Fachhochschule Nordwestschweiz

Software Transactional Memory (STM)

- Motivation
- ScalaSTM
- Implementation

The state of the art in concurrent programming

```
public void transfer(Account from, Account to, double amount)
                                throws InactiveException, OverdrawException {
    Account x, y;
    if (from.getNumber().compareTo(to.getNumber()) < 0) {
        x = from; y = to;
    } else {
        x = to; y = from;
    }
    synchronized (x) {
        synchronized (y) {
            from.withdraw(amount);
            try {
                to.deposit(amount);
            } catch (InactiveException e) {
                from.deposit(amount);
                throw e;
            }
        }
    }
}
```

Software Transactional Memory (STM)

- **Declaratively express what to do atomically, not how to do it!**

```
def transfer(from: Account, to: Account, amount: Double): Unit = {
  atomic { implicit tx =>
    from.withdraw(amount)
    to.deposit(amount)
  }
}
```

Software Transactional Memory (STM)

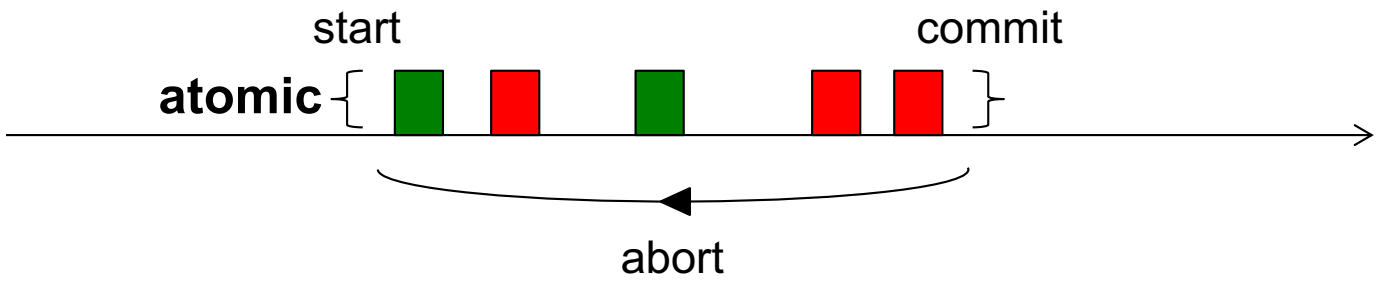
- **Coordination mechanism for shared memory concurrency**
- **Coordinates access to heap locations (as opposed to db tx)**

A transaction is

- **a sequence of read and write operations to shared memory**
- **which occurs logically at a single instant in time**
- **whereby intermediate states are not visible to other transactions**

Semantics of a transaction:
- **A**tomic: All or nothing
- **C**onsistent: Preserves invariants (programmers responsibility)
- **I**solation: No interference with concurrent txs

Optimistic Concurrency Control



1. **Begin transaction**
2. **Tentative state changes during execution**
3. **Conflict encountered?**
   - **Yes: Abort and retry**
   - **No: Commit, make changes permanent and visible**

Atomics: Single Reference Transactions

```
class Account {
    @volatile
    private bal: Int = 0;

    def deposit(amount: Int): Unit = {
        while (true) {
            val oldBal = bal;                // read current value
            val newBal = oldBal + amount; // compute new value
            if (compareAndSet(addr(bal), oldBal, newBal)) {
                return; // commit successful -> return
            }
            // conflict -> retry
        }
    }

    def withdraw(int amount): Unit = {/* analogous to deposit */}
}
```

STM: Multi Reference Transactions

```
public class STMConceptually {
   public void atomicTransfer(double amount,
                              Account from, Account to) {
      while(true) {
         int oldFromBal = from.bal;
         int newFromBal = oldFromBal - amount;

         int oldToBal = to.bal;
         int newToBal = oldToBal + amount;

         if(STM.multiCAS(addr(from.bal), oldFromBal, newFromBal,
                         addr(to.bal)  , oldToBal  , newToBal)) {
            return;
         }
         // retry
      }
   }
}
```

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ScalaSTM: Ref-s and atomic

- **ScalaSTM consists of two fundamental parts**
  - **Ref**: Mutable cell (wrapper), access is coordinated by the STM system

```
val as = Ref(Map[String, Account]()) /* Factory */
```

  - **atomic**: Executes the given function within a transaction

```
def atomic[Z](block: InTxn => Z): Z  /* simplified */
```

- **Example**

```
private val bal: Ref[Double] = Ref(0.0)

def withdraw(a: Double) {
  atomic { implicit tx => bal.set(bal.get - a) }
}
```

- **API: http://nbronson.github.io/scala-stm/**

ScalaSTM: Ref

- **A Ref is a mutable reference to immutable state**
  - Access to referenced state is coordinated by STM system

Refs have to be the only mutable abstraction within a program

- **Creation**

```
val ref = Ref[Type](initValue)
```

- **Read**

```
val insideRef = ref() | val insideRef = ref.get
```

- **Write**

```
ref() = newValue      | ref.set(newValue)
```

- **Transform**

```
ref.transform(insideRef => f(insideRef))
```

(read|write|transform) compile only within an atomic block!

ScalaSTM: atomic

- **atomic takes a function and executes it transactionally**

```
import scala.concurrent.stm._

atomic {
  implicit txn => code
}
```

context: `implicit txn`

Code block: `code`

- **The function takes a parameter of type InTxn**
  - This parameter
    - provides a context for the transaction (consumed by Ref accessors)
    - has to be marked implicit

ScalaSTM: Single Operation Transactions

- **Ref.View provides convenient single operation transactions**

```
val ref: Ref[Int] = Ref(1)
val refView: Ref.View[Int] = ref.single
```

- **Mental model**

```
val ref = Ref(1)
ref.single.operation(args)
```

acts like

```
val ref = Ref(1)
atomic{ implicit tx =>
  ref.operation(args)
}
```

- **Example**

```
val ref = Ref(1)
ref.single.set(2)
```

acts like

```
val ref = Ref(1)
atomic{ implicit tx =>
  ref.set(2)
}
```

Atomic vs Synchronized

```
atomic { implicit txn =>
  doA(); doB()
}
```

- delimits a transaction
- no explicit locking
- atomic to all other atomic blocks executed by another thread
- no deadlocks are possible
- composable

```
mutex.synchronized {
  doA(); doB()
}
```

- delimits a critical section
- acquires a specific lock
- atomic to other synchronized blocks that acquire the same lock
- nested synchronized blocks may deadlock
- not composable

Non composability of locks

```
class LockAccount(val id: Int) {
  private var balance = 0d

  def withdraw(a: Double) {
    synchronized {
      balance = balance - a
    }
  }
  def deposit(a: Double) {
    synchronized {
      balance = balance + a
    }
  }
}
```

```
class LockBank {
  def transfer(amount: Double,
   from: LockAccount, to: LockAccount) {

    val (fst, snd) =
      if(from.id > to.id) (from,to)
      else (to,from)

    fst.synchronized {
      snd.synchronized {
        from.withdraw(amount)
        to.deposit(amount)
      }
    }
  }
}
```

- **LockBank must know locking convention of Account**
- **Account must expose internals to be reusable**

Composability of atomic

```
class STMAccount(val id: Int) {
  private val balance = Ref(0d)

  def withdraw(a: Double) {
    atomic { implicit txn =>
      balance() = balance() – a
    }
  }
  def deposit(a: Double) {
    atomic { implicit txn =>
      balance() = balance() + a
    }
  }
}
```

```
class STMBank {

def transfer(amount: Double,
   from: STMAccount, to: STMAccount) {
    atomic { implicit txn =>
      to.deposit(amount)
      from.withdraw(amount)
    }
  }
}
```

- **STMBank knows nothing about internals of STMAccount**
- **Composable tx propagation strategy:**
  - **When arriving at an atomic block: Check if tx is already running:**

    Yes: join existing tx

    No: start new tx

Atomicity and Exceptions

```
atomic { implicit txn =>
  to.deposit(amount)
  from.withdraw(amount)
}
```

- **Atomicity makes error recovery easy**

```
def withdraw(amount: Double) {
  if(amount < 0) throw new IllegalArgumentException
  atomic { implicit txn =>
    if(!active()) throw new InactiveException
    if(balance() - amount < 0) throw new OverdrawException
    balance.transform(b => b - amount)
  }
}
```

- **If an exception is raised inside an atomic block**
  - it may be caught inside the atomic block, that's ok
  - if it is not caught, rollback and re-throw
- **Because of atomicity, changes are rolled back in case of an exception, no need to cleanup**

Lifecycle callbacks

- **Txn.afterCommit(handler: Status => Unit)**
  - Executed after a successful commit
  - Used for side effects which should only happen once

```
def transfer(from: STMAccount, to: STMAccount, amount: Double) {
  atomic { implicit txn =>
    to.deposit(amount)
    from.withdraw(amount)
    Txn.afterCommit { _ =>  sendMail(to.email, "You've got $" + amount) }
  }
}
```

- **Txn.afterRollback(handler: Status => Unit)**
  - Executed after rollback
  - Used for compensating actions

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Transactional Locking II

Setup:

- **Global version counter: Stores version of latest successfully committed tx**
- **Local version stamp: Each Ref is marked with the version of the last successfully committed tx which modified this reference**

1. **Tx start: Store the value of the global version counter local to the new tx (read version [rv])**
2. **Tx body:**
   a. **Before first reading / writing a Ref, make a local working copy of it**
      - **Abort and retry if version(Ref) > read version (NOT ONLY ON FIRST ACCESS)**
   b. **Read and write only to local copy**
3. **Tx commit:**
   a. **Lock all modified Refs (use a timeout to avoid deadlocks)**
   b. **Increment global version counter, store copy local to transaction (write version [wv])**
   c. **Check all Refs again. Abort and retry if**
      - **version(Ref) > read version [rv]**
      - **accessed object is locked (currently updated)**
   d. **Write values and write version [wv] back to the modified Refs**
   e. **Release locks**

http://www.cs.tau.ac.il/~shanir/nir-pubs-web/Papers/Transactional_Locking.pdf

Commit time locking

atomic { withdraw(A,2); deposit(B,2); }

Tx0

global version | 6

A: bal=5 [3]

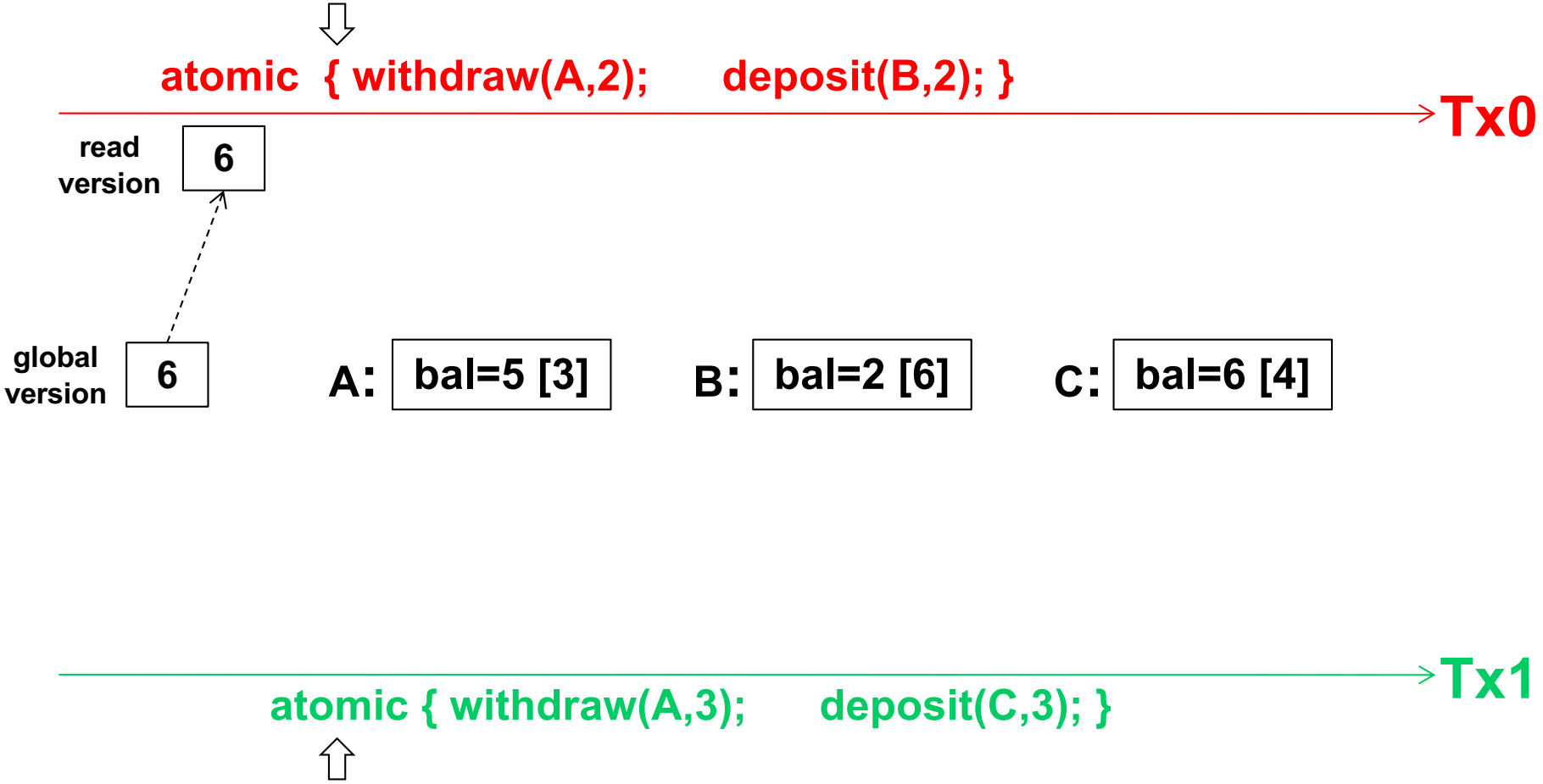
B: bal=2 [6]

C: bal=6 [4]

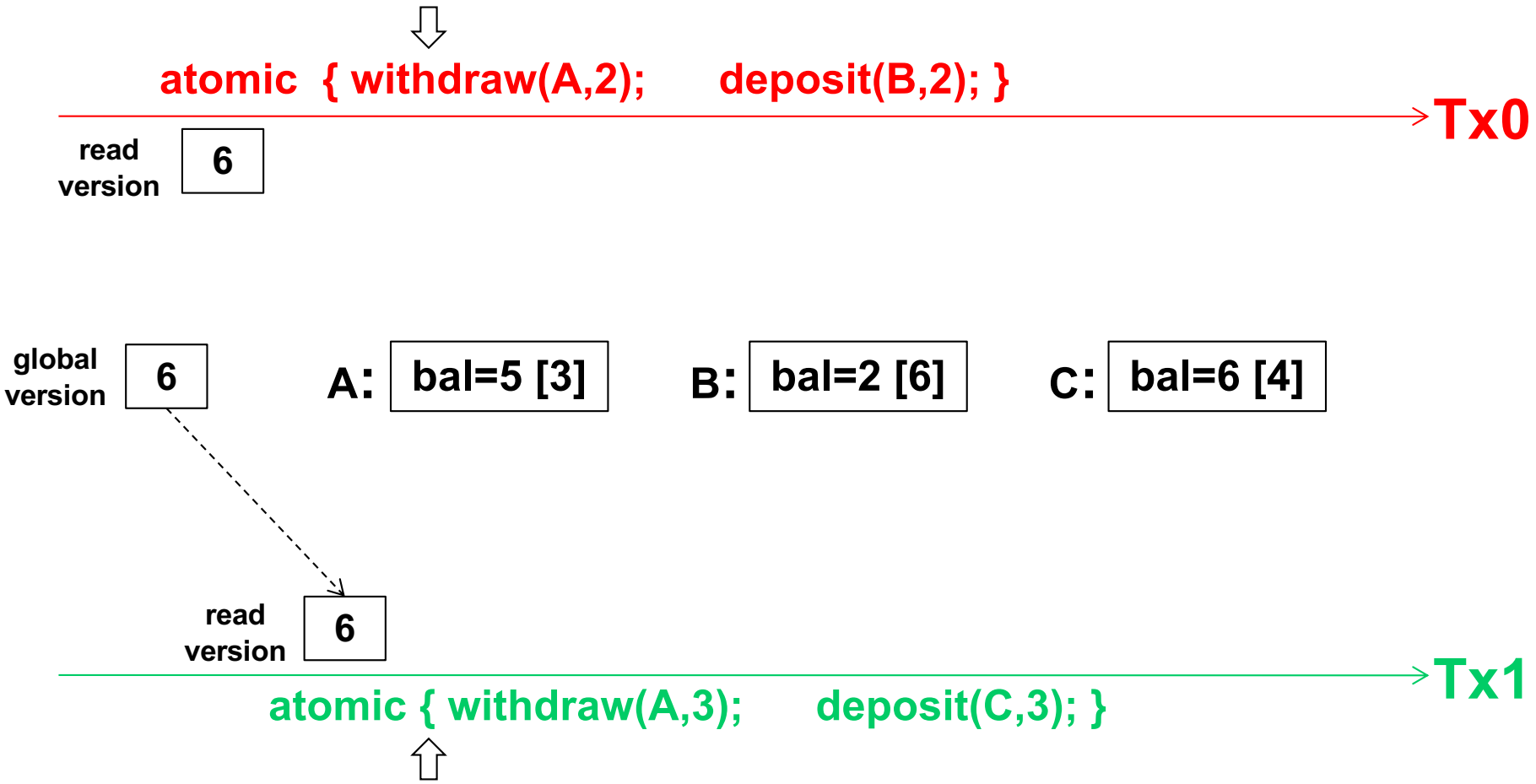
Tx1

atomic { withdraw(A,3); deposit(C,3); }

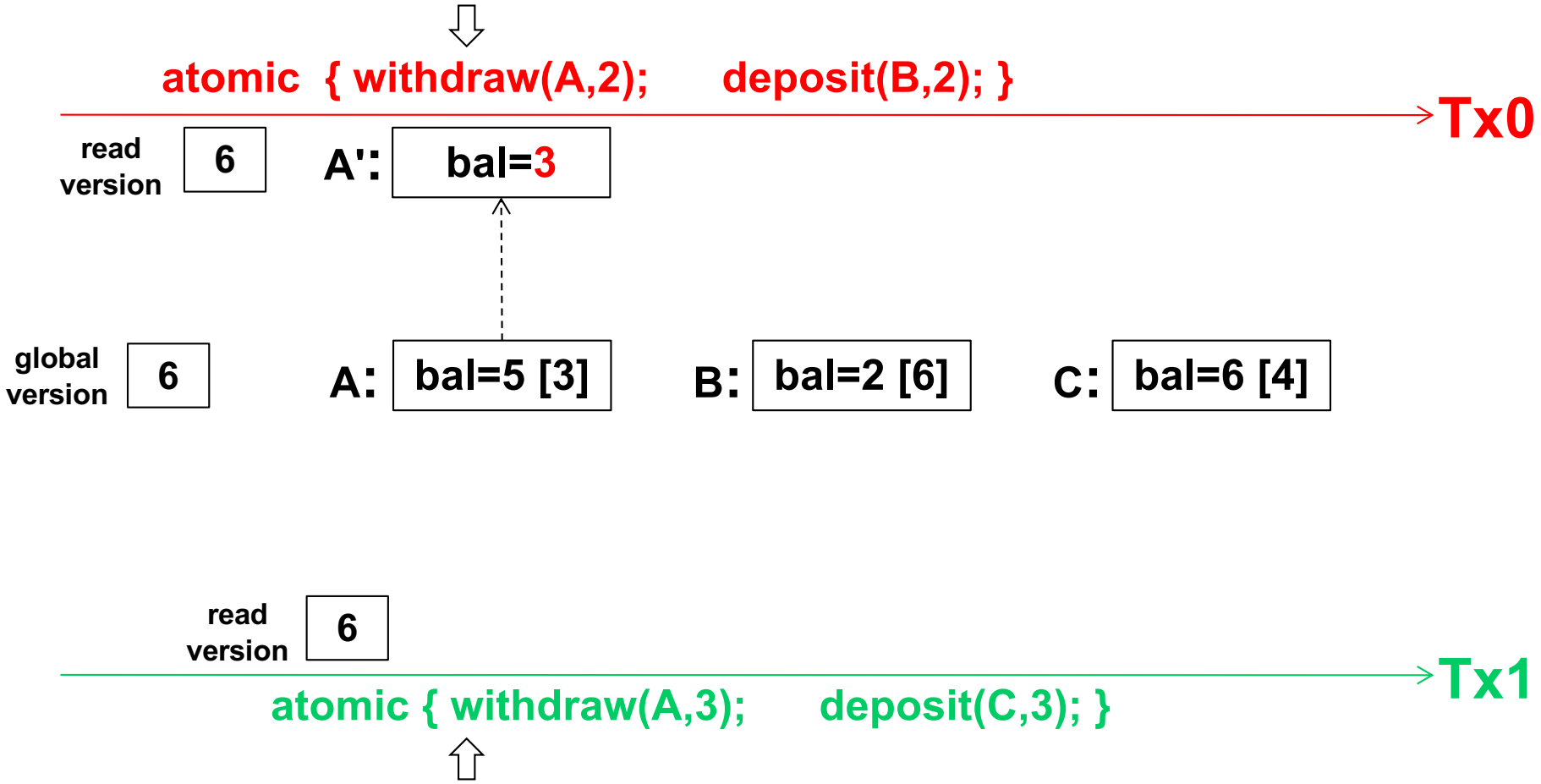
Commit time locking



Commit time locking



Commit time locking



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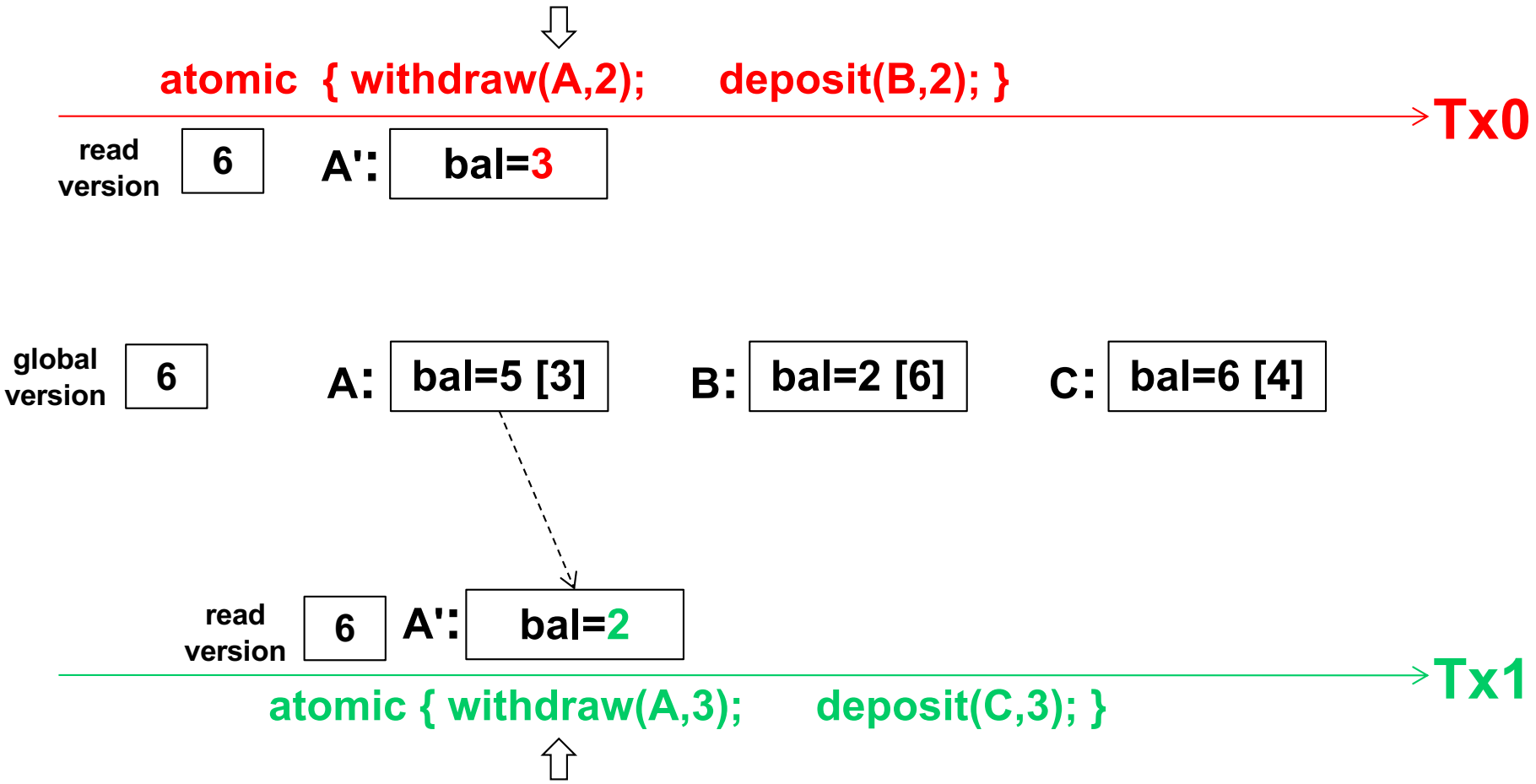

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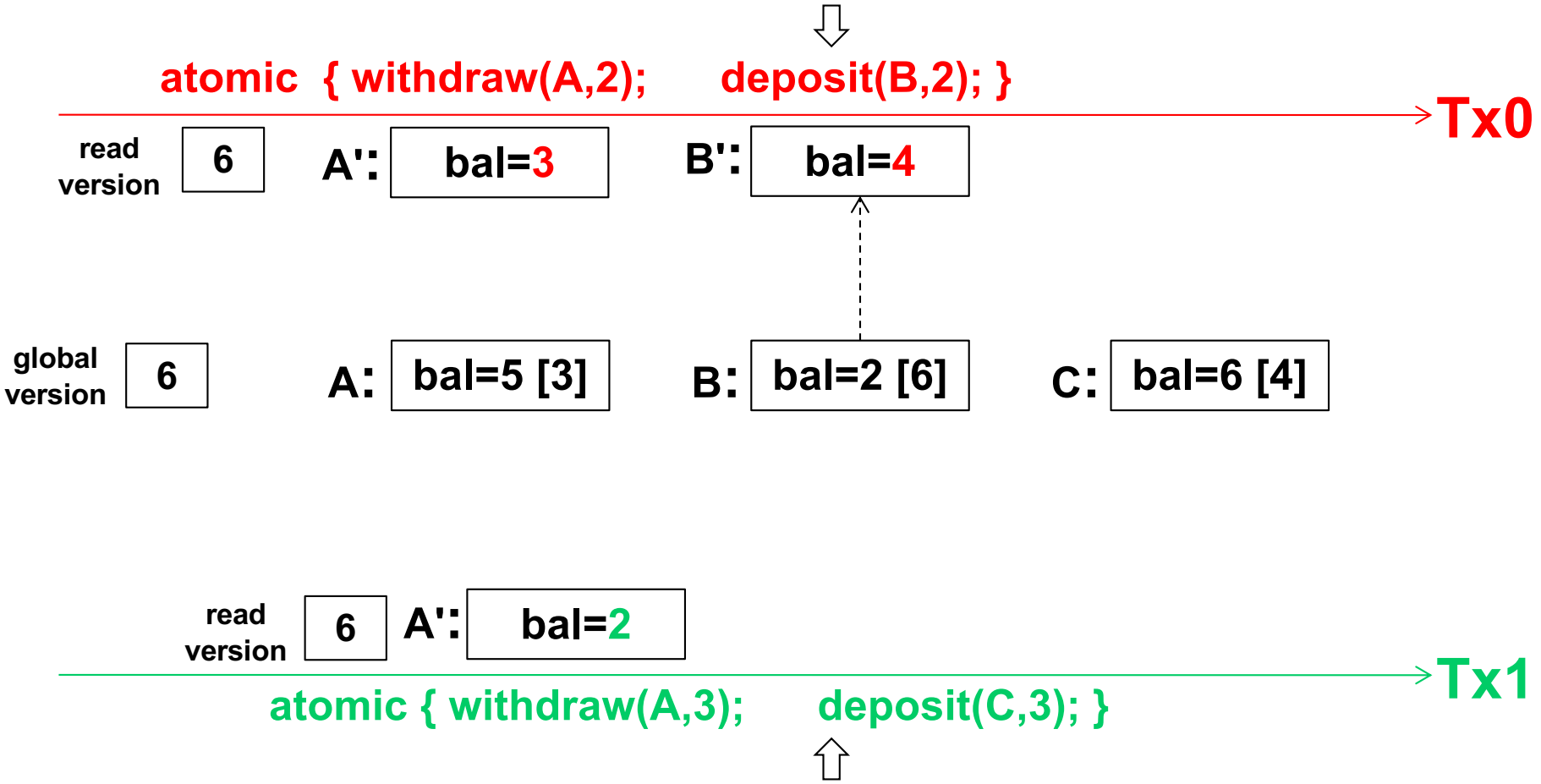

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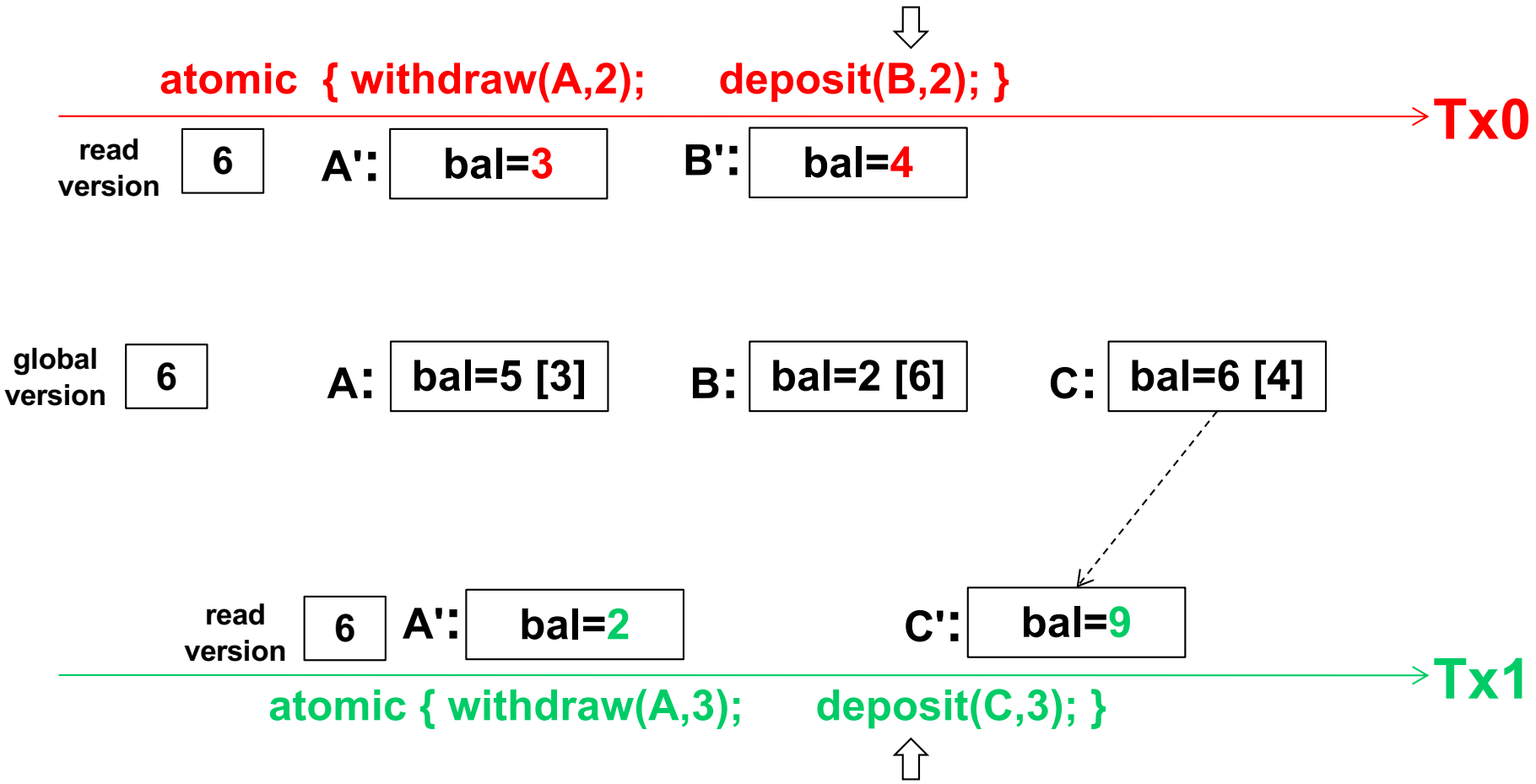

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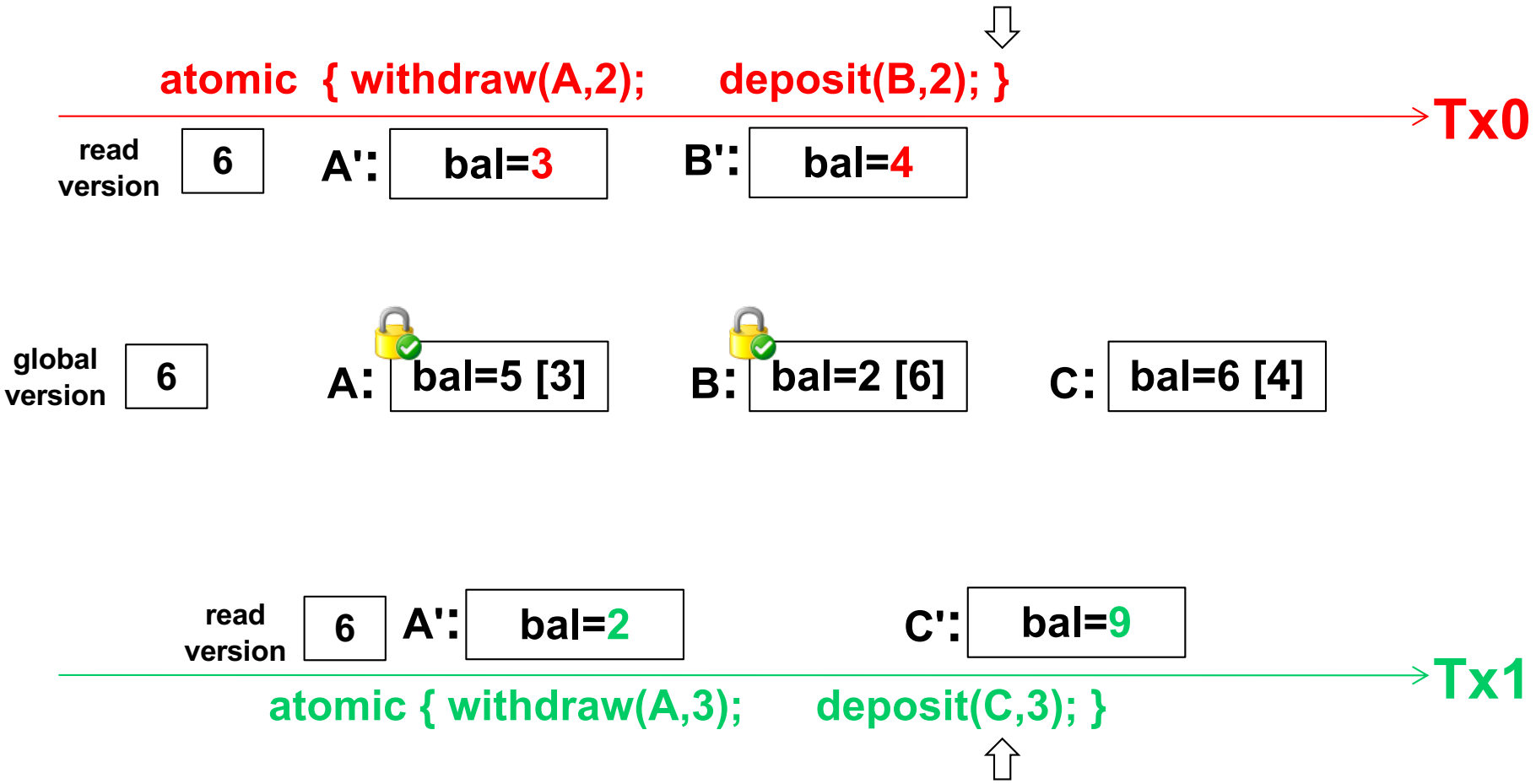

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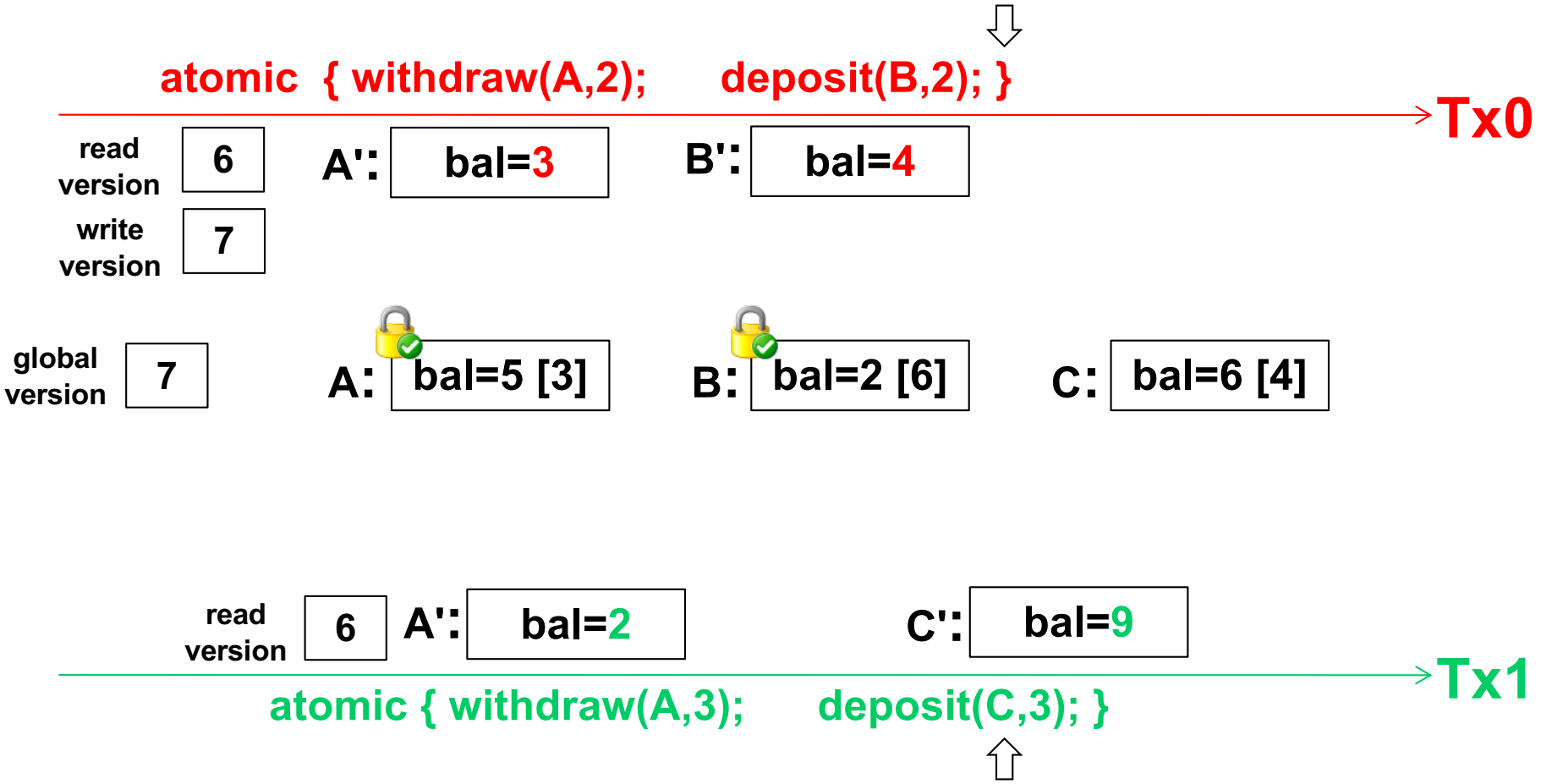

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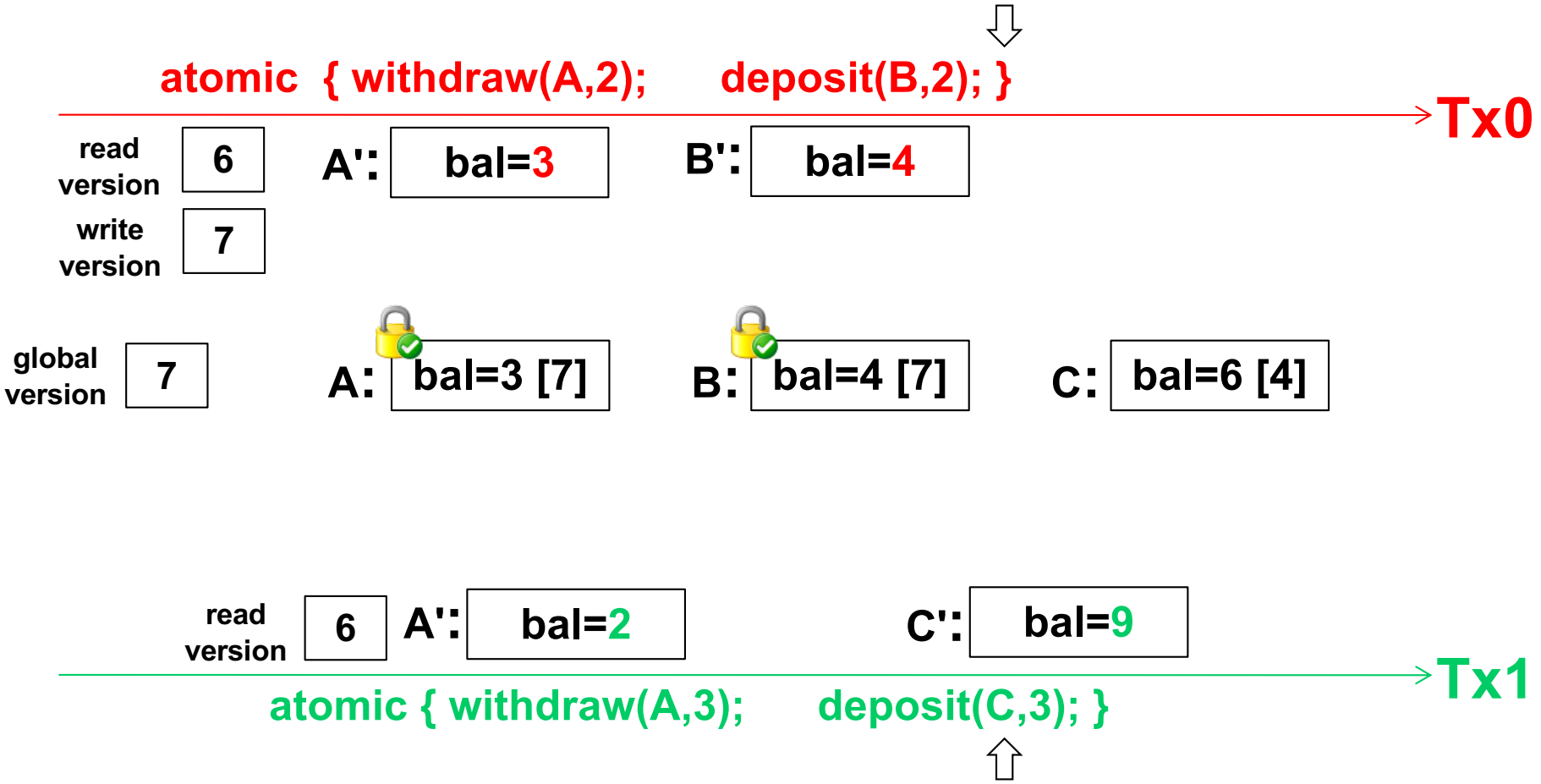

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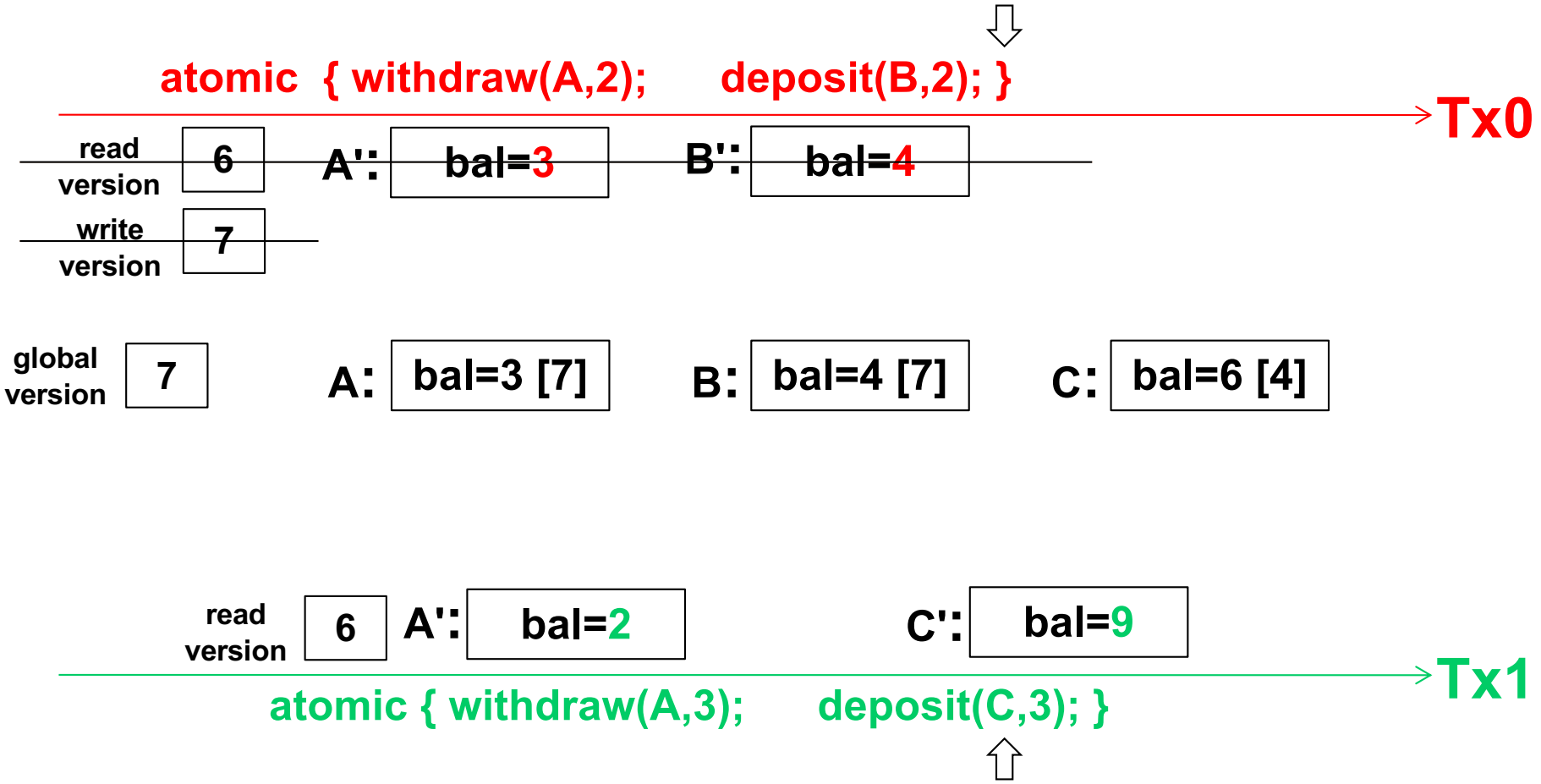

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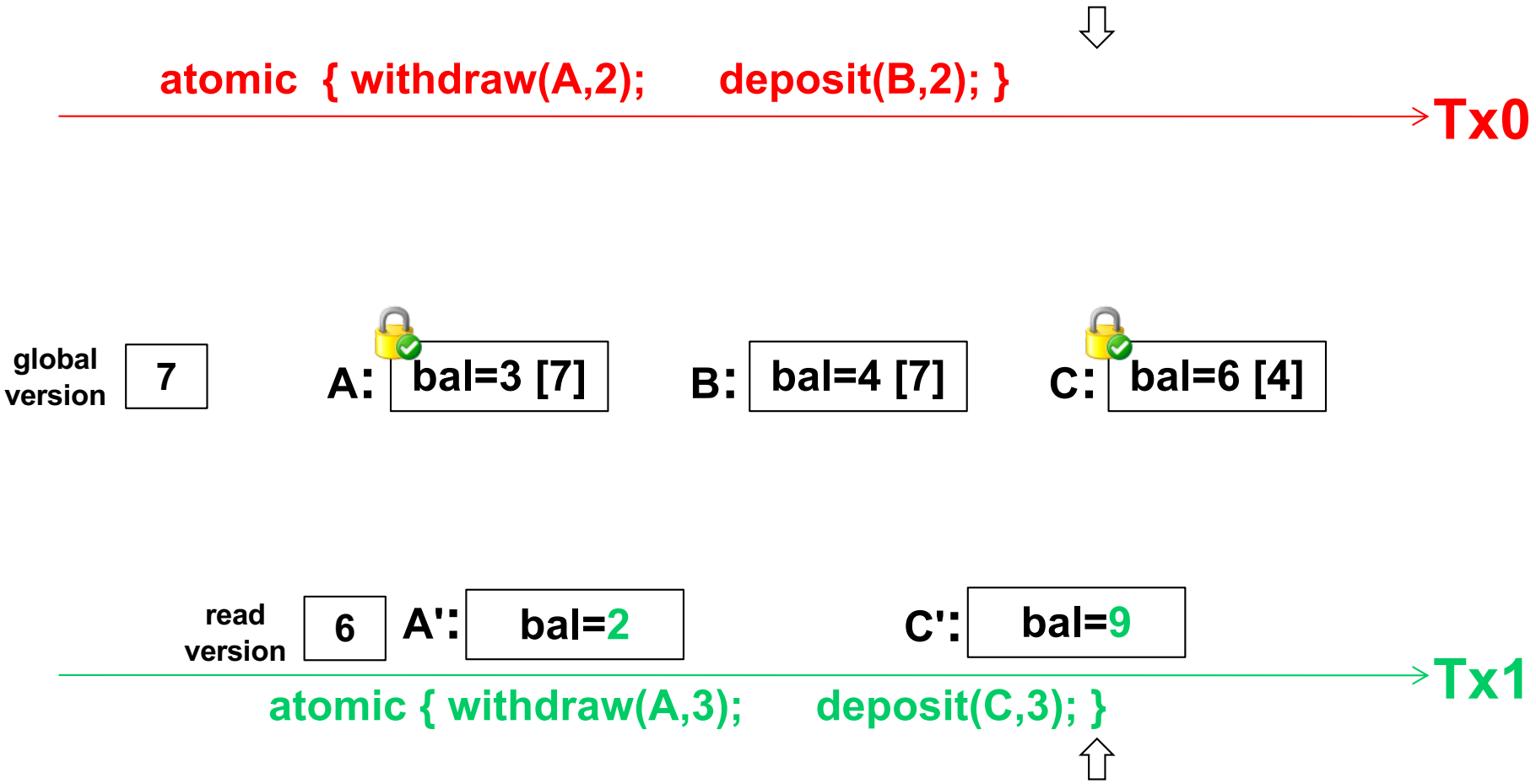

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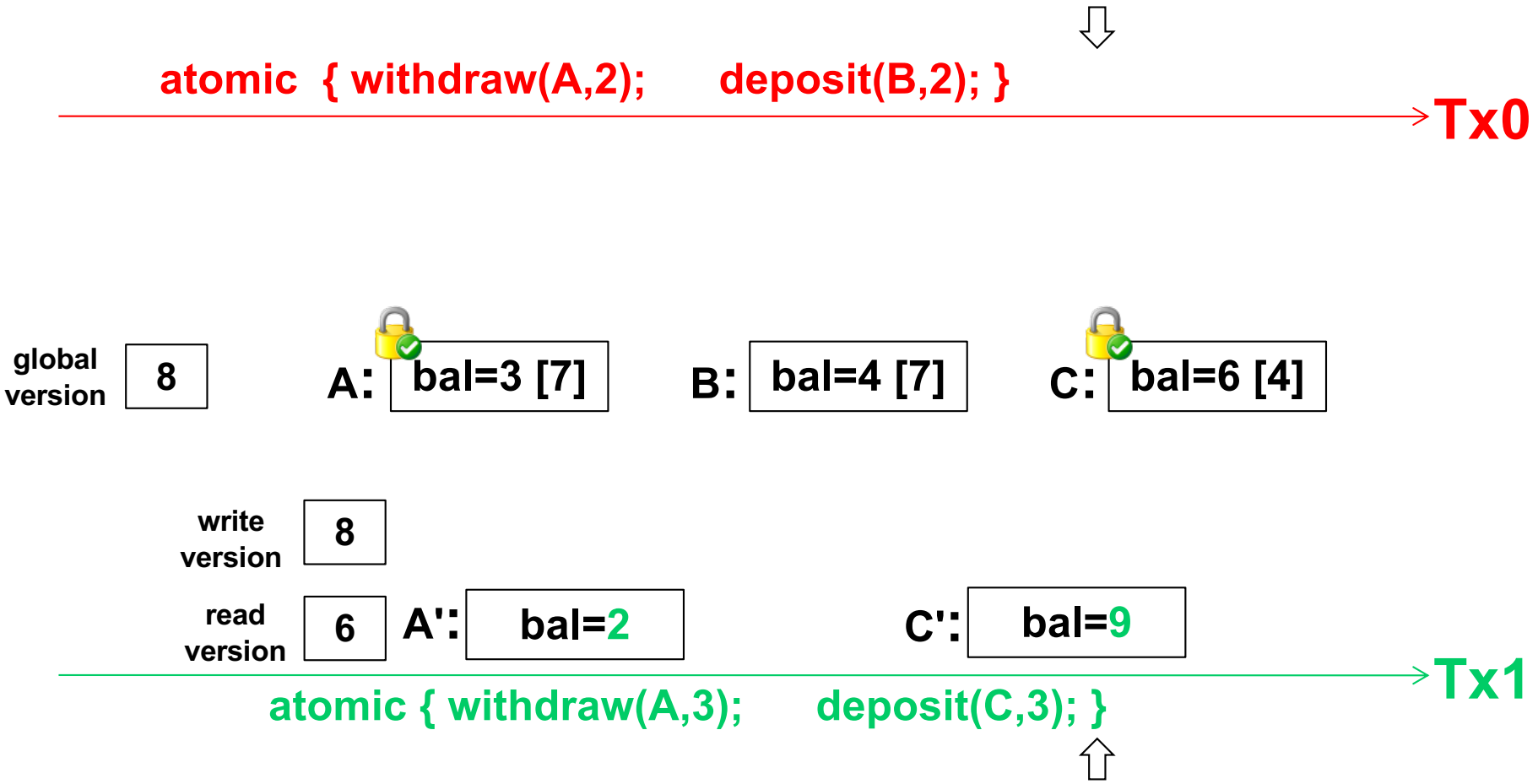

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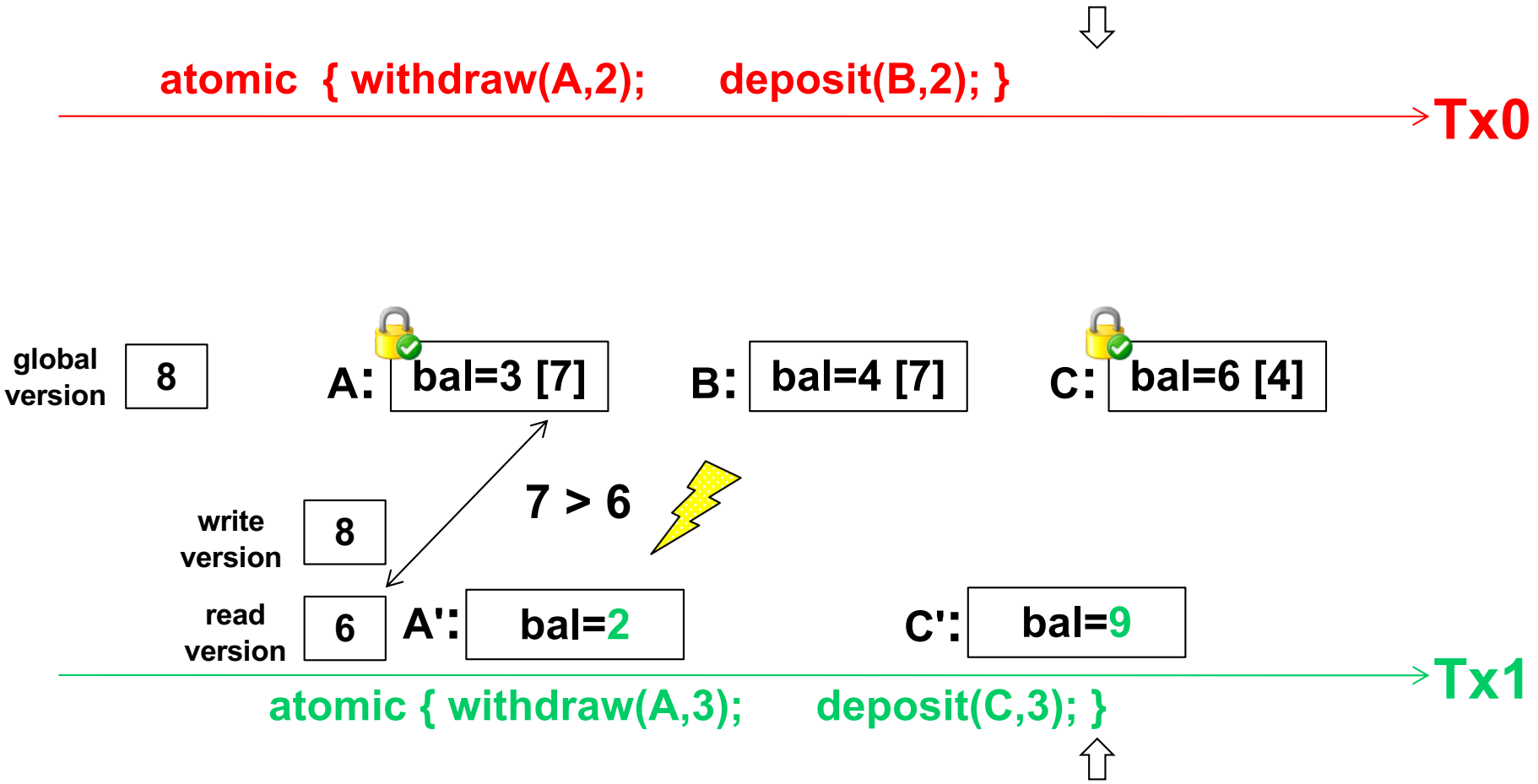

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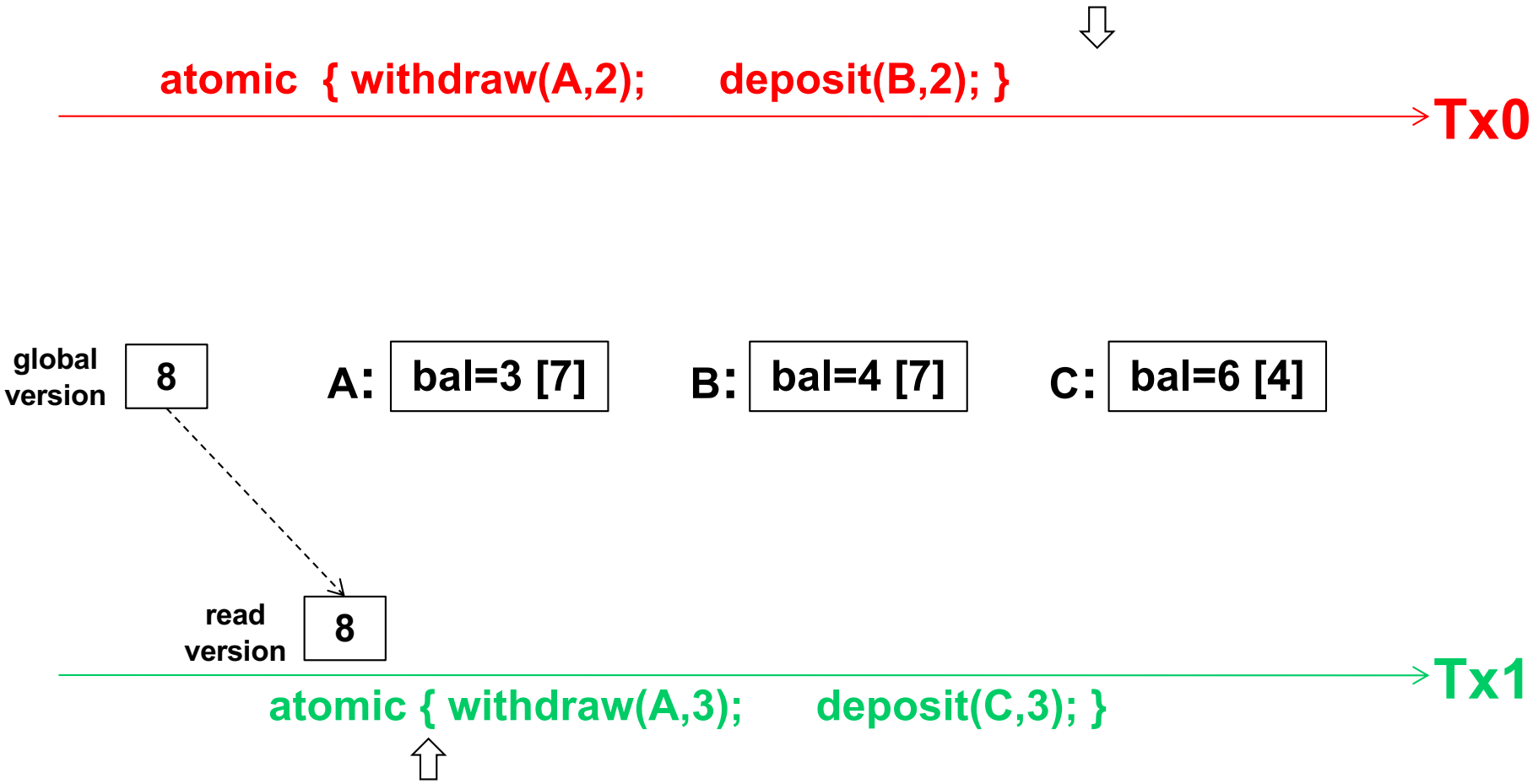

Summary: STM principles

- **A transaction is a sequence of steps executed by a single thread**
  - Atomic: All or nothing semantics
  - Consistent: Preserves invariants (programmers' responsibility)
  - Isolation: Changes made by concurrent transactions are invisible
- **Building blocks:**
  - atomic: delimits a transaction, atomics can be nested
  - Refs: mutable cells, managed by STM library

- **STM eliminates whole classes of low-level errors**
  - It's maybe a bit slower than lowlevel hacker code
  - But it's much easier to get right!