Concurrent systems

Lecture 7: Crash recovery, lock-free programming, and transactional memory

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Reminder from last time

- History graphs; good (and bad) schedules
- Isolation vs. strict isolation; enforcing isolation
- Two-phase locking; rollback
- Timestamp ordering (TSO)
- Optimistic concurrency control (OCC)
- Isolation and concurrency summary

This time

- Transactional durability: crash recovery and logging
  - Write-ahead logging
  - Checkpoints
  - Recovery
- Advanced topics
  - Lock-free programming
  - Transactional memory
- A few notes on supervision exercises

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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

The small print: we must keep in mind the limitations of **fail-stop**, even as we assume it. Failing hardware/software do weird stuff. Pay attention to hardware price differentiation.

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

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Write-ahead logging

- **Log**: an 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>
- We build composite-operation atomicity from fundamental atomic unit: **single-sector write**.
  - Much like building high-level primitives over **LL**/**SC** or **CAS**!

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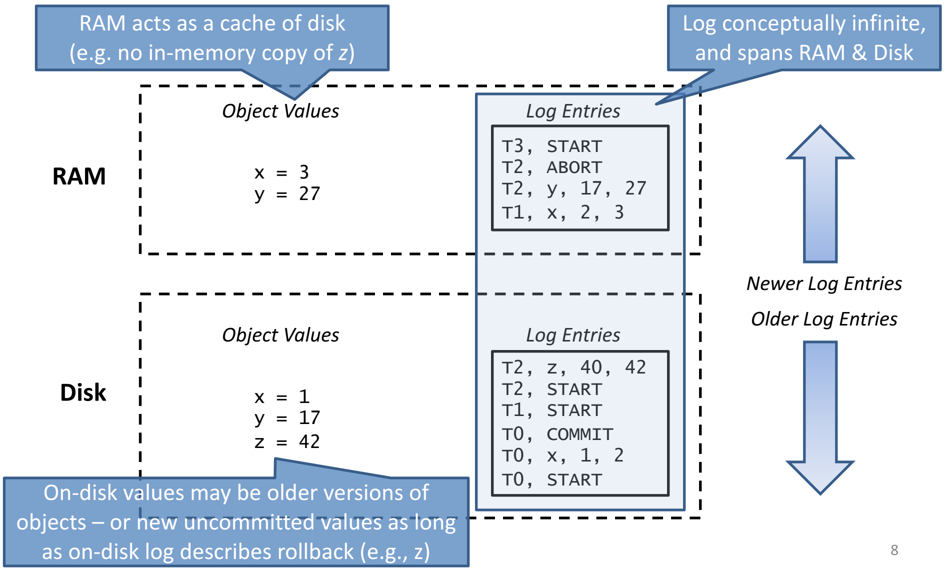
Using a write-ahead log

- When executing transactions, perform updates to objects in memory with **lazy write back**
  - I.e. the OS can delay disk writes to improve efficiency
- **Invariant: write log records before corresponding data**
- But when wish to *commit* a transaction, must first **synchronously** flush a commit record to the log
  - Assume there is a `fsync()` or `fsyncdata()` operation or similar which allows us to force data out to disk
  - Only report transaction committed when `fsync()` returns
- Can improve performance by delaying flush until we have a number of transaction to commit - **batching**
  - 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

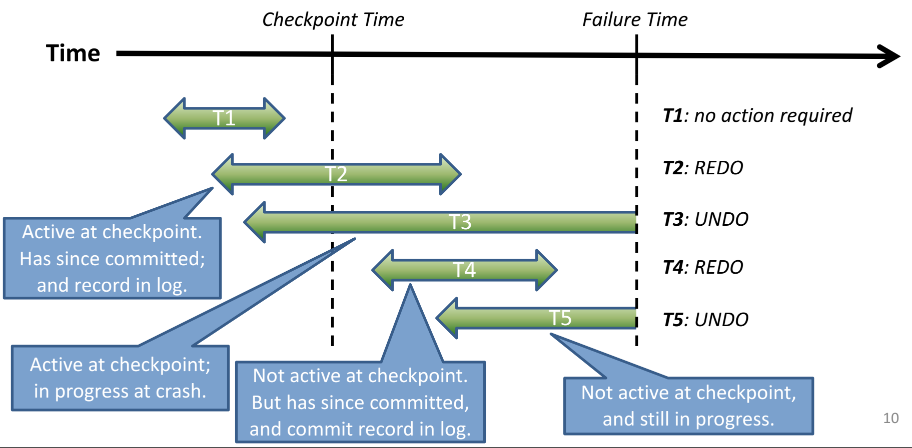


Checkpoints

- 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 transactions



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 transaction to **U**
  - If see a **COMMIT record**, move transaction 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**
- After recovery, we have effectively checkpointed
  - On-disk store is consistent, so can **truncate** the log

The order in which we apply undo/redo records is important to properly handling cases where multiple transactions touch the same data

Write-ahead logging: assumptions

- What can go wrong writing commits to disk?
- Even if **sector writes are atomic**:
  - All affected objects may not fit in a single sector
  - Large objects may span multiple sectors
  - Trend towards copy-on-write, rather than journaled, FSes
  - Many of the problems seen with in-memory commit (ordering and atomicity) apply to disks as well!
- Contemporary disks may not be entirely honest about sector size and atomicity
  - E.g., unstable write caches to improve efficiency
  - E.g., larger or smaller sector sizes than advertises
  - E.g., non-atomicity when writing to mirrored disks
- These assumes **fail-stop** – which is not true for some media

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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 used in databases + filesystems

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Advanced Topics

- Will briefly look at two advanced topics
  - lock-free data structures, and
  - transactional memory
- Then, next time, on to a case study

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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!
- Recall **TAS**, **CAS**, **LL/SC** from our first lecture: what if we used them to implement something other than locks?

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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 – or **LL/SC** on RISC)
- Typically used to build spinlocks (or mutexes, or semaphores, or whatever...)

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Lock-free approach

- Directly use **CAS** to update shared data
- As an example consider a lock-free linked list of integer values
  - list is singly linked, and sorted
  - Use **CAS** to update pointers
  - Handle **CAS** failure cases (i.e., races)
- Represents the 'set' abstract data type, i.e.
  - find(int) -> bool
  - insert(int) -> bool
  - delete(int) -> bool
- Assumption: hardware supports atomic operations on pointer-size types

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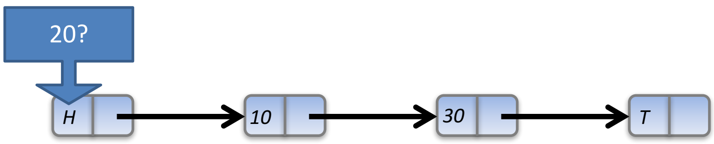
Searching a sorted list

- find(20):



find(20) -> false

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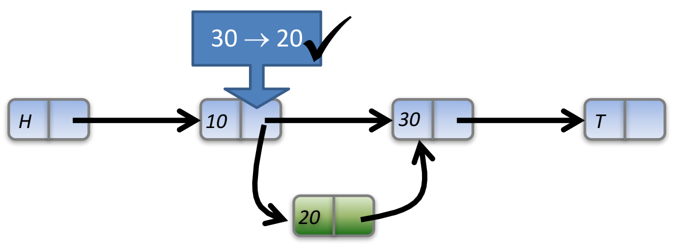
Inserting an item with CAS

- insert(20):



insert(20) -> true

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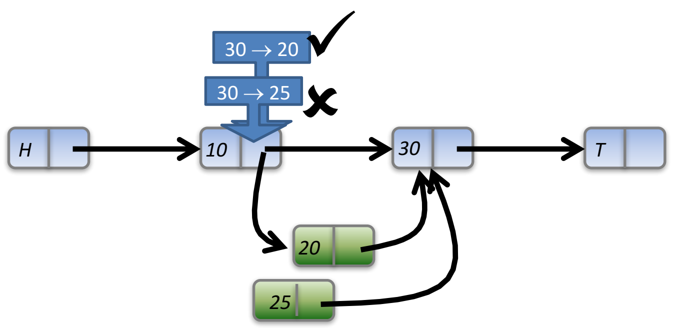
Inserting an item with CAS

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



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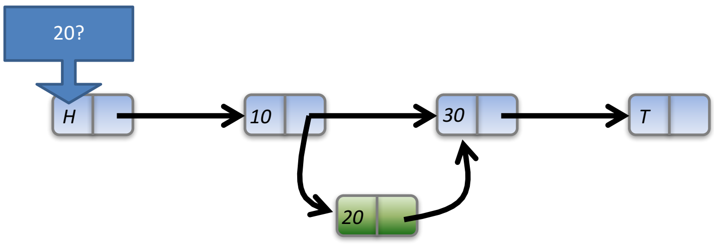
Concurrent find+insert

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

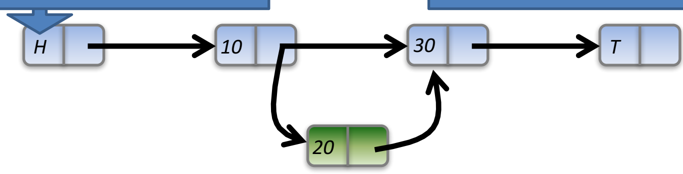


Concurrent find+insert

- 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?

Linearisability

- 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) are consistent with some serial view: we call this a **linearisable 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!
- NB: On current hardware, synchronisation does more than just provide atomicity
  - Also provides ordering: "happens-before"
  - Lock-free structures must take this into account as well

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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 live lock if not careful)
- No races (mostly):
  - 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
- There is still a simplicity vs. performance tradeoff
  - Too much **atomic {}** and implementation can't find concurrency. Too little, and race conditions.

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, ...)
- Recent x86 hardware has started to provide direct support for transactions; not widely used
  - … And promptly withdrawn in errata
  - Now back on the street again – but very new

Supervision questions + exercises

- Supervision questions
  - S1: Threads and synchronisation
    - Semaphores, priorities, and work distribution
  - S2: Transactions
    - ACID properties, 2PL, TSO, and OCC
  - Other C&DS topics also important, of course!
- Optional Java practical exercises
  - Java concurrency primitives and fundamentals
  - Threads, synchronisation, guarded blocks, producer-consumer, and data races

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!

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Summary + next time

- Transactional durability: crash recovery and logging
  - Write-ahead logging; checkpoints; recovery
- Advanced topics
  - Lock-free programming
  - Transactional memory
- Notes on supervision exercises

- Next time:
  - Concurrent system case study the FreeBSD kernel
  - Brief history of kernel concurrency
  - Primitives and debugging tools
  - Applications to the network stack

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