6.852 Lecture 23

- Transactional memory (continued)
- Shared memory vs networks
- Paxos
- Reading:
  - Herlihy, Luchangco, Moir, Scherer paper
  - Dice, Shalev, Shavit paper
  - Lynch, Chapter 17
  - Lamport: The Part-Time Parliament

Transactional memory

- Raise level of abstraction
  - programmer specifies atomicity boundaries: transactions
  - system guarantees atomicity
    - commits if it can
    - aborts if not (roll back any changes)
    - possibly retry on abort
  - system manages contention (possibly separable functionality)
  - compositional (due to nested transactions)
    - but large transactions may not commit
  - simplified interface: atomic blocks
    - atomic { code }
    - automatic retry

Using transactional memory

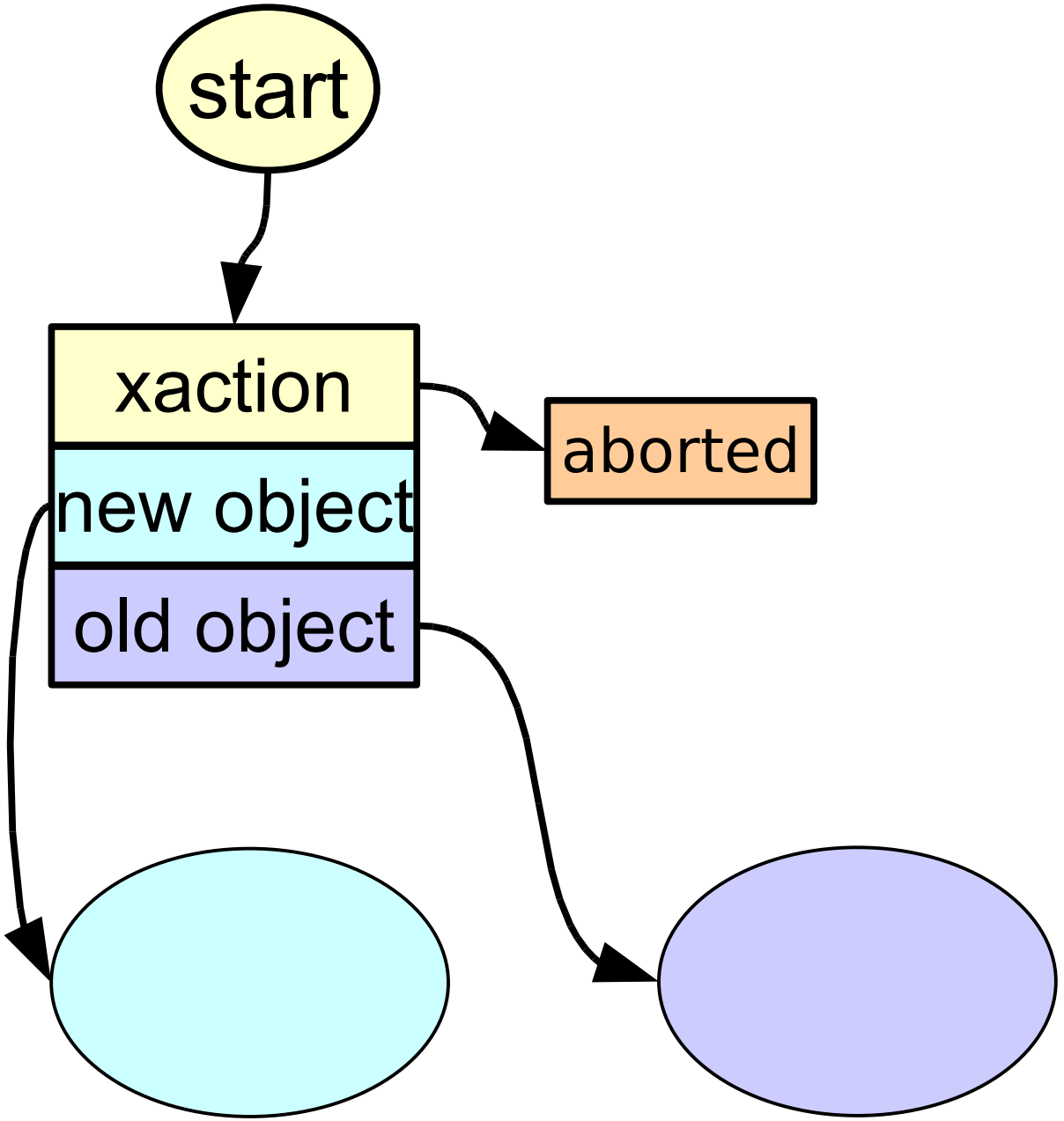
```
Q.enqueue(x)
  node = new Node(x)
  node.next := null
  atomic{
    oldtail = Q.tail
    Q.tail := node
    if oldtail = null then
      Q.head := node
    else
      oldtail.next := node
  }
```

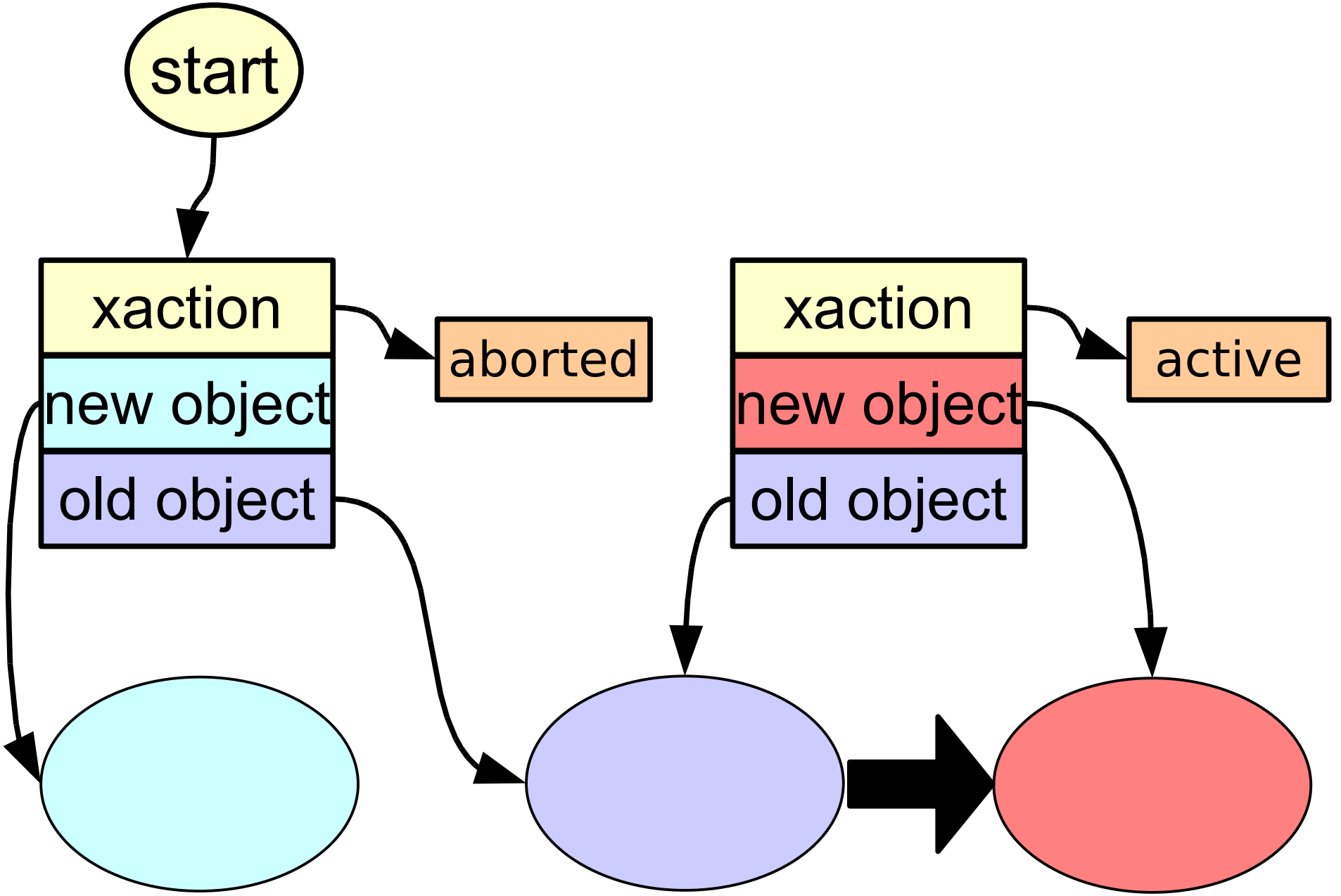
```
Q.dequeue()
  atomic{
    if Q.head = null then
      return null
    else
      node := Q.head
      Q.head := node.next
      if node.next = null then
        Q.tail := null
      return node.item
  }
```

```
transfer(Q,Q')
  atomic{
    x = Q.dequeue()
    if x  null then
      Q'.enqueue(x)
  }
```

Dynamic STM (DSTM)

- object-based (Java™ library)
- no locks (obstruction-free)
- supports dynamic allocation and access
- separable contention management
- pluggable implementations (2nd release)
  - added blocking “shadow” implementation


start
xaction
aborted
new object
old object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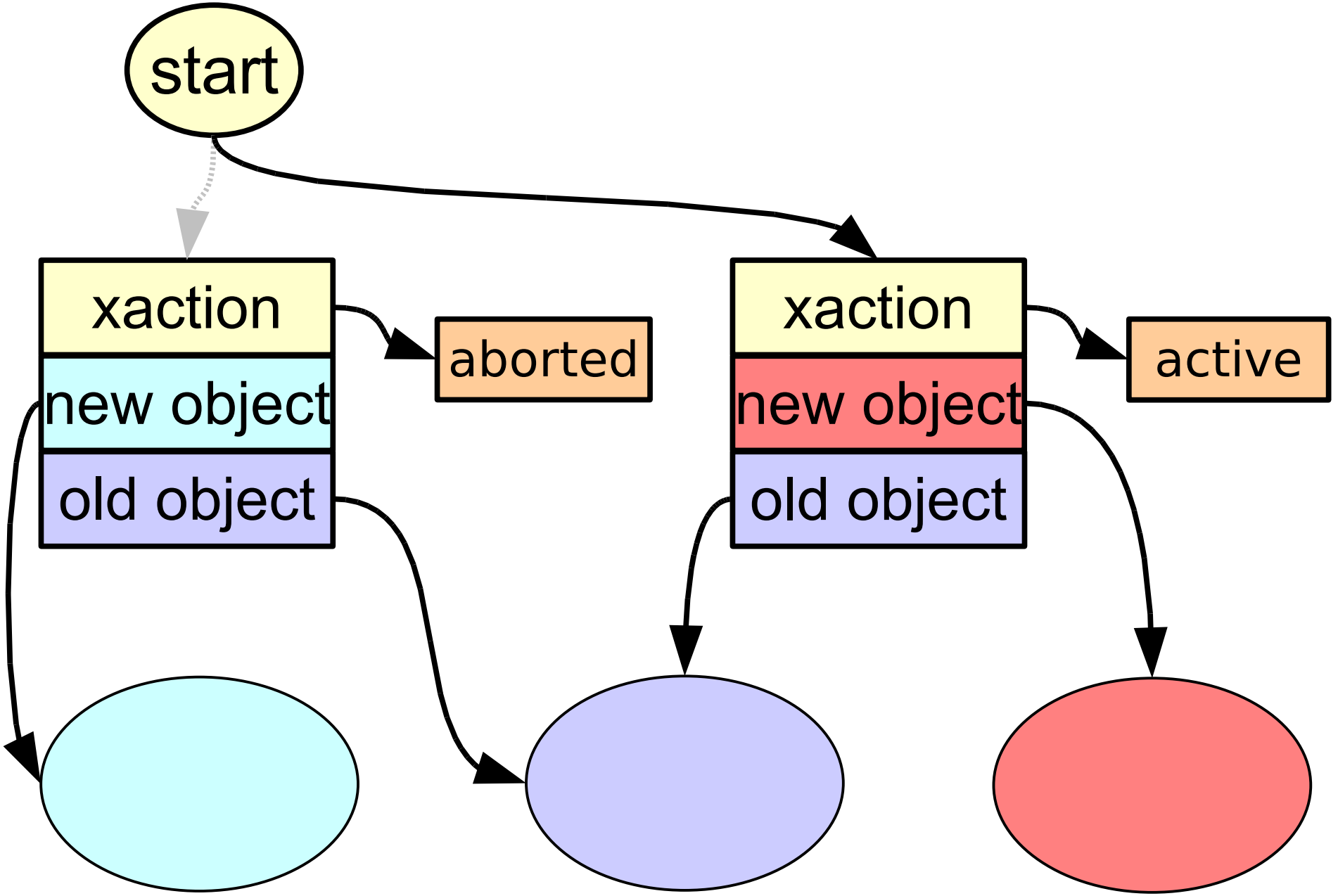
active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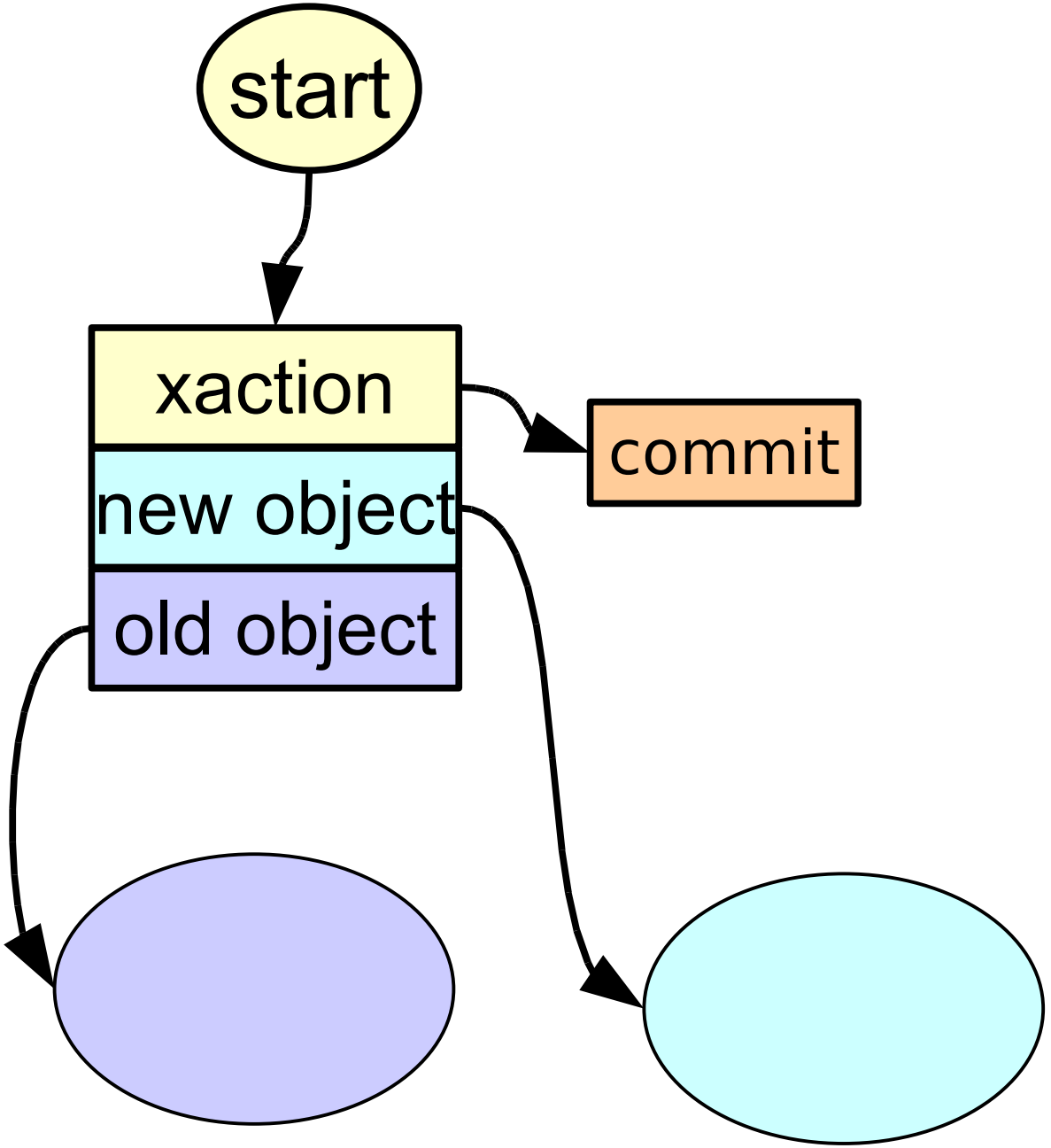
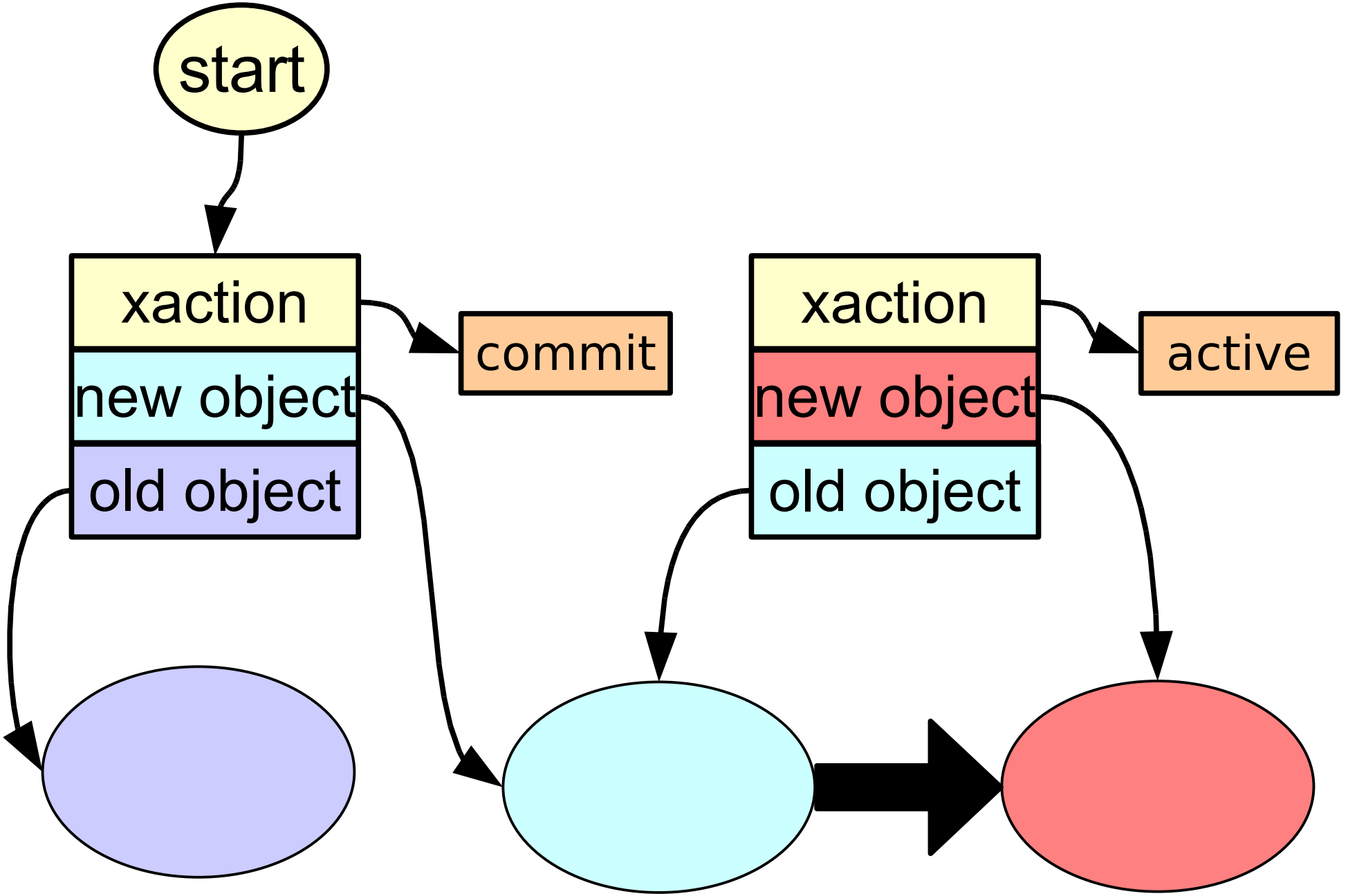
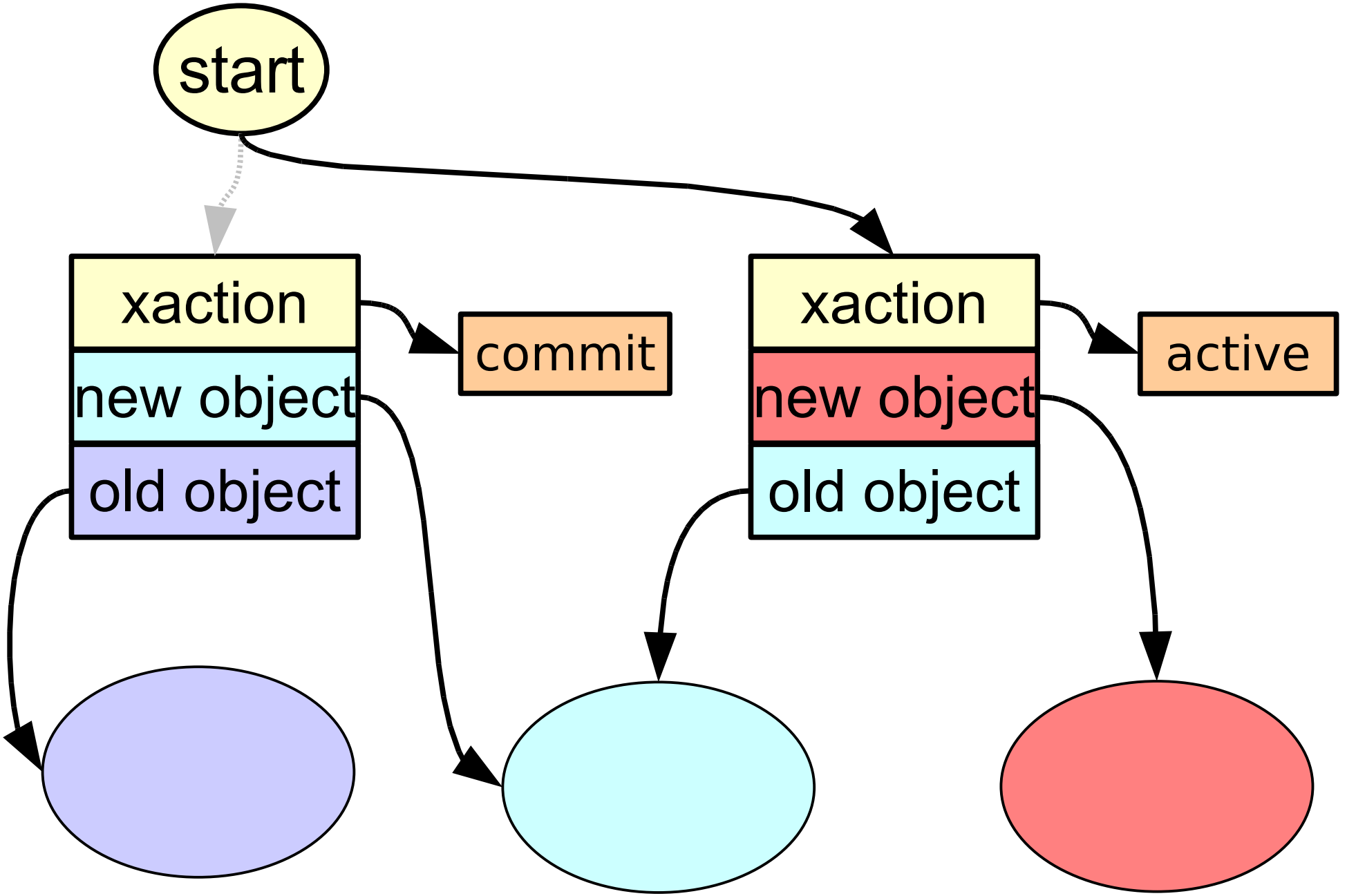
aborted
xaction
new object
old object
active


start
xaction
commit
new object
old object


start
xaction
new object
old object
commit
xaction
new object
old object
active


start
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old object
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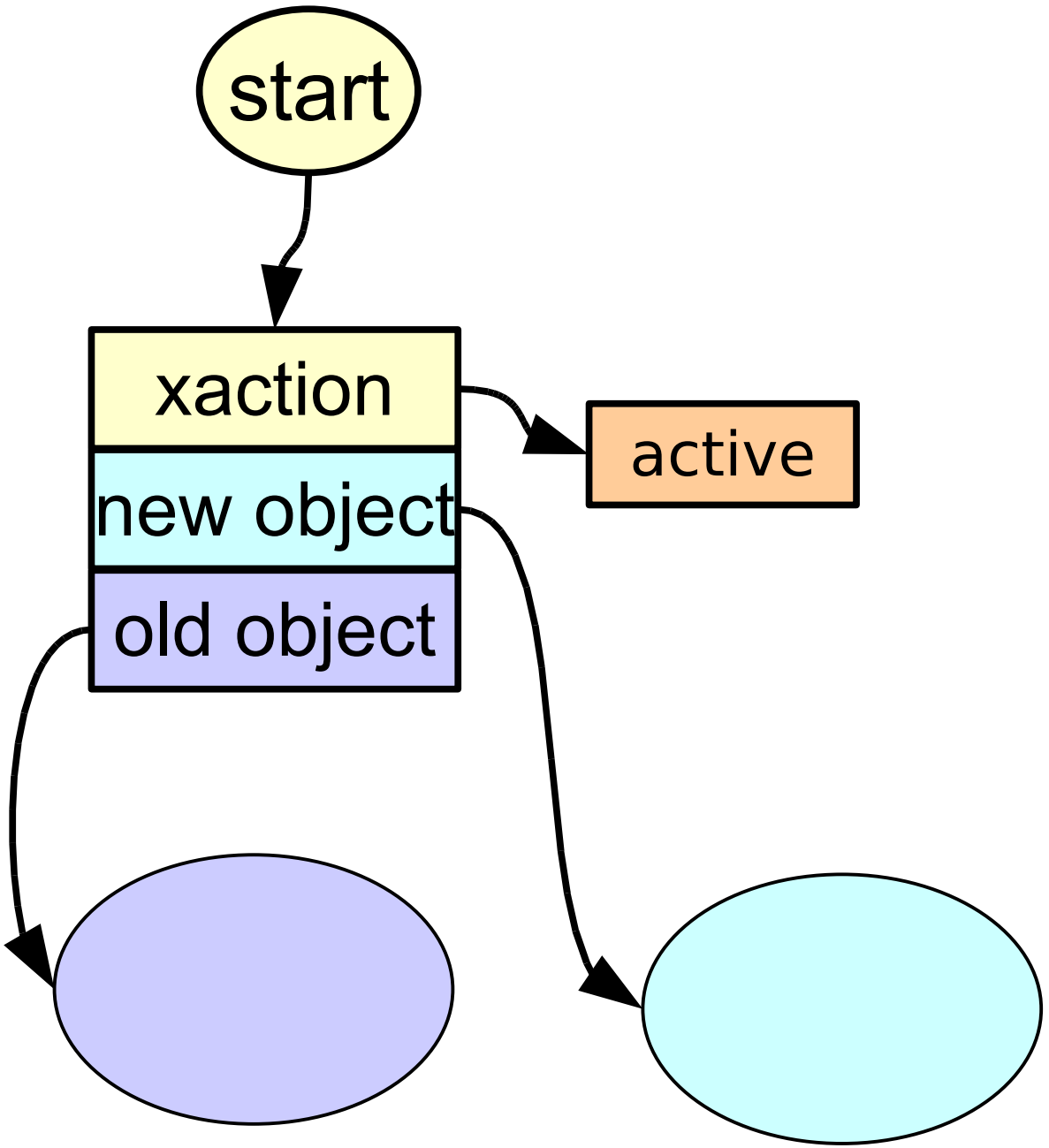
start
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new object
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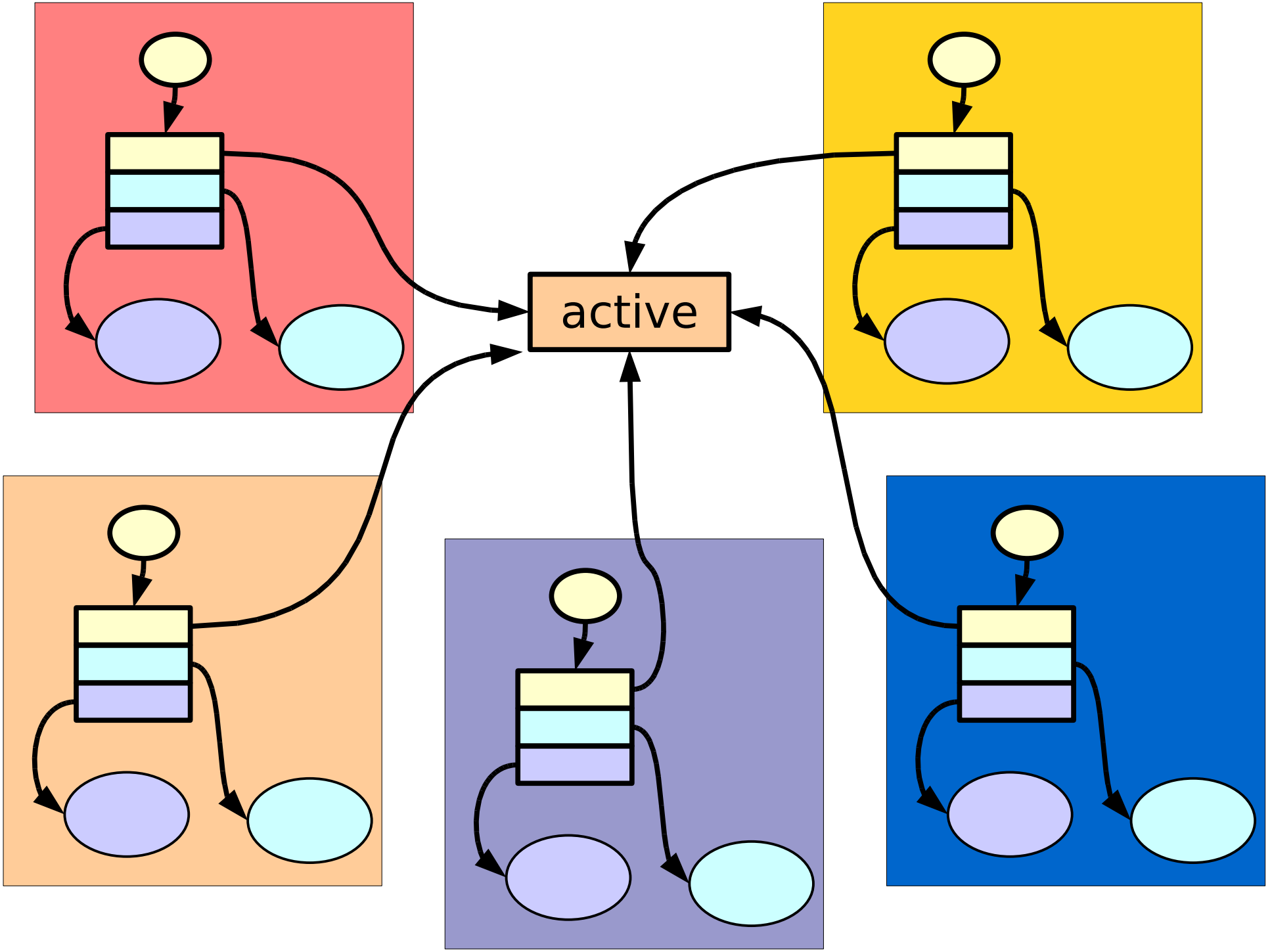
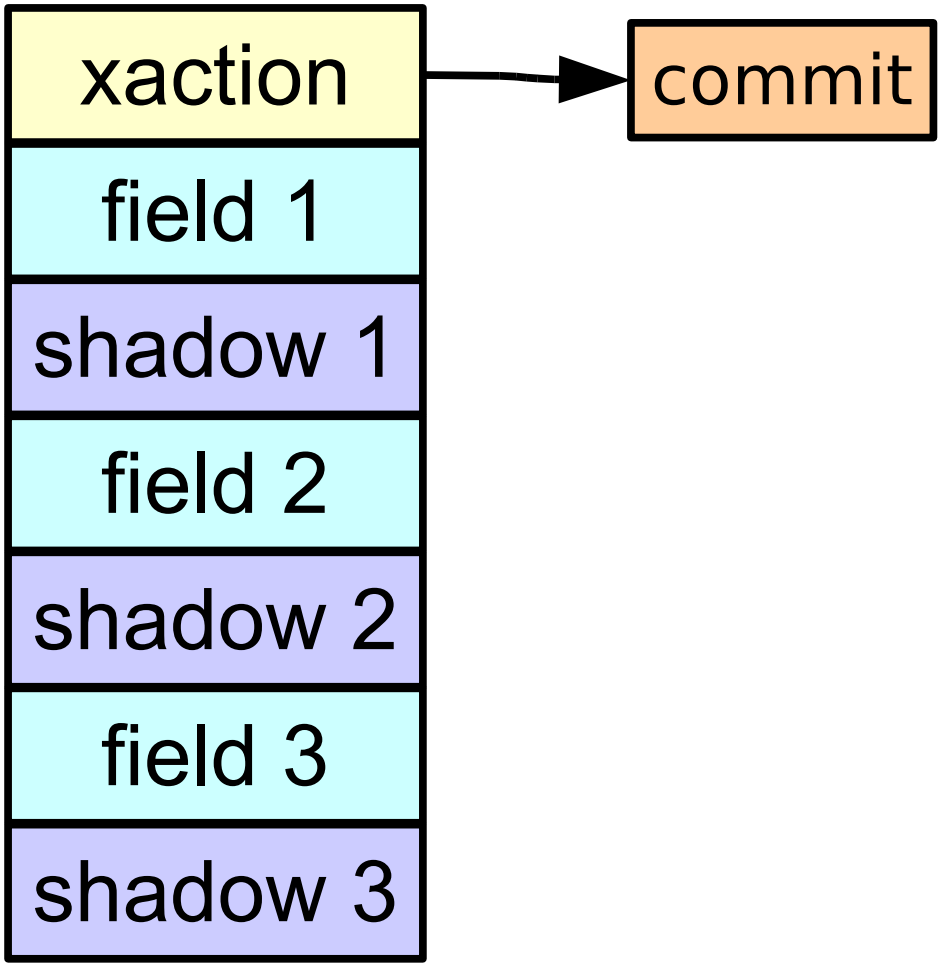
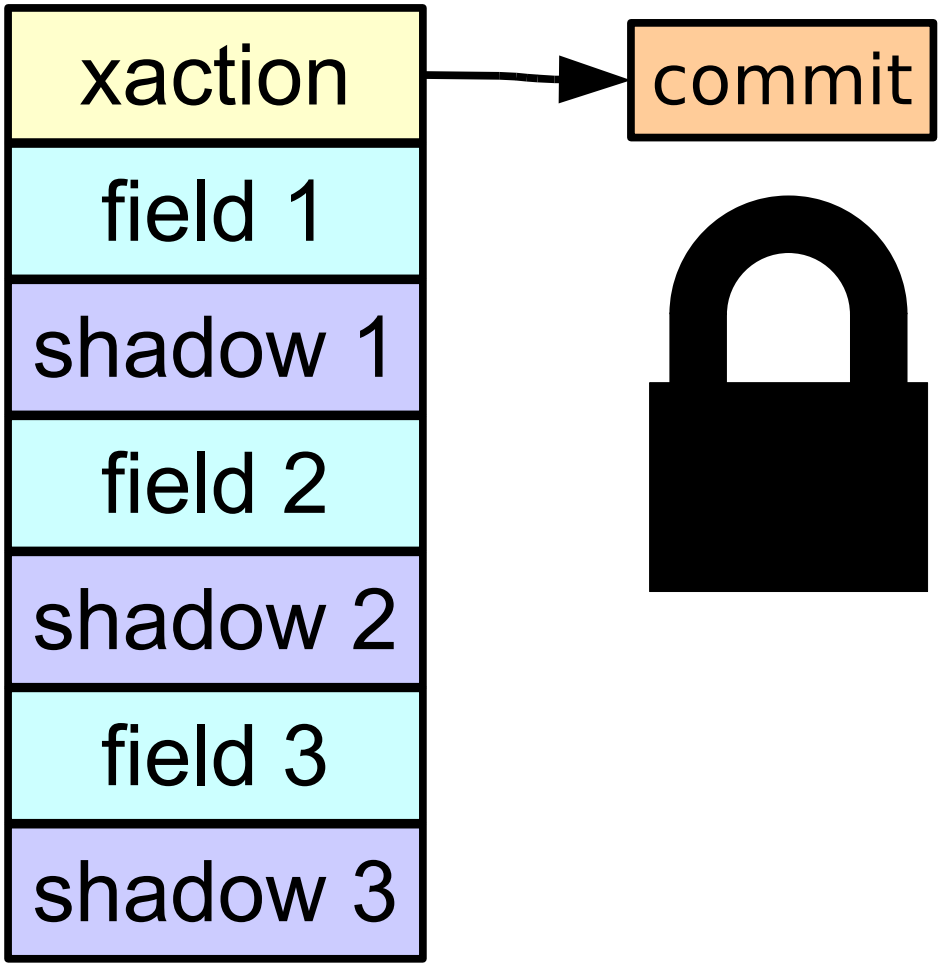

active

Enable “read-sharing”

- Invisible readers
  - keep thread-local “read set”: pairs of location and version read
  - validation checks no location in read set has changed
- Visible readers
  - keep set of active readers in “locator”
- Semi-visible readers
  - keep number of readers


xaction
commit
field 1
shadow 1
field 2
shadow 2
field 3
shadow 3


xaction
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field 1
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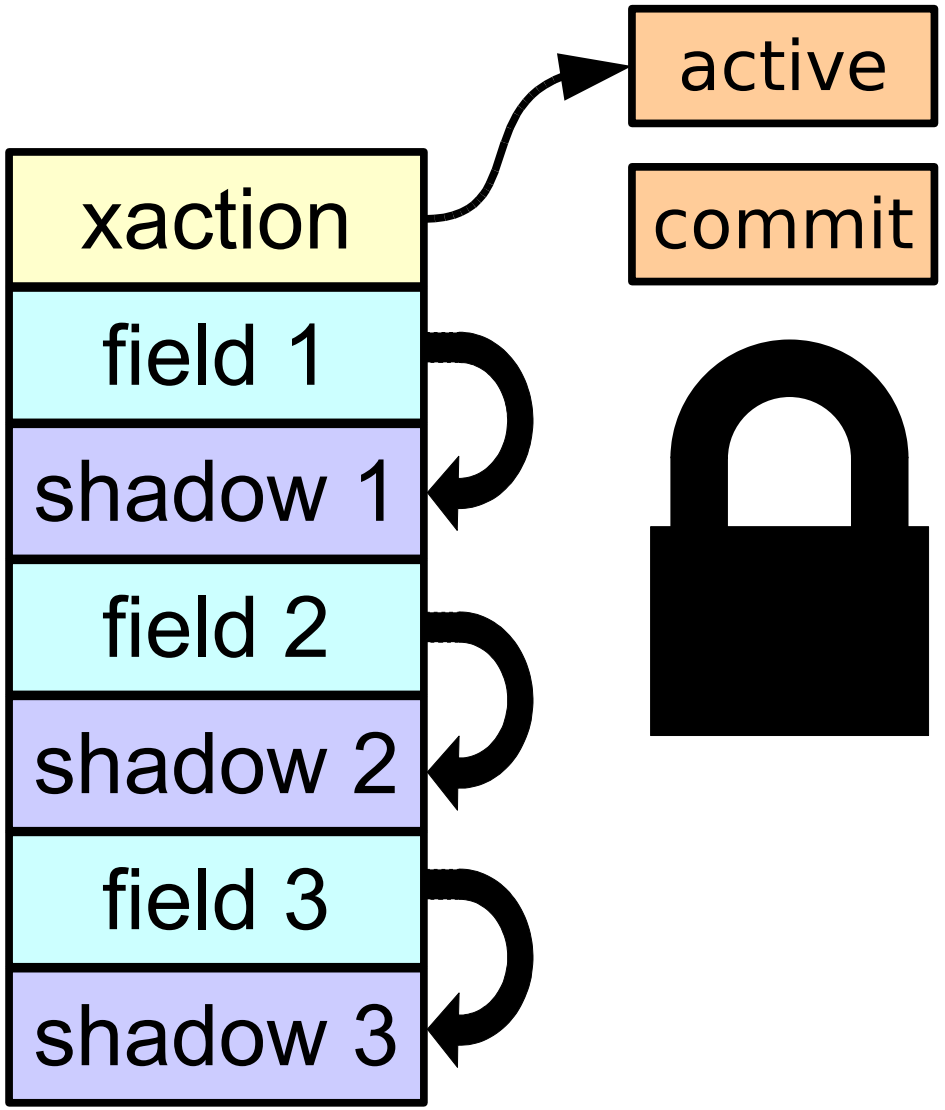
shadow 3


active
xaction
commit
field 1
shadow 1
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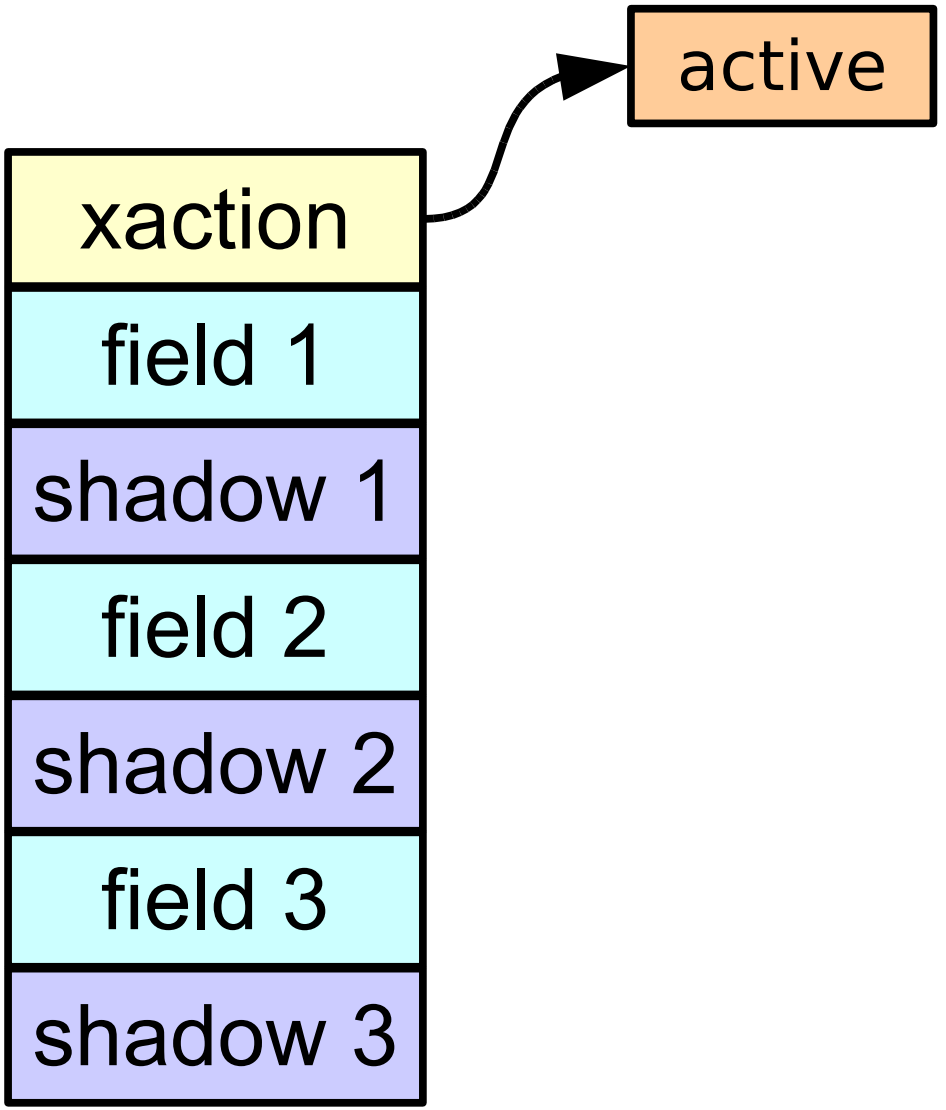
shadow 2
field 3
shadow 3


active
xaction
field 1
shadow 1
field 2
shadow 2
field 3
shadow 3

Transactional Locking II (TL2)

- Best (or one of the best) performing STM
  - also other nice properties beyond the scope of this lecture
- Lock-based, word-based STM
  - locks only held during commit phase (not executing user code)
- Uses global version number (potential bottleneck)
  - updated by each writing transaction (but could relax this)
- Every location also has version number
  - transaction that last wrote it

Transactional Locking II (TL2)

- Read global version counter
  - store locally: rv (for read version)
- Run transaction “speculatively”
  - track which locations are read and written
  - when location first accessed, check version counter
  - write values into write set
  - read values into read set (so transaction gets consistent reads)
    - if value was written by transaction, get value from write set
- At commit
  - lock write set
  - increment global version counter
  - validate read set
  - write-back values
  - release locks

Combining hardware and software

- Hardware-assisted transactional memory
  - new required hardware
  - hardware support can accelerate implementation
- Hybrid transactional memory
  - STM that can work with HTM
    - hardware transactions and software transactions must “play nicely”
    - can be used now (with no hardware support)
    - can exploit HTM support with little change
  - phased transactional memory
    - can switch dynamically between using STM and HTM

Shared memory vs networks

- Network algorithm to shared memory algorithm
  - "implement" network using shared memory
  - easy because shared memory is "stronger" than network
  - useful primarily for lower bounds (e.g., impossibility of consensus)
- Shared memory algorithm to network algorithm
  - "implement" shared memory over network (DSM)
  - easy if no failures
  - impossible if more than n/2 failures
  - Attiya-BarNoy-Dolev fault-tolerant algorithm
- Replicated state machine over network
  - Paxos

Network on shared memory

- State variables for each i (written by i)
  - $pstate_i$: states(P_i)
  - $sent(j)_i$ for each out-neighbor j: sequence of M, initially empty
  - $msgs\text{-}rcvd(i)_j$ for each in-neighbor j: **N**, initially 0
- Transitions for i
  - $send(m,j)_i$:
    - pre: $send(m)_{i,j}$ in $pstate_i$
    - eff: append m to $sent(j)_i$; update $pstate_i$ as for $send(m)_{i,j}$
  - $receive(m,j)_i$
    - pre: $|sent(i)_j| > msgs\text{-}rcvd(j)_i$; $m = sent(i)_j[msgs\text{-}rcvd(j)_i+1]$
    - eff: increment $msgs\text{-}rcvd(j)_i$; update $pstate_i$ as for $receive(m)_{j,i}$
  - all others: precondition/effect as in P_i with state $pstate_i$

Network on shared memory

- Impossibility of consensus on network
  - with reliable FIFO channels
  - with reliable broadcast
    - similar transformation

Shared memory over network

- Assume shared memory system A
  - n ports; user U_i for i = 1..n interacts with process i on port i
  - for each i, either user's turn, or process's turn (not both)
    - so we can use atomic objects instead of shared variables
- Design asynchronous network system B
  - same ports/user interface
  - execs of B are indistiguishable (to users) from execs of A
    - and same processes fail (if applicable)
- Non-fault-tolerant strategies: single-copy, multiple copy
- Impossibility of tolerating majority failures
- ABD fault-tolerant algorithm for read/write registers

Single-copy DSM

- Each shared variable is “owned” by some process
  - owner(X) known by all
  - handle each shared variable independently
- All actions other than shared-memory access as before
- To invoke op on X, send “inv(op,X)” to owner(X)
  - wait for response
  - continue to handle invocation msgs received
- Each process applies operations in order received
  - send response of each operation to appropriate process

Single-copy DSM

- Can implement any shared variable type
- Location of shared variables
- Elimination of busy-waiting
  - send “condition” to owner
  - works for multiple variables if they have the same owner
- Process stopping means no access to variables it owns

Multicopy DSM

- Goal: improve performance of read
  - maintain several copies
  - can be good if reading is more common than writing
  - still no fault tolerance
- Concern: “coherence” problems
  - inconsistency among various copies
  - problem even for single-writer shared variables
- Use transactions to maintain coherence
- See book for more details

Impossibility of n/2-fault-tolerance

- Theorem: In asynchronous reliable broadcast model with n = m+p processes, no implementation of m-writer p-reader atomic registers guarantees f-failure termination for f ≥ n/2.
- Proof: (same structure for many proofs against n/2-fault-tolerance)
  - Partition processes into two halves (each with size at most f)
    - some writer w in first half, some reader r in second half
  - Consider
    - α_w: fair exec starting with $write_w(1)$, all processes in second half fail
    - α_r: fair exec starting with $read_r$, all processes in first half fail
  - By f-failure-termination each must get a response (read gets 0)
    - Do α_w upto response, then α_r up to response, without failures and delaying all messages between two halves.
  - Violates atomicity because read comes after write but gets 0

ABD algorithm

- Implements atomic single-writer multireader register
- Tolerates $f < n/2$ stopping faults
- Assume reliable channels

ABD algorithm

STATE VARIABLES per process
val: V, initially v_0
tag: **N**, initially 0
readtag: **N**, initially 0
lots of "bookkeeping" variables

WRITER
on write(v)
  (val,tag) := (v,tag+1)
  send "write(val,tag)" to all readers
    - wait for ack from majority
  return ack

READERS
on receiving "write(v,t)" from writer
 if t > tag then
    (val,tag) := (v,t)
  send "write-ack(t)" to writer

READERS
on read
  readtag := readtag+1
  send "read(readtag)" to all other processes
    - wait for ack from majority
  let t be largest tag received
  if t > tag then (val,tag) := (v,t)
    where v is value received with t
  send "propagate(val,tag,readtag)" to all readers
    - wait for ack from majority
  return val

ALL PROCESSES
on receiving "read(rt)" from $_j$
  send "read-ack(val,tag,rt)" to j

READERS
on receiving "propagate(v,t)" from j
  if t > tag then (val,tag) := (v,t)
  send "prop-ack(t)" to j

ABD algorithm

- Correctness
  - well-formedness
  - f-failure-termination
  - atomicity
    - linearization point of write with tag t
      - when majority of processes have tag ≥ t
      - may linearize multiple writes at same point
    - linearization point of read returning value associated with tag t
      - immediately after linearization point of write with tag t, or
      - immediately after invocation of read, (why do we need this?)
      - whichever is later
    - book uses partial order method

ABD algorithm

- What kind of channels are required?
  - reliable?
  - nonduplicating?
  - FIFO?
  - Byzantine?
- What kind of faults are tolerated?
  - stopping?
  - omission?
  - Byzantine?

Agreement in asynchronous networks

- Impossible to reach agreement in asynchronous networks, even if we know that at most one failure will occur.
- But what if we really need to?
  - For transaction commit.
  - For agreeing on order of operations to perform.
  - …
- Some possibilities:
  - Randomized algorithm (Ben-Or), terminates with high probability.
  - Approximate agreement.
  - Use a failure detector service, implemented by timeouts.
- Best strategy:
  - Guarantee agreement, validity in all cases.
  - Guarantee termination only if the system eventually “stabilizes”:
    - Failures, recoveries stop.
    - Timing of messages, process steps within known “normal” bounds.
  - Actually, stable behavior need not continue forever, just long enough for termination to occur.

Eventually stable approach

- [Dwork, Lynch, Stockmeyer] first to present an algorithm with these properties.
- [Lamport, Part-Time Parliament]
  - Introduced the Paxos algorithm.
  - Relationship with [DLS]:
    - Achieves similar guarantees.
    - Paxos allows more concurrency, tolerates more kinds of failures.
    - Basic strategy for assuring safety similar to [DLS].
  - Background:
    - Paper unpublished for 10 years because of nonstandard style.
    - Eventually published “as is”, because others began recognizing its importance and building on its ideas.

Paxos consensus protocol

- Called “Single-Decree Synod” protocol.
- Assumptions:
  - Asynchronous processes, stopping failures, also recovery.
  - Messages may be lost.
- Paper also describes how to cope with crashes, where volatile memory is lost in a crash (skip this).
- We’ll present in two stages:
  - Describe a very nondeterministic algorithm that guarantees the safety properties (agreement, validity).
  - Constrain this to get termination soon after stabilization.

The nondeterministic “safe” algorithm: Ballots

- Uses ballots, each of which represents an attempt to reach consensus.
- Ballot = (id, value) pair.
  - id $\in$ BId, a totally ordered set of ballot identifiers.
  - Value in $V \cup \{ \perp \}$, where V is the consensus domain.
- Somehow, ballots get started, and get values assigned to them.
- Processes can vote for, or abstain from, particular ballots.
  - Abstention from a ballot is a promise never to vote for it.

The safe algorithm: Quorums

- The fate of a ballot depends on the actions of quorums of processes on that ballot.
- Quorum configuration:
  - A set of read-quorums, finite subsets of process index set I.
  - A set of write-quorums, finite subsets of I, such that
  - R ∩ W nonempty for every read-quorum R and write-quorum W.
- Generalization of majorities.
- Ballot becomes dead if every node in some read-quorum abstains from it.
- A ballot can succeed only if every node in a write-quorum votes for it.

Safe algorithm, centralized version

- Anyone can create a new ballot with id b:
  - make-ballot(b)
  - provided no ballot with id b has yet been created.
  - val(b) is set to $\perp$.
- A process i can abstain, in one step, from an entire set of ballots:
  - abstain(B,i), $B \subseteq BId$
  - provided i has not previously voted for any ballot in B.
  - B may be any set of ballot ids, not necessarily associated with already-created ballots.
    - For example, B = all ballot ids in some range $[b_{min}, b_{max}]$.
    - This will be important in the algorithm…

Safe algorithm, centralized version

- Anyone can assign a value v to a ballot id b, assign-val(b,v), provided:
  - A ballot with id = b has been created.
  - val(b) is undefined.
  - v is someone's consensus input.
    - ** For every b' < b, either val(b') = v or b' is dead.
- Recall: b' dead means read-quorum R has abstained from b'.
- Refers to every b' ∈ BId, not just created ones.
  - relies on "set abstentions".
- Thus, we can assign a value to a ballot b only if we know it won't make b conflict with lower-numbered ballots b'.
- Motivation:
  - several ballots can be created, collect votes.
  - more than one might succeed in collecting a write quorum of votes.
  - but we don't want successful ballots to conflict.

Next time

- Continue Paxos algorithm
- Self-stabilization
- Reading:
  - Lamport: Part-Time Parliament
  - Dijkstra paper on self-stabilization
  - Dolev book on self-stabilization, Chapter 2