Concurrent systems

Lecture 6: Concurrency without shared data, composite operations and transactions, and serialisability

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(Thanks to Dr Robert N. M. Watson)

Reminder from last time

- Liveness properties
- Deadlock (requirements; resource allocation graphs; detection; prevention; recovery)
- The Dining Philosophers
- Priority inversion
- Priority inheritance

Concurrency is so hard!

If only there were some way that programmers could accomplish useful concurrent computation without…

(1) the hassles of shared memory concurrency
(2) blocking synchronisation primitives

This time

- Concurrency without shared data
  - Use same hardware+OS primitives, but expose higher-level models via **software libraries** or **programming languages**
- **Active objects**
  - Ada
- **Message passing**; the **actor model**
  - Occam, Erlang
- **Composite operations**
  - **Transactions, ACID properties**
  - **Isolation** and **serialisability**
- **History graphs**; **good** (and **bad**) **schedules**

This material has significant overlap with **databases** and **distributed systems** – but is presented here from a concurrency perspective

Concurrency without shared data

- The examples so far have involved threads which can arbitrarily read & write shared data
  - A key need for mutual exclusion has been to avoid race-conditions (i.e. ‘collisions’ on access to this data)
- An alternative approach is to have only one thread access any particular piece of data
  - Different threads can own distinct chunks of data
- Retain concurrency by allowing other threads to ask for operations to be done on their behalf
  - This ‘asking’ of course needs to be concurrency safe…

Fundamental design dimension: concurrent access via **shared data** vs. concurrent access via **explicit communication**

Example: Active Objects

- A monitor with an associated **server** thread
  - Exports an **entry** for each operation it provides
  - Other (**client**) threads 'call' methods
  - Call returns when operation is done
- All complexity bundled up in an **active object**
  - Must manage mutual exclusion where needed
  - Must queue requests from multiple threads
  - May need to delay requests pending conditions
    - E.g. if a producer wants to insert but buffer is full

Observation: the code of **exactly** one thread, and the data that only it accesses, effectively experience **mutual exclusion**

Producer-Consumer in Ada

```
task-body ProducerConsumer is
  ...
  loop
    SELECT
      when count < buffer-size
        ACCEPT insert(item) do
          // insert item into buffer
        end;
      count++;
    or
      when count > 0
        ACCEPT consume(item) do
          // remove item from buffer
        end;
      count--;
    end SELECT
  end loop
```

Clause is ***active*** only when condition is true

ACCEPT dequeues a client request and performs the operation

Single thread: no need for mutual exclusion

Non-deterministic choice between a set of ***guarded*** ACCEPT clauses

Message passing

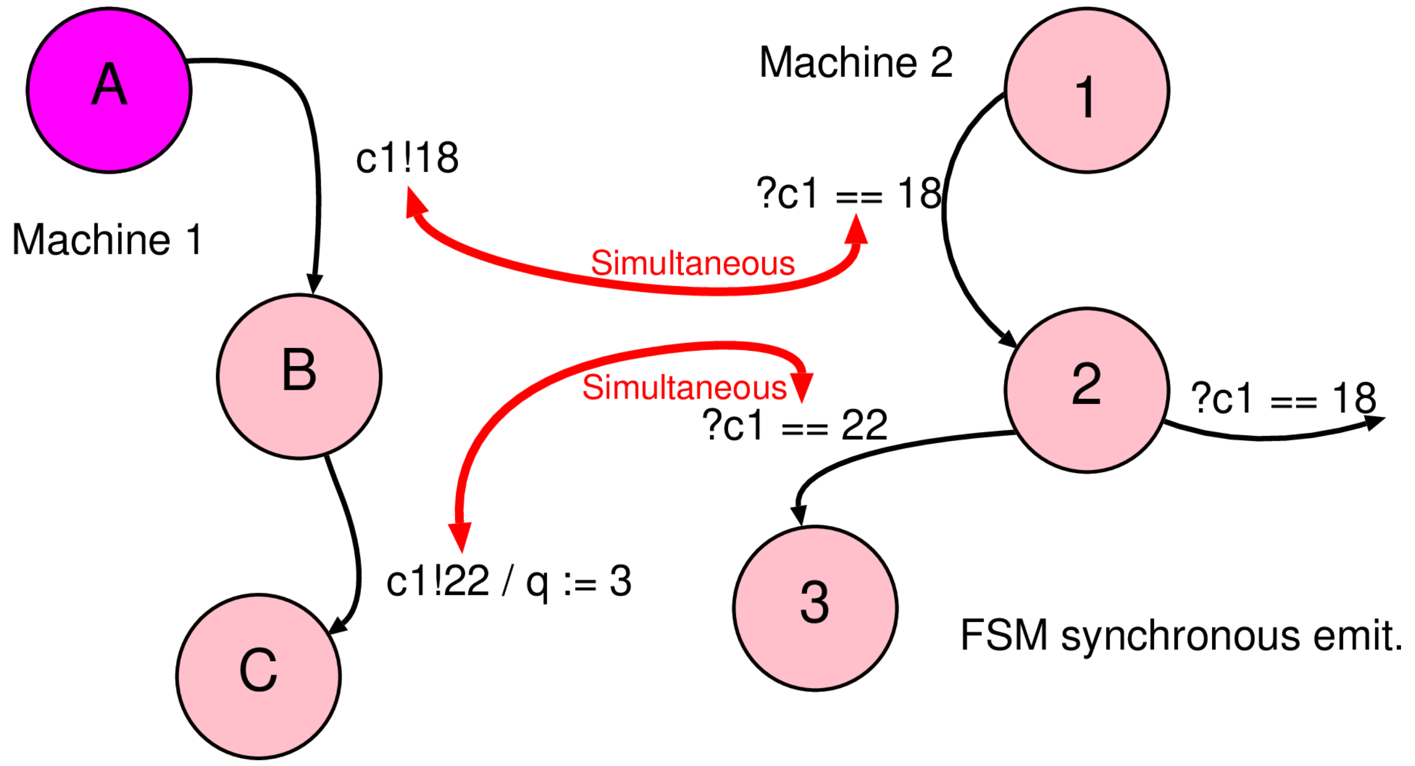
- Dynamic invocations between threads can be thought of as general **message passing**
  - Thread X can send a message to Thread Y
  - Contents of message can be arbitrary data values
- Can be used to build **Remote Procedure Call** (RPC)
  - Message includes name of operation to invoke along with as any parameters
  - Receiving thread checks operation name, and invokes the relevant code
  - Return value(s) sent back as another message
- (Called **Remote Method Invocation** (RMI) in Java)

We will discuss message passing and RPC in detail 2nd half; a taster now, as these ideas apply to local, not just distributed, systems.

Message passing semantics

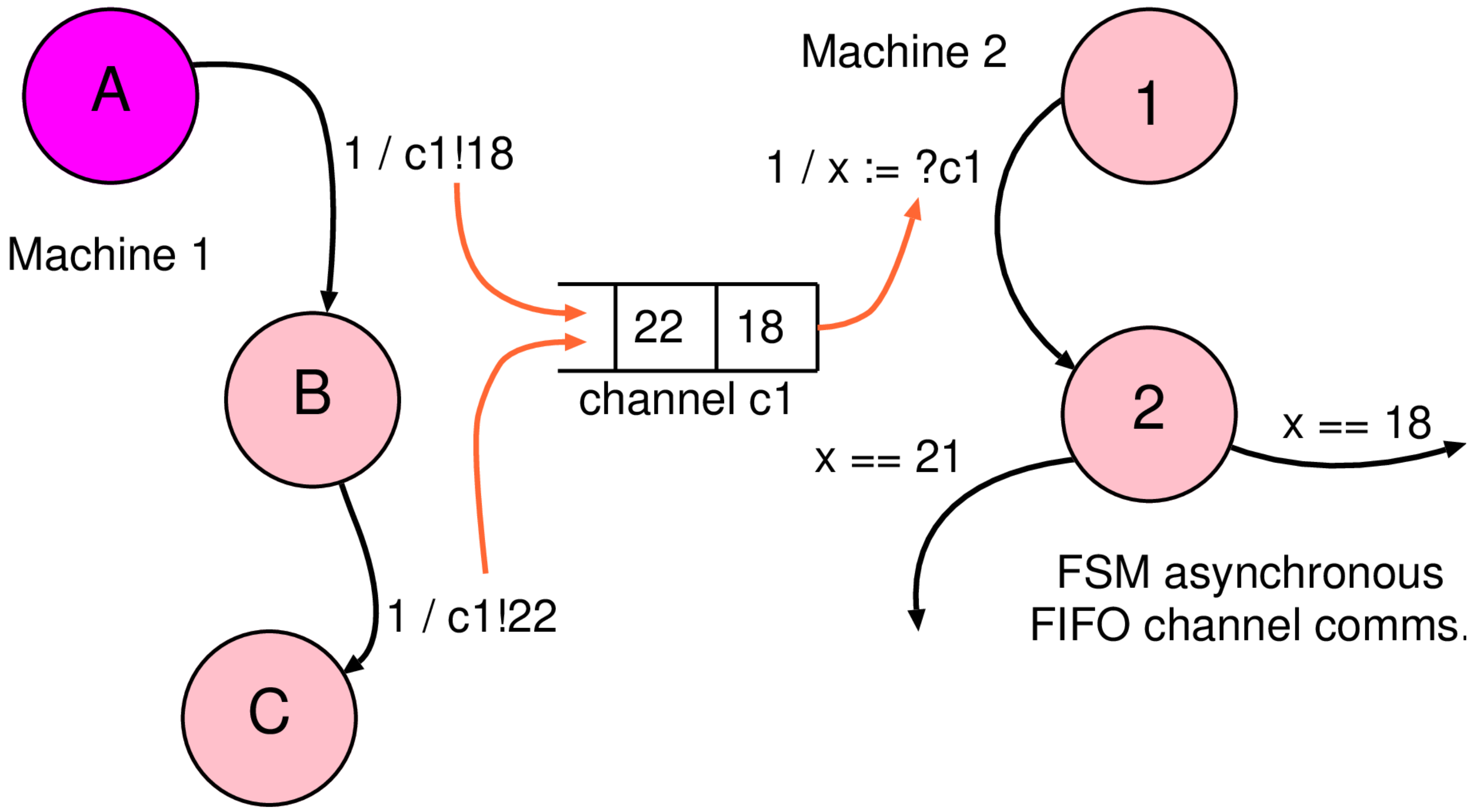
- Can conceptually view sending a message to be similar to sending an email:
  1. Sender prepares contents locally, and then sends
  2. System eventually delivers a **copy** to receiver
  3. Receiver checks for messages
- In this model, sending is **asynchronous**:
  - Sender doesn't need to wait for message delivery
  - (but they may, of course, choose to wait for a reply)
  - Bounded FIFO may ultimately apply sender back pressure
- Receiving is also asynchronous:
  - messages first **delivered** to a mailbox, later **retrieved**
  - message is a **copy** of the data (i.e. no actual sharing)

Synchronous Message Passing



- FSM view: both (all) participating FSMs execute the message passing primitive simultaneously.
- Send and receive operations must be part of edge guard (before the slash).

Asynchronous Message Passing



- We will normally assume asynchronous unless obviously or explicitly otherwise.
- Send and receive operations in action part (after slash).

Message passing advantages

- **Copy semantics** avoid race conditions
  - At least directly on the data
- Flexible API: e.g.
  - **Batching**: can send *K* messages before waiting; and can similarly batch a set of replies
  - **Scheduling**: can choose when to receive, who to receive from, and which messages to prioritize
  - **Broadcast**: can send messages to many recipients
- Works both within and between machines
  - i.e. same design works for **distributed systems**
- Explicitly used as basis of some languages…

Example: Occam

- Language based on Hoare's **Communicating Sequential Processes** (CSP) formalism
  - A projection of a process algebra into a real-world language
- No shared variables
- Processes **synchronously** communicate via **channels**

```
<channel> ? <variable>    // an input process
<channel> ! <expression>  // an output process
```

- Build complex processes via SEQ, PAR and ALT, e.g.

```
ALT
  count1 < 100 & c1 ? Data
    SEQ
      count1:= count1 + 1
      merged ! data
  count2 < 100 & c2 ? Data
    SEQ
      count2:= count2 + 1
      merged ! data
```

Example: Erlang

- Functional programming language designed in mid 80's, made popular more recently (especially in eternal systems such as telephone network).
- Implements the **actor model**
- **Actors**: lightweight language-level processes
  - Can spawn() new processes very cheaply
- **Single-assignment**: each variable is assigned only once, and thereafter is immutable
  - But values can be sent to other processes
- **Guarded receives** (as in Ada, occam)
  - Messages delivered in order to local mailbox
- Message/actor-oriented model allows run-time restart or replacement of modules to limit downtime

Proponents of Erlang argue that lack of synchronous message passing prevents deadlock. Why might this claim be misleading?

Producer-Consumer in Erlang

```
-module(producerconsumer).
-export([start/0]).

start() ->
  spawn(fun() -> loop() end).

loop() ->
  receive
    {produce, item } ->
      enter_item(item),
      loop();
    {consume, Pid } ->
      Pid ! remove_item(),
      loop();
    stop ->
      ok
end.
```

Invoking start() will spawn an actor…

receive matches messages to patterns

explicit tail-recursion is required to keep the actor alive…

… so if send ‘stop’, process will terminate.

Message passing: summary

- A way of sidestepping (at least some of) the issues with shared memory concurrency
  - No direct access to data => no **data** race conditions
  - Threads choose actions based on message
- Explicit message passing can be awkward
  - Many weird and wonderful languages ;-)
- Can also use with traditional languages, e.g.
  - Transparent messaging via RPC/RMI
  - Scala, Kilim (actors on Java, or for Java), …

We have eliminated some of the issues associated with shared memory, but these are still concurrent programs subject to deadlock, livelock, etc.

Composite operations

- So far have seen various ways to ensure safe concurrent access to a single object
  - e.g. monitors, active objects, message passing
- More generally want to handle **composite operations**:
  - i.e. build systems which act on multiple distinct objects
- As an example, imagine an internal bank system which allows account access via three method calls:

```
int amount = getBalance(account);
bool credit(account, amount);
bool debit(account, amount);
```

- If each is thread-safe, is this sufficient?
  - Or are we going to get into trouble???

Composite operations

- Consider two concurrently executing client threads:
  - One wishes to transfer 100 quid from the savings account to the current account
  - The other wishes to learn the combined balance

```
// thread 1: transfer 100
// from savings->current
  debit(savings, 100);
  credit(current, 100);
```

```
// thread 2: check balance
  s = getBalance(savings);
  c = getBalance(current);
  tot = s + c;
```

- If we're unlucky then:
  - Thread 2 could see balance that's too small
  - Thread 1 could crash after doing debit() – ouch!
  - Server thread could crash at any point – ouch?

Problems with composite operations

Two separate kinds of problem here:

1. **Insufficient Isolation**
   – Individual operations being atomic is not enough
   – E.g., want the credit & debit making up the transfer to happen as one operation
   – Could fix this particular example with a new transfer() method, but not very general ...
2. **Fault Tolerance**
   – In the real-word, programs (or systems) can fail
   – Need to make sure we can recover safely

Transactions

- Want programmer to be able to specify that a set of operations should happen **atomically**, e.g.

```
// transfer amt from A -> B
transaction {
 if (getBalance(A) > amt) {
     debit(A, amt);
     credit(B, amt);
     return true;
  } else return false;
}
```

- A **transaction** either executes correctly (in which case we say it **commits**), or has no effect at all (i.e. it **aborts**)
  - <u>regardless of other transactions, or system crashes</u>!

ACID Properties

Want committed transactions to satisfy four properties:

- **Atomicity**: either all or none of the transaction’s operations are performed
  - Programmer doesn’t need to worry about clean up
- **Consistency**: a transaction transforms the system from one consistent state to another – i.e., preserves **invariants**
  - Programmer must ensure e.g. conservation of money
- **Isolation**: each transaction executes [as if] isolated from the concurrent effects of others
  - Can ignore concurrent transactions (or partial updates)
- **Durability**: the effects of committed transactions survive subsequent system failures
  - If system reports success, must ensure this is recorded on disk

This is a different use of the word “**atomic**” from previously; we will just have to live with that, unfortunately.

ACID Properties

Can group these into two categories

1. **Atomicity** & **Durability** deal with making sure the system is safe even across failures
   - (**A**) No partially complete txactions
   - (**D**) Transactions previously reported as committed don't disappear, even after a system crash
2. **Consistency** & **Isolation** ensure correct behavior even in the face of concurrency
   - (**C**) Can always code as if invariants in place
   - (**I**) Concurrently executing transactions are indivisible

Isolation

- To ensure a transaction executes in isolation could just have a server-wide lock… simple!

```
// transfer amt from A -> B
transaction {  // acquire server lock
 if (getBalance(A) > amt) {
    debit(A, amt);
    credit(B, amt);
    return true;
  } else return false;
}              // release server lock
```

- But doesn't allow any concurrency…
- And doesn't handle mid-transaction failure
  (e.g. what if we are unable to credit the amount to **B**?)

Isolation – Serialisability

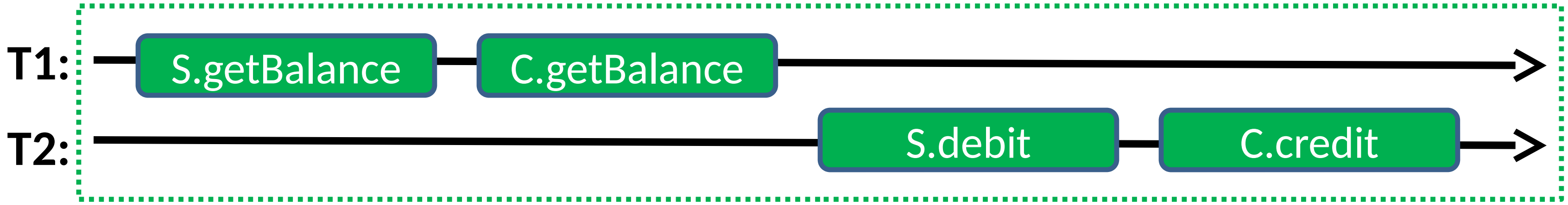
- The idea of executing transactions **serially** (one after the other) is a useful **model for the programmer**:
  - To improve performance, **transaction systems** execute many transactions concurrently
  - But programmers must only observe behaviours consistent with a possible serial execution: **serialisability**
- Consider two transactions, **T1** and **T2**

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

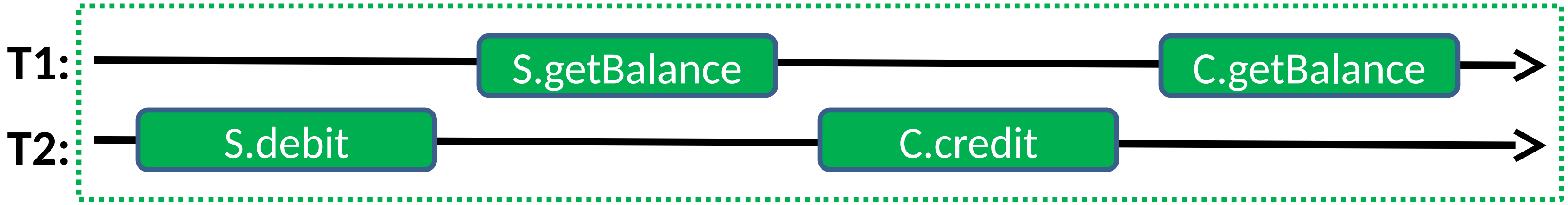
```
T2 transaction {
  debit(S, 100);
  credit(C, 100);
  return true;
}
```

- If assume individual operations are atomic, then there are six possible ways the operations can interleave…

Isolation – serialisability

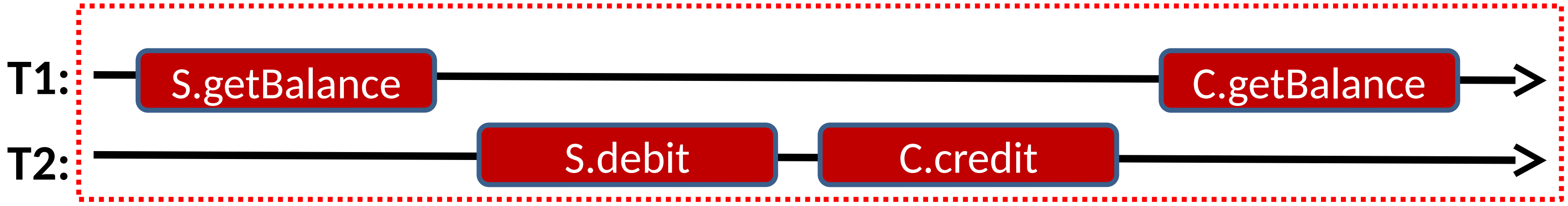


- First case is a **serial execution** and hence **serialisable**

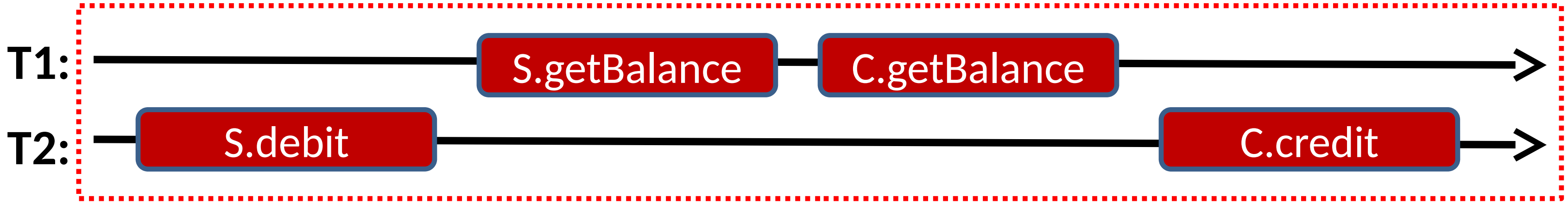


- Second case is **not serial** as transactions are interleaved
  – Its results are identical to serially executing **T2** and then **T1**
  – The schedule is therefore **serialisable**
- Informally: it is serialisable because we have only swapped the execution orders of **non-conflicting operations**
  – All of **T1**'s operations on any objects happen after **T2**'s update

Isolation – serialisability



- This execution is neither **serial** nor **serialisable**
  - **T1** sees inconsistent values: old **S** and new **C**



- This execution is also neither **serial** nor **serialisable**
  - **T1** sees inconsistent values: new **S**, old **C**
- Both orderings swap **conflicting operations** such that there is no matching serial execution

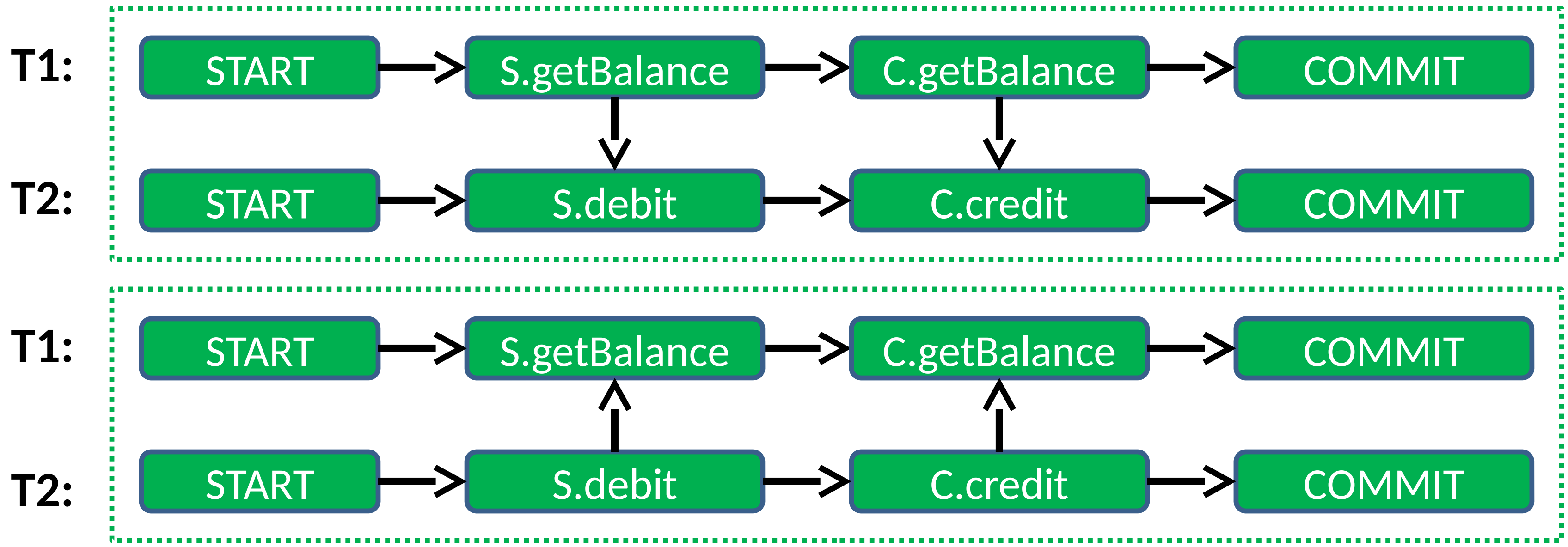
Conflict Serialisability

- There are many flavours of serialisability
- **Conflict serialisability** is satisfied for a schedule **S** if (and only if):
  - It contains the same set of operations as some serial schedule **T**; and
  - All **conflicting operations** are ordered the same way as in **T**
- Define **conflicting** as **non-commutative**
  - I.e., differences are permitted between the execution ordering and **T**, but they can't have a visible impact

History graphs

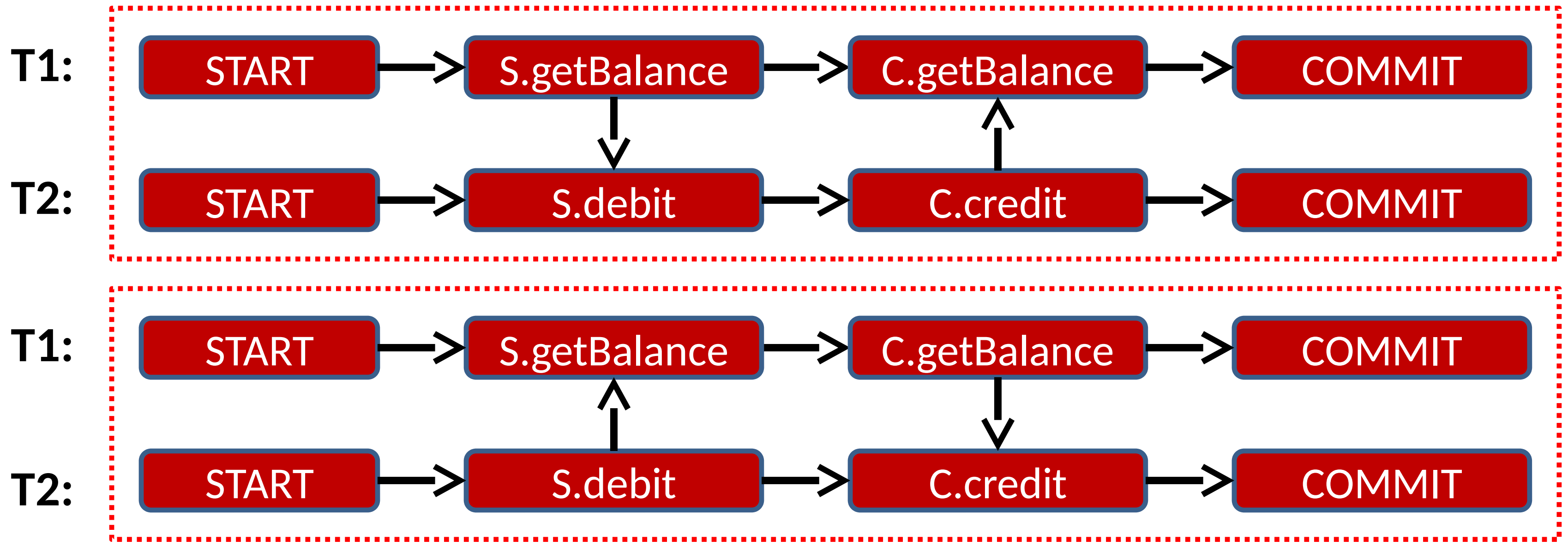
- Can construct a graph for any execution schedule:
  - Nodes represent individual operations, and
  - Arrows represent "**happens-before**" relations
- Insert edges between operations within a given transaction in **program order** (i.e., as written)
- Insert edges between **conflicting** operations operating on the same objects, ordered by execution schedule
  - e.g. A.credit(), A.debit() commute [don't conflict]
  - A.credit() and A.addInterest() **do** conflict
- NB: Graphs represent **particular execution schedules** not **sets of allowable schedules**

History graphs: good schedules



- Same schedules as before (both ok)
- Can easily see that everything in **T1** either happens before everything in **T2**, or vice versa
  - Hence schedule can be serialised

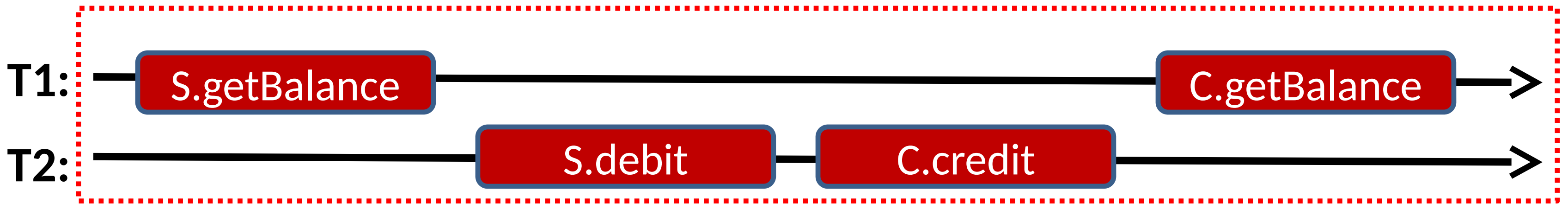
History graphs: bad schedules



- Cycles indicate that schedules are bad :-(
- Neither transaction strictly "happened before" the other:
  - Arrows from **T1** to **T2** mean "**T1** must happen before **T2**"
  - But arrows from **T2** to **T1** => "**T2** must happen before **T1**"
  - Notice the **cycle** in the graph!
- Can't both be true --- schedules are **non-serialisable**

Same as earlier slide.

Isolation – serialisability



- This execution is neither **serial** nor **serialisable**
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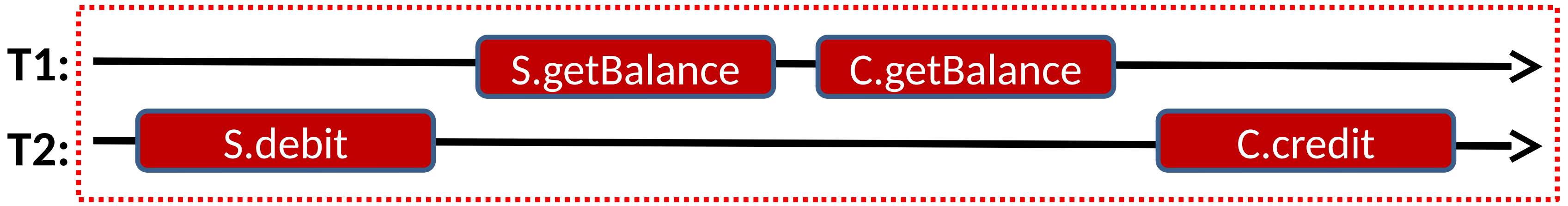

- This execution is also neither **serial** nor **serialisable**
  - **T1** sees inconsistent values: new **S**, old **C**
- Both orderings swap **conflicting operations** such that there is no matching serial execution

The **transaction system** must ensure that, regardless of any actual concurrent execution used to improve performance, only results consistent with **serialisable orderings** are visible to the **transaction programmer**.

Summary + next time

- Concurrency without shared data (Active Objects)
- Message passing, actor model (Occam, Erlang)
- Composite operations; transactions; ACID properties
- Isolation and serialisability
- History graphs; good (and bad) schedules

- Next time – more on transactions:
  - Isolation vs. strict isolation; enforcing isolation
  - Two-phase locking; rollback
  - Timestamp ordering (TSO); optimistic concurrency control (OCC)
  - Isolation and concurrency summary