Identity, State and Values

Clojure's approach to concurrency

Rich Hickey

Agenda

- Functions and processes
- Identity, State, and Values
- Persistent Data Structures
- Clojure’s Managed References
- Q&A

Functions

- Function
    - Depends only on its arguments
    - Given the same arguments, always returns the same value
    - Has no effect on the world
    - Has no notion of time

Functional Programming

- Emphasizes functions
  - Tremendous benefits
- But - most programs are not functions
  - Maybe compilers, theorem provers?
    - But - They execute on a machine
    - Observably consume compute resources

Processes

- Include some notion of change over time
- Might have effects on the world
- Might wait for external events
- Might produce different answers at different times (i.e. have state)
- Many real/interesting programs are processes
- This talk is about one way to deal with state and time *in the local context*

State

- Value of an identity at a time
- Sounds like a variable/field?
  - Name that takes on successive ‘values’
- Not quite:
  - i = 0
  - i = 42
  - j = i
  - j is 42? - depends

Variables

- Variables (and fields) in traditional languages are predicated on a single thread of control, one timeline
- Adding concurrency breaks them badly
    - Non-atomicity (e.g. of longs)
    - volatile, write visibility
    - Composite operations require locks
    - All workarounds for lack of a time model

Time

- When things happen
  - Before/after
  - Later
  - At the same time (concurrency)
  - Now
- Inherently relative

Value

- An immutable magnitude, quantity, number... *or composite thereof*
- 42 - easy to understand as value
- But traditional OO tends to make us think of composites as something other than values
  - Big mistake
    - aDate.setMonth(“January”) - ugh!
  - Dates, collections etc are all values

Identity

- A logical entity we associate with a series of causally related values (states) over time
- Not a name, but can be named
  - I call my mom ‘Mom’, but you wouldn’t
- Can be composite - the NY Yankees
- Programs that are processes need identity

State

- Value of an identity at a time
- Why not use variables for state?
  - Variable might not refer to a proper value
  - Sets of variables/fields never constitute a proper composite value
  - No state transition management
    - I.e., no time coordination model

Philosophy

- Things don't change in place
- Becomes obvious once you incorporate time as a dimension
  - Place includes time
- The future is a function of the past, and doesn’t change it
- Co-located entities can observe each other without cooperation
- Coordination is desirable in local context

Race-walker foul detector

- Get left foot position
  - off the ground
- Get right foot position
  - off the ground
- Must be a foul, right?

- Snapshots are critical to perception and decision making
- Can’t stop the runner/race (locking)
- Not a problem if we can get runner’s value
- Similarly don’t want to stop sales in order to calculate bonuses or sales report

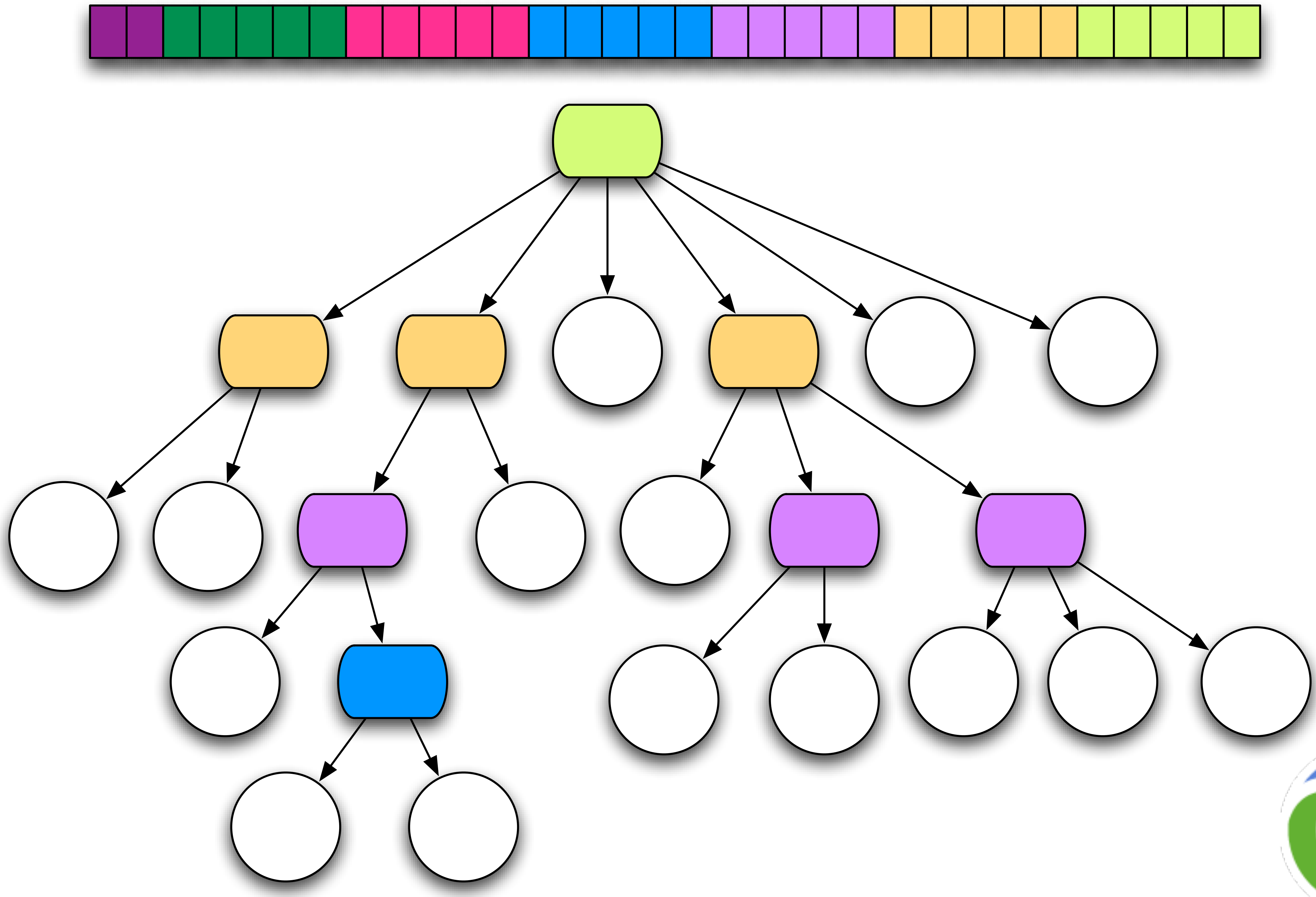
Approach

- Programming with values is critical
- By eschewing morphing in place, we just need to manage the succession of values (states) of an identity
- A timeline coordination problem
  - Several semantics possible
- Managed references
  - Variable-like cells with coordination semantics

Persistent Data Structures

- Composite values - immutable
- ‘Change’ is merely a function, takes one value and returns another, ‘changed’ value
- Collection maintains its performance guarantees
    - Therefore new versions are not full copies
- Old version of the collection is still available after 'changes', with same performance
- Example - hash map/set and vector based upon array mapped hash tries (Bagwell)

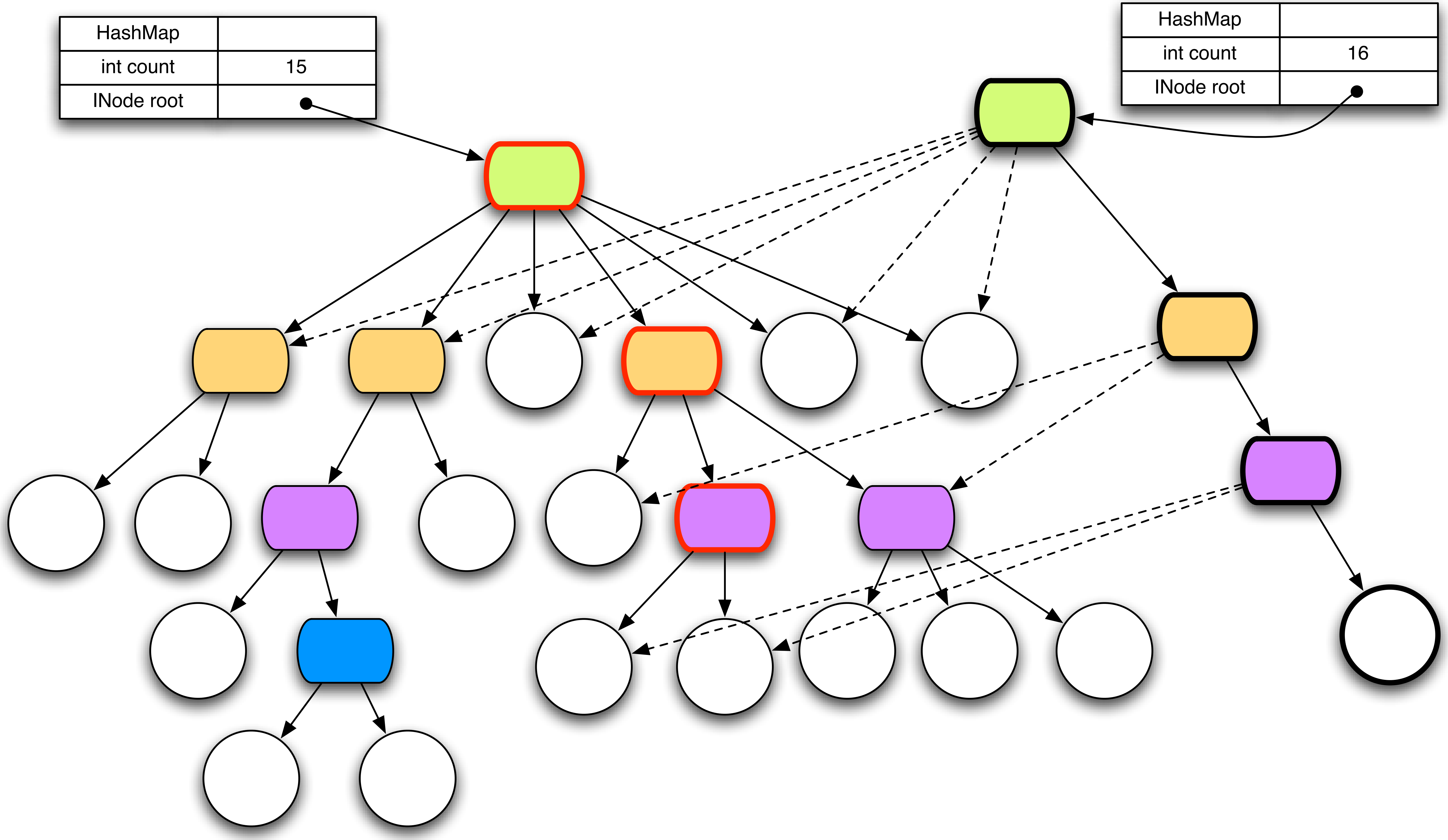
Bit-partitioned hash tries



Structural Sharing

- Key to efficient ‘copies’ and therefore persistence
- Everything is immutable so no chance of interference
- Thread safe
- Iteration safe

Path Copying



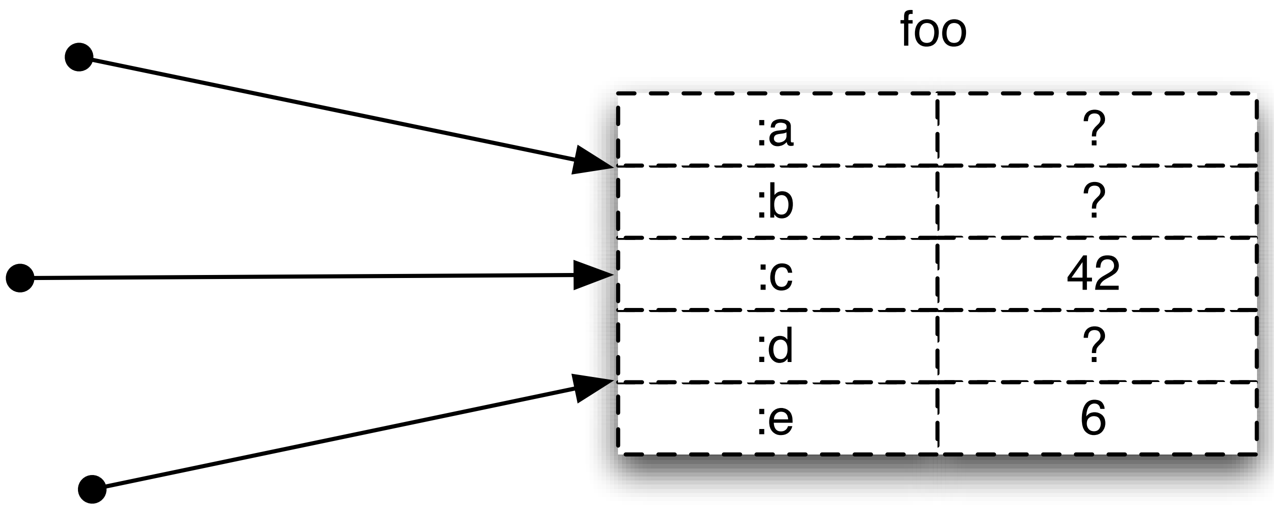
HashMap	
int count	15
INode root	●

HashMap	
int count	16
INode root	●

Coordination Methods

- Conventional way:
  - Direct references to mutable objects
  - Lock and worry (manual/convention)
- Clojure way:
  - Indirect references to immutable persistent data structures (inspired by SML's `ref`)
  - Concurrency semantics for references
    - Automatic/enforced
    - No locks in user code!

Typical OO - Direct references to Mutable Objects

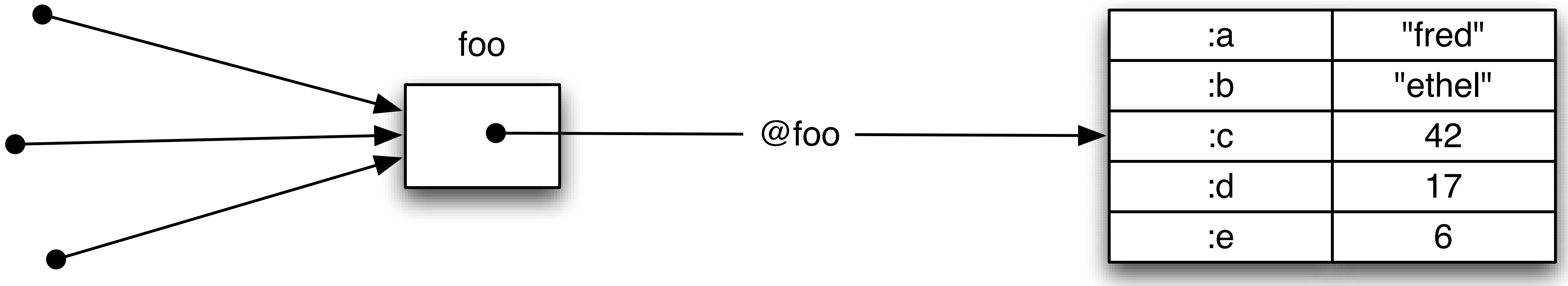


foo

:a	?
:b	?
:c	42
:d	?
:e	6

- Unifies identity and value
- Anything can change at any time
- Consistency is a user problem
- Encapsulation doesn’t solve concurrency problems

Clojure - Indirect references to Immutable Objects



foo

@foo

:a	"fred"
:b	"ethel"
:c	42
:d	17
:e	6

- Separates identity and value
  - Obtaining value requires explicit dereference
- Values can never change
  - Never an inconsistent value
- Encapsulation is orthogonal

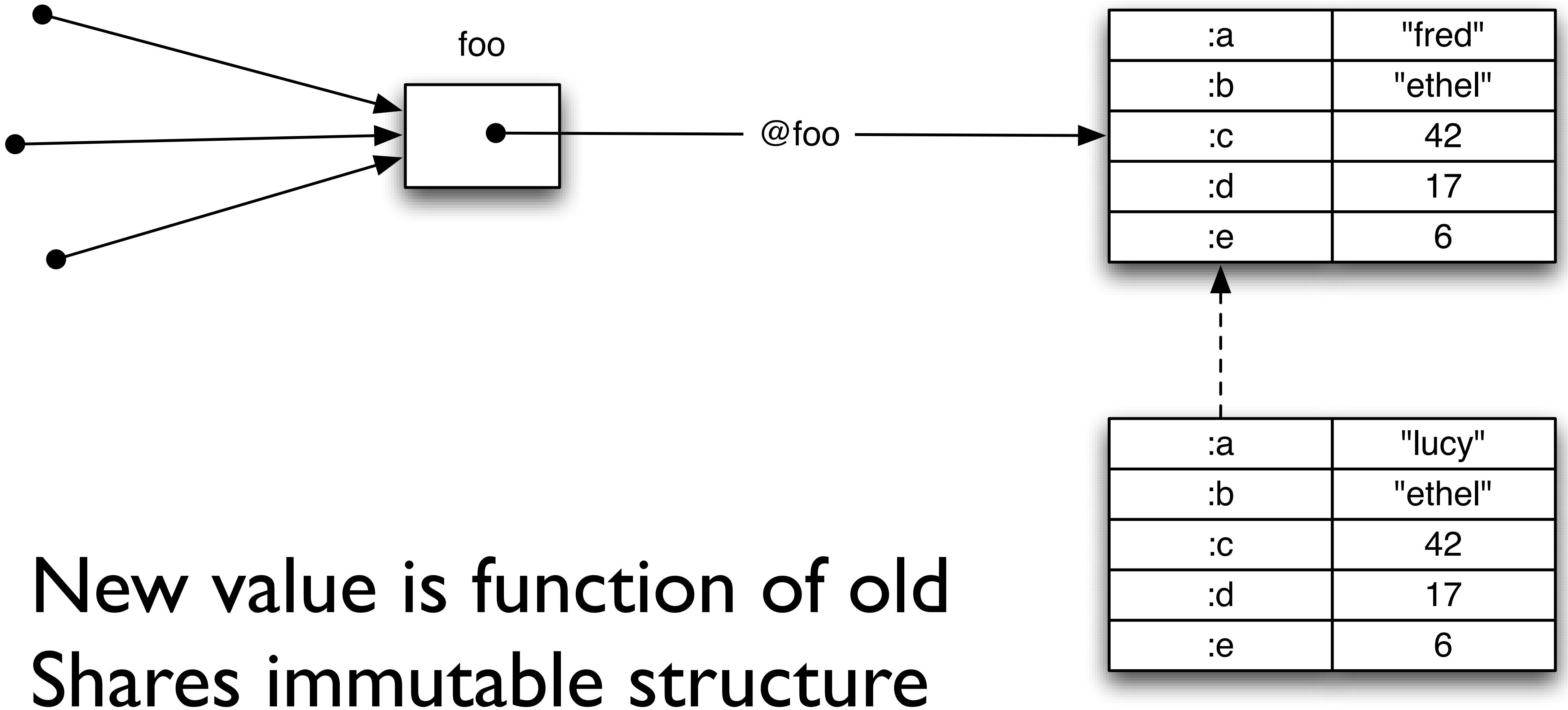
Clojure References

- The only things that mutate are references themselves, in a controlled way
- 4 types of mutable references, with different semantics:
  - Refs - shared/synchronous/coordinated
  - Agents - shared/asynchronous/autonomous
  - Atoms - shared/synchronous/autonomous
  - Vars - Isolated changes within threads

Uniform state transition model

- (‘change-state’ reference function [args*])
- function will be passed current state of the reference (plus any args)
- Return value of function will be the next state of the reference
- Snapshot of ‘current’ state always available with deref
- No user locking, no deadlocks

Persistent ‘Edit’

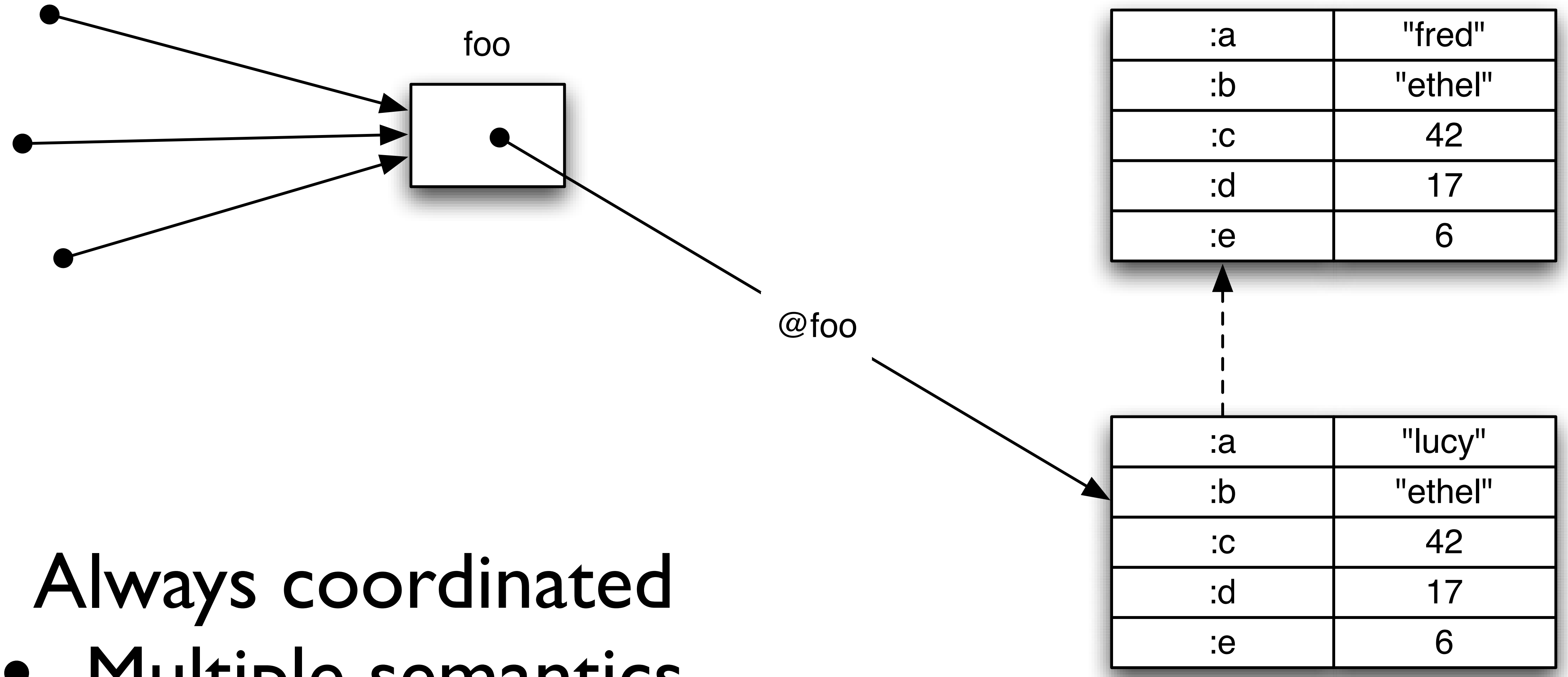


:a	"fred"
:b	"ethel"
:c	42
:d	17
:e	6

:a	"lucy"
:b	"ethel"
:c	42
:d	17
:e	6

- New value is function of old
- Shares immutable structure
- Doesn’t impede readers
- Not impeded by readers

Atomic State Transition



foo

@foo

:a	"fred"
:b	"ethel"
:c	42
:d	17
:e	6

:a	"lucy"
:b	"ethel"
:c	42
:d	17
:e	6

- Always coordinated
  - Multiple semantics
- Next dereference sees new value
- Consumers of values unaffected

Refs and Transactions

- Software transactional memory system (STM)
- Refs can only be changed within a transaction
- All changes are Atomic and Isolated
  - Every change to Refs made within a transaction occurs or none do
  - No transaction sees the effects of any other transaction while it is running
- Transactions are speculative
  - Will be retried automatically if conflict
  - Must avoid side-effects!

The Clojure STM

- Surround code with (dosync ...), state changes through *alter/commute*, using ordinary function (state=>new-state)
- Uses Multiversion Concurrency Control (MVCC)
- All reads of Refs will see a consistent snapshot of the 'Ref world' as of the starting point of the transaction, + any changes it has made.
- All changes made to Refs during a transaction will appear to occur at a single point in the timeline.

Refs in action

```
(def foo (ref {:a "fred" :b "ethel" :c 42 :d 17 :e 6}))

@foo -> {:d 17, :a "fred", :b "ethel", :c 42, :e 6}

(assoc @foo :a "lucy")
-> {:d 17, :a "lucy", :b "ethel", :c 42, :e 6}

@foo -> {:d 17, :a "fred", :b "ethel", :c 42, :e 6}

(alter foo  assoc :a "lucy")
-> IllegalStateException: No transaction running

(dosync (alter foo  assoc :a "lucy"))
@foo -> {:d 17, :a "lucy", :b "ethel", :c 42, :e 6}
```

Implementation - STM

- Not a lock-free spinning optimistic design
- Uses locks, latches to avoid churn
- Deadlock detection + barging
- One timestamp CAS is only global resource
- No read tracking
- Coarse-grained orientation
    - Refs + persistent data structures
- Readers don't impede writers/readers, writers don't impede readers, supports commute

STM - commute

- Often a transaction will need to update a jobs-done counter or add its result to a map
- If done with `alter`, update is a read-modify-write, so if multiple transactions contend, one wins, one retries
- If transactions don’t care about resulting value, and operation is commutative, can instead use commute
- Both transactions will succeed without retry
- Always just an optimization

STM - ensure

- MVCC is subject to *write-skew*
  - Where validity of transaction depends on stability of value unchanged by it
  - e.g. one of two accounts can go negative but not both
- Simply reading does not preclude modification by another transaction
- Can use ensure for values that are read but must remain stable
- More efficient than dummy write

Agents

- Manage independent state
- State changes through actions, which are ordinary functions (state=>new-state)
- Actions are dispatched using *send* or *send-off*, which return immediately
- Actions occur *asynchronously* on thread-pool threads
- Only one action per agent happens at a time

Agents

- Agent state always accessible, via deref/@, but may not reflect all actions
- Any dispatches made during an action are held until *after* the state of the agent has changed
- Agents coordinate with transactions - any dispatches made during a transaction are held until it commits
- Agents are not Actors (Erlang/Scala)

Agents in Action

```
(def foo (agent {:a "fred" :b "ethel" :c 42 :d 17 :e 6}))

@foo -> {:d 17, :a "fred", :b "ethel", :c 42, :e 6}

(send foo assoc :a "lucy")

@foo -> {:d 17, :a "fred", :b "ethel", :c 42, :e 6}

... time passes ...

@foo -> {:d 17, :a "lucy", :b "ethel", :c 42, :e 6}
```

Atoms

- Manage independent state
- State changes through *swap!*, using ordinary function (state=>new-state)
- Change occurs *synchronously* on caller thread
- Models compare-and-set (CAS) spin swap
- Function may be called more than once!
  - Guaranteed atomic transition
  - Must avoid side-effects!

Atoms in Action

```
(def foo (atom {:a "fred" :b "ethel" :c 42 :d 17 :e 6}))

@foo -> {:d 17, :a "fred", :b "ethel", :c 42, :e 6}

(swap! foo assoc :a "lucy")

@foo -> {:d 17, :a "lucy", :b "ethel", :c 42, :e 6}
```

Uniform state transition

```
;refs
(dosync
  (alter foo  assoc :a "lucy"))

;agents
(send foo assoc :a "lucy")

;atoms
(swap! foo assoc :a "lucy")
```

Summary

- Immutable values, a feature of the functional parts of our programs, are a critical component of the parts that deal with time
- Persistent data structures provide efficient immutable composite values
- Once you accept immutability, you can separate time management, and swap in various concurrency semantics
- Managed references provide easy to use and understand time coordination

Thanks for listening!

http://clojure.org

Questions?