Concurrent Systems
8L for Part IB

Handout 4

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2PL: Rollback

- Recall that transactions can **abort**
  - Could be to run-time conflicts (non-strict 2PL), or could be programmed (e.g. on an exception)
- Using locking for isolation works, but means that updates are made ‘in place’
  - i.e. once acquire write lock, can directly update
  - If txaction aborts, need to make sure no effects visible
- **Rollback** is the process of returning the world to the state it in was before the start of the txaction

Implementing Rollback: Undo

- One strategy is to **undo** operations, e.g.
  - Keep a log of all operations, in order: O_1, O_2, .. O_n
  - On abort, undo changes of O_n, $O_{(n-1)}$, .. O_1
- Must know how to undo an operation:
  - Assume we log both operations and parameters
  - Programmer can provide an explicit counter action
    - UNDO(credit(A, x)) ⇔ debit(A, x);
- May not be sufficient (e.g. setBalance(A, x))
  - Would need to record previous balance, which we may not have explicitly read within transaction…

Implementing Rollback: Copy

- A more brute-force approach is to take a copy of an object before [first] modification
  - On abort, just revert to original copy
- Has some advantages:
  - Doesn't require programmer effort
  - Undo is simple, and can be efficient (e.g. if there are many operations, and/or they are complex)
- However can lead to high overhead if objects are large … and may not be needed if don't abort!
  - Can reduce overhead with partial copying

Timestamp Ordering (TSO)

- 2PL and Strict 2PL are widely used in practice
  - But can limit concurrency (certainly the latter)
  - And must be able to deal with deadlock
- **TSO** is an alternative approach:
  - As a transaction begins, it is assigned a timestamp
  - Timestamps are comparable, and unique (can think of as e.g. current time – or as a ticket from a sequencer)
  - Every object O records the timestamp of the last transaction to successfully access it: **V**(O)
  - T can access object O iff **V**(T) >= **V**(O), where **V**(T) is the timestamp of T (otherwise rejected as "***too late***")

TSO Example 1

```
T1 transaction {
  s = getBalance(S);
  c = getBalance(C);
  return = s + c;
}
```

```
T2 transaction {
  debit(S, 100);
  credit(C, 100);
  return true;
}
```

Imagine S and C start off with version 10

1. T1 and T2 both start concurrently:
   - T1 gets timestamp **27**, T2 gets timestamp **29**
2. T1 reads S => **ok**! (27 >= 10); S gets timestamp 27
3. T2 does debit S, 100 => **ok**! (29 >= 27); S gets timestamp 29
4. T1 reads C => **ok**! (27 => 10); C gets timestamp 27
5. T2 does credit C, 100 => **ok**! (29 >= 27); C gets timestamp 29
6. Both transactions commit.

TSO Example 2

```
T1 transaction {
  s = getBalance(S);
  c = getBalance(C);
  return = s + c;
}
```

```
T2 transaction {
  debit(S, 100);
  credit(C, 100);
  return true;
}
```

As before, S and C start off with version 10

1. T1 and T2 both start concurrently:
   - T1 gets timestamp **27**, T2 gets timestamp **29**
2. T1 reads S => **ok**! (27 >= 0); S gets timestamp 27
3. T2 does debit S, 100 => **ok**! (29 >= 27); S gets timestamp 29
4. T2 does credit C, 100 => **ok**! (29 >= 0); C gets timestamp 29
5. T1 reads C => **FAIL**! (27 < 29); T1 aborts
6. T2 commits; T1 restarts, gets timestamp **30**...

Advantages of TSO

- Deadlock free
- Can allow more concurrency than 2PC
- Can be implemented in a decentralized fashion
- Can be augmented to distinguish reads & writes
  - objects have read timestamp **R** & write timestamp **W**

```
READ(O, T) {
  if(V(T) < W(O)) abort;
  // do actual read
  R(O): = MAX(V(T), R(O));
}
```

Only safe to read if no-one wrote "after" us

R(O) holds timestamp of *latest* transaction to read

```
WRITE(O, T) {
  if(V(T) < R(O)) abort;
  if(V(T) < W(O)) return;
  // do actual write
  W(O) := V(T);
}
```

Unsafe to write if later txaction has read value

But if later txaction *wrote* it, just skip write (he won!). Or?

However…

- TSO needs a rollback mechanism (like 2PC)
- TSO does not provide strict isolation:
  - hence subject to cascading aborts
  - (can provide strict TSO by locking objects when access is granted – still remains deadlock free)
- TSO decides *a priori* on one serialization
  - even if others might have been possible
- And TSO does not perform well under contention
  - will repeatedly have transactions aborting & retrying & …
- In general TSO is a good choice for *distributed* systems [decentralized management] where conflicts are rare

Optimistic Concurrency Control

- **OCC** is an alternative to 2PC or TSO
- Optimistic since assume conflicts are rare
  - Execute transaction on a **shadow** [copy] of the data
  - On commit, check if all "OK"; if so, apply updates; otherwise discard shadows & retry
- "OK" means:
  - All shadows read were mutually consistent, and
  - No-one else has committed changes to any object that we are hoping to update
- Advantages: no deadlock, no cascading aborts
  - And "rollback" comes pretty much for free!

Implementing OCC

- Various efficient schemes for shadowing
  - e.g. write buffering, page-based copy-on-write.
- Complexity arises in performing **validation** when a transaction T finishes & tries to commit
- Read Validation:
  - Must ensure that all versions of data read by T (all shadows) were valid at some particular time *t*
  - This becomes the tentative **start time** for T
- Serializability Validation:
  - Must ensure that there are no conflicts with any transactions which have an earlier start time

OCC Example (1)

- All objects are tagged with a version
  - Validation timestamp of the transaction which most recently wrote its updates to that object
- Many threads execute transactions
  - When wish to read an object, take a shadow copy, and take note of the version number
  - If wish to write: first take copy, then update that
- When a thread finishes a transaction, it submits the versions to a single threaded validator

OCC Example (2)

- Validator keeps track of last k validated transactions, their timestamps, and the objects they updated

Transaction	Validation Timestamp	Objects Updated	Writeback Done?
T5	10	A, B, C	Yes
T6	11	D	Yes
T7	12	A, E	No

- The versions of the objects are as follows:
  - T7 has started, but not finished, writeback
  - (A has been updated, but not E)

Object	Version
A	12
B	10
C	10
D	11
E	9

OCC Example (3)

- Consider T8: { write(B), write(E) };
- T8 executes and makes shadows of B & E
  - Records timestamps: B@10, E@9
  - When done, T8 submits for validation
- Phase 1: read validation
  - Check shadows are part of a consistent snapshot
  - Latest committed start time is 11 = ok (10, 9 < 11)
- Phase 2: serializability validation
  - Check T8 against all later transactions (here, T7)
  - Conflict detected! (T7 updates E, but T8 read old E)

Issues with OCC

- Preceding example uses a simple validator
  - Possible will abort even when don't need to
  - (e.g. can search for a 'better' start time)
- In general OCC can find more serializable schedules than TSO
  - Timestamps assigned after the fact, and taking the actual data read and written into account
- However OCC is not suitable when high conflict
  - Can perform lots of work with 'stale' data => wasteful!
  - Livelock possible if conflicting set continually retries

Isolation & Concurrency: Summary

- **2PL** explicitly locks items as required, then releases
  - Guarantees a serializable schedule
  - Strict 2PC avoids cascading aborts
  - Can limit concurrency; & prone to deadlock
- **TSO** assigns timestamps when transactions start
  - Cannot deadlock, but may miss serializable schedules
  - Suitable for distributed/decentralized systems
- **OCC** executes with shadow copies, then validates
  - Validation assigns timestamps when transactions end
  - Lots of concurrency, & admits many serializable schedules
  - No deadlock but potential livelock when contention is high

Crash Recovery & Logging

- Transactions require ACID properties
  - So far have focused on I (and implicitly C).
- How can we ensure Atomicity & Durability?
  - Need to make sure that if a transaction always done entirely or not at all
  - Need to make sure that a transaction reported as committed remains so, even after a crash
- Consider for now a **fail-stop** model:
  - If system crashes, all in-memory contents are lost
  - Data on disk, however, remains available after reboot

Using Persistent Storage

- Simplest "solution": write all updated objects to disk on commit, read back on reboot
  - Doesn't work, since crash could occur during write
  - Can fail to provide Atomicity and/or Consistency
- Instead split update into two stages
  1. Write proposed updates to a **write-ahead log**
  2. Write actual updates
- Crash during #1 => no actual updates done
- Crash during #2 => use log to redo, or undo

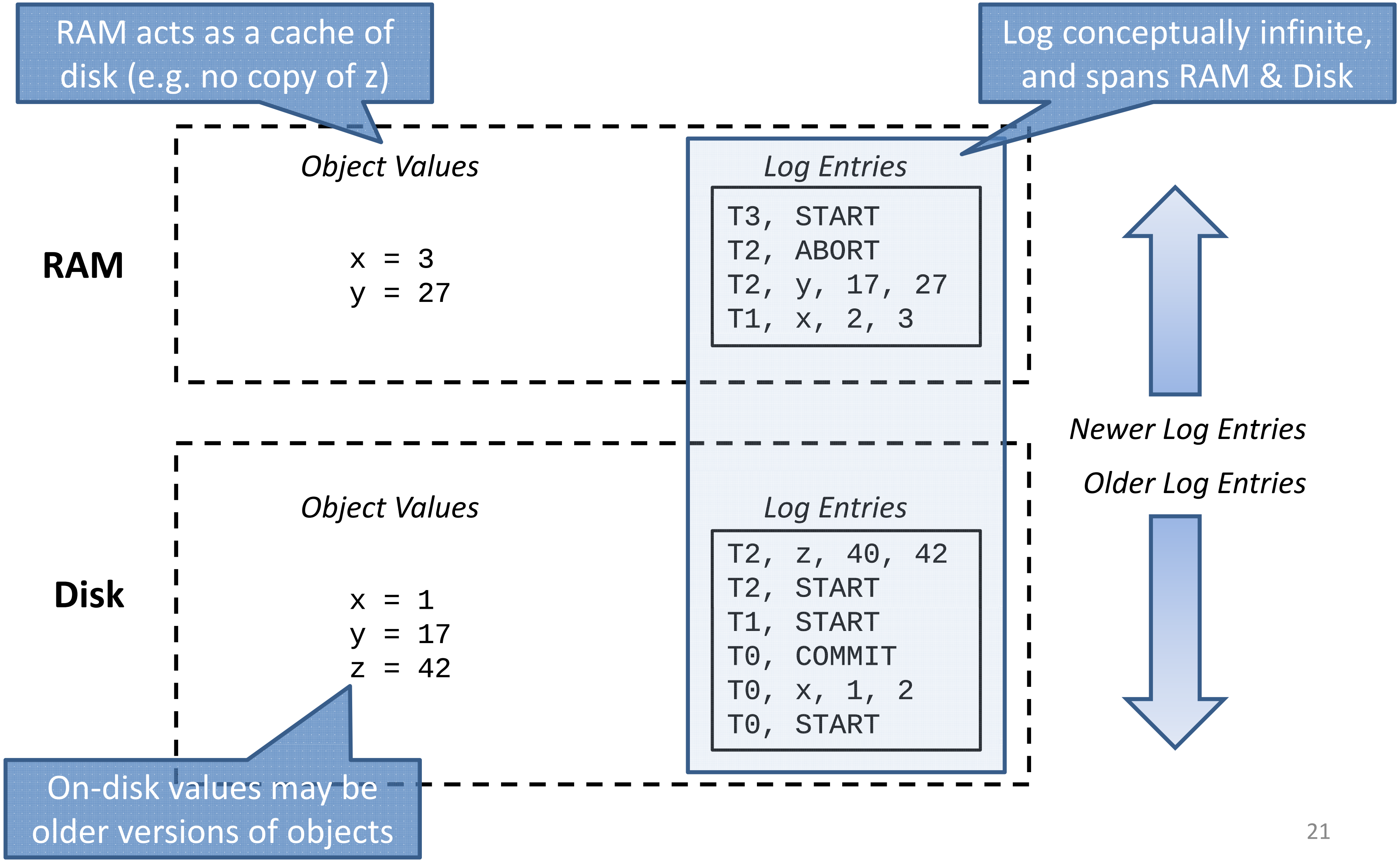
Write-Ahead Logging

- Ordered append-only file on disk
- Contains entries like <txid, obj, op, old, new>
  - ID of transaction, object modified, (optionally) the operation performed, the old value **and** the new value
  - This means we can both "roll forward" (redo operations) and "rollback" (undo operations)
- When persisting a transaction to disk:
  - First log a special entry <txid, START>
  - Next log a number of entries to describe operations
  - Finally log another special entry <txid, COMMIT>

Using a Write-Ahead Log

- When executing transactions, perform updates to objects in memory with lazy write back
  - i.e. the OS can push changes to disk whenever it wants
- Initially can do the same with the log entries…
- But when wish to *commit* a transaction, must first **synchronously** flush a commit record to the log
  - Assume there is a 'fsync' operation or similar which allows us to force data out to disk
  - Only report transaction as committed when fsync returns
- Can improve performance by delaying flush until we have a number of transaction to commit
  - Hence at any point in time we have some prefix of the write-ahead log on disk, and the rest in memory

The Big Picture

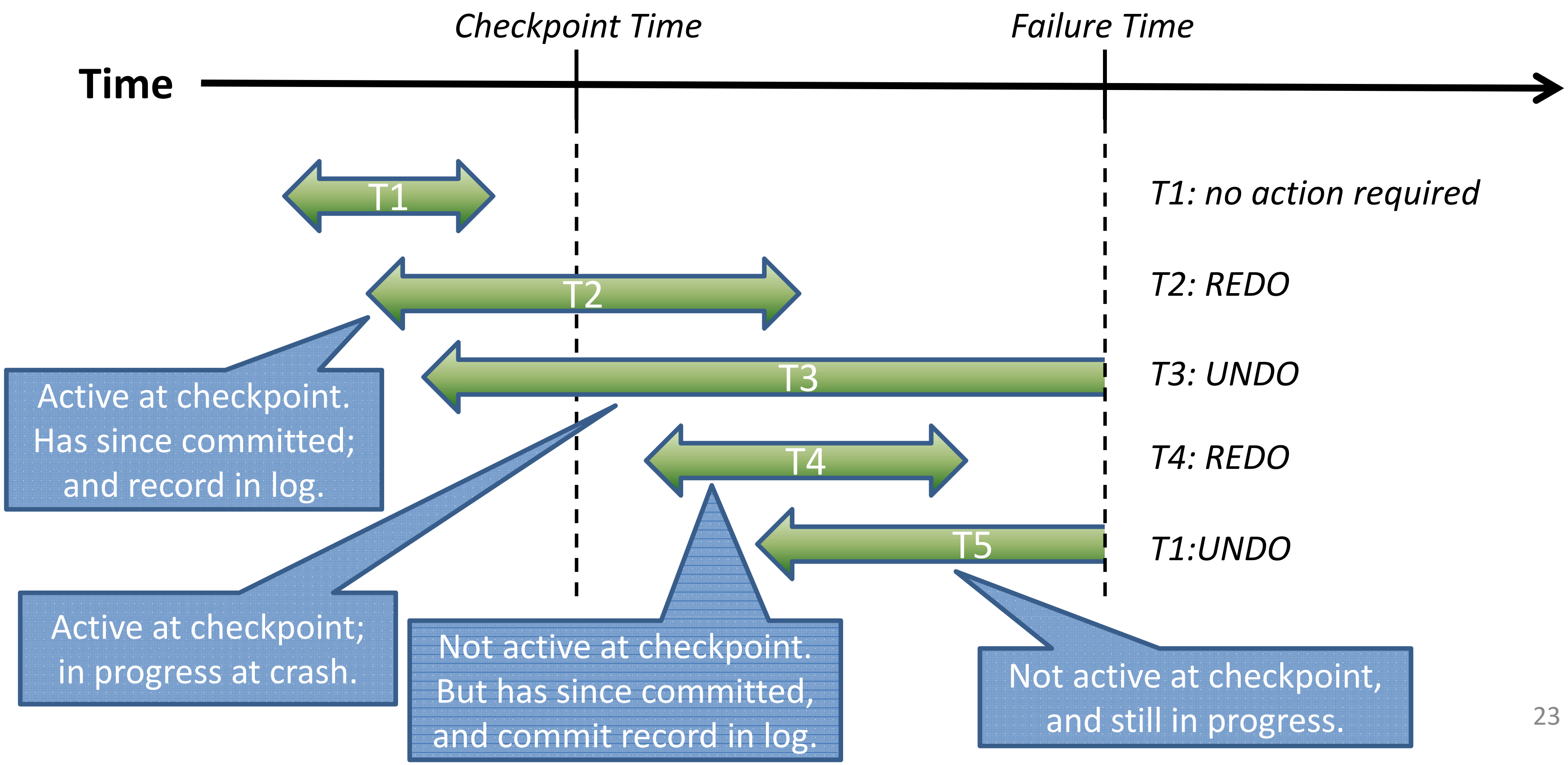


Checkpoints

- As described, log will get very long
  - And need to process every entry in log to recover
- Better to periodically write a **checkpoint**
  - Flush all current in-memory log records to disk
  - Write a special checkpoint record to log which contains a list of active transactions
  - Flush all 'dirty' objects (i.e. ensure object values on disk are up to date)
  - Flush location of new checkpoint record to disk
- (Not fatal if crash during final write)

Checkpoints and Recovery

- Key benefit of a checkpoint is it lets us focus our attention on possibly affected txactions



Recovery Algorithm

- Initialize undo list **U** = { set of active txactions }
- Also have redo list **R**, initially empty
- Walk log forward from checkpoint record:
  - If see a START record, add txaction to **U**
  - If see a COMMIT record, move txaction from **U**->**R**
- When hit end of log, perform undo:
  - Walk backward and undo all records for all Tx in **U**
- When reach checkpoint record again, Redo:
  - Walk forward, and re-do all records for all Tx in **R**

Transactions: Summary

- Standard mutual exclusion techniques not great for dealing with >1 object
  - intricate locking (& lock order) required, or
  - single coarse-grained lock, limiting concurrency
- Transactions allow us a better way:
  - potentially many operations (reads and updates) on many objects, but should execute as if atomically
  - underlying system deals with providing isolation, allowing safe concurrency, and even fault tolerance!
- Transactions widely used in database systems

Advanced Topics

- Will briefly look at two advanced topics
  – lock-free data structures, and
  – transactional memory
- This is informational & not examinable!
  – but worth knowing at least something about
- (Those of you who are super keen are invited to attend Tim Harris's ACS course:
  – 4pm-6pm on Thu Nov 3, 10 and 17; in SW01)

Lock-free Programming

- What's wrong with locks?
  - Difficult to get right (if locks are fine-grained)
  - Don't scale well (if locks too coarse-grained)
  - Don't compose well (deadlock!)
  - Poor cache behavior (e.g. convoying)
  - Priority inversion
  - And can be expensive
- Lock-free programming involves getting rid of locks ... but not at the cost of safety!

Assumptions

- We have a shared memory system
- Low-level (assembly instructions) include:

```
val  = read(addr);              // atomic read from memory
(void) write(addr, val);        // atomic write to memory
done = CAS(addr, old, new);     // atomic compare-and-swap
```

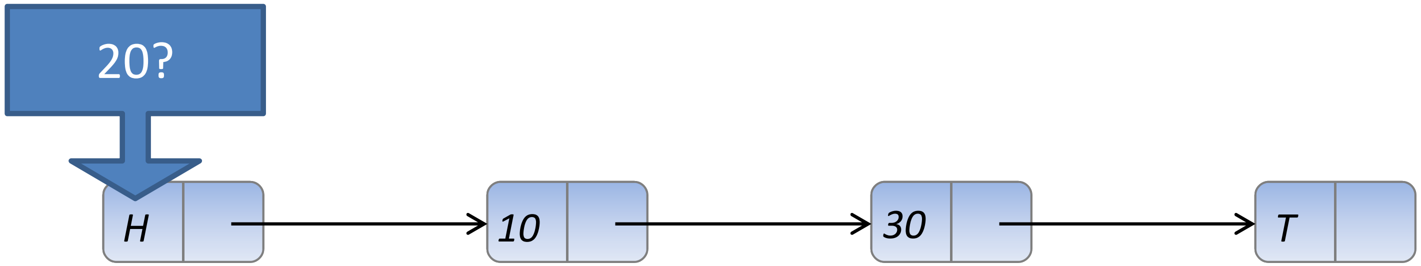
- Compare-and-Swap (CAS) is **atomic**
  - reads value of addr (‘val’), compares with ‘old’, and updates memory to ‘new’ iff old==val -- without interruption!
  - something like this instruction common on most modern processors (e.g. cmpxchg on x86)
- Typically used to build spinlocks (or mutexes, or semaphores, or sequencers, or whatever...)

Lock-free Approach

- Directly use CAS to update shared date
- As an example consider a lock-free linked list of integer values
  - list is singly linked, and sorted
- Represents the ‘set’ abstract data type, i.e.
  - find(int) -> bool
  - insert(int) -> bool
  - delete(int) -> bool

Searching a sorted list

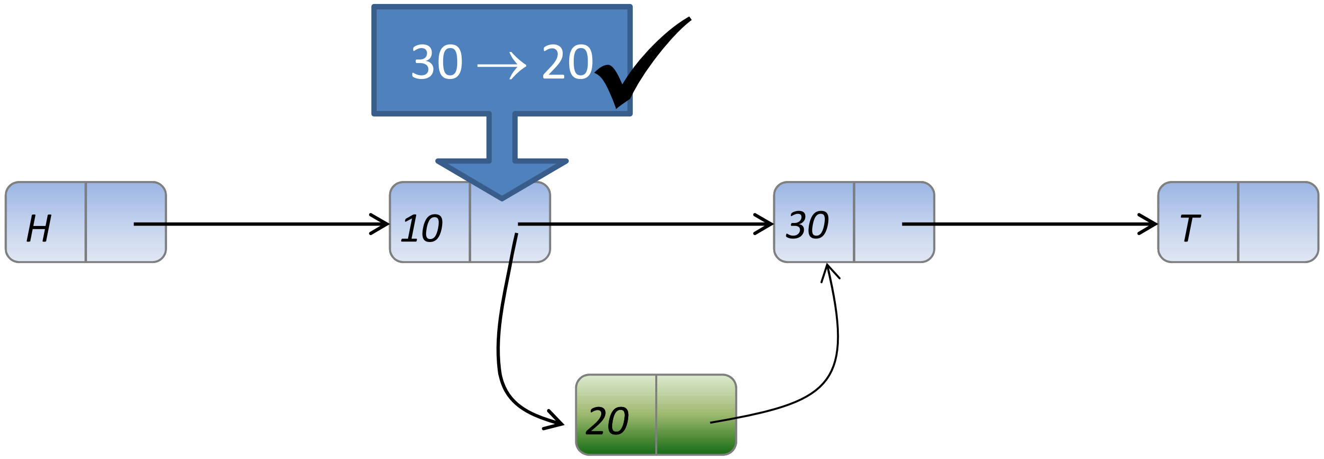
- find(20):



find(20) -> false

Inserting an item with CAS

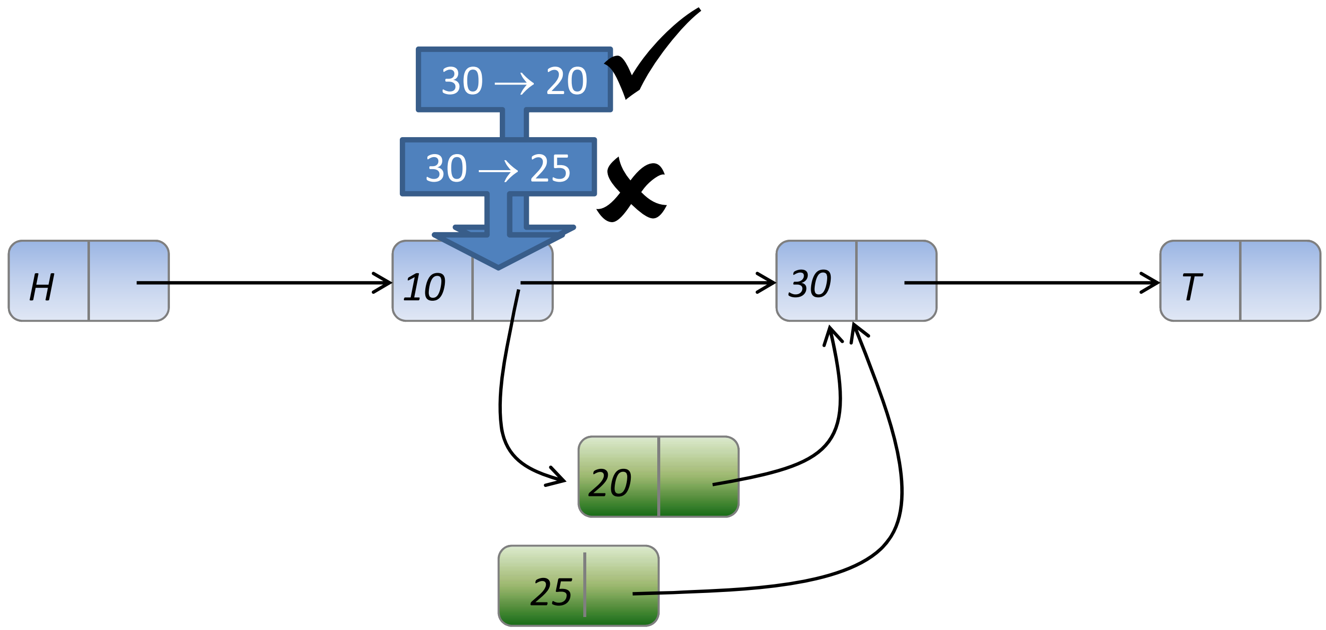
- insert(20):



insert(20) -> true

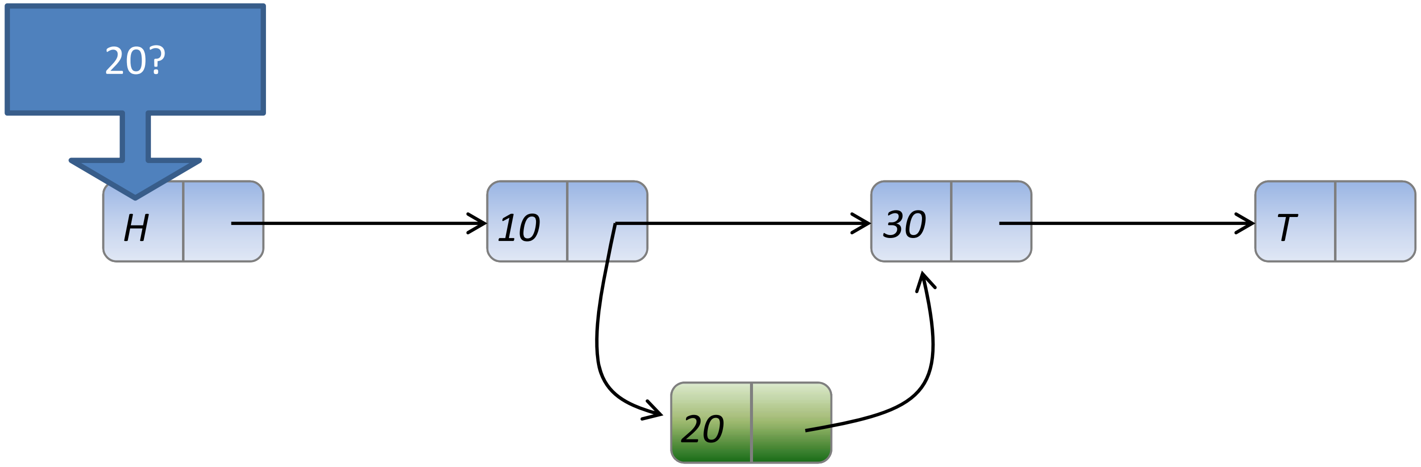
Inserting an item with CAS

- insert(20):
- insert(25):



Searching and finding together

- find(20) -> false
- insert(20) -> true

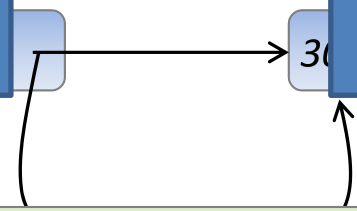


Searching and finding together

- find(20) -> false
- insert(20) -> true

This thread saw 20 was not in the set...

...but this thread succeeded in putting it in!



- Is this a correct implementation of a set?
- Should the programmer be surprised if this happens?
- What about more complicated mixes of operations?

Linearizability

- As with transactions, we return to a conceptual model to define correctness
  - a lock-free data structure is 'correct' if all changes (and return values) consistent with some serial view: we call this a **linearizable** schedule
- Hence in the previous example, we were ok:
  - can just deem the find() to have occurred first
- Gets a lot more complicated for more complicated data structures & operations!
  - see Tim Harris's course for more gory details...

Transactional Memory (TM)

- Steal idea from databases!
- Instead of:

```
lock(&mylock);
shared[i] *= shared[j] + 17;
unlock(&mylock);
```

  - Use:

```
atomic {
      shared[i] *= shared[j] + 17;
}
```

  - Has “obvious” semantics, i.e. all operations within block occur as if atomically
  - Transactional since under the hood it looks like:

```
do { txid = tx_begin(&thd);
      shared[i] *= shared[j] + 17;
} while !(tx_commit(txid));
```

TM Advantages

- Simplicity:
  - programmer just puts atomic { } around anything he/she wants to occur in isolation
- Composability:
  - unlike locks, atomic { } blocks nest, e.g:

```
credit(a, x) = atomic {
      setbal(a, readbal(a) + x);
}
debit(a, x) = atomic {
      setbal(a, readbal(a) - x);
}
transfer(a, b, x) = atomic {
      debit(a, x);
      credit(b, x);
}
```

TM Advantages

- Cannot deadlock:
  - No locks, so don’t have to worry about locking order
  - (Though may get livelock if not careful)
- No races (kinda):
  - Cannot forget to take a lock (although you can forget to put atomic { } around your critical section ;-)
- Scalability:
  - High performance possible via OCC
  - No need to worry about complex fine-grained locking

TM is very promising…

- Essentially does 'ACI' but no D
  - no need to worry about crash recovery
  - can work entirely in memory
  - some hardware support emerging (or promised)
- But not a panacea
  - Contention management can get ugly
  - Difficulties with irrevocable actions (e.g. IO)
  - Still working out exact semantics (type of atomicity, handling exceptions, signaling, ...)
- For more details, see Tim Harris's course

Concurrent Systems: Summary

- Concurrency is essential in modern systems
  - overlapping I/O with computation
  - exploiting multi-core
  - building distributed systems
- But throws up a lot of challenges
  - need to ensure safety, allow synchronization, and avoid issues of liveness (deadlock, livelock, ...)
- Major risk of over-engineering
  - generally worth building sequential system first
  - and worth using existing libraries, tools and design patterns rather than rolling your own!