Practical Concurrent and Parallel Programming 9

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Plan for today

- What's wrong with lock-based atomicity
- Transactional memory STM, Multiverse library
- A transactional bank account
- Transactional blocking queue
- Composing atomic operations
  - transfer from one queue to another
  - choose first available item from two queues
- Philosophical transactions
- Other languages with transactional memory
- Hardware support for transactional memory
- **NB: Course evaluation ongoing**

Transactional memory

- Based on transactions, as in databases
- Transactions are composable
  - unlike lock-based concurrency control
- Easy to implement blocking
  - no **`wait`** and **`notifyAll`** or semaphore trickery
- Easy to implement blocking choice
  - eg. get first item from any of two blocking queues
- Typically *optimistic*
  - automatically very scalable read-parallelism
  - unlike *pessimistic* locks
- No deadlocks and usually no livelocks

Transactions

- Know from databases since 1981 (Jim Gray)
- Proposed for programming languages 1986
  - (In a functional programming conference)
- Became popular again around 2004
  - due to Harris, Marlow, Peyton-Jones, Herlihy
  - Haskell, Clojure, Scala, ... and Java Multiverse
- A transaction must be
  - **A**tomic: if one part fails, the entire transaction fails
  - **C**onsistent: maps a valid state to a valid state
  - **I**solated: A transaction does not see the effect of any other transaction while running
  - (But *not* **D**urable, as in databases)

Difficulties with lock-based atomicity

- Transfer money from account ac1 to ac2
  - No help that each account operation is atomic
  - Can lock both, but then there is deadlock risk
- Transfer an item from queue bq1 to bq2
  - No help that each queue operation is atomic
  - Locking both, nobody can put and take; deadlock
- Get an item from either queue bq1 or bq2
  - (when both queues are blocking)
  - Should block if both empty
  - But just calling **`b1.take()`** may block forever even if there is an available item in **`bq2`**

A la Herlihy & Shavit §18.2

Transactions make this trivial

- Transfer amount from account ac1 to ac2:

Pseudo-code

```
atomic {
    ac1.deposit(-amount);
    ac2.deposit(+amount);
}
```

- Transfer one item from queue bq1 to bq2:

```
atomic {
  T item = bq1.take();
  bq2.put(item);
}
```

- Take item from queue bq1 if any, else bq2:

```
atomic {
  return bq1.take();
} orElse {
  return bq2.take();
}
```

A la Herlihy & Shavit § 18.2

Transactional account

Pseudo-code

```
class Account {
  private long balance = 0;
  public void deposit(final long amount) {
    atomic {
      balance += amount;
    }
  }
  public long get() {
    atomic {
      return balance;
    }
  }
  public void transfer(Account that, final long amount) {
    final Account thisAccount = this, thatAccount = that;
    atomic {
      thisAccount.deposit(-amount);
      thatAccount.deposit(+amount);
    }
} }
```

Composite transaction without deadlock risk

Transactional memory in Java

- Multiverse Java library 0.7 from April 2012
  - Seems comprehensive and well-implemented
  - Little documentation apart from API docs
  - ... and those API docs are quite cryptic
- A transaction must be wrapped in
  - `new Runnable() { ... }` if returning nothing
  - `new Callable<T>() { ... }` if returning a T value
  - or just a lambda `() -> { ... }` in either case
- Runs on unmodified JVM
  - Thus is often slower than locks/volatile/CAS/...
- To compile and run:

```
$ javac -cp ~/lib/multiverse-core-0.7.0.jar TestAccounts.java
$ java -cp ~/lib/multiverse-core-0.7.0.jar:. TestAccounts
```

Transactional account, Multiverse

stm/TestAccounts.java

```
class Account {
  private final TxnLong balance = newTxnLong(0);
  public void deposit(final long amount) {
    atomic(() -> balance.set(balance.get() + amount));
  }

  public long get() {
    return atomic(() -> balance.get());
  }

  public void transfer(Account that, final long amount) {
    final Account thisAccount = this, thatAccount = that;
    atomic(() -> {
      thisAccount.deposit(-amount);
      thatAccount.deposit(+amount);
    });
  }
}
```

Composite transaction without deadlock risk

Consistent reads

- Auditor computes balance sum during transfer

stm/TestAccounts.java

```
long sum = atomic(() -> account1.get() + account2.get());
System.out.println(sum);
```

- Must read both balances in same transaction
  - Does not work to use a transaction for each reading
- Should print the sum only outside transaction
  - After the transaction committed
  - Otherwise risk of printing multiple times...
- Multiverse: Does not work if **`deposit(amount)`** uses **`balance.increment(amount)`** ????

How do transactions work?

- A transaction txn typically keeps
  - Read Set: all variables read by the transaction
  - Write Set: *local copy* of variables it has updated
- When trying to commit, check that
  - no variable in Read Set or Write Set has been updated by another transaction
  - if OK, write Write Set to global memory, *commit*
  - otherwise, discard Write Set and *restart* txn again
- So the Runnable may be called many times!
- How long to wait before trying again?
  - Exponential backoff: wait **`rnd.nextInt(2)`**, **`rnd.nextInt(4)`**, **`rnd.nextInt(8)`**, ...
  - Should prevent transactions from colliding forever

Nested transactions

- By default, an **`atomic`** within an **`atomic`** reuses the outer transaction: So if the inner fails, the outer one fails too
- Several other possibilities, see org.multiverse.api.PropagationLevel
  - Default is PropagationLevel.Requires: if there is a transaction already, use that; else create one

Multiverse transactional references

- Only transactional variables are tracked
  - TxnRef<T>, a transactional reference to a T value
  - TxnInteger, a transactional **`int`**
  - TxnLong, a transactional **`long`**
  - TxnBoolean, a transactional **`boolean`**
  - TxnDouble, a transactional **`double`**
- Methods, used in a transaction, inside **`atomic`**
  - **`get()`**, to read the reference
  - **`set(value)`**, to write the reference
- Several other methods, eg
  - **`getAndLock(lockMode)`**, for more pessimism
  - **`await(v)`**, block until value is **`v`**

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Lock-based bounded queue (wk 8)

```
class SemaphoreBoundedQueue <T> implements BoundedQueue<T> {
  private final Semaphore availableItems, availableSpaces;
  private final T[] items;
  private int tail = 0, head = 0;

  public void put(T item) throws InterruptedException {
    availableSpaces.acquire();
    doInsert(item);
    availableItems.release();
  }


  private synchronized void doInsert(T item) {
    items[tail] = item;
    tail = (tail + 1) % items.length;
  }

  public T take() throws InterruptedException { ... }
  ...
}
```

Use semaphore to block until room for new item

Use lock for atomicity

TestBoundedQueueTest.java

Transactional blocking queue

```
class StmBoundedQueue<T> implements BoundedQueue<T> {
  private int availableItems, availableSpaces;
  private final T[] items;
  private int head = 0, tail = 0;

  public void put(T item) {      // at tail
    atomic {
      if (availableSpaces == 0)
        retry();
      else {
        availableSpaces--;
        items[tail] = item;
        tail = (tail + 1) % items.length;
        availableItems++;
      }
    }
  }
  public T take() {
    ... availableSpaces++; ...
  }
}
```

Atomic action

Use **retry()** to block

Pseudo-code

A la Herlihy & Shavit § 18.2

Real code, using Multiverse library

```
class StmBoundedQueue<T> implements BoundedQueue<T> {
  private final TxnInteger availableItems, availableSpaces;
  private final TxnRef<T>[] items;
  private final TxnInteger head, tail;

  public void put(T item) {      // at tail
    atomic(() -> {
      if (availableSpaces.get() == 0)
        retry();
      else {
        availableSpaces.decrement();
        items[tail.get()].set(item);
        tail.set((tail.get() + 1) % items.length);
        availableItems.increment();
      }
    });
  }
  public T take() {
    ... availableSpaces.increment(); ...
  }
}
```

Atomic action

Use **retry()** to block

stm/TestStmQueues.java

How does blocking work?

- When a transaction executes **`retry()`** ...
  - The Read Set says what variables have been read
  - No point in restarting the transaction until one of these variables have been updated by other thread
- Hence NOT a busy-wait loop
  - but automatic version of **`wait`** and **`notifyAll`**
  - or automatic version of **`acquire`** on Semaphore
- Often works out of the box, idiot-proof
- Must distinguish:
  - *restart* of transaction because could not commit
    - exponential backoff, random sleep before restart
  - an explicit **`retry()`** request for blocking
    - waits passively in a queue for Read Set to change

Atomic transfer between queues

```
static <T> void transferFromTo(BoundedQueue<T> from,
                               BoundedQueue<T> to)
{
  atomic(() -> {
    T item = from.take();
    to.put(item);
  });
}
```

stm/TestStmQueues.java

- A direct translation from the pseudo-code
- Can hardly be wrong

Blocking until some item available

```
static <T> T takeOne(BoundedQueue<T> bq1,
                     BoundedQueue<T> bq2) throws Exception
{
  return myOrElse(() -> bq1.take(),
                  () -> bq2.take());
}
```

Do this

or else that

stm/TestStmQueues.java

- If **bq1.take()** fails, try instead **bq2.take()**
- Implemented using general **myOrElse** method
  - taking as arguments two Callables

Implementing method myOrElse

```
static <T> T myOrElse(Callable<T> either, Callable<T> orelse)
  throws Exception
{
  return atomic(() -> {
    try {
      return either.call();
    } catch (org.multiverse.api.exceptions.RetryError retry) {
      return orelse.call();
    }
  });
}
```

stm/TestStmQueues.java

- Exposes Multiverse's internal machinery
  - **`retry()`** is implemented by throwing an exception
- Hand-made implementation
  - Because Multiverse's OrElseBlock seems faulty...

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- **Philosophical transactions**
- Other languages with transactional memory
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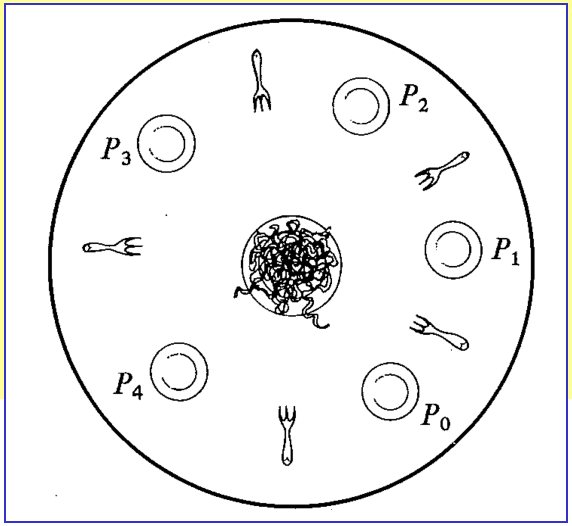
P Old

Philosophical Transactions

TestPhilosophers.java

```
class Philosopher implements Runnable {
  private final Fork[] forks;
  private final int place;
  public void run() {
    while (true) {
      int left = place, right = (place+1) % forks.length;
      synchronized (forks[left]) {
        synchronized (forks[right]) {
          System.out.print(place + " "); // Eat
        }
      }
      try { Thread.sleep(10); } // Think
      catch (InterruptedException exn) { }
    }
  }
}
```

Exclusive use of forks



- Lock-based philosopher (wk 8)
  - Likely to deadlock in this version

TxnBooleans as Forks A

P A

stm/TestStmPhilosophersA.java

```
class Philosopher implements Runnable {
  private final TxnBoolean[] forks;
  private final int place;
  public void run() {
    while (true) {
      final int left = place, right = (place+1) % forks.length;
      atomic(() -> {
        if (!forks[left].get() && !forks[right].get()) {
          forks[left].set(true);
          forks[right].set(true);
        } else
          retry();
      });
      System.out.printf("%d ", place);  // Eat
      atomic(() -> {
        forks[left].set(false);
        forks[right].set(false);
      });
      try { Thread.sleep(10); }          // Think
      catch (InterruptedException exn) { }
    }
  }}
```

Exclusive use of forks

Release forks

TxnBooleans as Forks B

stm/TestStmPhilosophersB.java

```
class Philosopher implements Runnable {
  private final TxnBoolean[] forks;
  private final int place;
  public void run() {
    while (true) {
      final int left = place, right = (place+1) % forks.length;
      atomic(() -> {
        forks[left].await(false);
        forks[left].set(true);
        forks[right].await(false);
        forks[right].set(true);
      });
      System.out.printf("%d ", place);  // Eat
      atomic(() -> {
        forks[left].set(false);
        forks[right].set(false);
      });
      try { Thread.sleep(10); }         // Think
      catch (InterruptedException exn) { }
    }
  }
}
```

Exclusive use of forks

Release forks

Transaction subtleties

- What is wrong with this Philosopher?
  - Variant of B that "eats" inside the transaction

BAD

```
public void run() {
  while (true) {
    final int left = place, right = (place+1) % forks.length;
    atomic(() -> {
      forks[left].await(false);
      forks[left].set(true);
      forks[right].await(false);
      forks[right].set(true);
      System.out.printf("%d ", place);// Eat
      forks[left].set(false);
      forks[right].set(false);
    });
    try { Thread.sleep(10); }          // Thi
    catch (InterruptedException exn) { }
  }
}
```

Transaction has its own view of the world until commit

Other transactions may have taken all the forks!

Optimism and multiple universes

- A transaction has its own copy of data (forks)
- At commit, it checks that data it used is valid
  - if so, writes the updated data to common memory
  - otherwise throws away the data, and restarts
- Each transaction works in its own “universe”
  - until it succesfully commits
- This allows higher concurrency
  - especially when write conflicts are rare
  - but means that a Philosopher cannot know it has exclusive use of a fork until transaction commit
- Transactions + optimism = multiple universes
- No I/O or other side effects in transactions!

Lazy vs. Eager

- **Lazy** commit strategy:
  - Keep everything in transaction's universe until commit
  - Conflict resolution at commit time
  - Keep redo log of what should be redone on retry
- **Eager** commit strategy:
  - Commit changes upon making them
  - Detect conflicts as transaction proceeds
  - Conflict resolution happens at multiple places
  - Keep an undo log of things that need to be reverted on conflict

Lazy vs. Eager

- **Lazy**:
  - Rollback is faster (just drop local data)
  - Slower commits (commits everything at once!)
  - Memory not inconsistent on crashes
- **Eager:**
  - Rollback is slower
  - Conflicts detected earlier
  - Memory may be inconsistent on crashes

Optimistic Concurrency and Game Theory

- View transactions as competing entities
- Transactions have knowledge of system
- E.g. long-running transactions get priority
- Why should we keep transactions short?
- Conversely, we also want fairness
- Paper by Eidenbenz and Wattenhofer
- Conclusion: Any deterministic policy can be gamed/exploited
- Optimistic, **cooperative** concurrency (next week)

Pessimistic Concurrency and Game Theory

- Same principle applies to pessimistic concurrency
- Why should I let go of a lock?
- Keep holding on to object associated with lock
- Security concern: Locking on **`this`**
- Any code with a reference to your object can block everyone else
- Use a private lock object instead

Hints and warnings

- Transactions should be short
  - When a long transaction finally tries to commit, it is likely to have been undermined by a short one
  - ... and must abort, and a lot of work is wasted
  - ... and it restarts, so this happens again and again
- For example, concurrent hash map
  - short: **`put`**, **`putIfAbsent`**, **`remove`**
  - long: **`reallocateBuckets`** – not clear it will ever succeed when others **`put`** at the same time
- Some STM implementations avoid aborting the transaction that has done most work
  - Many design tradeoffs

Some languages with transactions

- Haskell – in GHC implementation
  - TVar T, similar to TxnRef<T>, TxnInteger, ...
- Scala – ScalaSTM, on Java platform
  - Ref[T], similar to TxnRef<T>, TxnInteger, ...
- Clojure – on Java platform
  - (ref x), similar to TxnRef<T>, TxnInteger, ...
- C, C++ – future standards proposals
- Java – via Multiverse library
  - Creator Peter Ventjeer is on ScalaSTM team too
- Java – DeuceSTM, other research prototypes
- And probably many more ...

Transactional memory in perspective

- Works best is a mostly immutable context
  - eg functional programming: Haskell, Clojure, Scala
- Mixes badly with side effects, input-output
- Requires transactional (immutable) collection classes and so on
- Some loss of performance in software-only TM
- Still unclear how to best implement it
- Some think it will remain a toy, Cascaval 2008
  - ... **but** they use C/C++, too much mutable data
- Multicore hardware support would help
  - can be added to cache coherence (MESI) protocols

Hardware support for transactions

- Eg Intel TSX for Haswell CPUs, since 2013
  - New XBEGIN, XEND, XABORT instructions
  - https://software.intel.com/sites/default/files/m/9/2/3/41604
- Could be used by future JVMs, .NET/CLI, ...
- Uses core's cache for transaction's updates
- Extend cache coherence protocol (MESI, wk 7)
  - Messages say when another core writes data
  - On commit, write cached updates back to RAM
  - On abort, invalidate cache, do not write to RAM
- Limitations:
  - Limited cache size, ...

This week

- Reading
  - Herlihy and Shavit sections 18.1-18.2
  - Harris et al: *Composable memory transactions*
  - Cascaval et al: *STM, Why is it only a research toy*
  - Eidenbenz and Wattenhofer: Good programming in transactional memory Game theory meets multicore architecture
- Exercises
  - Show you can use transactional memory to implement histogram and concurrent hashmap
- Read before next week
  - Goetz et al chapter 15