Verifying Software Transactions

C. Scott Ananian

Computer Science and Artifical Intelligence Laboratory
Massachusetts Institute of Technology

Outline

- Concurrency control with non-blocking transactions (review)
- Introduction to the Spin Model Checker
- Modelling a software transaction implementation
- Conclusions

Non-blocking Transactions

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.

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.

Non-blocking algorithms are hard!

- In published work on Synthesis, a non-blocking operating system implementation, three separate races were found:
  - One ABA problem in LIFO stack.
  - One likely race in MP-SC FIFO queue.
  - One interesting corner case in quaject callback handling.
- It's hard to get these right! Ad hoc reasoning doesn't cut it.

The Spin Model Checker

The Spin Model Checker

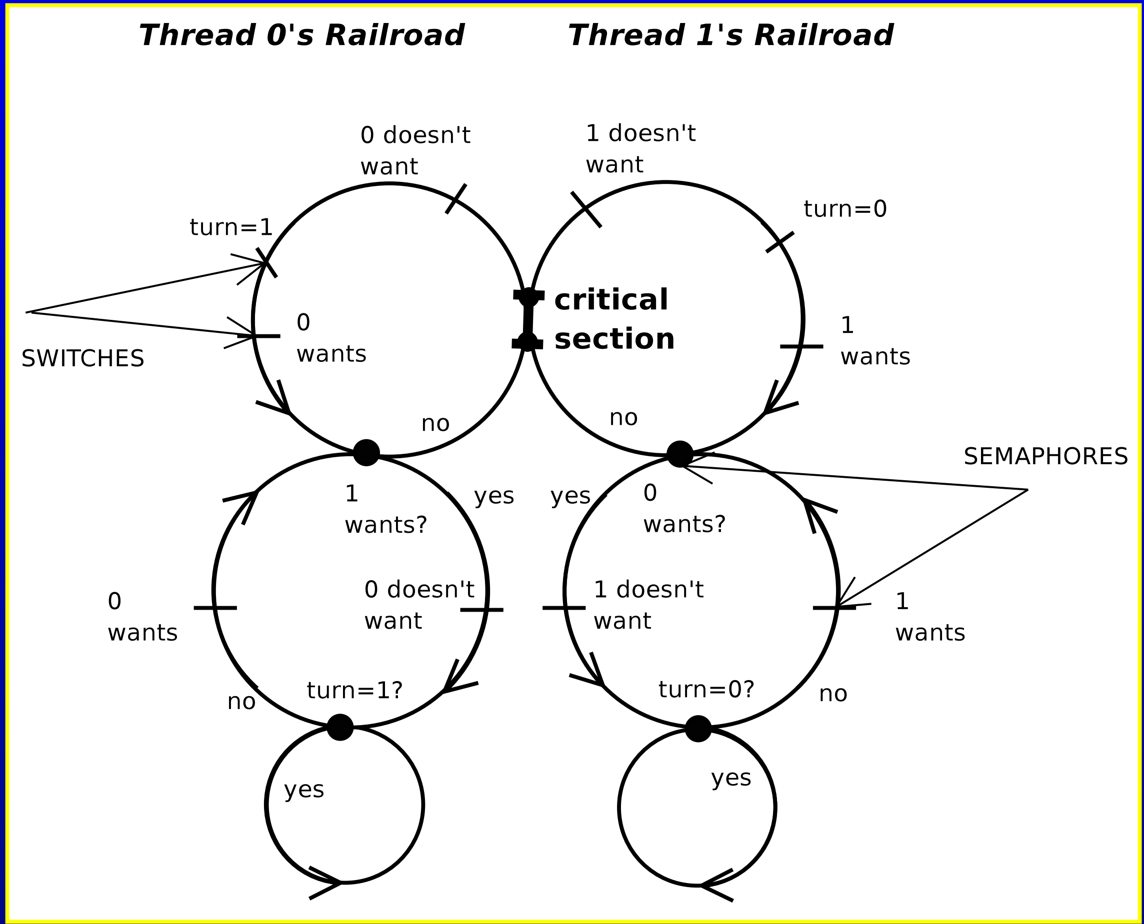
- Spin is a model checker for communicating concurrent processes. It checks:
  - Safety/termination properties.
  - Liveness/deadlock properties.
  - Path assertions (requirements/never claims).
- It works on finite models, written in the Promela language, which describe infinite executions.
- Explores 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.

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();
}
```

Dekker's "railroad"



Railroad visualization of Dekker's algorithm for mutual exclusion. The threads "move" in the direction shown by the arrows. [from lecture 5 scribe 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
}
```

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.

Spin theory

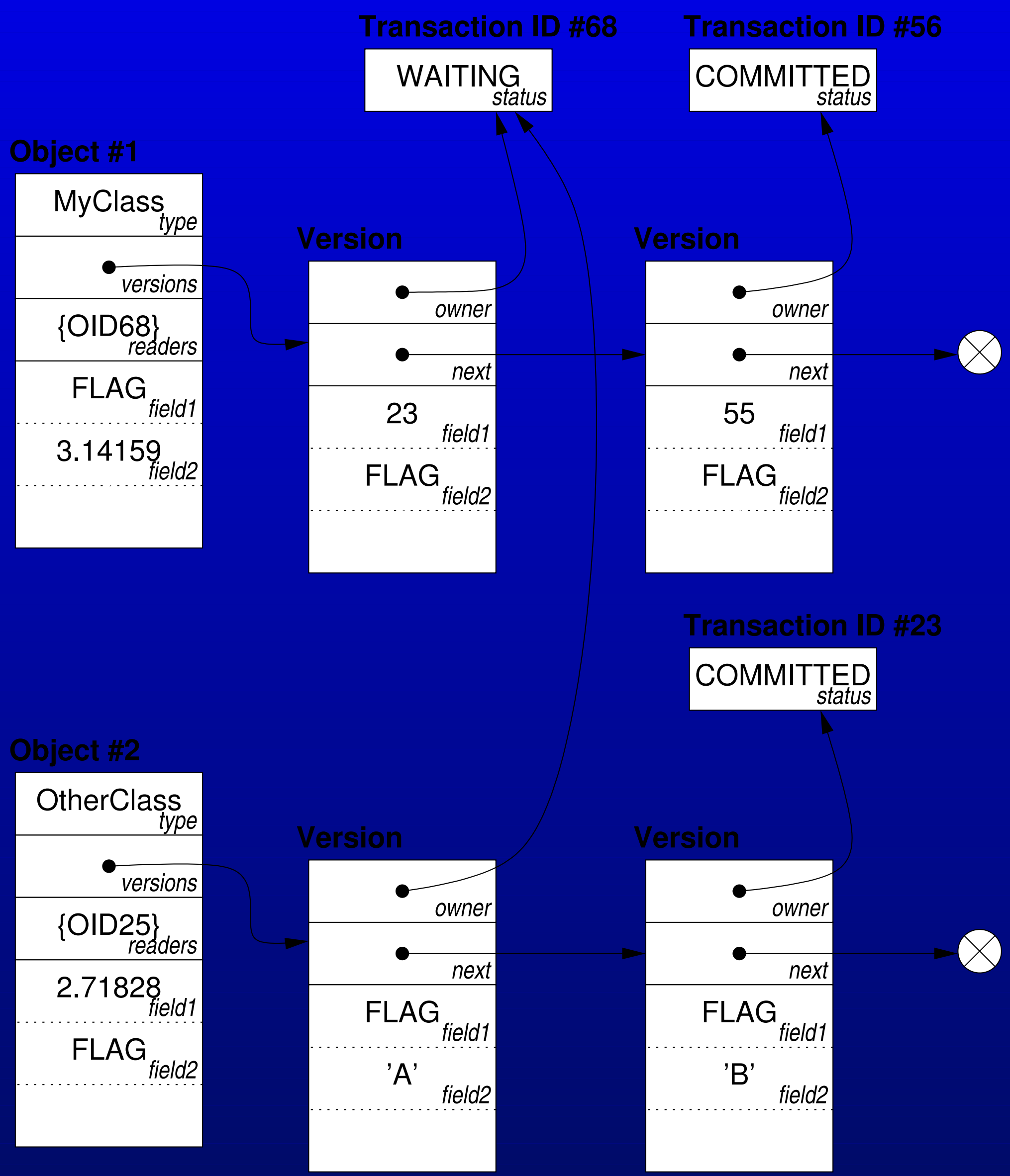
- Generates a Büchi Automaton from the Promela specification.
  - Finite-state machine w/ special acceptance conditions.
  - Transitions correspond to executability of statements.
- Depth-first search of state space, with each state stored in a hashtable to detect cycles and prevent duplication of work.
  - 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.

Modeling software transactions

software transaction implementation

- 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.”

Transactions using version lists



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.
    - Used the 16G on memory on `yggdrasil` to good advantage.

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
}
```

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;
}
```

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...

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. . .

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. . .

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!

Conclusions

Conclusions

- Non-blocking transactions are a useful and intuitive means of concurrency control.
- Software implementations of non-blocking transactions are possible and may be efficient, but hard to get right!
- The Spin model checking tool is an excellent way to nail down indeterminacies in parallel code and more rigorously show correctness.