Software Transactional Memory for Dynamic-sized Data Structures

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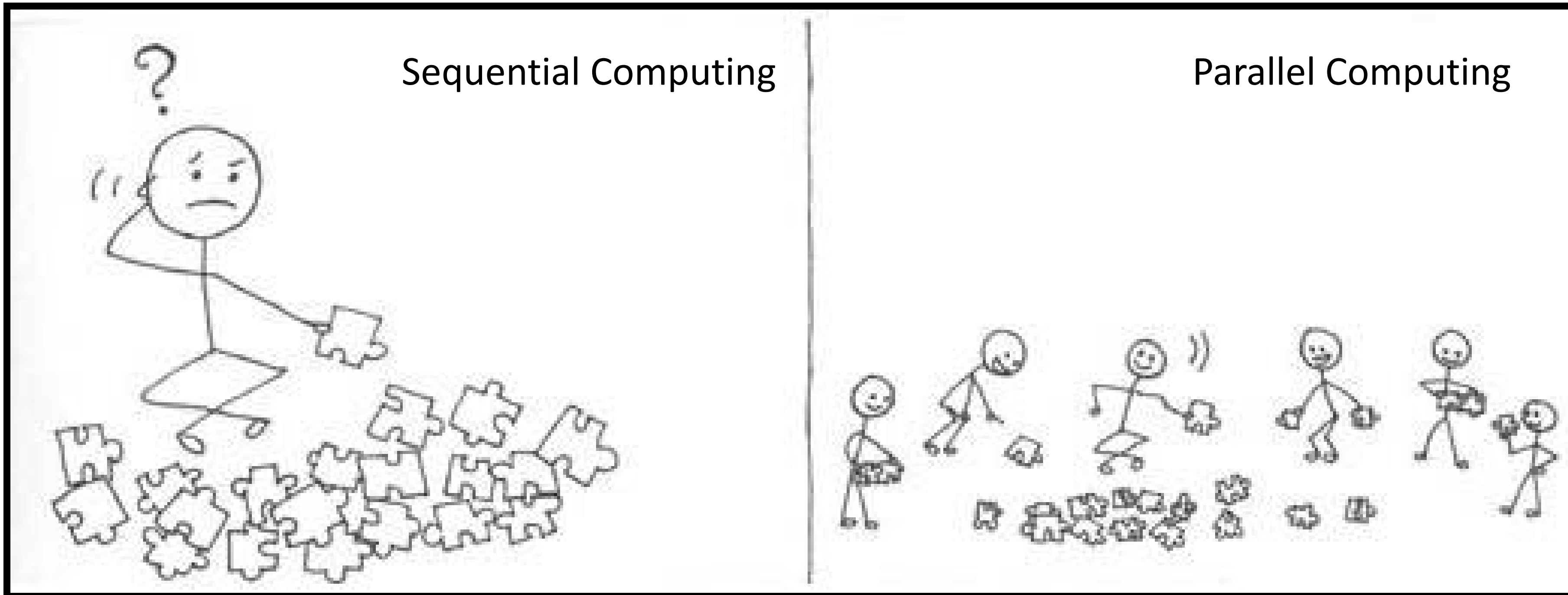
Outline

- Introduction
- Dynamic Software Transactional Memory (DSTM)
- DSTM Implementation
  - Transactions and Transactional Objects
  - Contention Management
- DSTM performance
- DSTM2
- DSTM2 performance



Parallel Computing

Moore's law => chip multiprocessing (CMP) => Increased Parallelism

Complex problems can be divided into smaller ones which can be then executed in parallel

Concurrent Access to Shared Data

T1	**T2**
int x[N];	
i := N-1;	…
…	
if (i < N){	
	i := i+1;
x[i] := i;	
}	

Locking

- Coarse-grained or fine-grained locking
- Locking conventions
- Vulnerability to thread failures and delays
- Poor support for code composition and reuse

=> too difficult to develop, debug, understand and maintain programs

T1	**T2**
lock()	
i := N-1;	
…	
if (i<N)	
x[i]:=i;	
unlock()	
	lock()
	i := i + 1;
	unlock()

Coarse-grained locking

Software Transactional Memory (STM)

- Low-level API for synchronizing access to shared data without using locks
  - Alleviates the difficulty of programming
  - Maintains performance
- Transactional Model
  - Transaction = atomic sequence of steps executed by a single thread (process); protects access to shared (transactional) objects
- Only for static data structures
  - Transactional objects and transactions defined apriori

From STM to D(ynamic)STM

- Transactions and transactional objects can be created dynamically

```
if (object1.value == 1)
    object2.value = 2;
else
    object3.value = 2;
```

- Well suited for dynamic-sized data structures, like linked lists and trees

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Transactional Object

- Container for a shared object

- Creation

```
List newNode = new List(v);
TMObject newTMNode = new TMObject(newNode);
```

- Access

```
List current = (List)newTMNode.open(WRITE);
current.value = 1;
```

Transaction

- Short-lived single-threaded computation that either commits (the changes take effect) or aborts (the changes are discarded)

- Linearizability = transactions appear as if they were executed one-at-a-time

Linked List Example

```
public boolean insert (int v){

    List newList = new List(v);
    TMObject newNode = new TMObject(newList);
    TMThread thread = (TMThread)thread.currentThread();
    while(true){
        thread.beginTransaction();
        boolean result = true;
        try{
                List prevList = (List)this.first.open(WRITE);
                List currList = (List)prevList.next.open(WRITE);
                while (currList.value < v){…}
        } catch (Denied d){}
        if (thread.commitTransaction())
                return result;
    }
}
```

Synchronization Conflict

- Two transactions attempting to access the same object and at least one of them wants to write it

Check Synchronization Conflicts

- If a conflict occurs, *open*() throws a Denied exception
  – The transaction *knows* it will not commit successfully and will retry execution

```
public boolean insert (int v){
        …
        while(true){
                thread.beginTransaction();
                try{
                        List prevList = (List)this.first.open(READ);
                        …
                } catch (Denied d){}
                if  (thread.commitTransaction())
                        return result;
        }
}
```

Conflict Reduction = Early Release

- *Release* an object opened in READ mode before commit
- Useful for shared pointer-based data structures (e.g., lists, trees)
- Programmer's job to ensure correctness (linearizability)

A	**B**
	open(i, READ)
…	…
	release(i)
open(i,WRITE)	
	open(j,READ)
…	…
	commit

Progress Guarantee

- Wait-freedom
  - Every thread makes progress
- Lock-freedom
  - At least one thread makes progress
- ***Obstruction-freedom***
  - Any thread that runs by itself for long enough makes progress

Obstruction-Freedom

- A transaction can abort any other transaction

- **+** Simpler and more efficient (in absence synchronization conflicts) than lock-freedom
- **-** Livelocks possible

Livelock

- Two competing processes constantly change state with respect to one another, none making progress

- E.g., two people meeting in a narrow corridor, each trying to be polite by moving aside to let the other pass*

*http://en.wikipedia.org/wiki/Livelock#Livelock

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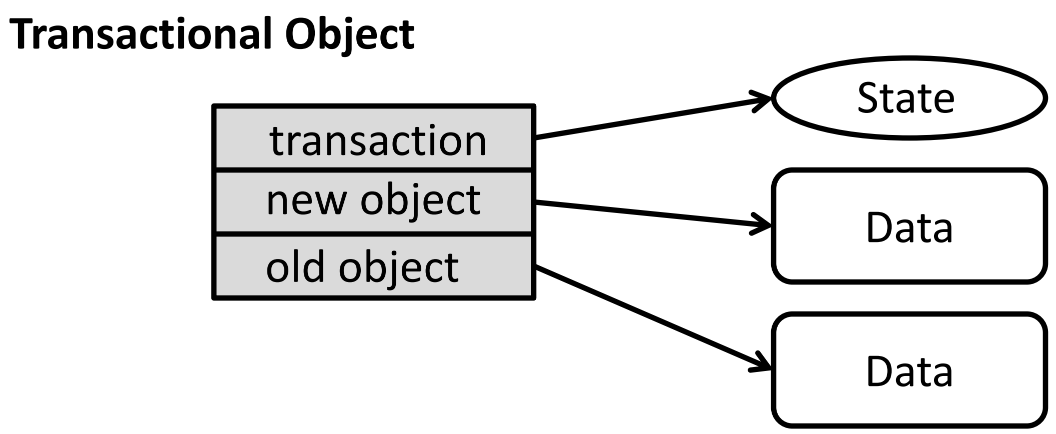
Transactional Object Implementation

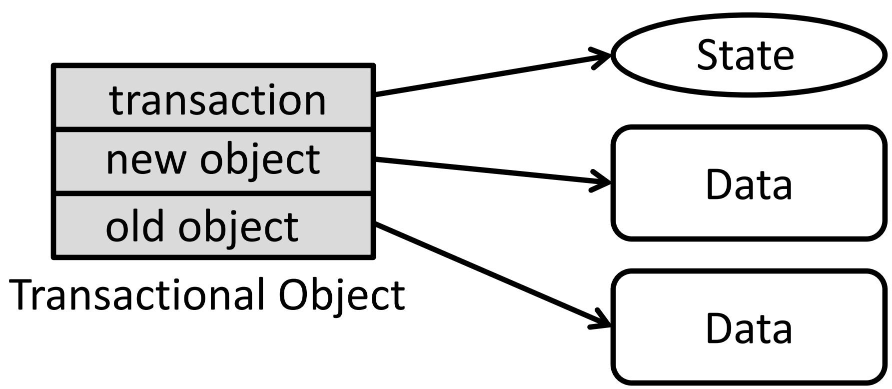


"transaction" points to the transaction that most recently opened the object in WRITE mode

Transaction State	Old Object	New Object
Committed	Meaningless	Current object
Aborted	Current Object	Meaningless
Active	Current Object	Tentative new current object

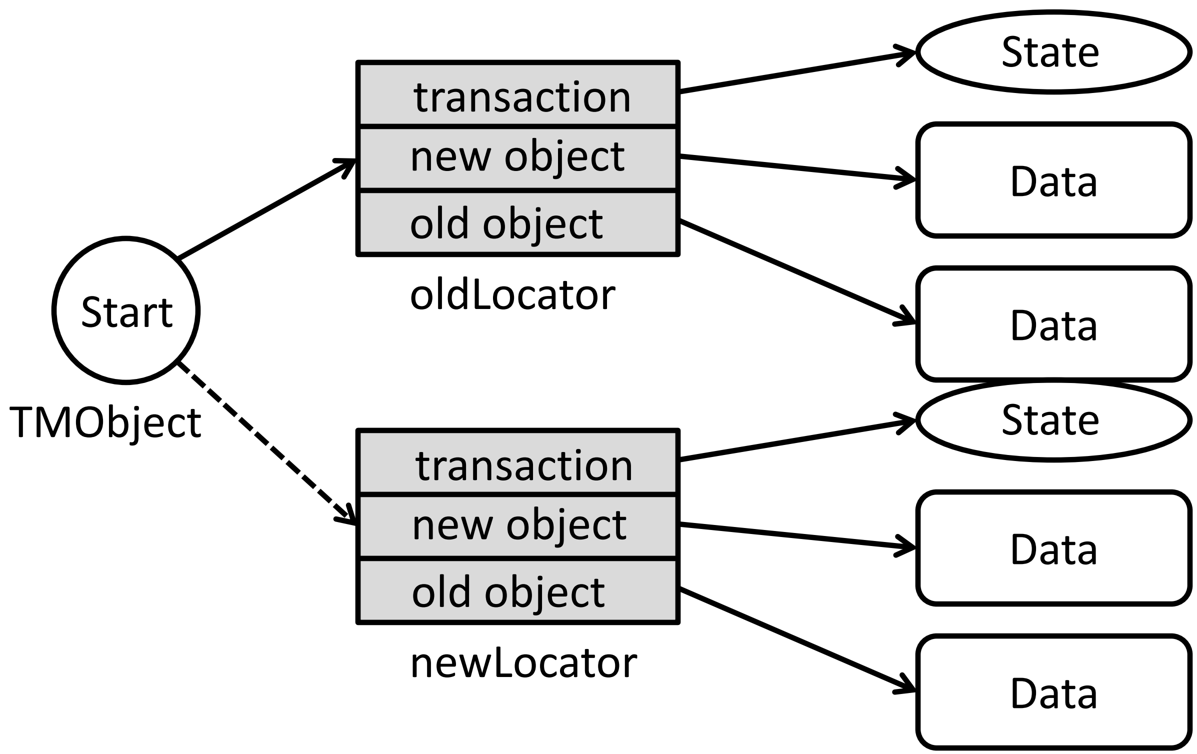
Transactional Object Access

- Avoid generating inconsistencies
- How to atomically access all three fields?

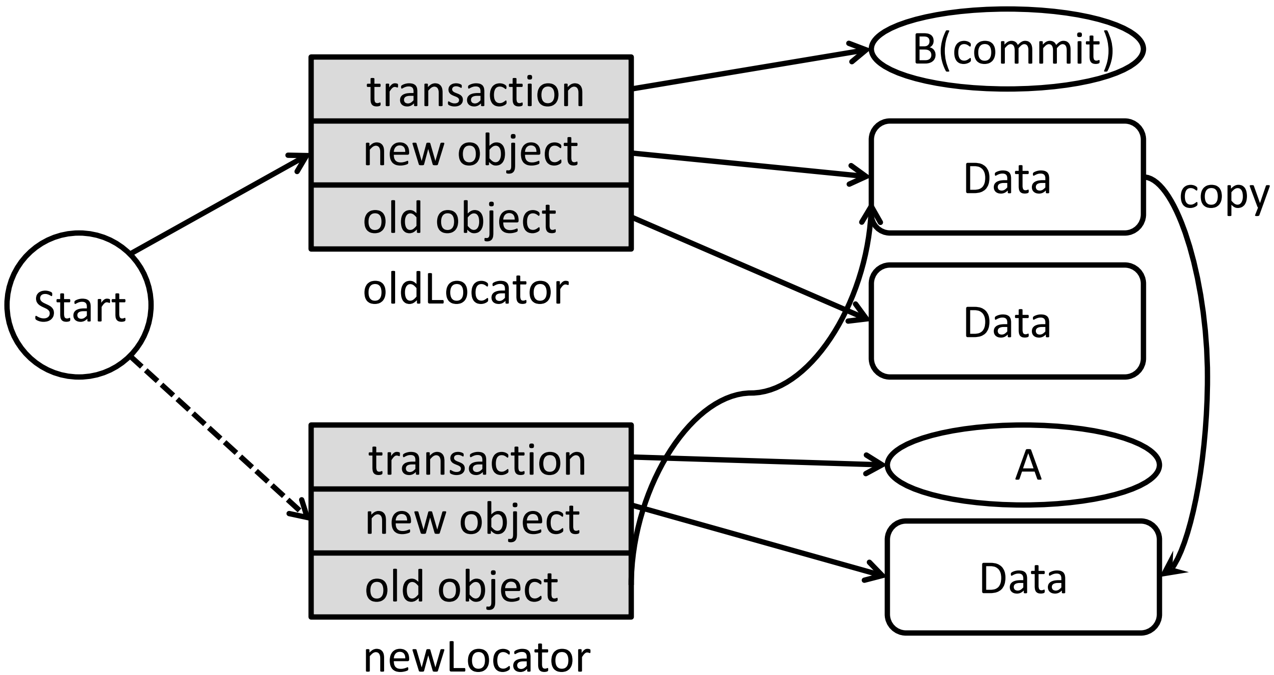


Atomically Access the Transactional Object's Fields

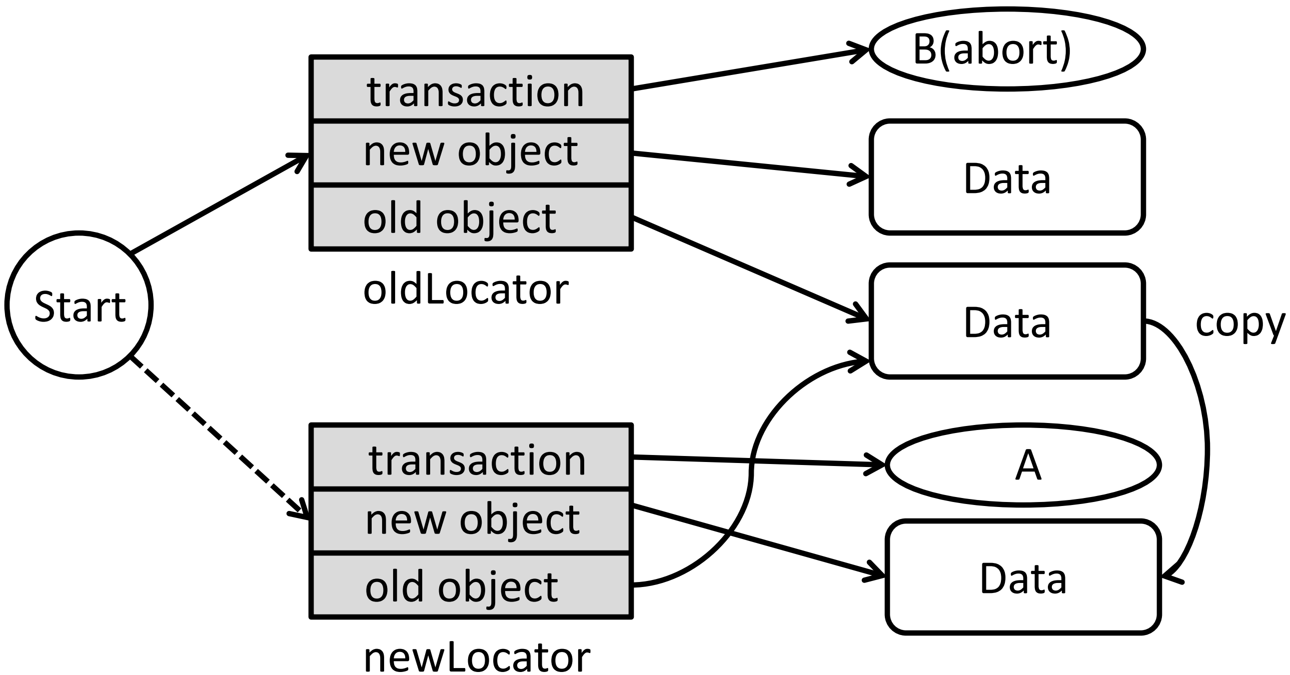
- Introduce another level of indirection
  - CAS (Compare and Swap) to swing the Start object from one locator object to the other



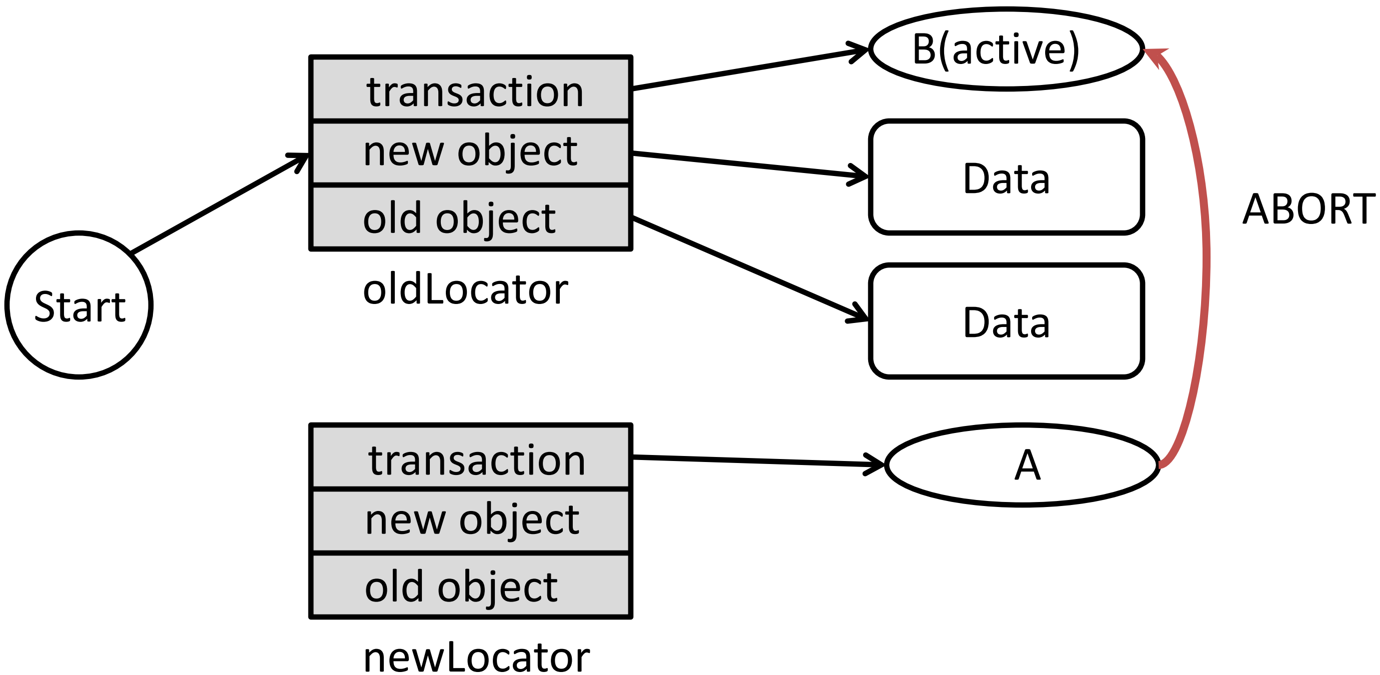
Open Transactional Object in WRITE Mode (Previous Transaction Committed)



Open Transactional Object in WRITE Mode (Previous Transaction Aborted)

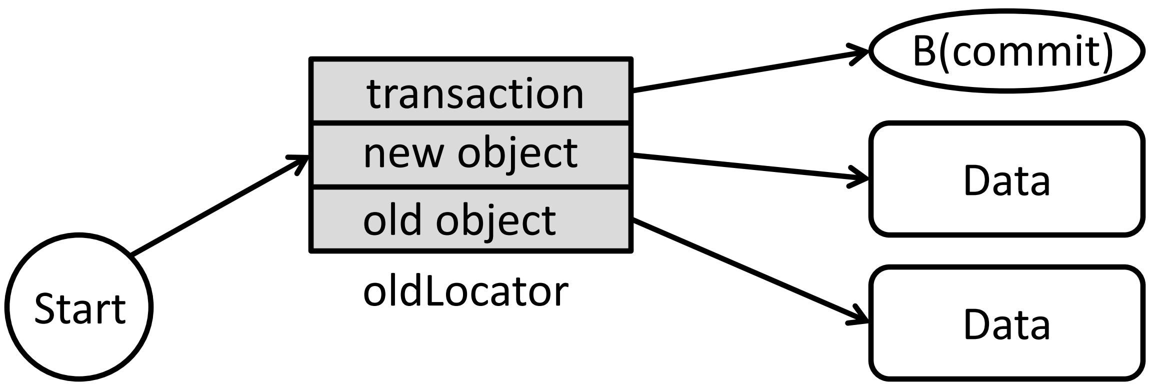


Open Transactional Object in WRITE Mode (Previous Transaction Active)



Open Transactional Object in READ Mode

1. Identify the last committed version of the transactional object (exactly as for WRITE)
2. Add the pair (O,V) to a thread-local read-only table



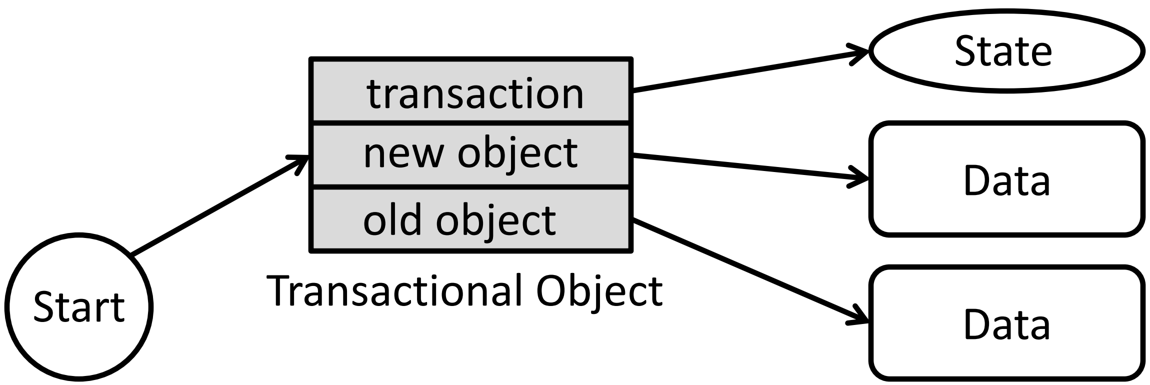
Read-only table

Object	Version	Open
O1	V1	2
O2	V2	1
O3	**V**	**1**

Transaction Validation

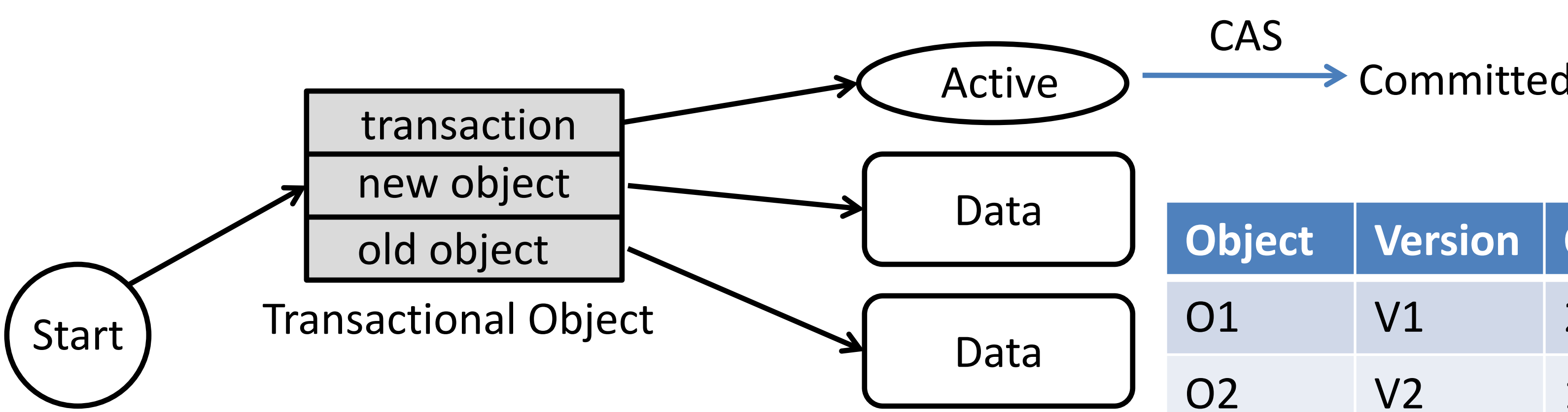
- Ensure that the user never sees an inconsistent state
- After open() determined the version
    1. For each pair (O, V) verify that V is still the most recently committed version of the object O
    2. Check that status field of transaction still ACTIVE

Object	Version	Open
O1	V1	2
O2	V2	1
O3	V	1



Transaction Commit

1. Validate entries in the read-only table
2. Change the status field of the transaction from ACTIVE to COMMITTED



Object	Version	Open
O1	V1	2
O2	V2	1
O3	V	1

Contention Management

- Ensures progress
- Each thread has a Contention Manager
  - Consults it to decide whether to force another conflicting thread to abort
- Correctness requirement for contention managers
  - Any active transaction can eventually abort another transaction (“obstruction-freedom”)
  - Should avoid livelock

Contention Manager Policies Examples

- Aggressive
  - Always and immediately grants permission to abort any conflicting transaction
- Polite
  - In case of a conflict, sleep for a time interval t
    * Idea: wait for the other transaction to finish
  - Retry and increase waiting time with each attempt
  - After a fixed number of tries, immediately abort the other transaction

Costs

- W – number of objects opened in WRITE mode
- R – number of objects opened in READ mode

- *In the absence of conflicts*
  - (W+1) CAS operations (for each open() call and one commit)
- *Synchronization conflicts*
  - More CAS operations to abort other transactions
- *Costs of copying objects* (uses simple load and store operations)
- *Validating a transaction*
  - Requires O(R) work

- Total overhead due to DSTM implementation
  - O((R+W)R) + clone each object opened for writing once

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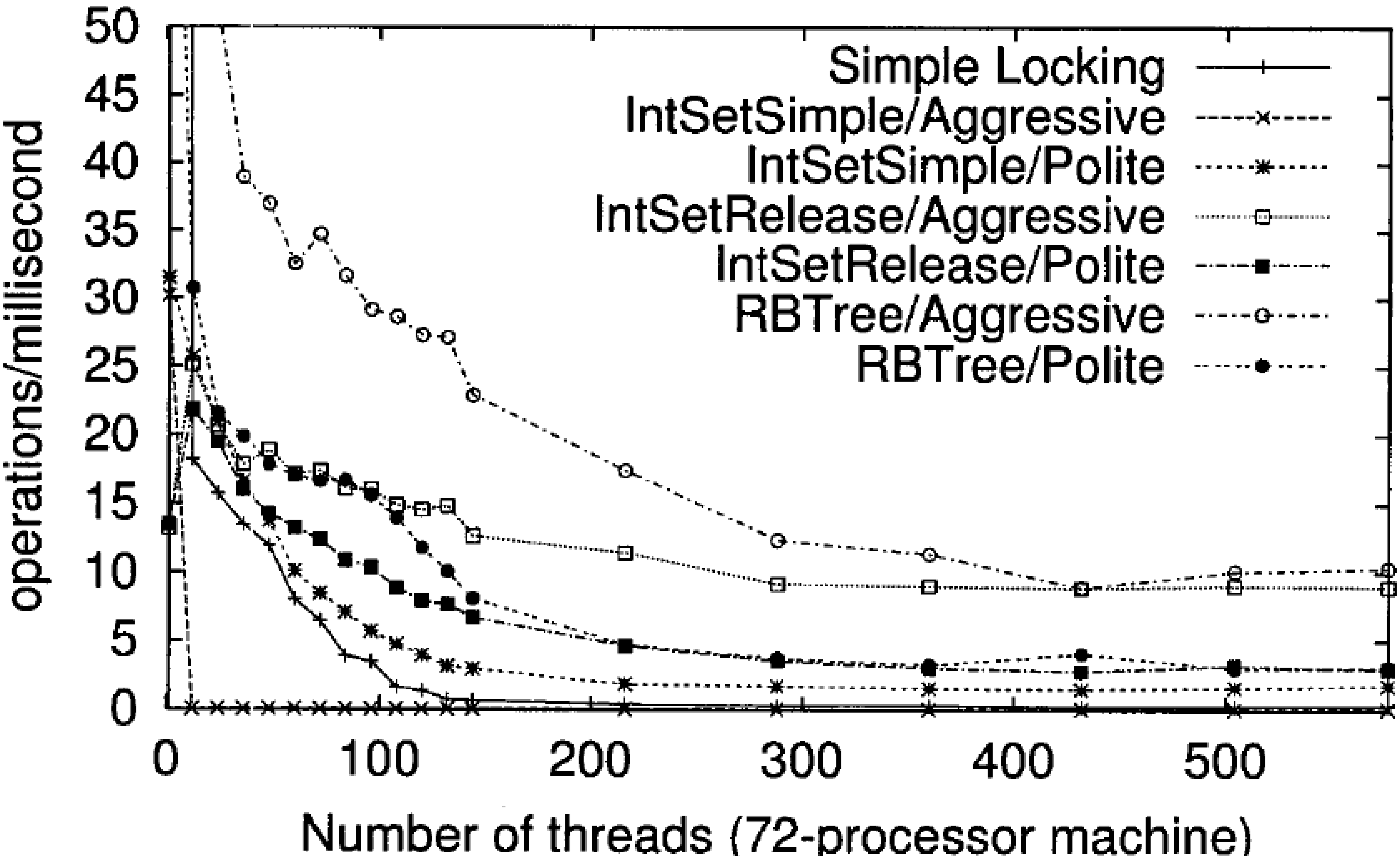
Experimental Setup

- Integer Set and Red-black tree
- Measure: how many operations completed in 20 seconds, varying the number of threads
- Goal: compare performance of different implementation approaches

Experimental Results



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Lessons Learned from DSTM

```
TMObject<Node> tmNode= new TMObject<node>(new Node());
Node rNode = tmNode.open(READ);
Node wNode = tmNode.open(WRITE);
```

- The programmer must not modify the object referenced by rNode
- If wNode is opened before rNode, changes to wNode are visible through rNode, but not if they are opened in the opposite order
- rNode and wNode references must not linger (programmer's job)
- The Node class must provide a clone() method
- Programmers must be aware of the container based implementation:

```
Class Node{
    Int value;
    TMObject<Node> next; //not Node
}
```

DSTM2

- Software transactional memory library (a collection of Java packages that supports transactional API)

- Safe, convenient and flexible API for application programmers

- Allows users to plug-in their own synchronization and recovery mechanisms (*transactional factories*)

Atomic Classes Comparison

DSTM

```
TMObject<Node> newNode= new
    TMObject<node>(new Node());
Node rNode = newNode.open(READ);
Node wNode =
    newNode.open(WRITE);

Class Node{
    Int value;
    TMObject<Node> next; //not
        Node
}
```

DSTM2

```
@atomic public interface INode{
    int getValue();
    void setValue(int value);
    INode getNext();
    void setNext(INode value);
    …
}

Factory<INode> factory =
    dstm2.Thread.makeFactory(INode.
    class);

INode newNode = factory.create();
```

Atomic Interface

- @atomic
  - Objects satisfying this interface should be safe to share
- Defines one or more *properties* (pairs of get and set) of certain type
- Property type: either *scalar* or @atomic interface
- May define other specialized methods

```
@atomic public interface INode{
    int getValue();
    void setValue(int value);
    INode getNext();
    void setNext(INode value);
    …
}
```

Transactional Factory

- Atomic interface is passed to a transactional factory constructor

- Use specific methods to create class implementing the interface

- The factory then creates instances of the class

```
Factory<INode> factory =
    dstm2.Thread.makeFactory
    (INode.class);

INode newNode = factory.create();
```

Atomic Interface and Transactional Factory

- Semantics of get and set is clear
- Each factory is free to provide its own implementation for the methods declared

```
@atomic public interface INode{
    int getValue();
    void setValue(int value);
    INode getNext();
    void setNext(INode value);
    …
}

Factory<INode> factory =
    dstm2.Thread.makeFactory
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INode newNode =
    factory.create();
```
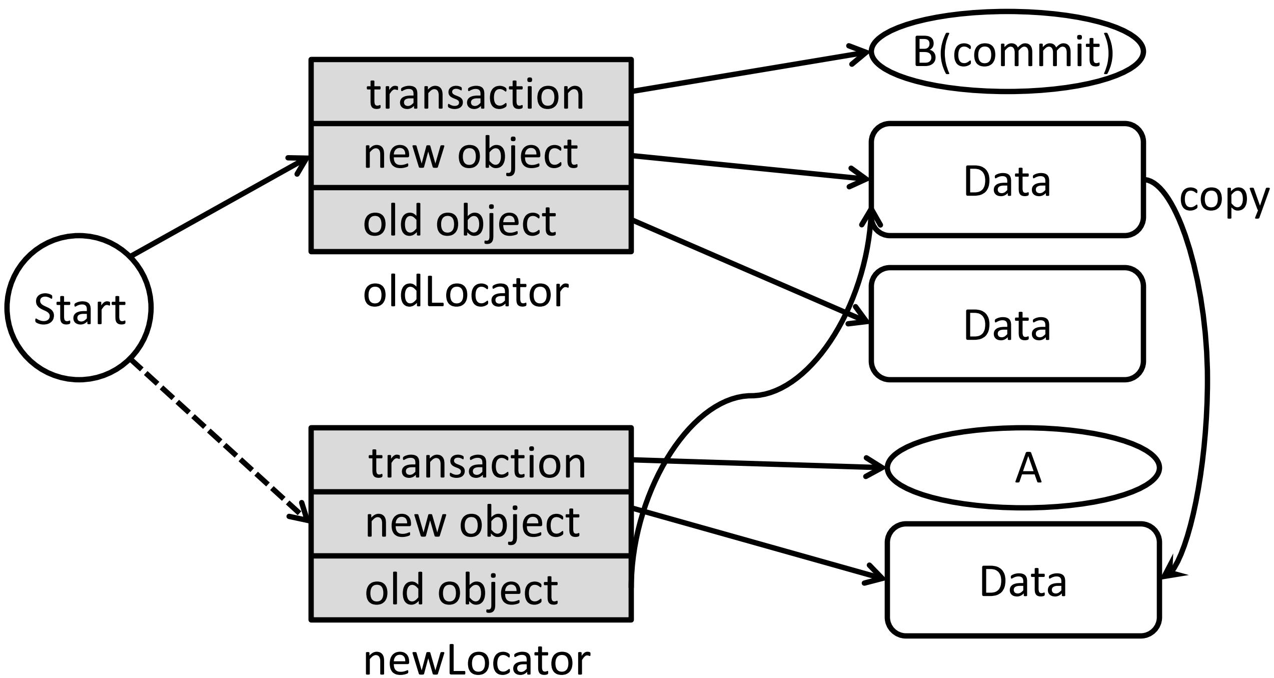
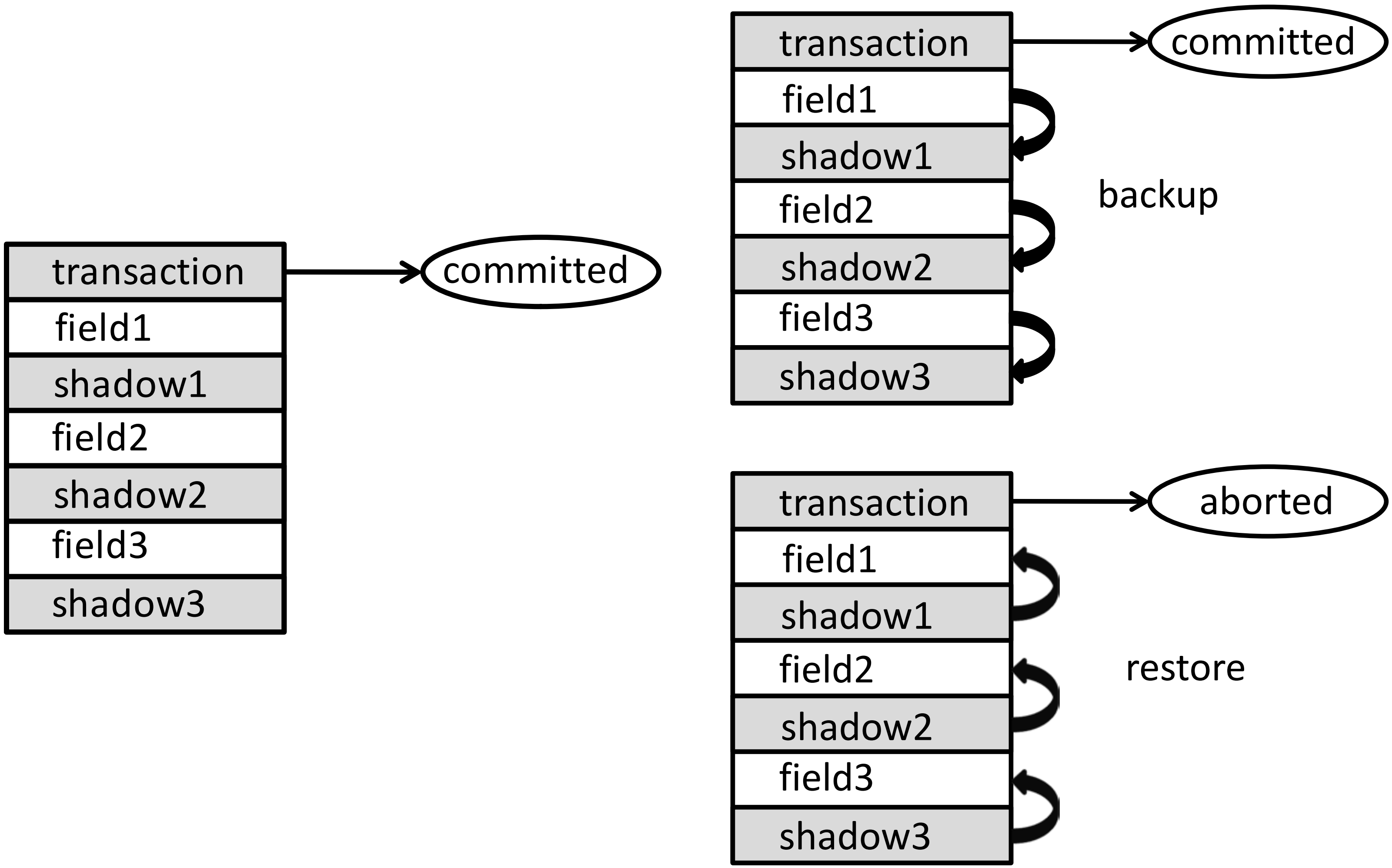

Obstruction-Free Factory



Obstruction-Free Factory Variants

- Invisible reads
  - At commit time, a transaction must validate itself
    - Checks that the versions read are still current
- Visible reads
  - Each object maintains a list of reader transactions descriptors
  - A transaction intending to modify the object must first abort them

Shadow Factory



Transactions

DSTM

```
public boolean insert (int v){
    …

    TMThread thread =
        (TMThread)thread.currentThread();

    while(true){
        thread.beginTransaction();
        try{
                …
        } catch (Denied d){}
        if (thread.commitTransaction())
                return result;
    }
}
```

DSTM2

```
result = Thread.doIt (new Callable<Boolean>(){
    public boolean call(){
        return intSet.insert(v);
    }
}

public static <T> T doIt(Callable<T> xaction){
    while (!Thread.stop){
        beginTransaction();
        try{
            result=xaction.call();
        }catch (AbortedException d){}
        if (commitTransaction()){
            return result;
        }
    }
}
```

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DSTM2 Experimental Setup

- Linked-list and Skip List
- Configurations: obstruction-free factory (visible reads), obstruction-free factory with invisible reads, shadow factory
- 0%, 50%, 100% updates out of all operations
- Measure: transactions/second in a 20 second period
- Goal: show how DSTM2 can be used experimentally to evaluate the relative performance of different factories

DSTM2 Performance

- Linked List
  - The shadow factory 3-5 times higher throughput than the obstruction-free factories
    - Slightly higher when the percentage of updates decreases
  - Obstruction-free factories roughly the same results
- Skip List
  - Shadow factory better for high percentage of updates

Conclusions

- STM – API for low-level synchronized access to shared data without using locks
- DSTM – dynamic STM
  - Dynamic creation of transactions and transactional objects
  - Detect and reduce synchronization conflicts
  - Contention Manager (obstruction-freedom)
- DSTM2
  - Flexible API for application programmers