A Universal Construction for Transaction-based Programs

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More developments in

- Tyler Crain, Damien Imbs, Michel Raynal, *Towards a universal construction for transaction-based multiprocess programs* Tech Report 1971, 16 pages, IRISA, Université de Rennes 1 (France), 2011

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Summary

- Motivation, issues and problem statement
- A (proved) Universal construction
- Discussion and conclusion

Concurrent programming

- A set of n processes p_1, p_2, ..., p_n
  - ⋆ Sequential
  - ⋆ Reliable
- A set a concurrent objects
  - ⋆ Each object is a linearizable (atomic)
  - ⋆ All operations on an object appear as if they have been executed sequentially and this order that respects real-time order

    $op1$ returns before $op2$ starts $\Rightarrow$ $op1$ appears before $op2$
  - ⋆ Linearizability (atomicity) is composable

Accessing several objects simultaneously

- Provide the programmer with locks
- Aim of a lock:

  prevent data from being accessed concurrently

  Data point of view: its environment is then sequential
- According to the "syntactic sugar" and the language locks are semaphores, signals, monitors, serializers, etc.
- Are locks good???
  - ⋆ Creating and forking threads is easy, but
  - ⋆ Synchronizing them is hard!
  - ⋆ Managing locks is difficult!
  - ⋆ Locks cannot be composed!

The concept of a transaction

- The answer: provide the application programmer with a synchronization abstraction called transaction which is an atomic procedure

  - ⋆ Simple to use (with the hope to be efficient)
  - ⋆ No more locks, no need to handle conflicts, etc.

- Instead of
  lock x; read x; lock y; read y; write x; unlock y; unlock x

  the programmer has only to write something like

  transaction { read x; read y; write x }

  (s)he no longer has to manage the underlying synchronization needed to face the concurrent accesses to the shared objects: this is now the job of the STM system!

The notion of abstraction level

- Aim: allow the programmer to concentrate on the problem (s)he has to solve and not on the base machinery needed to solve it
- Example 1: high level languages
- Example 2: Automatic garbage collection
- Example 3: “double click”
- Now STM:
  hide synchro “implementation details” to programmers

How to implement transaction atomicity

- Conservative approach
  - ⋆ a lock (few locks) that serializes the transactions
  - ⋆ works but is inefficient
- Optimistic approach: allows for speculative execution
  - ⋆ If no conflict: commit the corresponding transaction
  - ⋆ If conflict on a concurrent object: abort and restart
  - ⋆ Remark: this is similar to deadlock resolution in classical parallel systems (with conflict = deadlock)

Managing transaction aborts

- Left to the application (similar to exception handling)
- Best effort approach
- Modify the pair "compiler + scheduler" in order each transaction is "practically always" committed
- Design schedulers that behave particularly well in appropriate workloads (e.g., read dominated workloads)
- Notion of irrevocable transactions: executed exactly once and cannot be aborted
- Notion of deadline-aware transactions
- Etc.

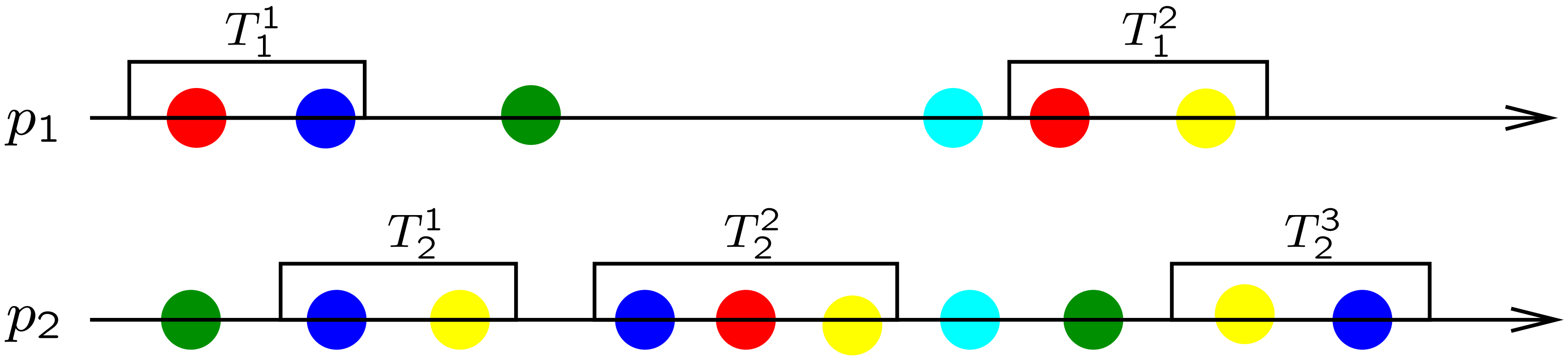
This talk

- At the programming level:
  - ⋆ no notion of abort/commit
  - ⋆ each transaction is executed exactly once
- No modification of the compiler or the scheduler
- The proposed STM system is a universal construction
  - ⋆ Its input: any transaction-based concurrent program P
  - ⋆ Its output: an execution of P on a multiprocessor
  - ⋆ It is proved (no transaction typing, not best effort!)

A universal construction: user programming level

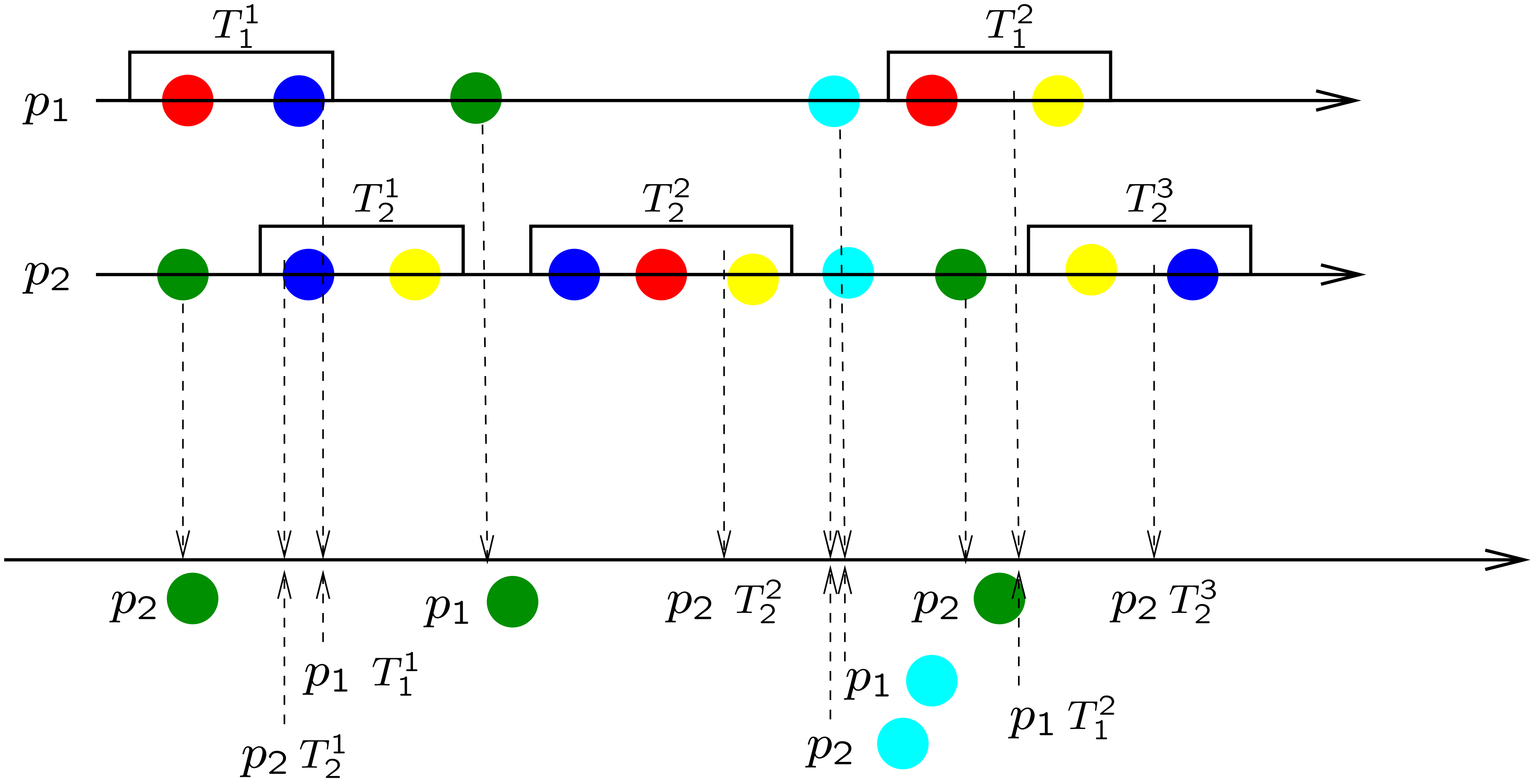
- Transaction (atomic procedure)
  - $\star$ Can access any nb of concurrent objects: t-objects
  - $\star$ Assumption:
    when executed alone, a transaction always terminates
- Non-transactional code
  - $\star$ Can access any nb of concurrent objects: nt-objects
  - $\star$ Includes inputs/outputs (irrevocable code)
- t-objects $\cap$ nt-objects $= \emptyset$ (this adds no limitation)
- Process $=$ (transaction ; non-trans code)*

Example (1)



- Two processes
- Three t-objects: Red, blue, yellow
- Two nt-objects: green, cyan

Example (2)



From an extrernal observer's point of view

A universal construction: Underlying system

- m $(1 \leq m \leq n)$ processors (simulators) P_1, P_2, ...,P_m
- They communicate through
  - atomic read/write registers
  - Compare&Swap registers:

```
$X$.Compare&Swap$(old, new)$=
    [if $(X = old)$ then $X \leftarrow new$; return$(true)$
                     else return$(false)$
    end if]
```

  - Fetch&Increment register:

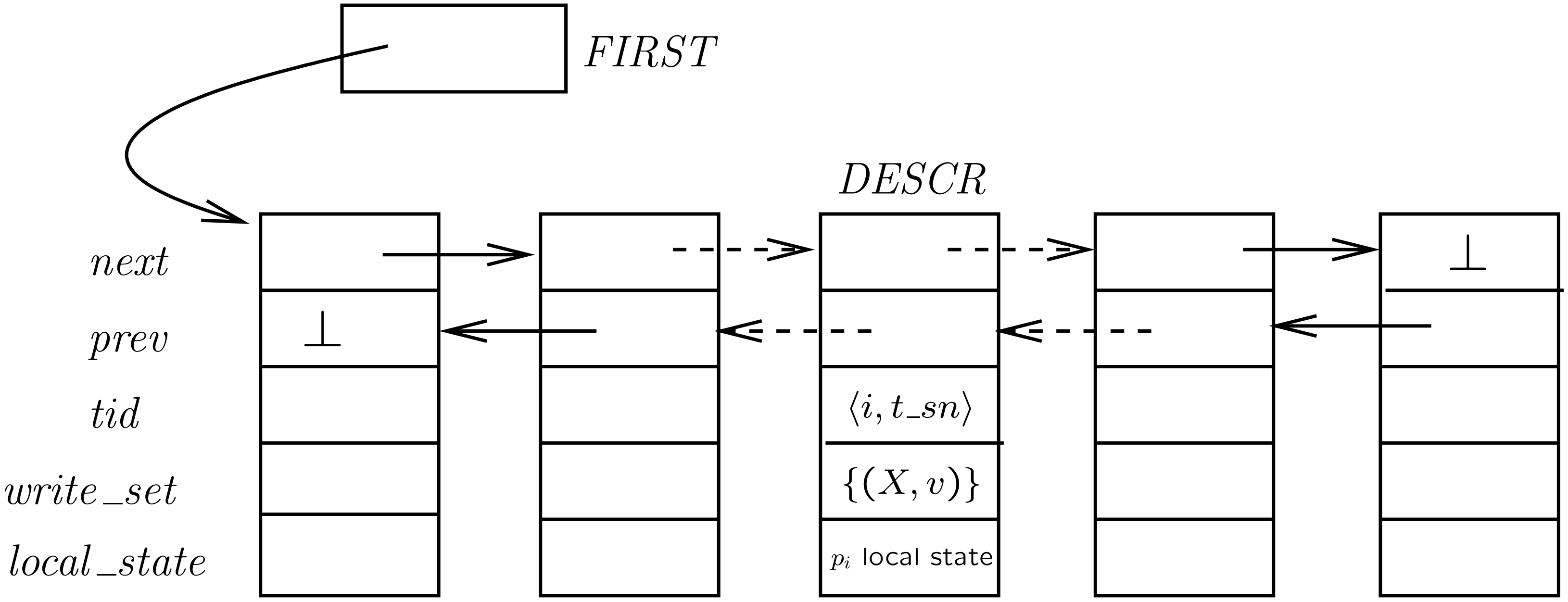
X.Fetch&Increment()= $[X \leftarrow X + 1$; return$(X)]$

Representing the nt-objects

- Directly in the memory shared by the m processors
- Reminder: by definition they are linearizable
- It exists very nice packages with efficient linearizable implementations for base objects such as stacks, lists, sets, queues, etc.

Representing the t-objects

- Can be retrieved from a list shared by the processors
- This list contains all "committed" transactions
- Compare &Swap is used by a processor when it wants to commit a transaction on behalf of a process p_i



Process ownership

- Each processor P_x $(1 \leq x \leq m)$
  is responsible for the progress of a set of processes
- array $OWNED\_BY[1..m]$ such that
- $OWNED\_BY[x]$ = the set of processes “owned” by P_x

Helping mechanism

- A processor P_x speculatively executes the next transaction of a process p_i it owns and then tries to "commit" it
- If it does not succeed it requires the other processors to help it
- To that end, the processors share two data structures:
  - ⋆ A logical clock $CLOCK$ (accessed by Fetch&Add)
  - ⋆ An array $STATE[1..n]$

The size n array $STATE$

$STATE[i]$ = current state of the simulation of process p_i

- $STATE[i].tr\_n$: seq nb of p_i's next transaction
- $STATE[i].local\_state$: local state of p_i just before executing its next transaction
- $STATE[i].help\_date$:
  - ⋆ $STATE[i].help\_date = +\infty$: no help is required
  - ⋆ $STATE[i].help\_date \neq +\infty$: help is required
- $STATE[i].last\_ptr$: initially points to $FIRST$, then updated to shortcut a prefix of the list

Three (non-trivial) technical issues

- Prevent a processor from always helping the others without making any progress on the processes it owns
- As the list of "committed" transactions pointed to by $FIRST$ can increase forever, ensure that an (asynchronous) processor will eventually attain the end of this list when it wants to "commit" a transaction
- Ensure that each transaction is "committed" no more than once
- These issues are solved by appropriate enrichments of the base helping mechanism

Structure of a simulator P_x

- Select from $STATE[1..n]$ a process p_i in order to execute its next transaction T
- Speculative execution of T (in P_x local memory)
- If T has not yet been committed and its "commit predicate" is true, tries to commit it
- If p_i is owned by P_x and has been committed (by P_x or another processor P_y)
  - ⋆ Execute non-transactional code that follows T in p_i
  - ⋆ Modify $STATE[i]$ accordingly
  - ⋆ If p_i has terminated, suppress it from $OWNED[x]$
- If $OWNED[x] \neq \emptyset$: restart from the first item

Proof

: see the tech report

- It is 4.5 (11 point, A4) pages long (11 lemmas)
- Let P be a transaction-based multiprocess program
- Theorem:
  Any simulation of P by the universal construction (on m processors) is an execution of P that could have been produced by executing P on n processors (i.e., it is a correct execution of P)

Summarizing the construction

- It is for time-free transaction-based programs
- It is lock-free (no lock is ever used)
- It uses Compare&Swap on pointer registers
- It imposes no restriction on the concurrency pattern
- It works for finite and infinite programs
- The nb of tries to commit a transaction is bounded
- Helping mechanism can be improved to be more efficient
- Crash of a processor entails only the crash of the processes it owns

Conclusion

- A universal construction for transaction-based programs
- Proved!
- Better understanding of the nature of the atomicity provided to programmers in order to cope with concurrency issues
- Next step: replace the list of “committed” transactions by something more efficient
- Next step: make it tolerant to processor crashes