
      (list (deref today)
            (deref yesterday)))
T2: (dosync
      (ref-set today "tue")
      (ref-set yesterday "mon"))
```

global "ref" state

Ref	rev 0	rev 1
today	"mon"	
yesterday	"sun"	

in-transaction-values of T1

Ref	val	rev
today	"mon"	0
yesterday	**"sun"**	**0**

in-transaction-values of T2

Ref	val	rev
today	"tue"	0
yesterday	"mon"	0

```
 T2: (ref-set today "tue")
 T1: (deref today)
 T2: (ref-set yesterday "mon")
>T1: (deref yesterday)
 T2: commit
 T1: commit
```

MVCC: Example

```
(def today (ref “mon”))
(def yesterday (ref “sun”))
T1: (dosync
      (list (deref today)
            (deref yesterday)))
T2: (dosync
      (ref-set today “tue”)
      (ref-set yesterday “mon”))
```

global “ref” state

Ref	rev 0	rev 1
today	“mon”	**“tue”**
yesterday	“sun”	**“mon”**

T2 has write-point 1, updates global ref state atomically

in-transaction-values of T1

Ref	val	rev
today	“mon”	0
yesterday	“sun”	0

in-transaction-values of T2

Ref	val	rev
today	“tue”	0
yesterday	“mon”	0

```
 T2: (ref-set today “tue”)
 T1: (deref today)
 T2: (ref-set yesterday “mon”)
 T1: (deref yesterday)
>T2: commit
 T1: commit
```

MVCC: Example

```
(def today (ref “mon”))
(def yesterday (ref “sun”))
T1: (dosync
      (list (deref today)
            (deref yesterday)))
T2: (dosync
      (ref-set today “tue”)
      (ref-set yesterday “mon”))
```

global “ref” state

Ref	rev 0	rev 1
today	“mon”	“tue”
yesterday	“sun”	“mon”

in-transaction-values of T1

Ref	val	rev
today	“mon”	0
yesterday	“sun”	0

T1 has read consistent versions of both refs, no conflict

in-transaction-values of T2

Ref	val	rev
today	“tue”	0
yesterday	“mon”	0

```
 T2: (ref-set today “tue”)
 T1: (deref today)
 T2: (ref-set yesterday “mon”)
 T1: (deref yesterday)
 T2: commit
>T1: commit
```

MVCC: Example of a conflict

```
(def today (ref “mon”))
(def yesterday (ref “sun”))
T1: (dosync
      (ref-set today “sun”)
      (ref-set yesterday “sat”))
T2: (dosync
      (ref-set today “tue”)
      (ref-set yesterday “mon”))
```

global “ref” state

Ref	rev 0	rev 1
today	“mon”	
yesterday	“sun”	

MVCC: Example of a conflict

```
(def today (ref "mon"))
(def yesterday (ref "sun"))
T1: (dosync
      (ref-set today "sun")
      (ref-set yesterday "sat"))
T2: (dosync
      (ref-set today "tue")
      (ref-set yesterday "mon"))
```

global "ref" state

Ref	rev 0	rev 1
today	"mon"	
yesterday	"sun"	

Both T1 and T2 start with read-point 0

in-transaction-values of T1

Ref	val	rev

in-transaction-values of T2

Ref	val	rev

```
>
 T1: (ref-set today "sun")
 T2: (ref-set today "tue")
 T1: (ref-set yesterday "sat")
 T2: (ref-set yesterday "mon")
 T1: commit
 T2: commit
```

MVCC: Example of a conflict

```
(def today (ref "mon"))
(def yesterday (ref "sun"))
T1: (dosync
      (ref-set today "sun")
      (ref-set yesterday "sat"))
T2: (dosync
      (ref-set today "tue")
      (ref-set yesterday "mon"))
```

global "ref" state

Ref	rev 0	rev 1
today	"mon"	
yesterday	"sun"	

in-transaction-values of T1

Ref	val	rev
today	**"sun"**	**0**

in-transaction-values of T2

Ref	val	rev

```
>T1: (ref-set today "sun")
 T2: (ref-set today "tue")
 T1: (ref-set yesterday "sat")
 T2: (ref-set yesterday "mon")
 T1: commit
 T2: commit
```

MVCC: Example of a conflict

```
(def today (ref “mon”))
(def yesterday (ref “sun”))
T1: (dosync
      (ref-set today “sun”)
      (ref-set yesterday “sat”))
T2: (dosync
      (ref-set today “tue”)
      (ref-set yesterday “mon”))
```

global “ref” state

Ref	rev 0	rev 1
today	“mon”	
yesterday	“sun”	

in-transaction-values of T1

Ref	val	rev
today	“sun”	0

in-transaction-values of T2

Ref	val	rev
today	**“tue”**	**0**

```
 T1: (ref-set today “sun”)
>T2: (ref-set today “tue”)
 T1: (ref-set yesterday “sat”)
 T2: (ref-set yesterday “mon”)
 T1: commit
 T2: commit
```

MVCC: Example of a conflict

```
(def today (ref "mon"))
(def yesterday (ref "sun"))
T1: (dosync
      (ref-set today "sun")
      (ref-set yesterday "sat"))
T2: (dosync
      (ref-set today "tue")
      (ref-set yesterday "mon"))
```

global "ref" state

Ref	rev 0	rev 1
today	"mon"	
yesterday	"sun"	

in-transaction-values of T1

Ref	val	rev
today	"sun"	0
yesterday	**"sat"**	**0**

in-transaction-values of T2

Ref	val	rev
today	"tue"	0

```
 T1: (ref-set today "sun")
 T2: (ref-set today "tue")
>T1: (ref-set yesterday "sat")
 T2: (ref-set yesterday "mon")
 T1: commit
 T2: commit
```

MVCC: Example of a conflict

```
(def today (ref “mon”))
(def yesterday (ref “sun”))
T1: (dosync
      (ref-set today “sun”)
      (ref-set yesterday “sat”))
T2: (dosync
      (ref-set today “tue”)
      (ref-set yesterday “mon”))
```

global “ref” state

Ref	rev 0	rev 1
today	“mon”	
yesterday	“sun”	

in-transaction-values of T1

Ref	val	rev
today	“sun”	0
yesterday	“sat”	0

in-transaction-values of T2

Ref	val	rev
today	“tue”	0
yesterday	**“mon”**	**0**

```
 T1: (ref-set today “sun”)
 T2: (ref-set today “tue”)
 T1: (ref-set yesterday “sat”)
>T2: (ref-set yesterday “mon”)
 T1: commit
 T2: commit
```

MVCC: Example of a conflict

```
(def today (ref "mon"))
(def yesterday (ref "sun"))
T1: (dosync
      (ref-set today "sun")
      (ref-set yesterday "sat"))
T2: (dosync
      (ref-set today "tue")
      (ref-set yesterday "mon"))
```

global "ref" state

Ref	rev 0	rev 1
today	"mon"	**"sun"**
yesterday	"sun"	**"sat"**

T1 has write-point 1, updates global ref state atomically

in-transaction-values of T1

Ref	val	rev
today	"sun"	0
yesterday	"sat"	0

in-transaction-values of T2

Ref	val	rev
today	"tue"	0
yesterday	"mon"	0

```
 T1: (ref-set today "sun")
 T2: (ref-set today "tue")
 T1: (ref-set yesterday "sat")
 T2: (ref-set yesterday "mon")
>T1: commit
 T2: commit
```

MVCC: Example of a conflict

```
(def today (ref “mon”))
(def yesterday (ref “sun”))
T1: (dosync
      (ref-set today “sun”)
      (ref-set yesterday “sat”))
T2: (dosync
      (ref-set today “tue”)
      (ref-set yesterday “mon”))
```

global “ref” state

Ref	rev 0	rev 1
today	“mon”	“sun”
yesterday	“sun”	“sat”

T2 notices that the refs it modified have already been modified, since the latest version of the refs (1) is no longer equal to its read-point (0)

in-transaction-values of T1

Ref	val	rev
today	“sun”	0
yesterday	“sat”	0

in-transaction-values of T2

Ref	val	rev
today	“tue”	0
yesterday	“mon”	0

```
 T1: (ref-set today “sun”)
 T2: (ref-set today “tue”)
 T1: (ref-set yesterday “sat”)
 T2: (ref-set yesterday “mon”)
 T1: commit
>T2: commit
```

T2 will abort and retry, this time with read-point 1

Transactions, side effects, retries

```
(dosync body)
```

- Transactions may be aborted and retried.
- The transaction `body` may be executed multiple times.
  - Should avoid side-effects other than assigning to refs
  - Especially: avoid any form of I/O (`launchMissiles()`)

Clojure’s concurrency primitives

state change is	**Asynchronous**	**Synchronous**
Coordinated	-	Refs
Independent	Agents	**Atoms**

Atoms

- For uncoordinated (independent), synchronous updates
- More lightweight than refs: atoms are updated independently, no need for transactions
- Two or more atoms cannot be updated in a coordinated way

```
(def today-idx (atom 0))

@today-idx
=> 0
```

Updating Atoms

- To update an atom, use swap!

```
(swap! today-idx inc)
```

- swap! calculates new value and performs an atomic **test-and-set**: if the atom's value was changed concurrently (by another thread), it will **retry**
  - The update function may be called multiple times => should be **side-effect free**
  - Concurrently calling `swap!` on the same atom is thread-safe

Clojure’s concurrency primitives

state change is	**Asynchronous**	**Synchronous**
Coordinated	-	Refs
Independent	**Agents**	Atoms

Agents

- Both refs and atoms can be updated synchronously
- If you can tolerate updates happening asynchronously, use agents

```
(agent initial-state)
```

- Can `send` a function (“action”) to an agent to update its state at a later point in time:

```
(send agent update-fn)
```

- `send` queues an update-fn to run later, on a thread in a thread pool

Agents: example

```
(defn make-account [init]
  (agent init))

(defn deposit [account amnt]
  (send account (fn [bal] (+ bal amnt))))

(defn withdraw [account amnt]
  (send account (fn [bal] (- bal amnt))))

(def a (make-account 0))
(deposit a 100) ; asynchronous
(withdraw a 50) ; asynchronous
(await a)
@a
=> 50
```

Unified Update Model

- Refs, Atoms and Agents all enable mutation of state by applying a function on an "old state" returning a "new state":
  - Refs: `(alter a-ref update-fn)`
  - Atoms: `(swap! an-atom update-fn)`
  - Agents: `(send an-agent update-fn)`
- To read, call `deref/@`

state change is	**Asynchronous**	**Synchronous**
Coordinated	-	Refs
Independent	Agents	Atoms

Part 3: A meta-circular STM in Clojure

Goal

- We have seen Clojure's built-in support for STM via refs

- Recall:

```clojure
(defn make-account [sum]
  (ref sum))

(defn transfer [amount from to]
  (dosync
    (alter from (fn [bal] (- bal amount)))
    (alter to (fn [bal] (+ bal amount)))))

(def accountA (make-account 1500))
(def accountB (make-account 200))

(transfer 100 accountA accountB)
(println @accountA) ; 1400
(println @accountB) ; 300
```

Goal

- Build our own STM system in Clojure to better understand its implementation

```clojure
(defn make-account [sum]
  (mc-ref sum))

(defn transfer [amount from to]
  (mc-dosync
    (mc-alter from (fn [bal] (- bal amount)))
    (mc-alter to (fn [bal] (+ bal amount)))))

(def accountA (make-account 1500))
(def accountB (make-account 200))

(transfer 100 accountA accountB)
(println (mc-deref accountA)) ; 1400
(println (mc-deref accountB)) ; 300
```

Almost-meta-circular implementation

- We represent refs via atoms
- We call such refs “mc-refs” (meta-circular refs)
- Recall: atoms support synchronous but *uncoordinated* state updates
- We have to add the coordination through transactions ourselves

Iterative approach

- Developed 4 versions:
  - v1: does not use MVCC, simple but transactions may have an inconsistent view on the world (~120 loc)
  - v2: uses MVCC (like real Clojure), simple version with 1 global lock (~155 loc)
  - v3: adds support for advanced features (commute and ensure) (~197 loc)
  - v4: uses fine-grained locking (1 lock / mc-ref) (~222 loc)
- v5 upcoming: introduce contention management to ensure liveness (current versions prone to livelock)

Demo

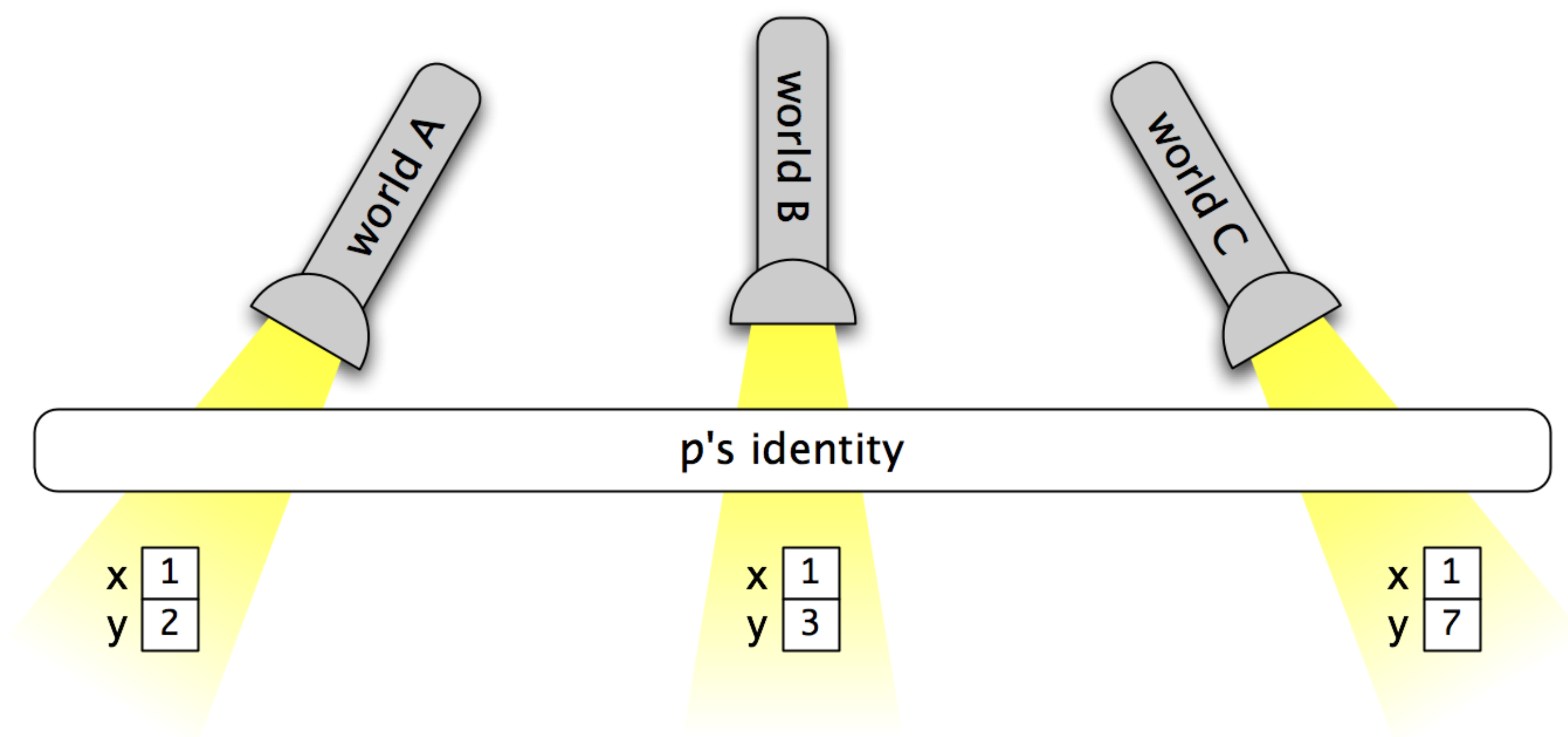
- https://github.com/tvcutsem/stm-in-clojure

Part 4: Worlds

Worlds

- ECOOP 2011 paper by Alex Warth (Viewpoints Research Institute)
- Goal: scoped side-effects

```
p = new Point(1, 2);
```

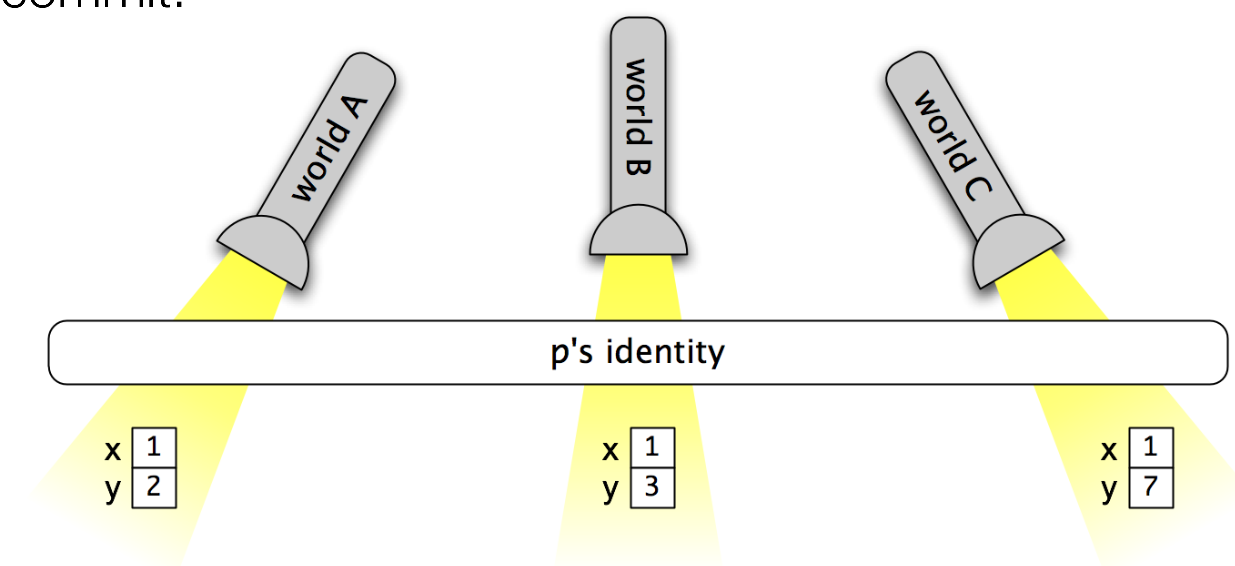


Worlds/JS

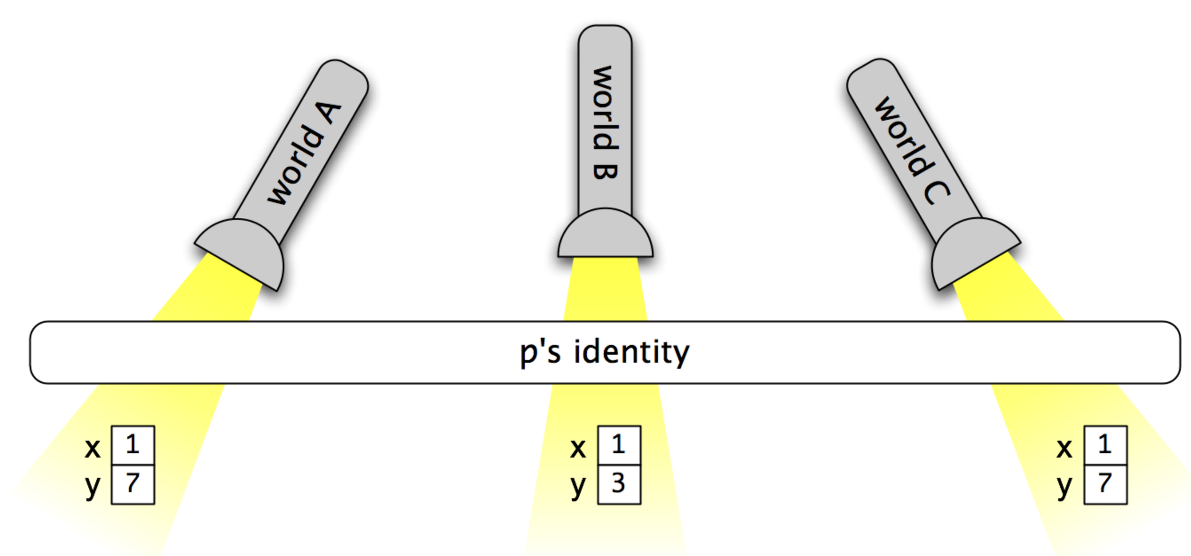
- Javascript implementation of Worlds:

```
A = thisWorld;

p = new Point(1, 2);

B = A.sprout();
in B { p.y = 3; }

C = A.sprout();
in C { p.y = 7; }

C.commit();
```

Before commit:



After commit:



clj-worlds

- A Clojure Library for Worlds
- As in the STM experiment, we implemented our own new type of “ref”
    - A “world-aware” ref or **w-ref**

```
A = thisWorld;

p = new Point(1, 2);

B = A.sprout();
in B { p.y = 3; }

C = A.sprout();
in C { p.y = 7; }

C.commit();
```

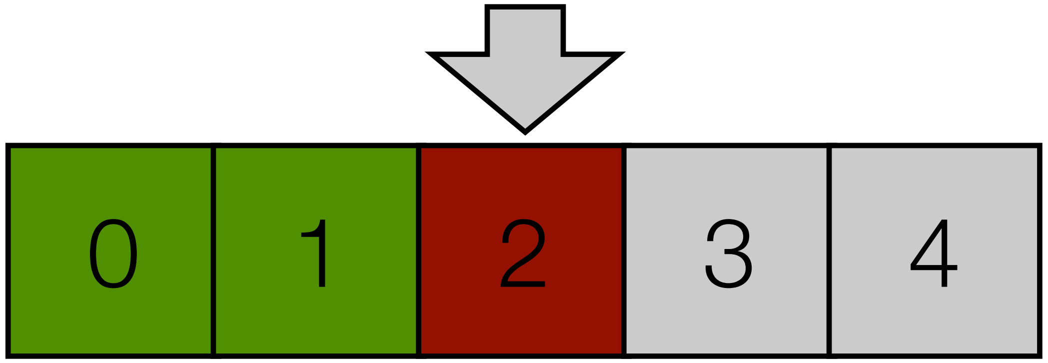
```
(let [A (this-world)

      p (new Point 1 2)

      B (sprout A)]
  (in-world B
    (w-ref-set (:y p) 3))
  (let [C (sprout A)]
    (in-world C
      (w-ref-set (:y p) 7))
    (commit C)))
```

Example

```
(let [w (sprout (this-world))
      r (w-ref 0)]
  (w-deref r)            ; 0
  (in-world w
    (w-deref r)          ; also 0
    (w-ref-set r 1))
  (w-deref r)            ; still 0!
  (commit w)
  (w-deref r))           ; 1
```

Example: safe exception handling

```
(try
  (doseq [elt seq]
    (alter elt update-fn))
  (catch e
    ; undo successful updates
    ))
```

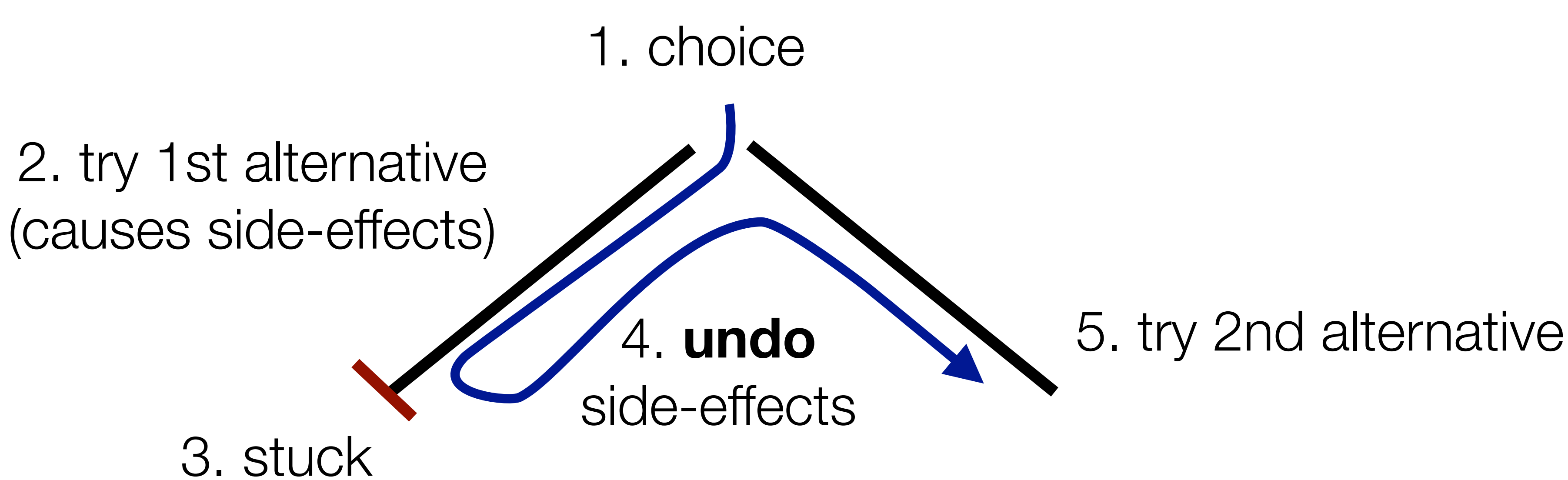


Example: safe exception handling

```
(try
  (in-world (sprout (this-world))
    (doseq [elt seq]
      (w-alter elt update-fn))
    (commit (this-world)))
  (catch e
    ; no cleanup required!
    ))
```

More examples

- **“undo”** functionality for objects / applications
- Scoped **monkey-patching**. E.g. extending java.lang.Object, but only for your application
- Safe **backtracking** in a logic language with side-effects (think Prolog assert)
    - Or in any kind of backtracking search in general...



Future steps

- Experiment with concurrent Worlds
  - How to merge concurrent updates to parallel worlds?

Conclusion

- Clojure: Lisp on the JVM
- Functional, but not pure
- Unified update model: refs, atoms, agents
- Experiments with extending the unified update model:
  - MC-STM: implementing meta-circular refs
  - clj-worlds: adding “world-refs” for scoped side-effects