Advances in Programming Languages

Lecture 10: Other Programming-Language Approaches to Concurrency

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THE UNIVERSITY *of* EDINBURGH

Programming-Language Techniques for Concurrency

This is the third in a block of lectures looking at programming-language techniques for concurrent programs and concurrent architectures.

- Introduction, basic Java concurrency
- Concurrency abstractions in Java
- Some other programming-language approaches to concurrency
- Current challenges in concurrency

No lecture this Friday !

There will be no APL lecture on Friday 28 October.

Next week's lectures will be as follows.

Tuesday 1 November Cautionary Tales in Concurrency

Friday 4 November Specification and Verification

The lecture tab on the course web pages gives details for later weeks.

Outline

Reminder: Some challenges with locks

Locks provide a sound mechanism for enforcing separation and safely implementing shared-memory concurrency. They have many pitfalls, though, and can themselves introduce new difficulties. For example:

Deadlock when two threads try to acquire the same locks in different orders;

Priority inversion when a scheduler preempts a lower-priority thread that holds a lock needed for a higher-priority one;

Lock Convoys / Thundering Herd when many threads are waiting on a single lock;

Lack of compositionality as there is no straightforward way to build large thread-safe programs by composing small thread-safe programs.

Ways to program concurrency

There is a large design space for concurrent language mechanisms. Two key requirements are *separation*, to prevent inconsistent access to shared resources, and *co-operation* for communication between tasks.

Many different language paradigms have been proposed to manage this, including:

locks and conditions: tasks share memory and use that to exclude and signal one another (e.g., Java);

channel-based message-passing: tasks send and receive messages over named *channels* (e.g. Go, Rust, Concurrent ML);

actor-style message-passing: a task offers a *mailbox* which receives messages (e.g. Scala + Akka, Erlang);

A key distinction here is between *shared-memory concurrency* like that from Java, and *share-nothing concurrency* where all co-operation is through message-passing.

Ways to program concurrency

There is a large design space for concurrent language mechanisms. Two key requirements are *separation*, to prevent inconsistent access to shared resources, and *co-operation* for communication between tasks.

Many different language paradigms have been proposed to manage this, including:

futures and promises: computations are executed some time between when they are created and when required (e.g., Oz, E);

dataflow/datastream programming: computations are described as a network of data dependencies (e.g., Lustre, Hume);

lock-free algorithms / transactional memory: tasks share memory but detect and repair conflicts (e.g., libraries in C, C++, . . .).

Language designs have also been influenced by mathematical models used to capture and analyse the essence of concurrent systems, for example, *CSP*, *CCS*, *π-calculus*, *join calculus*, and the *ambient calculus*.

Outline

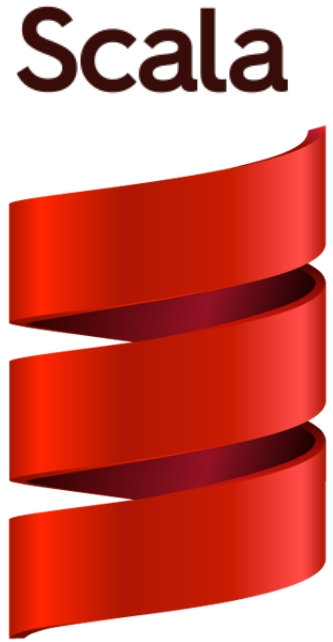
Scala

Scala is a strongly-typed object-oriented language that compiles to the Java Virtual Machine. This allows full interoperability with Java, both providing and using libraries and code.

Scala draws extensively on features of functional programming languages, offering among other things:

- Pattern matching
- Algebraic datatypes (with case classes)
- Parameterized types
- Type inference
- Higher-order functions
- Lazy (call-by-need) evaluation

Scala is designed by Martin Odersky and his team at EPFL, Lausanne, Switzerland.



http://www.scala-lang.org

The Actor model

The *actor model* is used for concurrency in several programming languages.

- An actor is a process abstraction that interacts with other actors by message passing. Message sending is *asynchronous* (non-blocking).
- Each actor has a mailbox which buffers incoming messages until they are processed by *pattern matching*.
- Actors may create new actors, and can communicate the mailbox addresses of other actors.
- Actors have private variables, which can be updated in response to messages, but no actor can directly access the state of another.

Although an underlying implementation will use threads or processes to run actor code, this isn't explicit in the model.

It's usual to provide some support for *distribution* of actors, which is made easier by the lack of shared state.

Akka: Actors in Scala

Scala supports actor programming through the Akka toolkit (now also available for Java and .NET — see http://akka.io).

Sending

```
// send message to
// another actor
actor ! message

// sender() is the actor
// who sent the last message
sender() ! message
```

Receiving

```
// Pick up messages
// and act on them
def receive {
  case pattern => action
  ...
  case pattern => action
}
```

Note: Actor syntax in Scala has changed over time. This shows Scala 2.11 and Akka 2.0

Example: Counter

```
case object Reset
case object Increment
case object Decrement
case object Value

class Counter extends Actor {

  var count = 0

  def receive =  {  case Reset => count = 0
                    case Increment  => count = count+1
                    case Decrement => count = count−1
                    case Value => sender() ! count
                 }
}
```

Example: Bounded buffer

```
case class Put(x:String)
case object Get

class BoundedBuffer(size: Int) extends Actor {

  var buffer = new Array[String](size)
  var in, out, n = 0

  def receive = { case Put(x) if (n < size) => {  buffer(in) = x
                                                  in = (in + 1) % size
                                                  n = n+1 }

                  case Get if (n > 0) => {  val r = buffer(out)
                                            out = (out + 1) % size
                                            n = n−1
                                            sender() ! r }
                }
}
```

Supervision

As Scala/Akka actors create subsidiary actors and delegate work to them, these build up into a *hierarchy* of parent and child actors.

This hierarchy is used for supervision in Scala, where actors take responsibility for managing the other actors they have created.

When an actor fails in some way, its supervisor is notified and takes the action defined by its supervisorStrategy, chosen from:

Resume — Just let the actor continue

Restart — Re-initialise the actor state and start again

Stop — Terminate and remove the actor

Escalate — Signal the next level up in the hierarchy

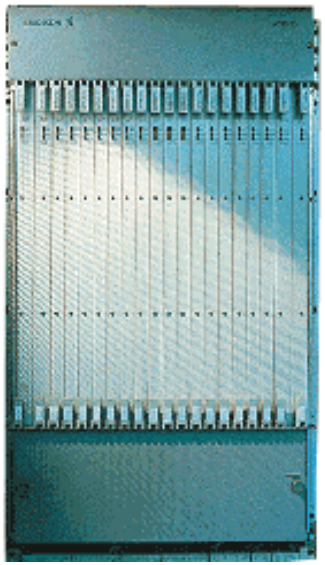
There are also standard strategies to propagate these actions:

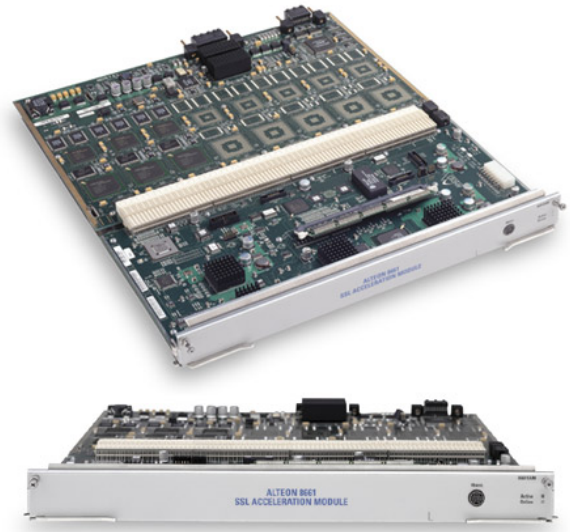
OneForOneStrategy — Apply action to just the failing actor

AllForOneStrategy — Apply action to all supervised actors

Erlang

Scala's actor concurrency is based closely on the *Erlang* system, developed by Ericsson for programming highly resilient and massively concurrent telecommunications equipment.





Ericsson AXD 301 multiservice 10–160Gbit/s switch

Nortel 8661 SSL Acceleration Ethernet Routing Switch

Outline

Software Transactional Memory

Transactional Memory is a lock-free way of managing shared memory between concurrent tasks, inspired by transaction processing in databases. It was proposed and refined by Herlihy, Moss, Shavit and others.

- Memory accesses are grouped into transactions: sequences of reads and writes;
- Each transaction is committed atomically from the point of view of other transactions;
- Transactions may be aborted and retried.

In practice, transactions are executed with *optimistic concurrency*, detecting interference. If two transactions conflict by reading and writing the same location, one will be aborted and retried.

Software Transactional Memory (STM) is an implementation in software, as part of a library or language runtime.

Using STM

Coding with transactional memory

Repeat
{
    Start transaction
    ...
    Read shared memory, navigate around data structures,
    perform computation, write shared memory, etc.
    ...
    End transaction
}
Until (transaction succeeds)

Crucially:

- No lock is held during the transaction.
- Multiple threads may work over the same memory at the same time.
- Most of the time, all is well and this goes really fast.

How can that possibly work?

Software transactional memory is one of a range of *lock-free algorithms* and *lock-free datastructures* that seek to enable shared-memory concurrency while avoiding some of the difficulties caused by locks.

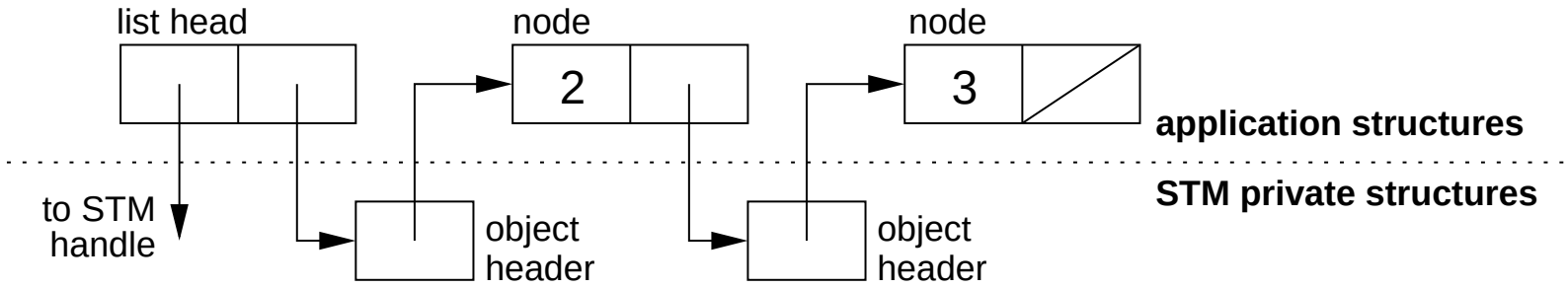
These lock-free algorithms rely on specialist atomic instructions:

TAS	Test-and-set (address)
CAS	Compare-and-swap (address,old,new)
LL/SC	Load-link (address) / Store conditional (address,value)

Each of these can emulate all the previous ones. Almost all current processors provide either CAS or LL/SC in hardware.

Lock-free algorithms use these instructions to make atomic changes to large datastructures, usually by switching pointers at carefully-chosen between carefully-chosen substructures.

Example implementation



Keir Fraser.

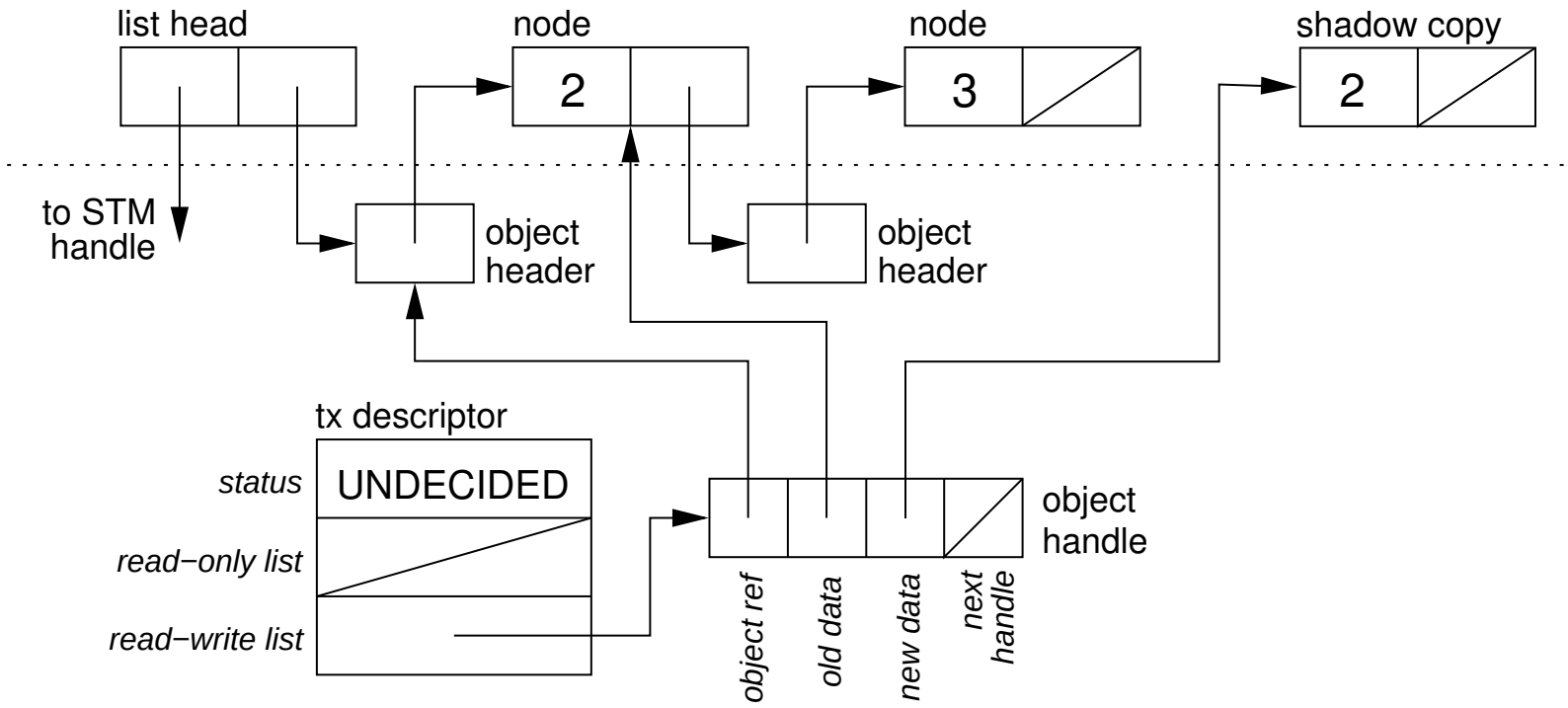
Practical Lock-Freedom.

PhD thesis, February 2004.

University of Cambridge Computer Laboratory Technical Report 579.

http://www.cl.cam.ac.uk/research/srg/netos/lock-free/

Example implementation



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Example STM library API

```
stm* new_stm (int object_size)                  // Create and discard STM
void free_stm (stm *mem)                        // for objects of this size

(stm_obj*, void*) new_object(stm *mem)          // Allocate and release
void free_object (stm *mem, stm obj *o)         // individual objects

stm_tx* new_transaction (stm *mem)              // Begin a transaction

void* open_for_reading (stm_tx *t, stm_obj *o)  // Obtain direct
void* open_for_writing (stm_tx *t, stm_obj *o)  // access to object

bool commit_transaction (stm_tx *t)             // Complete a transaction

void abort_transaction (stm_tx *t)              // Bail out now
bool validate_transaction (stm_tx *t)           // Check if already conflicted
```

Software Transactional Memory in Haskell

The *STM* library for the Glasgow Haskell Compiler (GHC) provides elegant high-level language support for STMs implemented by Simon Peyton Jones and others.

- Transactions are first-class values of *monadic* type STM a
- Transactions access shared memory in *transaction variables*, via readTVar and writeTVar operations.
- Transactions can be freely composed with monadic sequencing, nested atomically blocks and orElse choices.

See Chapter 24 of *Beautiful Code*, edited by Greg Wilson, O'Reilly 2007.

Clojure offers STM too, with doSync

Outline

Summary

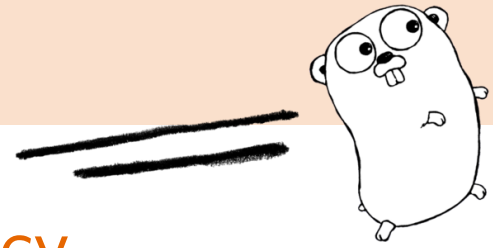
Message-Passing Concurrency with Actors

- Each actor has a *mailbox*, which receives messages asynchronously.
- Actors respond to received messages by *pattern-matching*.
- A *supervision hierarchy* makes sure that a system keeps going in the event of local or temporary failure.

Concurrency with Transactional Memory

- Transactions are sequences of operations committed atomically.
- Collisions are detected, transactions can be aborted and retried.
- They compose elegantly and cleanly.
- STM implementations hide a lot of clever tricks.

1. Homework: Read this



Channel-based message-passing concurrency

The *Go* language provides concurrent goroutines and named channels for communication between them. Read these two articles about this.

- An Introduction to Programming in Go: Concurrency
  https://www.golang-book.com/books/intro/10
- Visualizing Concurrency in Go
  https://divan.github.io/posts/go_concurrency_visualize

Optional Extras

Watch https://blog.golang.org/concurrency-is-not-parallelism
and https://is.gd/goconcurrencypatterns

Read *A Tour of Go: Goroutines* https://tour.golang.org/concurrency
and *Go by Example: Goroutines* https://gobyexample.com/goroutines

2. Homework: Do this !

Who uses Erlang? What do they do with it?

- Read up about Erlang, its use of actors, supervision, and live code replacement.
- Find an example of some software / a system / a service / a company that uses the language and where someone has written about that.
- Post the example to the mailing list or Piazza.

I shall collate examples on the blog and next Tuesday's lecture. For example:

Demonware: Erlang and First-Person Shooters
10s of millions of Call of Duty Black Ops fans loadtest Erlang

Presentation to *Erlang Factory*, London 2011 http://is.gd/erlangfps