Language-level Non-blocking Software Transactions (in Java!)

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Notes

Nothing should be said on the title slide.

Transactions (review)

- A transaction is a sequence of loads and stores that either commits or aborts.
- If a transaction commits, all the loads and store appear to have executed atomically.
- If a transaction aborts, none of its stores take effect.
- Transaction operations aren't visible until they commit or abort.

Notes

Non-blocking synchronization

- Although transactions can be implemented with mutual exclusion (locks), we are interested only in non-blocking implementations.
- In a non-blocking implementation, the failure of one process cannot prevent other processes from making progress. This leads to:
  - Scalable parallelism
  - Fault-tolerance
  - Safety: freedom from some problems which require careful bookkeeping with locks, including priority inversion and deadlocks.
- Little known requirement: limits on transaction suicide.

Notes

Scalable parallelism, because non-conflicting threads aren't blocked.
Fault-tolerance, because the failure of one thread won't stop the others.
Easier to program.
It turns out you have to be careful about which transaction to abort when there are conflicts in order to maintain the non-blocking properties. The original hardware transactions paper by Herlihy/Moss got this wrong, although correcting the problem is trivial.

Monitor Synchronization

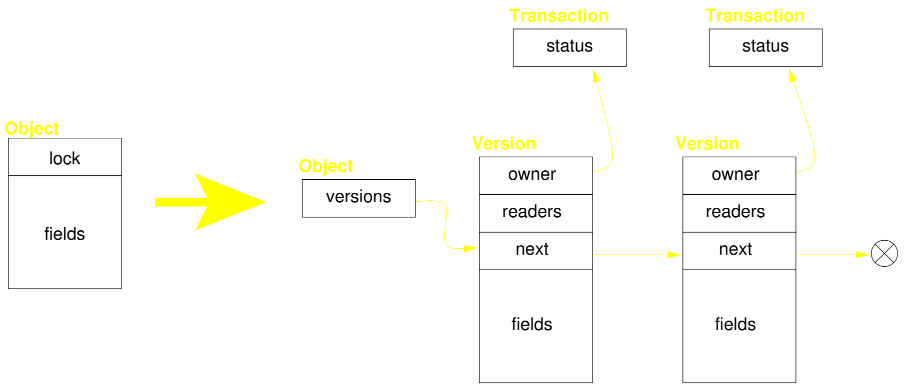
```
public class Count {        public class Count {
 private int cntr = 0;       private int cntr = 0;
 void inc() {                void inc() {
  synchronized(this) {  ⇒    atomically {
   cntr = cntr + 1;            cntr = cntr + 1;
  }                           }
 }                           }
}                           }
```

- Traditionally, monitors associated with each object provide mutual exclusion between concurrent accesses to the object. Instead we provide an `atomic` block, and make linearizablity

Notes

Synchronization in object-oriented systems can be performed with monitors, introduced by the Emerald system, which are basically per-object locks. This is how it looks in Java – the argument to synchronized states which object's monitor you wish to take. In general, you are only supposed to modify shared variables of an object after taking its monitor. This is not sufficient to prevent unexpected parallel behavior – but it helps.
Instead, we would like to specify synchronization as *atomic blocks*, which guarantee that the enclosed operations will be perceived as atomic by all other threads. This prevents some errors with monitors, especially in operations that use more than object.
Atomic blocks can be implemented with locks, but we'd prefer an optimistic non-blocking implementation.

Implementation Idea



Traditional ***Transactional***

Notes

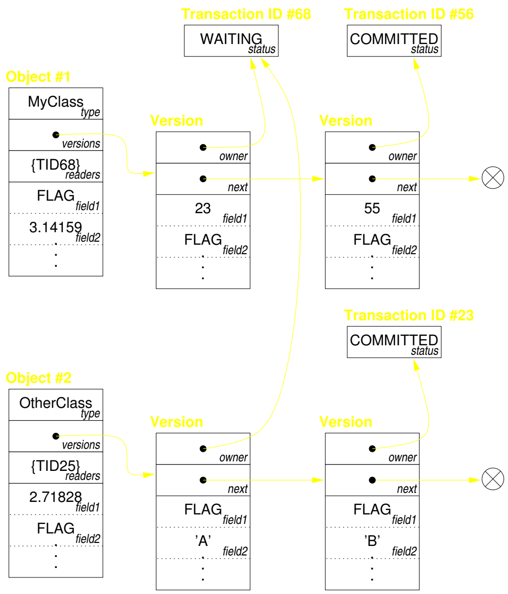
Here is how an optimistic vesion of `atomic` may be implemented. Instead of an object directly containing fields, it now points to a *version list*. Each version is associated with a transaction, which may be COMMITTED, WAITING, or ABORTING. The "current" value of the object is the value in the fields of the first committed version.
We must also keep a list of readers, so that we can detect when our atomicity guarantees are violated by concurrent operations. Whenever something like this goes wrong, we simply abort the transaction (by updating its status) and retry.
By ordering lists such that the relevant entries in the version and readers lists are likely to be first at the head, this scheme can be made efficient.

A software transaction impl.

- Goals:
  - Non-transactional operations should be fast.
  - Reads should be faster than writes.
  - Minimal amount of object bloat.
- Solution:
  - Use special `FLAG` value to indicate "location involved in a transaction".
  - Object points to a linked list of versions, containing values written by (in-progress, committed, or aborted) transactions.
  - Semantic value of a `FLAG`ged field is: "value of the first version owned by a committed transaction on the version list."

Notes

Transactions using version lists



Notes

Races, races, everywhere!

- Lots of possible races:
  - What if two threads try to `FLAG` a field at the same time?
  - What if two threads try to copy-back a `FLAG`ged field at the same time?
  - What if two transactions perform conflicting updates?
  - Do transactions commit atomically?
- Formulated model in Promela and used Spin to verify correctness (for bounded scope, etc).

Notes

Bugs found with model-checking

- Memory management (object recycling, reference counting)
- Read caching (check copies to local variables)
- “Real” bug: missing abort of readers during non-transactional write

Too much time spent minimizing/coalescing state. =(

Notes

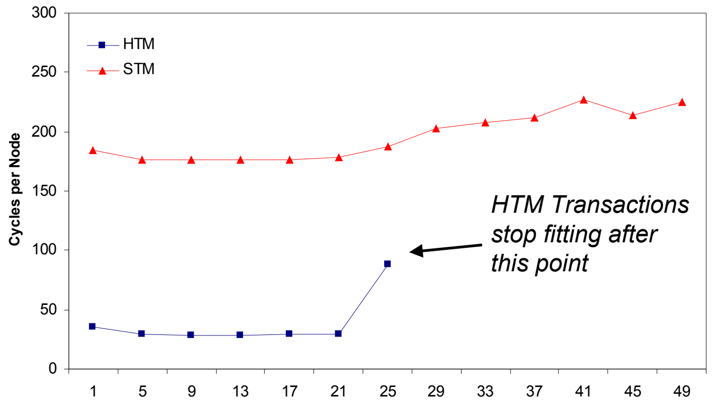
More Fun

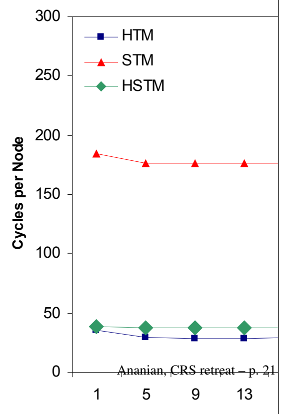
- Large objects
- Interaction with I/O
- Interaction with native methods
- Nested transactions
- Exposing abort/retry mechanism
- Supporting wait/notify

Notes

Cooperating HW/SW transactions

- Using “node-push” micro-benchmark with a hardware transaction mechanism (submitted ASPLOS-XI)
- Hardware starts to perform poorly for large or long-lived transactions.





Notes

Optimistic parallelism

```
for (...)
  optimistically {
    ...do an iteration ...
  }
```

```
conquer(A[n], n) {
  ...
  optimistic spawn
    conquer(A, n/2);
  optimistic spawn
    conquer(A+n/2, n-n/2);
}
```

Programmer notes that the iterations or spawns are *expected* to be independent. Iff there are dynamic dependencies, the computations are serialized.

Notes

There are different ways multiple transactions can interact. We could allow only one active transaction at a time, only allow non-overlapping transactions, allow nested transactions, concurrent transactions, subsumed transactions, nested independent transactions, or other variations.
We’d like the investigate using this mechanism to allow a programmer to specify *optimistic* parallelism. This is much easier to make safe, although potentially just as hard to make fast.

The End

Notes

The Spin Model Checker

- Spin is a model checker for communicating concurrent processes. It checks:
  - Safety/termination properties.
  - Liveness/deadlock properties.
  - Path assertions (requirements/never claims).
- It works on finite models, written in the Promela language, which describe infinite executions.
- Explores the entire state space of the model, including all possible concurrent executions, verifying that Bad Things don't happen.
- Not an absolute proof — but pretty useful in practice.

Notes

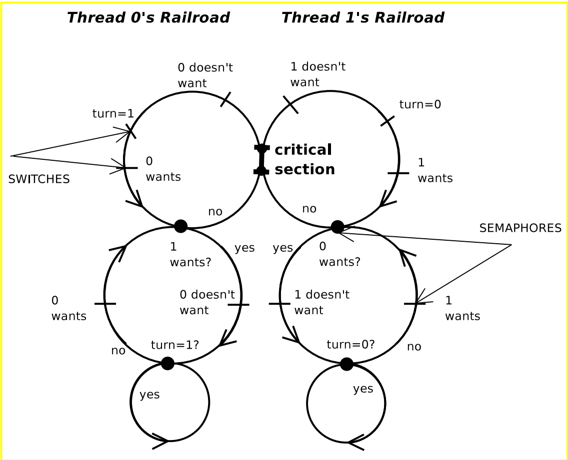
Dekker's mutex algorithm (C)

```
int turn;
int wants[2];

// i is the current thread, j=1-i is the other thread
while(1) {                 // trying
   wants[i] = TRUE;
   while (wants[j]) {
      if (turn==j) {
         wants[i] = FALSE;
         while (turn==j) ; // empty loop
         wants[i] = TRUE;
      }
  }
  critical_section();
  turn=j;                  // release
  wants[i] = FALSE;
  noncrit();
}
```


Notes

Dekker's "railroad"



Railroad visualization of Dekker's algorithm for mutual exclusion. The threads "move" in the direction shown by the arrows.

Notes

Dekker's mutex algorithm (Promela)

```
bool turn, flag[2]; byte cnt;
active [2] proctype mutex()     /* Dekker's 1965 algorithm */
{       pid i, j;
        i = _pid;
        j = 1 - _pid;
again:  flag[i] = true;
        do      /* can be 'if' - says Doran&Thomas */
        :: flag[j] ->
                if
                :: turn == j ->
                        flag[i] = false;
                        !(turn == j);
                        flag[i] = true
                :: else
                fi
        :: else -> break
        od;
        cnt++; assert(cnt == 1); cnt--; /* critical section */
        turn = j;
        flag[i] = false;
        goto again
}
```


Notes

Spin verification

```
$ spin -a mutex.pml
$ cc -DSAFETY -o pan pan.c
$ ./pan
(Spin Version 4.1.0 -- 6 December 2003)
        + Partial Order Reduction

Full statespace search for:
        never claim             - (none specified)
        assertion violations    +
        cycle checks            - (disabled by -DSAFETY)
        invalid end states      +

State-vector 20 byte, depth reached 65, errors: 0
     190 states, stored
     173 states, matched
     363 transitions (= stored+matched)
       0 atomic steps
hash conflicts: 0 (resolved)
(max size 2^18 states)
$
```

If an error is found, will give you execution trail producing the error.

Notes

Spin theory

- Generates a Büchi Automaton from the Promela specification.
  - Finite-state machine w/ special acceptance conditions.
  - Transitions correspond to executability of statements.
- Depth-first search of state space, with each state stored in a hashtable to detect cycles and prevent duplication of work.
  - If x followed by y leads to the same state as y followed by x, will not re-traverse the succeeding steps.
- If memory is not sufficient to hold all states, may ignore hashtable collisions: requires one bit per entry. # collisions provides approximate coverage metric.

Notes

Modeling software transactions

Notes

Non-transactional Read

```
inline readNT(o, f, v) {
  do
  :: v = object[o].field[f];
     if
     :: (v!=FLAG) -> break /* done! */
     :: else
     fi;
     copyBackField(o, f, kill_writers, _st);
     if
     :: (_st==false_flag) ->
        v = FLAG;
        break
     :: else
     fi
  od
}
```


Notes

Non-transactional Write

```
inline writeNT(o, f, nval) {
  if
  :: (nval != FLAG) ->
     do
     :: atomic {
          if /* this is a LL(readerList)/SC(field) */
          :: (object[o].readerList == NIL) ->
             object[o].fieldLock[f] = _thread_id;
             object[o].field[f] = nval;
             break /* success! */
          :: else
          fi
        }
        /* unsuccessful SC */
        copyBackField(o, f, kill_all, _st)
     od
  :: else -> /* create false flag */
     /* implement this as a short *transactional* write.  */
     /* start a new transaction, write FLAG, commit the transaction,
      * repeat until successful.  Implementation elided. */
  fi;
}
```


Notes

Copy-back Field, part I

```
inline copyBackField(o, f, mode, st) {
  _nonceV=NIL; _ver = NIL; _r = NIL; st = success;
  /* try to abort each version.  when abort fails, we've got a
   * committed version. */
  do
  :: _ver = object[o].version;
     if
     :: (_ver==NIL) ->
        st = saw_race; break /* someone's done the copyback for us */
     :: else
     fi;
      /* move owner to local var to avoid races (owner set to NIL behind
       * our back) */
     _tmp_tid=version[_ver].owner;
     tryToAbort(_tmp_tid);
     if
     :: (_tmp_tid==NIL || transid[_tmp_tid].status==committed) ->
        break /* found a committed version */
     :: else
     fi;
     /* link out an aborted version */
     assert(transid[_tmp_tid].status==aborted);
     CAS_Version(object[o].version, _ver, version[_ver].next, _);
  od;
```

continued. . .

Notes

Copy-back Field, part II

```
  /* okay, link in our nonce.  this will prevent others from doing the
   * copyback. */
  if
  :: (st==success) ->
     assert (_ver!=NIL);
     allocVersion(_retval, _nonceV, aborted_tid, _ver);
     CAS_Version(object[o].version, _ver, _nonceV, _cas_stat);
     if
     :: (!_cas_stat) ->
        st = saw_race_cleanup
     :: else
     fi
  :: else
  fi;
```

continued. . .

Notes

Copy-back Field, part III

```
/* check that no one's beaten us to the copy back */
if
:: (st==success) ->
   if
   :: (object[o].field[f]==FLAG) ->
      _val = version[_ver].field[f];
      if
      :: (_val==FLAG) -> /* false flag... */
         st = false_flag /* ...no copy back needed */
      :: else -> /* not a false flag */
         d_step { /* LL/SC */
           if
           :: (object[o].version == _nonceV) ->
              object[o].fieldLock[f] = _thread_id;
              object[o].field[f] = _val;
           :: else /* hmm, fail.  Must retry. */
              st = saw_race_cleanup /* need to clean up nonce */
           fi
         }
      fi
   :: else /* may arrive here because of readT, which doesn't set _val=FLAG*
      st = saw_race_cleanup /* need to clean up nonce */
   fi
:: else /* !success */
fi;
```

continued. . .

Notes

Copy-back Field, part IV

```
  /* always kill readers, whether successful or not.  This ensures that we
   * make progress if called from writeNT after a readNT sets readerList
   * non-null without changing FLAG to _val (see immediately above; st will
   * equal saw_race_cleanup in this scenario). */
  if
  :: (mode == kill_all) ->
     do /* kill all readers */
     :: moveReaderList(_r, object[o].readerList);
        if
        :: (_r==NIL) -> break
        :: else
        fi;
        tryToAbort(readerlist[_r].transid);
        /* link out this reader */
        CAS_Reader(object[o].readerList, _r, readerlist[_r].next, _);
     od;
  :: else /* no more killing needed. */
  fi;
  /* done */
}
```

done!

Notes

Synchronization Failures

```
class A { // OK!
    int x; // shared variable
    synchronized int inc() {
        return x++;
    }
}

class B { // Race-free, but not OK.
    int x; // shared variable
    synchronized int get() { return x; }
    synchronized void set(int y) { x=y; }
    int inc() { // not monitored
        int t = get();
        t++;
        set(t);
        return t;
    }
}
```


Notes

The class A here, shows what monitor synchronization looks like in Java. The `synchronized` keyword indicates that this is a monitored method. Only one thread may be hold the monitor at a time, thus only one thread may be inside `inc()` at a time. This guarantees that the increment behaves as we expect: this is a correctly synchronized method.

But look at class B, which implements the same functionality. Note that the only access to shared variable `x` is inside the monitored `get()` and `set()` methods — but this code is not safe! If n threads call `inc()`, the shared variable x may be incremented any number between 1 to n times.