Transactional Memory

EPFL, LPD

STiDC'07, 10.XII 2007

How to Deal with Multi-Threading?

- Locks?
- Wait-free, atomic objects?
- Transactional memory (this lecture)

A Counter (not thread-safe)

```
public class Counter {
  private int c = 0;

  public void inc() {
    c := c + 1;
  }
  public int get() {
    return c;
  }
}
```

```
Counter cnt = new Counter();

cnt.inc();
k := cnt.get();
```

A Counter with Locks

```
public class Counter {
  ...
  synchronized
  public void inc() {
    c := c + 1;
  }
  synchronized
  public int get() {
    return c;
  }
}
```

```
Counter cnt = new Counter();

cnt.inc();
k := cnt.get();

synchronized(cnt) {
  cnt.inc();
  k := cnt.get();
}
```

Difficult Issues

How to atomically:

1. Fetch & increment 100 counters?
2. Fetch & increment a subset S of 100 counters?
3. Fetch & increment a counter and put the value in a synchronized hash table?
4. ...

Ideal Transactional Memory (1)

```
public class Counter {
  ...
  @Atomic
  public void inc() {
    c := c + 1;
  }
  @Atomic
  public int get() {
    return c;
  }
}
```

```
Counter cnt = new Counter();

cnt.inc();
k := cnt.get();
```

Ideal Transactional Memory (2)

```
@Atomic
public class Counter {
  ...
  public void inc() {
    c := c + 1;
  }

  public int get() {
    return c;
  }
}
```

```
Counter cnt = new Counter();
k := incAndGet();

...

@Atomic {
  cnt.inc();
  return cnt.get();
}
```

Multiple Counters

```
@Atomic {
  for(Counter cnt : counters) {
    k[i++] := cnt.get();
    cnt.inc();
  }
}
```

Many Objects

```
@Atomic {
  k := cnt.get();
  cnt.inc();
  table.put(k);
}
```

Implementing Transactional Memory

- In hardware (e.g., [Herlihy and Moss 93])
- In software (library, compiler, VM, etc.). Examples: DSTM ([Herlihy et al. 03]), TL2 ([Dice et al. 06])
- Hardware-software hybrids

Basic Idea

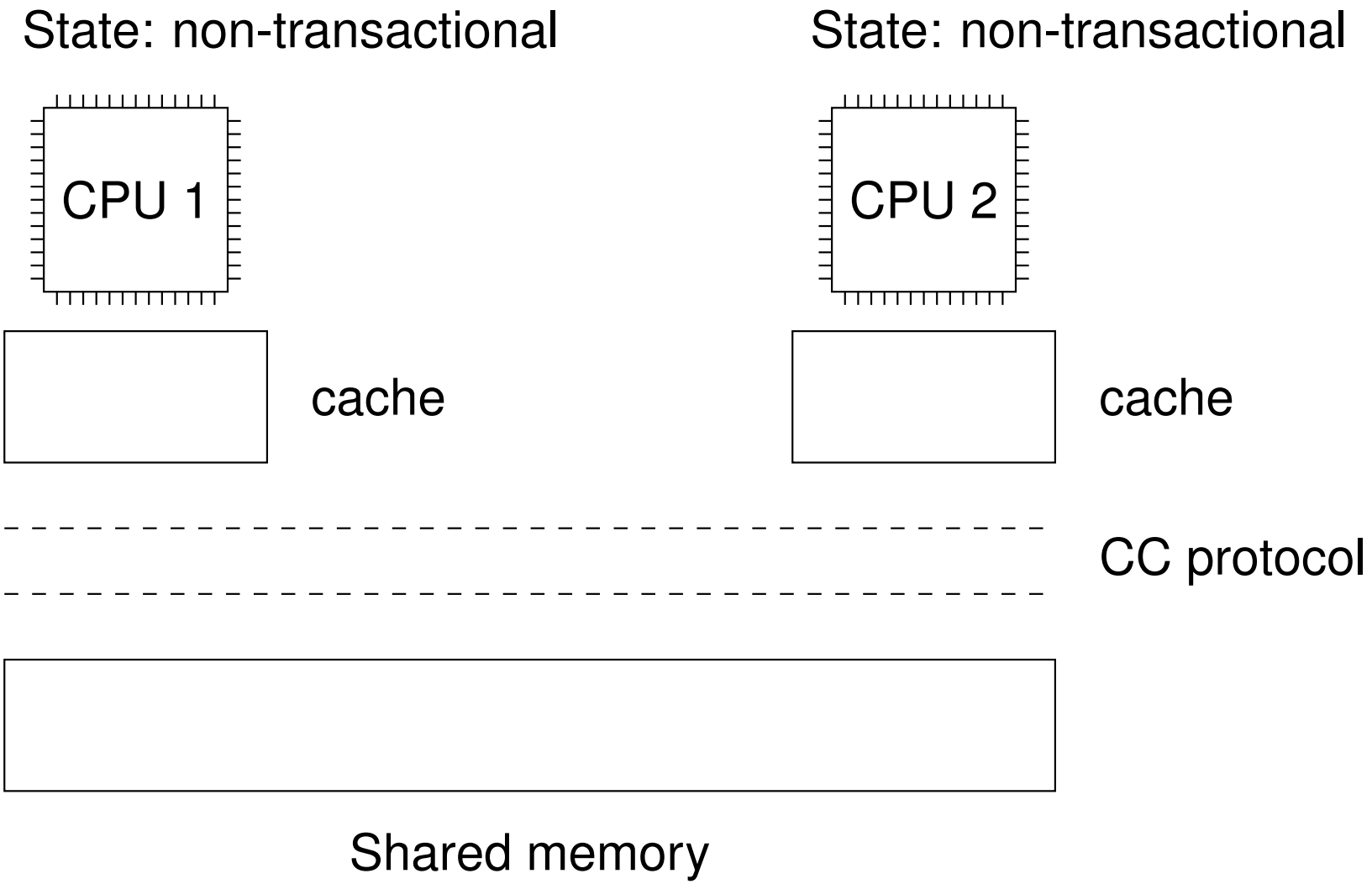
Atomicity = transactions do not observe any concurrency:

- Committed transactions: changes applied instantaneously
- Aborted transactions: changes never visible to others

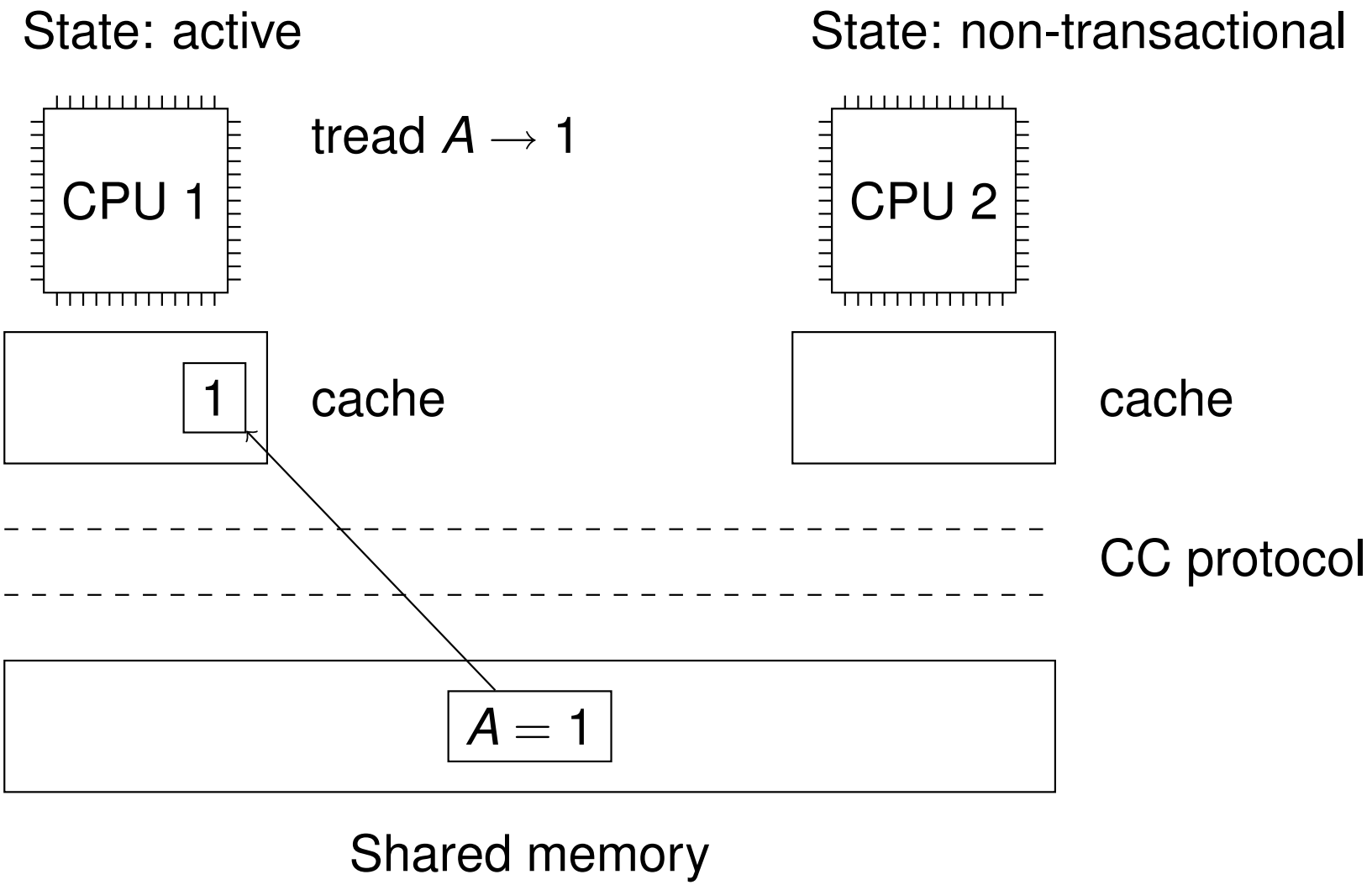
Possible implementation of transaction atomicity:

- Many transactions can read the same object
- Writing requires exclusive ownership
- Conflicts $\Rightarrow$ abort some transactions

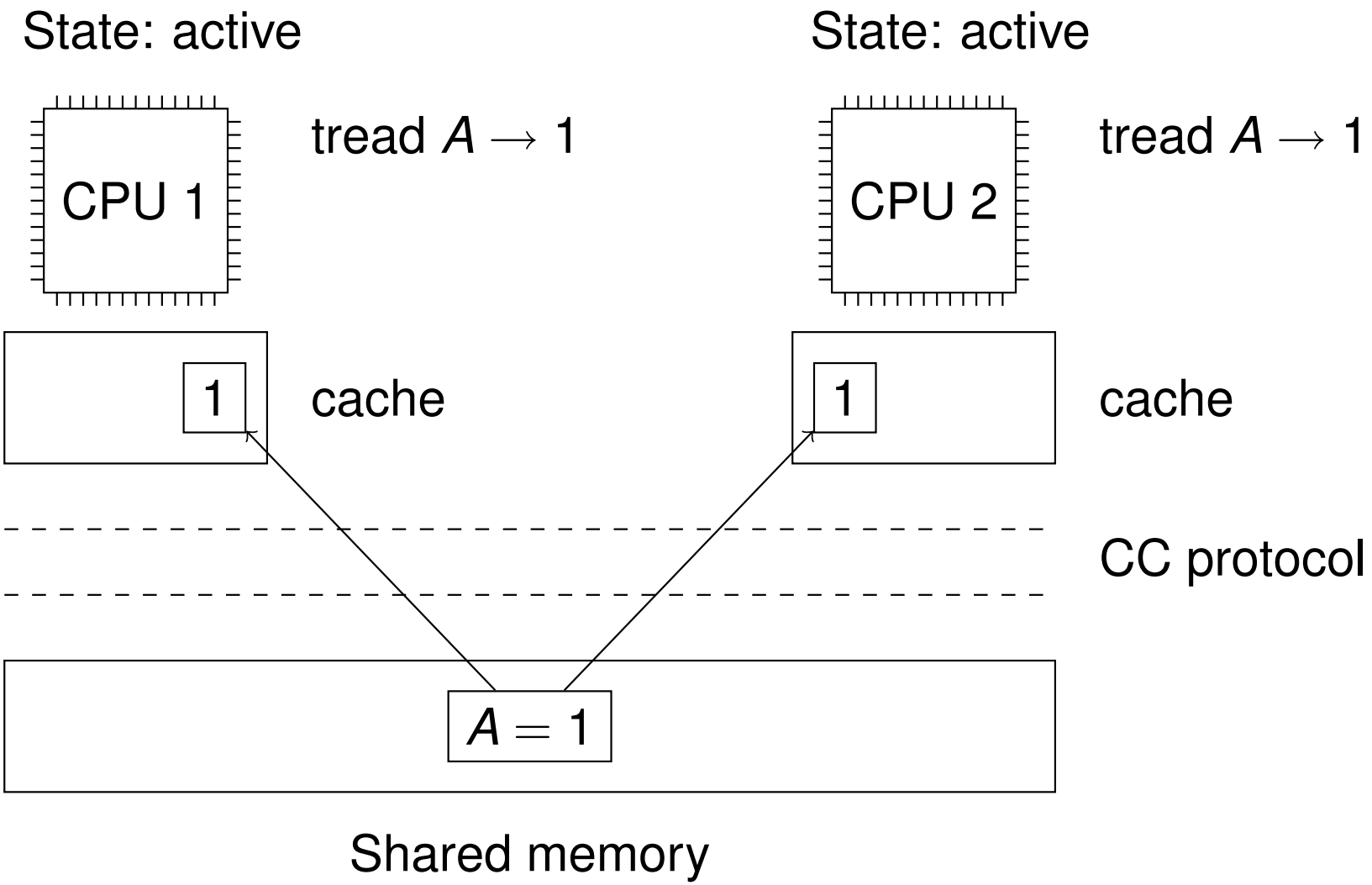
Hardware Transactional Memory



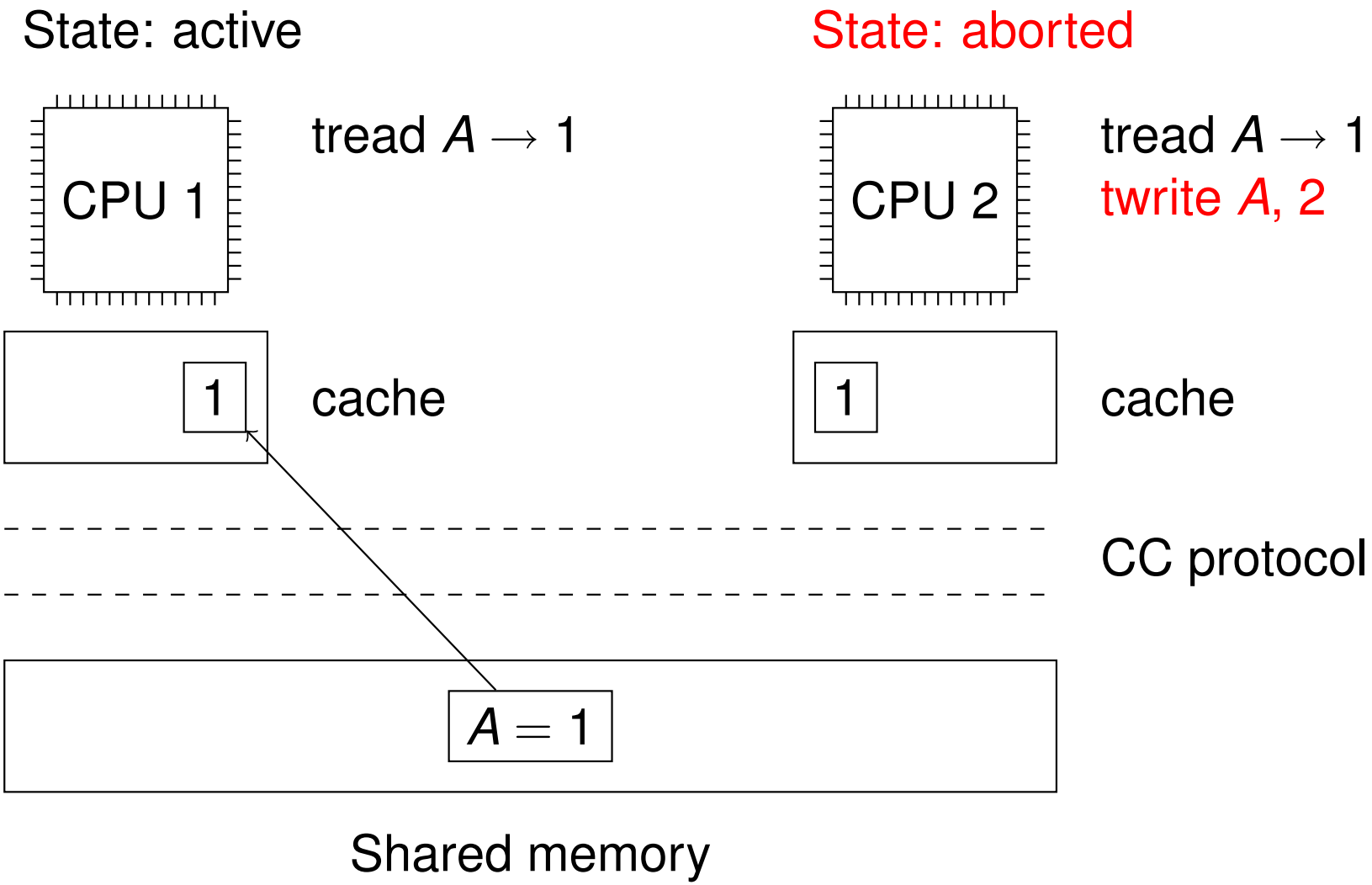
Hardware Transactional Memory



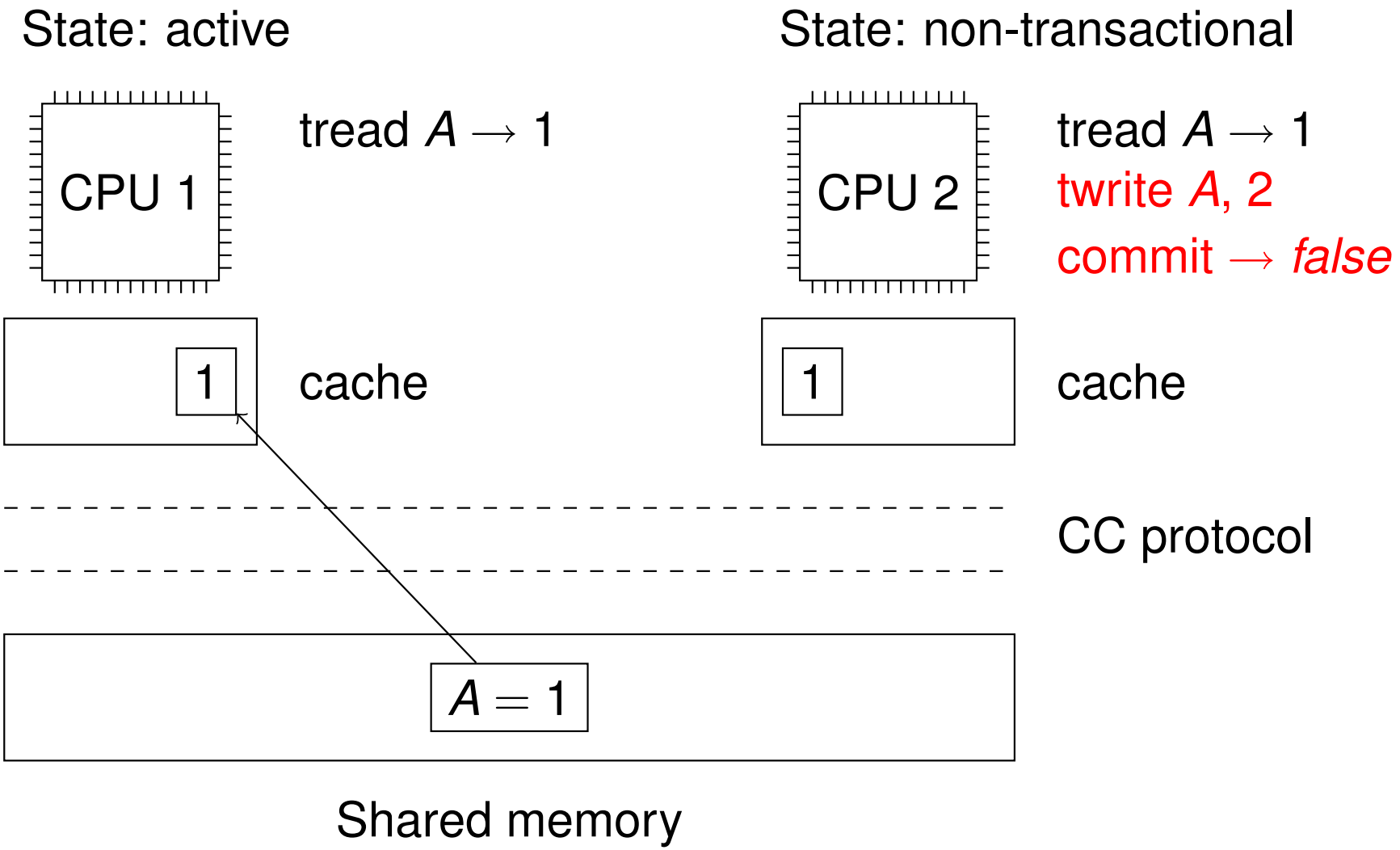
Hardware Transactional Memory



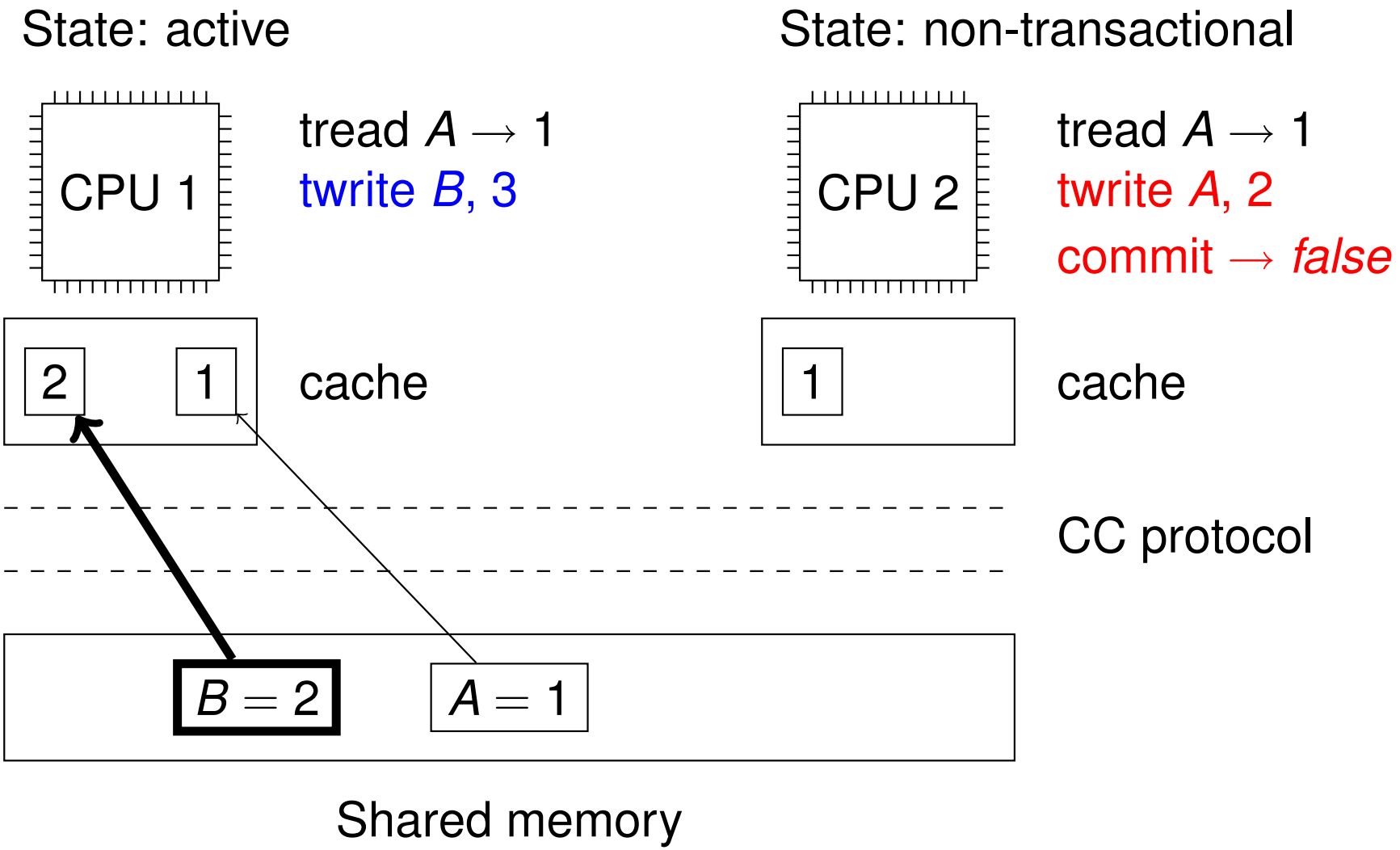
Hardware Transactional Memory



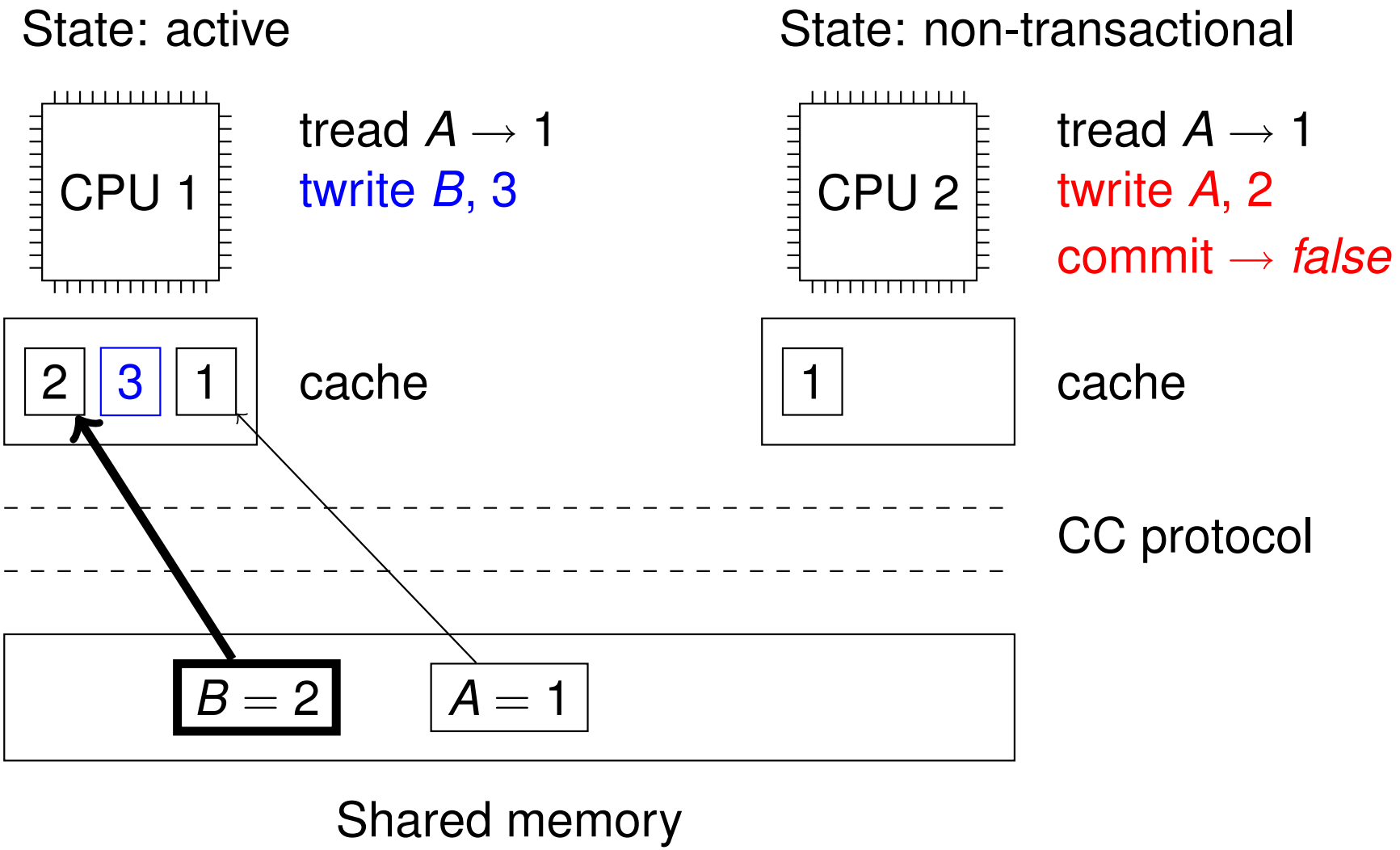
Hardware Transactional Memory



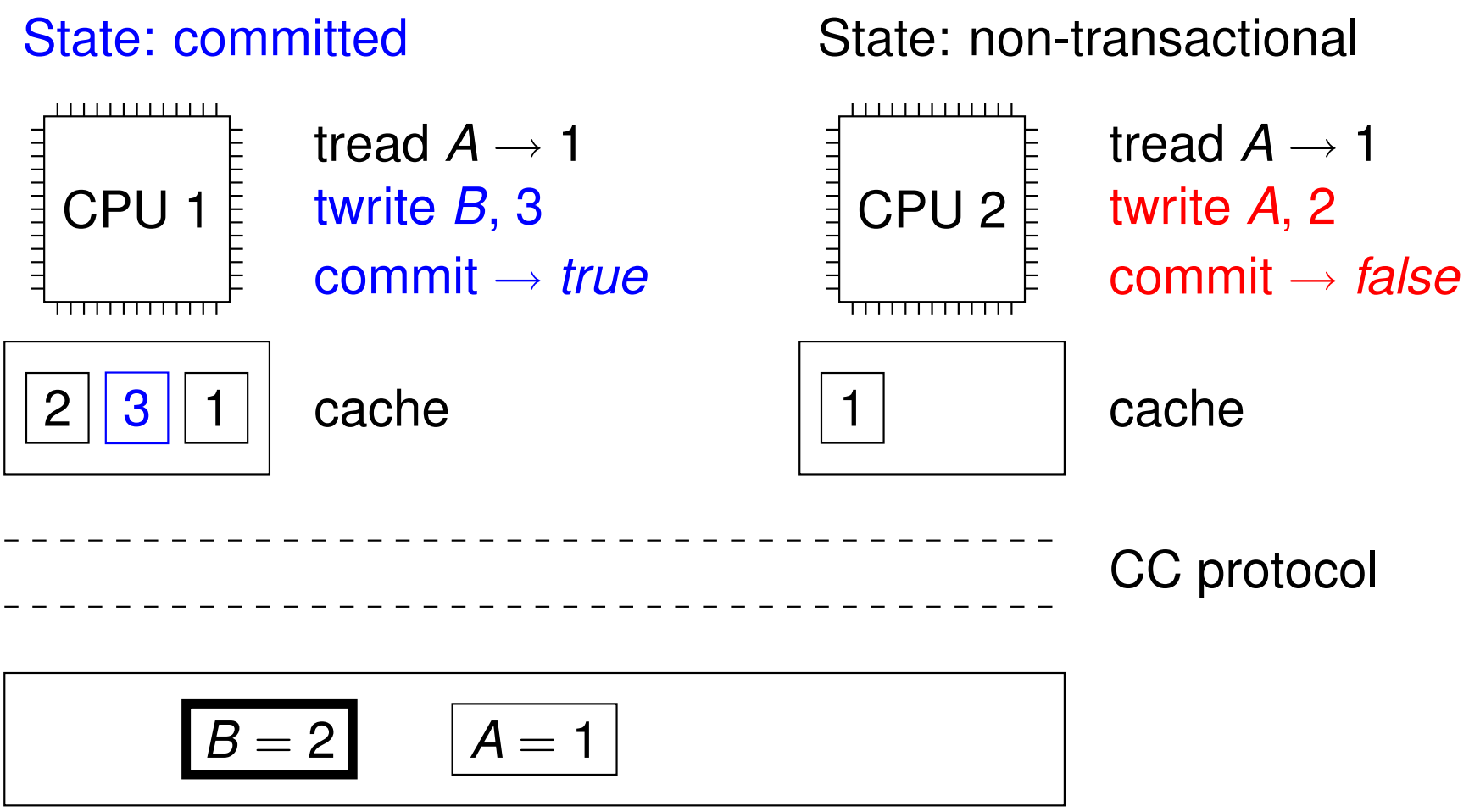
Hardware Transactional Memory



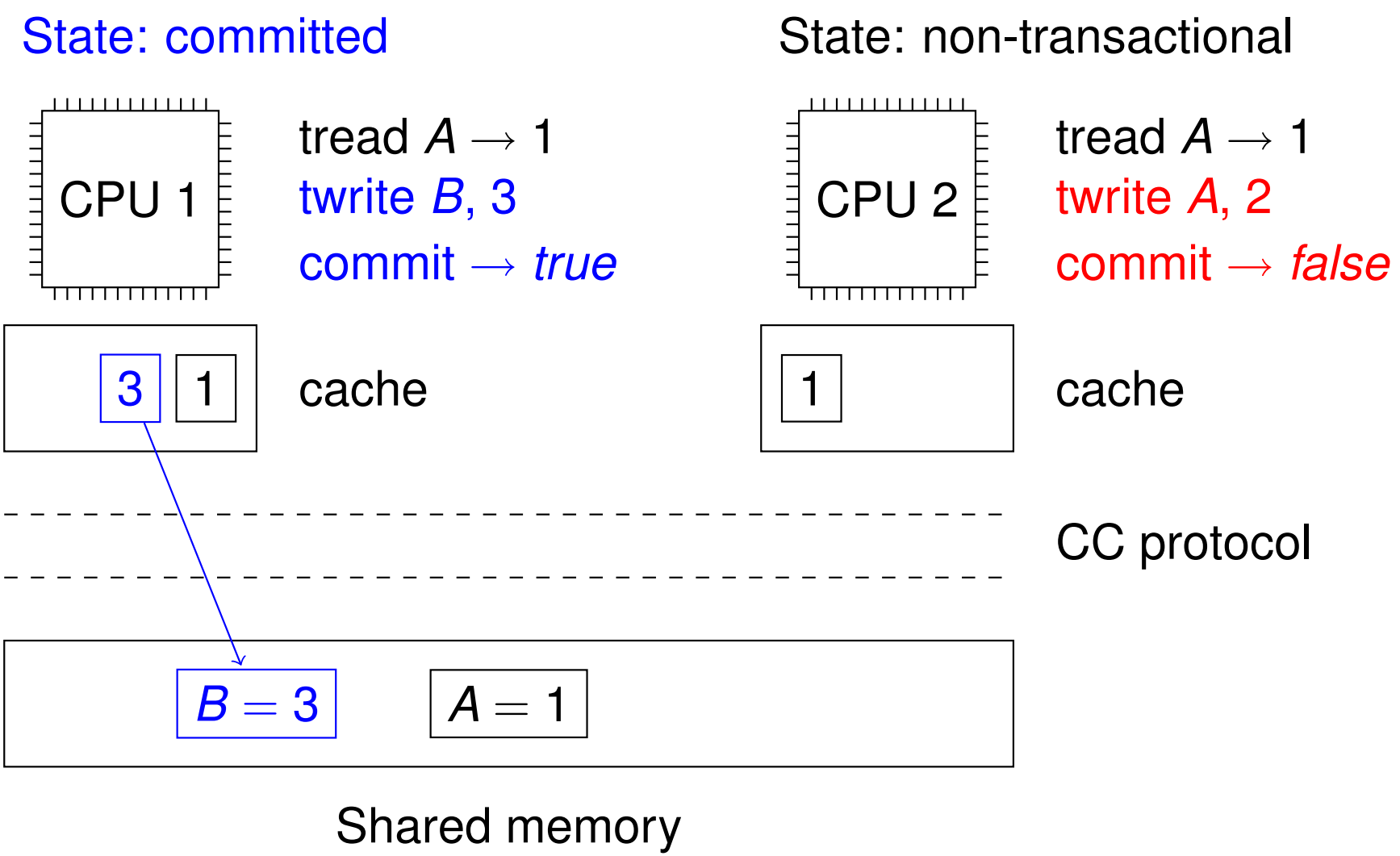
Hardware Transactional Memory



Hardware Transactional Memory

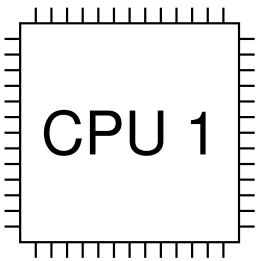


Hardware Transactional Memory

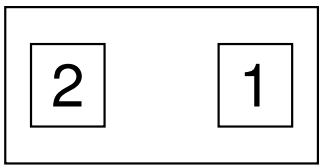


Hardware Transactional Memory

State: committed

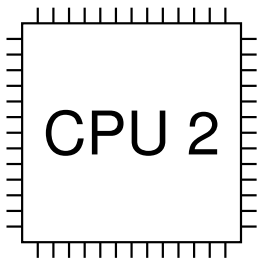


tread $A \rightarrow 1$
twrite B, 3
abort

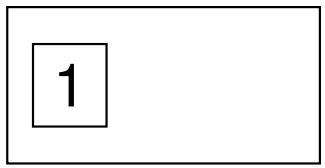


cache

State: non-transactional

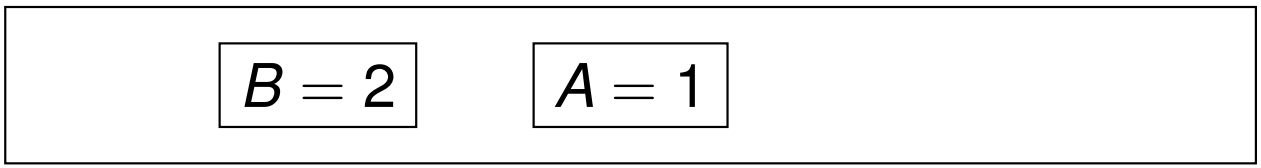


tread $A \rightarrow 1$
twrite A, 2
commit $\rightarrow$ *false*



cache

CC protocol



Shared memory

From Hardware TM to Software TM

Example: DSTM

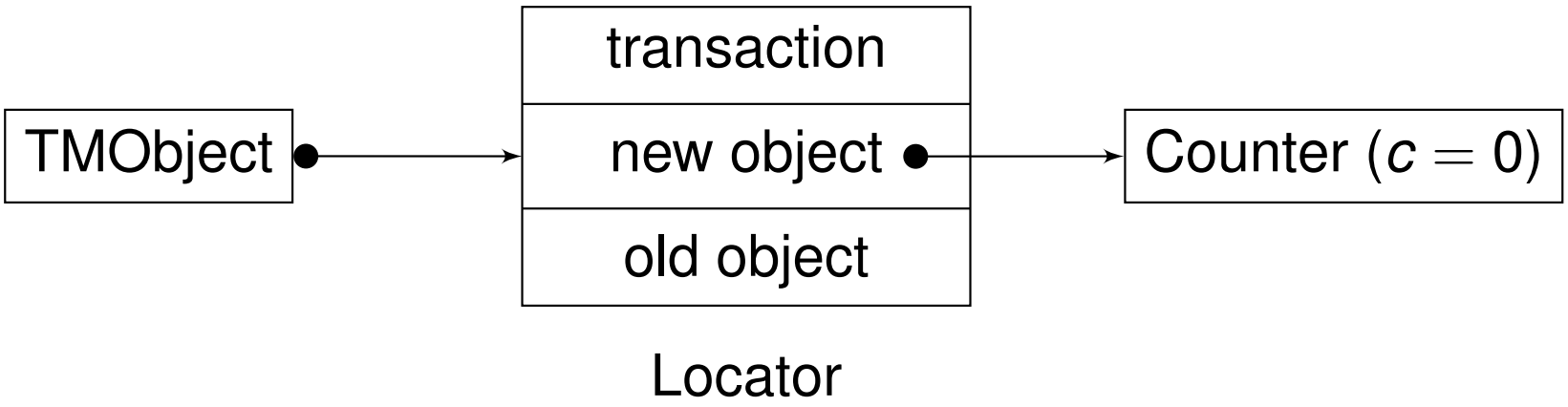
Thread-Safe Counter using DSTM

```
TMObject cnt = new TMObject(new Counter());

beginTransaction();
Counter tmp_cnt = cnt.openWrite();
tmp_cnt.inc();
boolean committed = commitTransaction();

beginTransaction();
tmp_cnt = cnt.openRead();
k := tmp_cnt.get();
committed = commitTransaction();
```

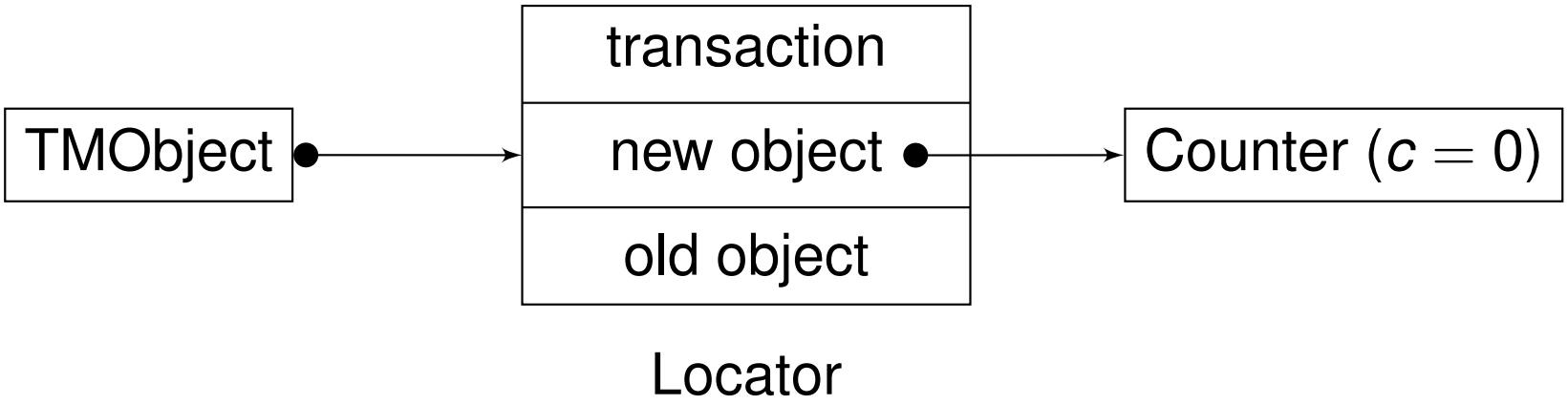
Thread-Safe Counter using DSTM

```
TMObject cnt = new TMObject(new Counter());

beginTransaction();
Counter tmp_cnt = cnt.openWrite();
tmp_cnt.inc();
k := tmp_cnt.get();
boolean committed = commitTransaction();
```

DSTM – The Idea

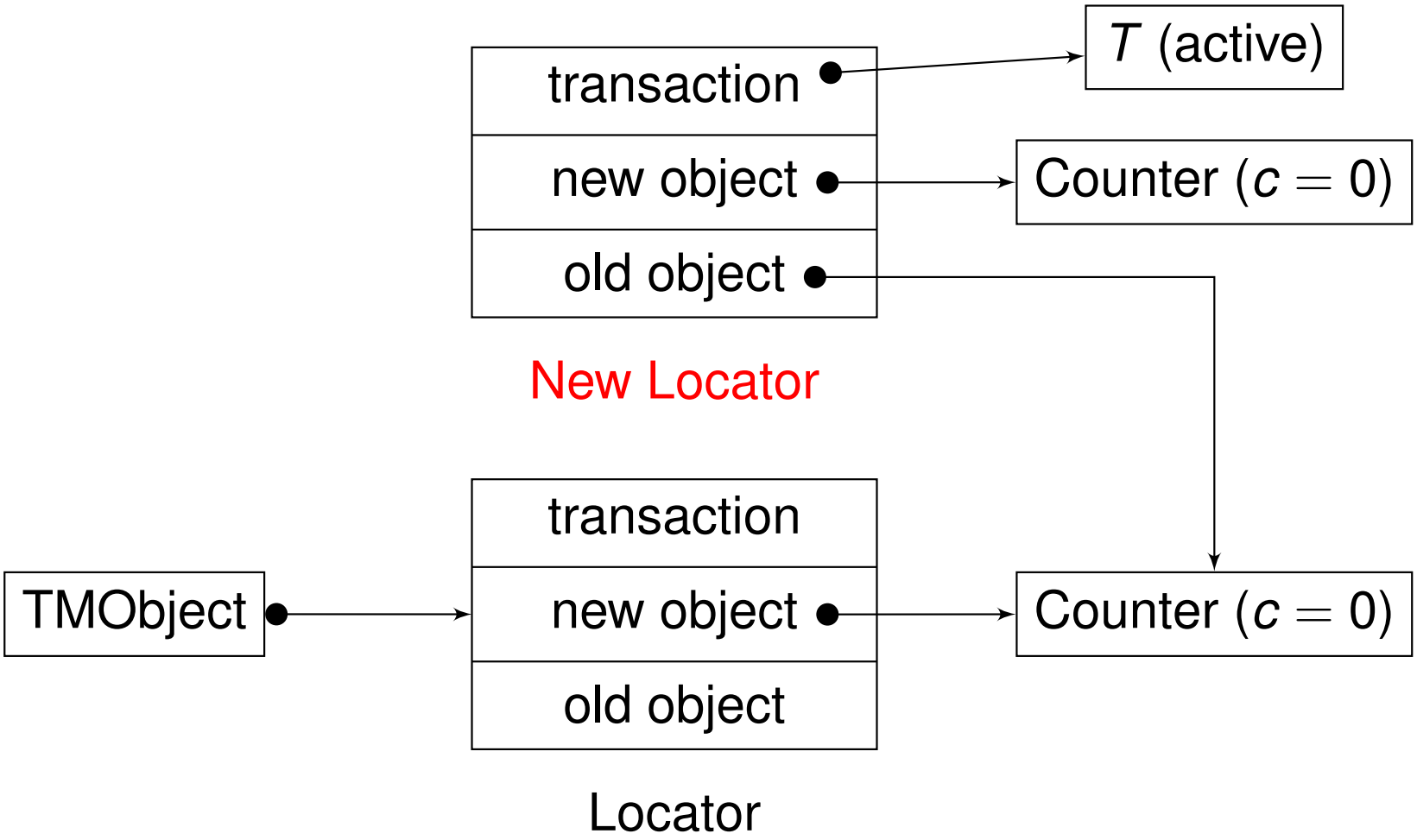


DSTM – The Idea



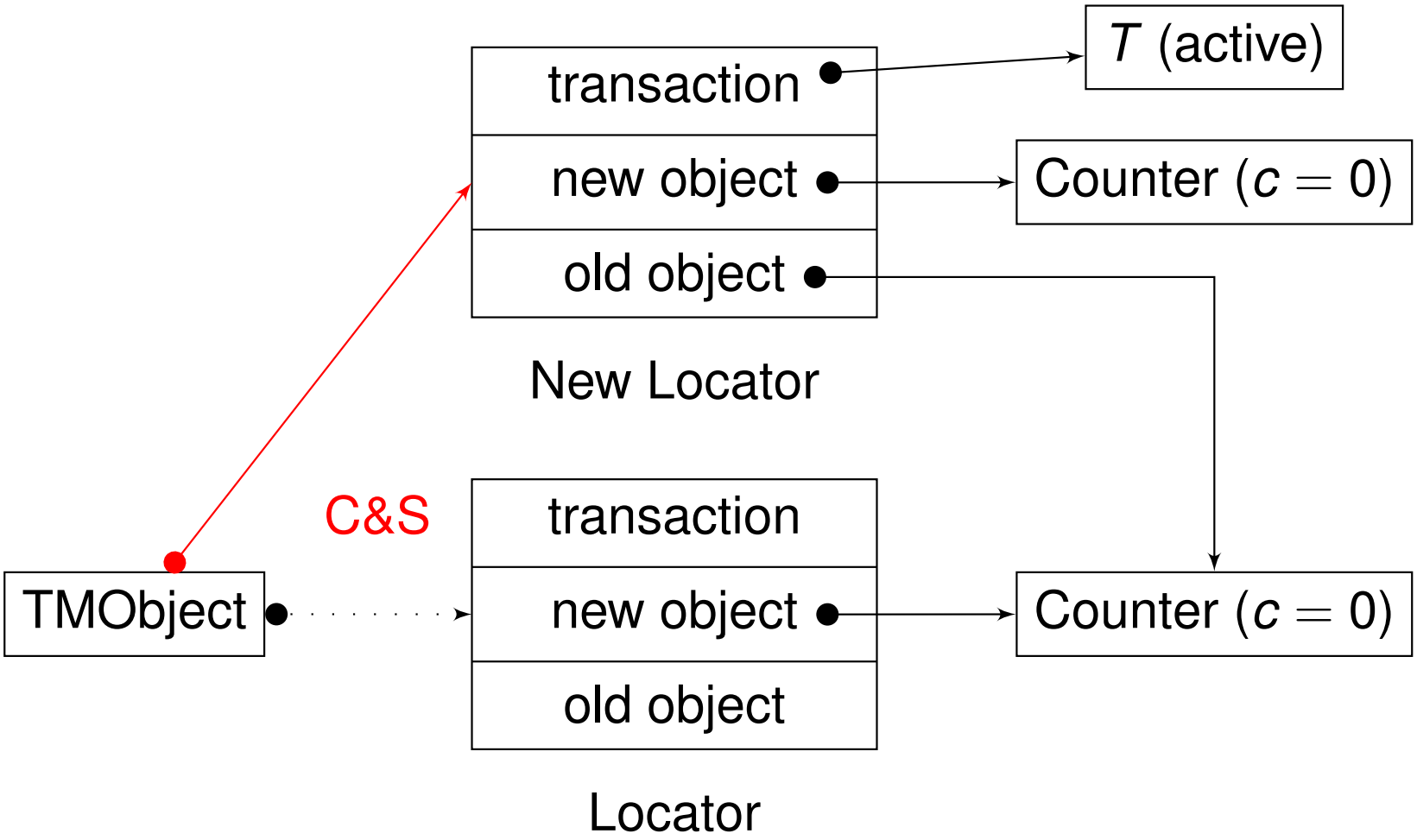
Transaction T wants to increment the counter

DSTM – The Idea



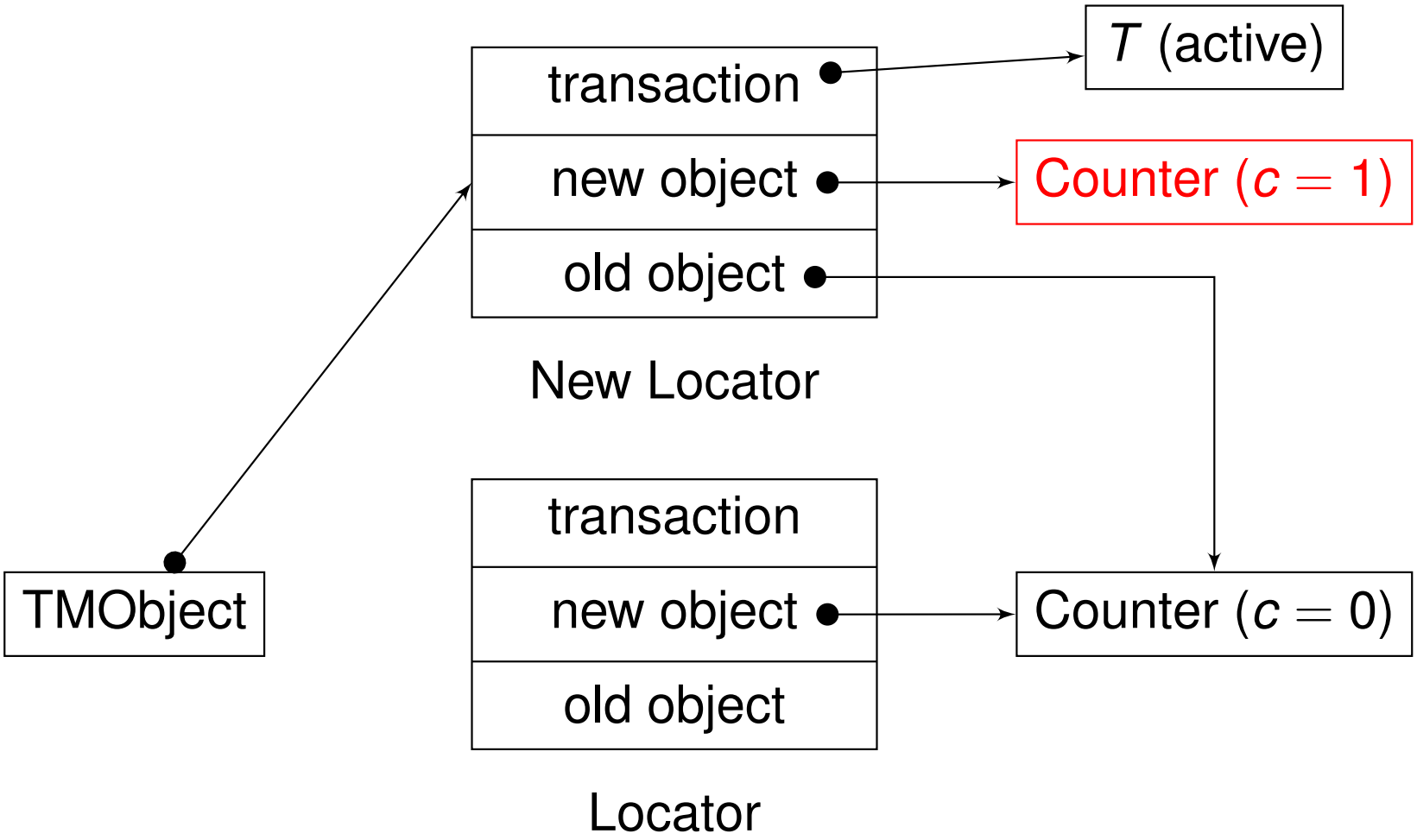
Step 1: Create new locator, clone the counter

DSTM – The Idea



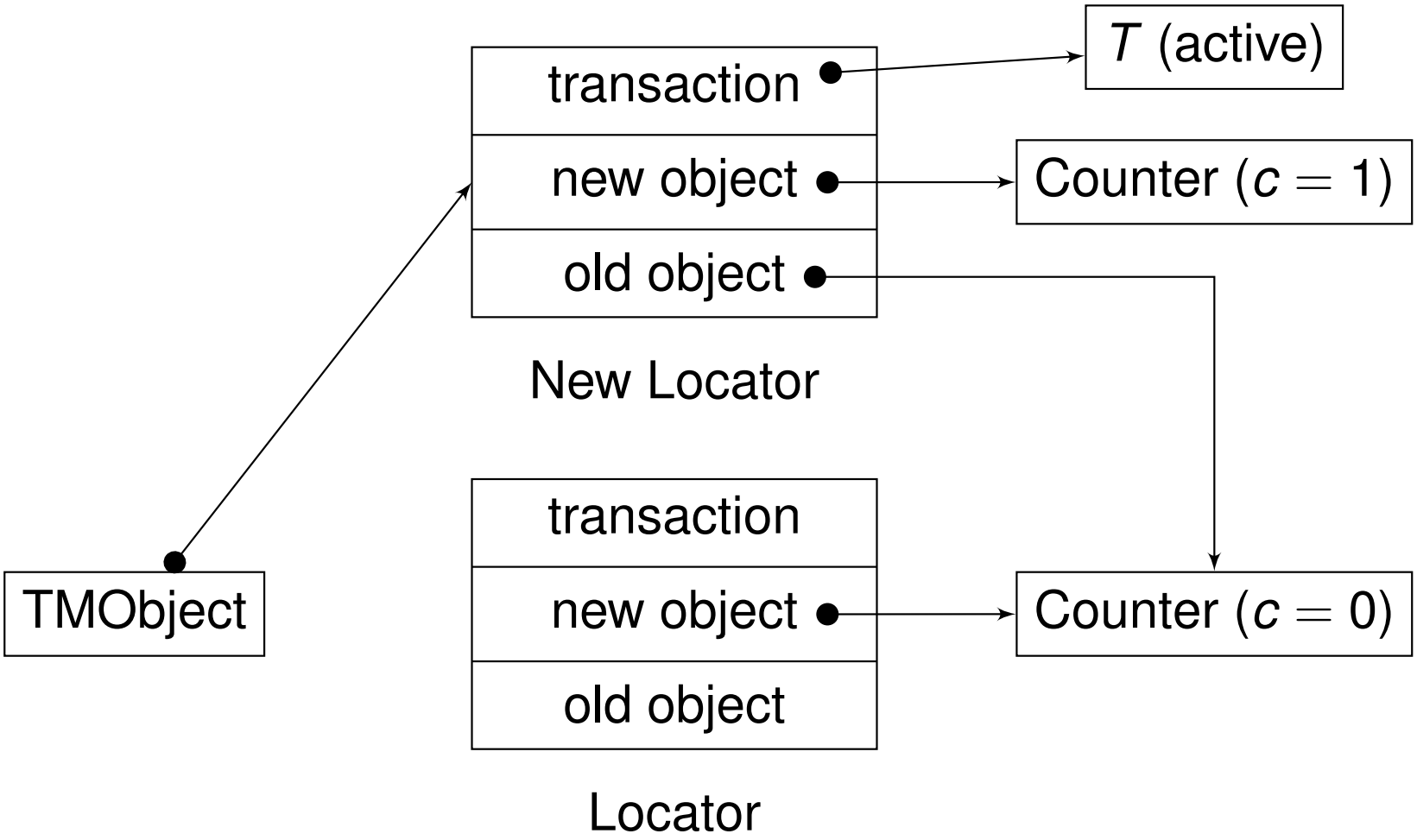
Step 2: Compare&Swap TMObject

DSTM – The Idea



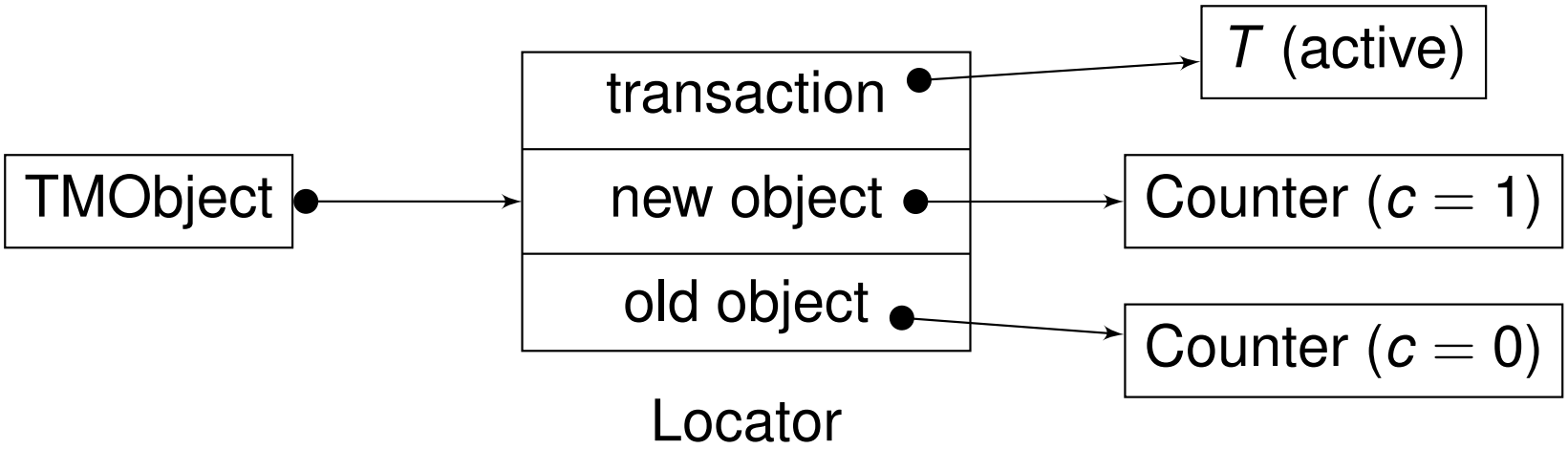
Step 3: Invoke `inc()` on the new counter

DSTM – The Idea



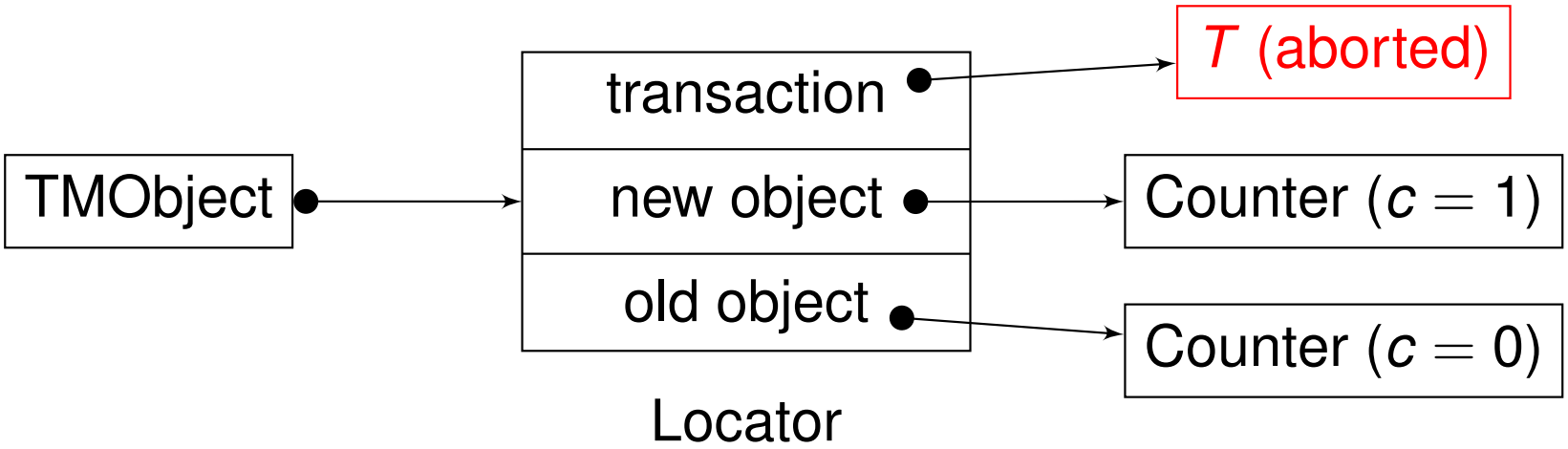
Old objects can be eventually garbage collected

Resolving Conflicts



Now another transaction T' wants to read the counter $\Rightarrow$ three possibilities:

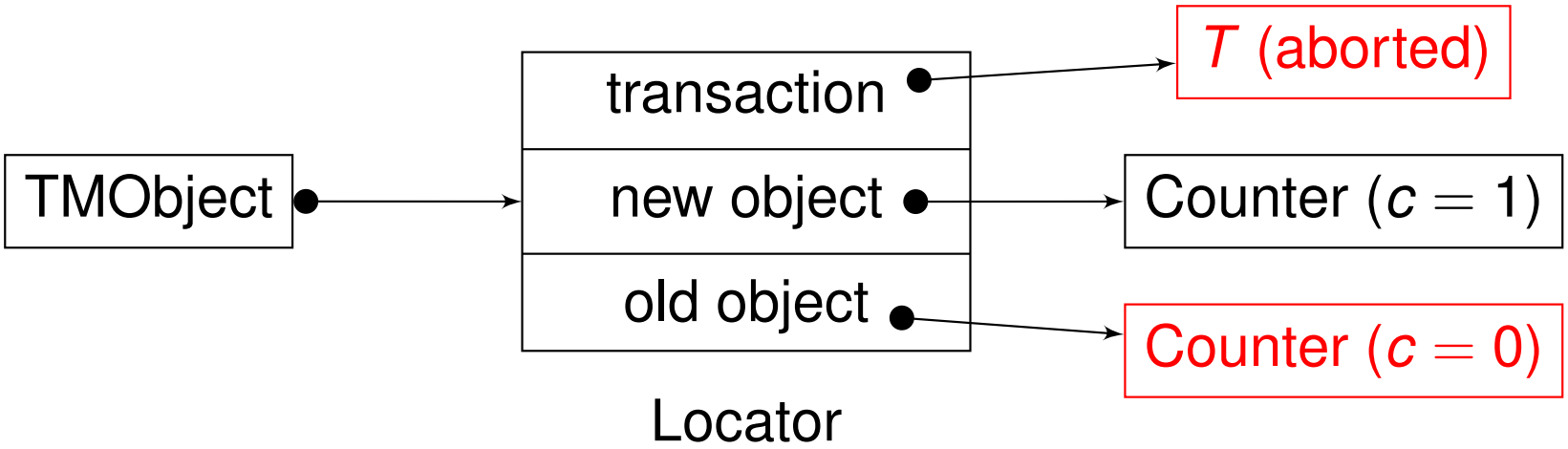
Resolving Conflicts



Now another transaction T' wants to read the counter $\Rightarrow$ three possibilities:

Variant 1: abort transaction T (Compare&Swap on state of T)

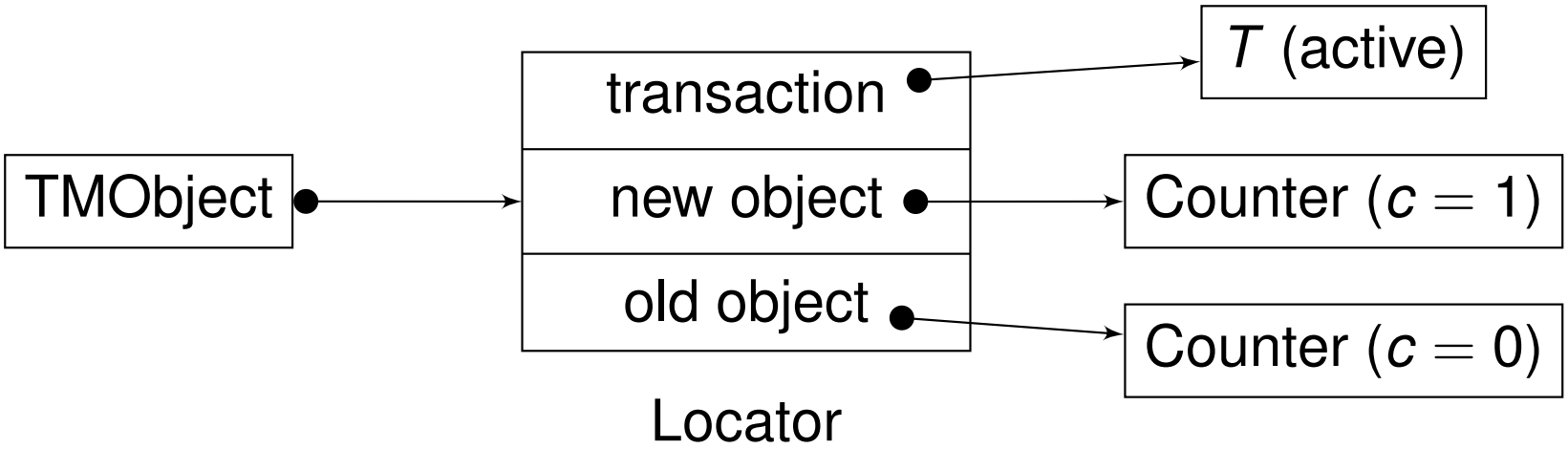
Resolving Conflicts



Now another transaction T' wants to read the counter $\Rightarrow$ three possibilities:

Variant 1: abort transaction T (Compare&Swap on state of T)
$\Rightarrow$ invoke `get()` on old counter

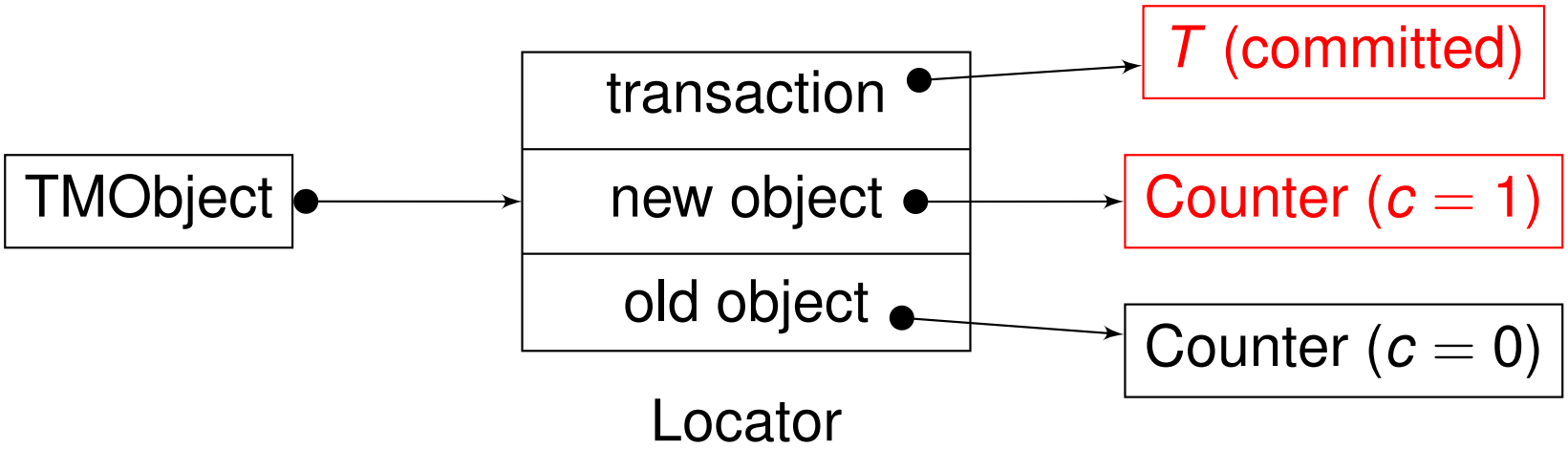
Resolving Conflicts



Now another transaction T' wants to read the counter $\Rightarrow$ three possibilities:

Variant 2: wait until T commits or aborts, then:

Resolving Conflicts

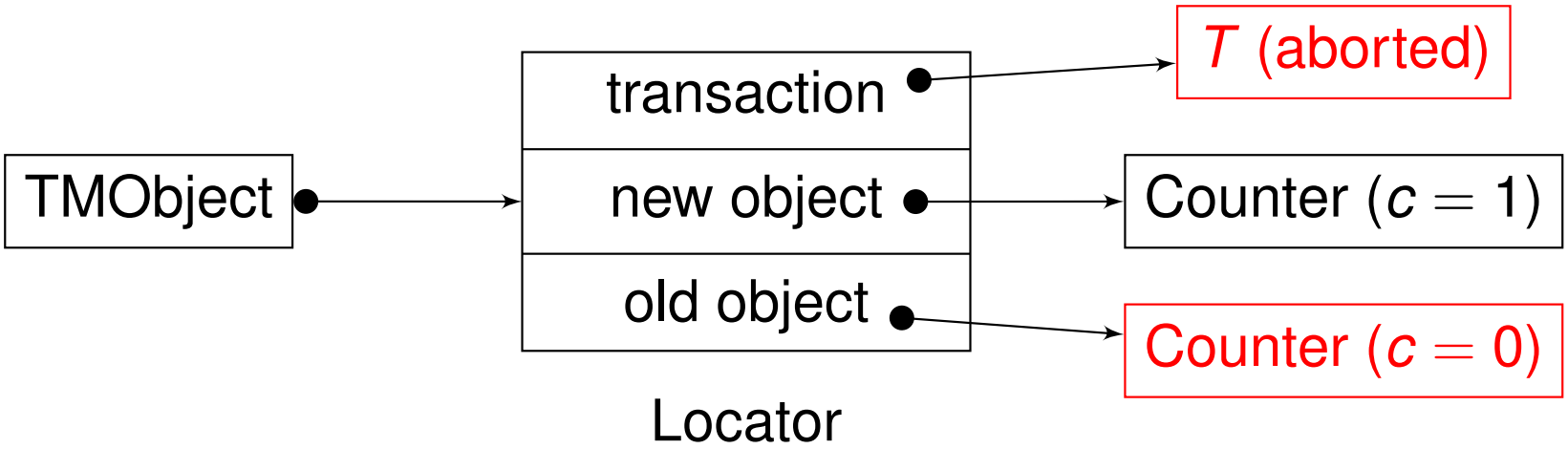


Now another transaction T' wants to read the counter $\Rightarrow$ three possibilities:

Variant 2: wait until T commits or aborts, then:

T committed $\Rightarrow$ invoke `get()` on new counter

Resolving Conflicts

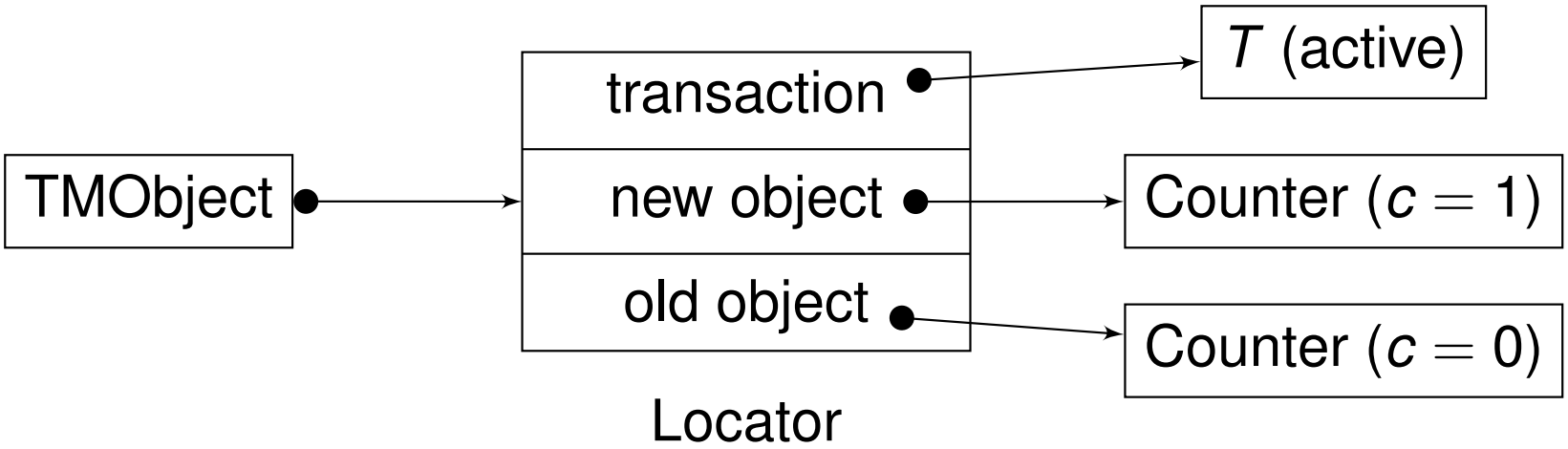


Now another transaction T' wants to read the counter $\Rightarrow$ three possibilities:

Variant 2: wait until T commits or aborts, then:

T aborted $\Rightarrow$ invoke `get()` on old counter

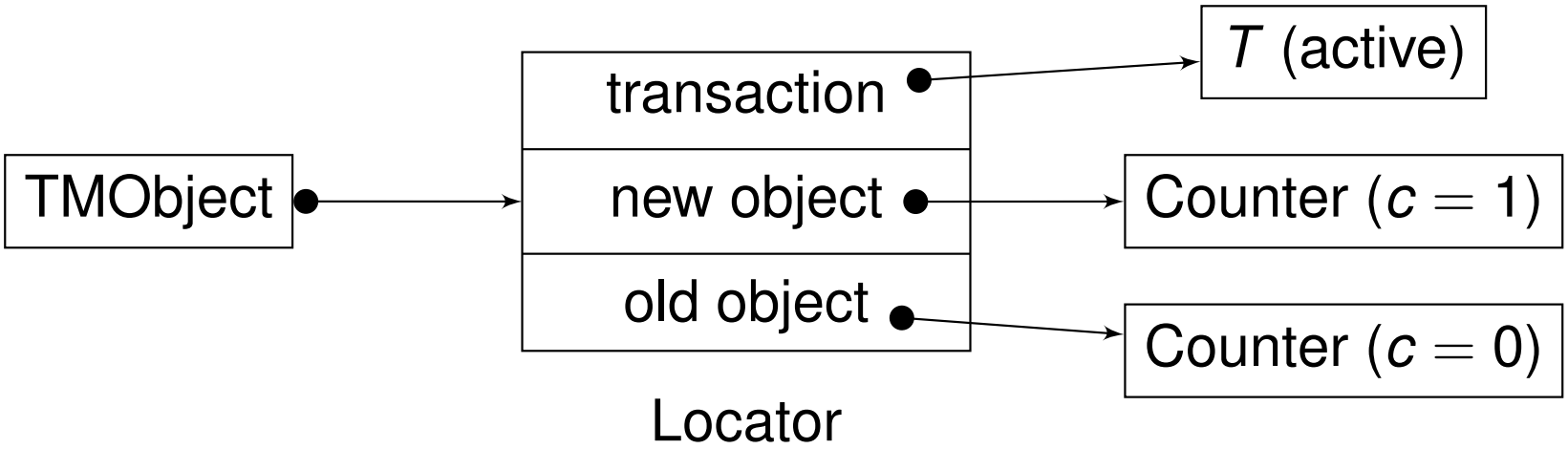
Resolving Conflicts



Now another transaction T' wants to read the counter $\Rightarrow$ three possibilities:

Variant 3: abort transaction T'

Resolving Conflicts



Now another transaction T' wants to read the counter $\Rightarrow$ three possibilities:

Which variant to choose? $\Rightarrow$ contention manager module decides

Reading Objects

Transaction T wants to read an object:

1. If the object written by an active transaction $\Rightarrow$ resolve conflict
2. Then, two techniques possible:
   - Visible reads: T adds itself to a shared list of readers (pointed by the locator) $\Rightarrow$ readers have to write to shared memory (cache!)
   - Invisible reads (DSTM): T reads the object and remembers locally the value $\Rightarrow$ writers do not know about readers $\Rightarrow$ need validation
3. Validation: make sure no object previously read has changed (for n objects read so far, $O(n)$ complexity in DSTM!)

The Last Steps

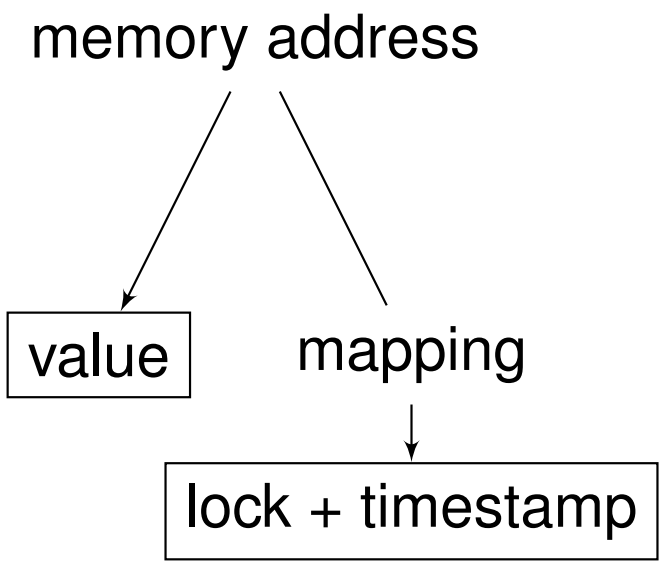
- *T* wants to commit:
  1. Validate (again!)
  2. Change state to “committed” (using C&S)
- *T* wants to abort: change state to “aborted”

From Hardware TM to Software TM

Example: TL2

TL2 – The Idea

- Use locks $\Rightarrow$ no copies, no indirection
- Invisible reads
- Make validation cheaper: timestamps
- Lock and write to objects only on commit time



The Algorithm (1)

Uses a global version (strong) counter V

Locks are 1-bit values ($1 =$ locked)

Local variables: *rver*, *rset*, *wver*, *wset*

upon *beginTransaction*
$\lfloor$ $rver \leftarrow V.read()$

upon *write(addr, val)*
$\lfloor$ $wset \leftarrow wset \cup \{(addr, val)\}$

(Note that this is just a rough approximation of the TL2 algorithm. For detailed description see [Dice et al. 06])

The Algorithm (2)

upon *read(addr)*

- **if** $addr \in wset$ **then return** $wset[addr].val$
- $(l_1, v_1) \leftarrow lockver[addr]$
- $val \leftarrow$ read value from $addr$
- $(l_2, v_2) \leftarrow lockver[addr]$
- **if** $l_1 = 1$ **or** $l_2 = 1$ **or** $v_1 \neq v_2$ **or** $v_2 > rver$ **then** abort
- $rset \leftarrow rset \cup \{(addr, val)\}$
- **return** val

The Algorithm (3)

upon *commitTransaction*

- **foreach** $(addr, val) \in wset$ **do**
  - try to acquire lock in $lockver[addr]$
  - **if** *failed to acquire* **then** abort
- $wver \leftarrow V.inc()$
- **if** $wver \neq rver + 1$ **then**
  - **foreach** $(addr, val) \in rset$ **do**
    - $(l, v) \leftarrow lockver[addr]$
    - **if** $v > rver$ **or** $l = 1$ **then** abort
- **foreach** $(addr, val) \in wset$ **do**
  - store val at address $addr$
  - $lockver[addr] \leftarrow (0, wver)$

Further Reading

M. Herlihy, J. E. B. Moss.

Transactional memory: architectural support for lock-free data structures.

In *Proceedings of the 20th Annual International Symposium on Computer Architecture*, pp. 289–300, 1993.

M. Herlihy, V. Luchangco, M. Moir, and W. N. Scherer III.

Software transactional memory for dynamic-sized data structures.

In *Proceedings of the 22th Annual ACM Symposium on Principles of Distributed Computing (PODC'03)*, pp. 92–101, 2003.

D. Dice, O. Shalev, and N. Shavit.

Transactional locking II.

In *Proceedings of the 20th International Symposium on Distributed Computing (DISC'06)*, 2006.