Concurrency and Parallelism in Functional Programming Languages

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Outline

- Programming models
- Concurrent
- Concurrent ML
- Multithreading via continuations (if there is time)

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- Parallel vs. concurrent vs. distributed.
- Implicitly parallel vs. implicitly threaded vs. explicitly threaded.
- Deterministic vs. non-deterministic.
- Shared state vs. shared-nothing.

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- Parallelism is about speed — exploiting parallel processors to solve problems quicker.
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- Distributed systems is about computing in a network — it involves aspects of both parallelism and concurrency, but also raises issues of fault-tolerance and trust.

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Implicitly parallel vs. implicitly threaded vs. explicitly threaded

In the space of parallel programming models, there are choices to be made about how programmers introduce parallelism.

- Implicitly parallel programming relies entirely on the compiler and runtime to determine when two computations should be run in parallel.
- Implicitly threaded parallelism relies on the programmer adding annotations that mark places where parallelism would be useful, but the language does not make explicit any notion of parallel threads.
- Explicit threading (*aka* concurrency) uses language-level threading mechanisms to specify parallelism.

Another, related, design axis is data-parallel vs. task-parallel

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Multiple threads/processors introduces the non-deterministic program execution; *i.e.*, two runs of a program may produce different results.

Parallel languages that are implicitly parallel or implicitly threaded usually hide this non-determinism and guarantee sequential semantics.

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- Shared-nothing requires that threads communicate via some form of messaging.

Note that shared-nothing languages can still be implemented in a shared address space!

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Why concurrency?

- Many applications are reactive systems that must cope with non-determinism (*e.g.*, users and the network).
- Concurrency provides a clean abstraction of such interactions by hiding the underlying interleaving of execution.
- Thread abstraction is useful for large-grain, heterogeneous parallelism.

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Synchronization and communication

There are two aspects to thread interaction:

- **Communication** — how does data get from one thread to another?
- **Synchronization** — how are the possible orderings of threads restricted?
  - **Mutual-exclusion synchronization** — protecting access to a shared resource
  - **Condition synchronization** — waiting for a signal from another thread

The choice of synchronization and communication mechanisms is a critical design choice

- Should these be independent or coupled?
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Concurrency is hard(?)

Concurrent programming has a reputation of being hard.

- The problem is that shared-memory concurrency using locks and condition variables is the dominant model in concurrent languages.
- Shared-memory programming requires a defensive approach: protect against data races.
- Synchronization and communication are decoupled.
- Shared state often leads to poor modularity.

Classic example:

$$x \leftarrow 0$$
$$\textbf{parbegin}\ x \leftarrow x + 1 \mid\mid x \leftarrow x + 1\ \textbf{parend}$$
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Software transactional memory

- Software transactional memory (STM) has been offered as a solution.
- Introduces **atomic** regions that are serialized with other atomic regions.

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- Uses non-blocking techniques to increase potential parallelism.
- Some hardware support in the latest processors
- Ideal semantics is appealing: simple and intuitive.
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Message passing

In 1978, Tony Hoare proposed a concurrent programming model based on independent processes that communicate via messages (CSP).

- Well-defined interfaces between independent, sequential, components.
- Natural encapsulation of state.
- Extends more easily to distributed implementation.
- Natural fit for functional programming (threads are just tail-recursive functions).
- Inspired many language designs, including Concurrent ML, go (and its predecessors), OCCAM, OCCAM-π, *etc.*.

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Message-passing design space

- Synchronous vs. asynchronous vs. RPC-style communication.
- Per-thread message addressing vs. channels
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Channels

For the rest of the lecture, we assume channel-based communication with synchronous message passing.

In SML, we can define the following interface to this model:

```
type 'a chan

val channel : unit -> 'a chan
val recv : 'a chan -> 'a
val send : ('a chan * 'a) -> unit
```

We also need to define a way to create threads:

```
val spawn : (unit -> unit) -> unit
```

Example: concurrent streams

We can connect threads together with channels to implement concurrent streams.

Here is a function that creates the stream of integers 2, 3, 4, ...

```
fun countFrom2 () = let
      val outCh = channel()
      fun lp n = (send(outCh, n); lp(n+1))
      in
        spawn (fn () => lp 2); outCh
      end
```

And here is a function that filters out multiples of a number from a stream

```
fun filter (inCh, p) = let
      val outCh = channel()
      fun lp () = let
            val n = recv inCh
            in
              if (n mod p = 0) then lp() else (send(outCh, n); lp())
            end
      in
        spawn lp; outCh
      end
```

Example: concurrent streams *(continued ...)*

Using these two functions

```
val countFrom2 : unit -> int chan
val filter     : int chan * int -> int chan
```

we can implement the Sieve of Eratosthenes for finding prime numbers:

```
fun sieve () = let
      val outCh = channel()
      fun head ch = let
            val p = recv ch
            in
              send (outCh, p);
              head (filter (ch, p))
            end
      in
        spawn (fn () => head (countFrom2 ()));
        outCh
      end
```

Example: client-server concurrency

The other common pattern in concurrent programming is client-server interactions.

A very simple example is a memory cell with the following API:

```
type 'a cell

val cell : 'a -> 'a cell
val get  : 'a cell -> 'a
val set  : 'a cell * 'a -> unit
```

We define a datatype to represent the two kinds of client requests:

```
datatype 'a req = GET | SET of 'a
```

And we represent a `cell` by a pair of channels

```
datatype 'a cell = CELL of {
    reqCh : 'a req chan,
    replyCh : 'a chan
  }
```

Example: client-server concurrency *(continued ...)*

The `cell` function creates a new server and returns the pair of channels used to communicate with it:

```
fun cell init = let
      val reqCh = channel() and replyCh = channel()
      fun lp state = (case (recv reqCh)
             of GET => (send(replyCh, state); lp state)
              | SET v => lp v)
      in
        spawn (fn () => lp init);
        CELL{reqCh = reqCh, replyCh = replyCh}
      end
```

We can then define the matching client-side operations

```
fun get (CELL{reqCh, replyCh}) = (send(reqCh, GET); recv replyCh)

fun set (CELL{reqCh, ...}, v) = send(reqCh, SET v)
```

Notice that the client and server message operations match; if they did not match, then there would be deadlock.

Choice

To support monitoring communications on multiple channels, we need a choice operator that allows a thread to block on multiple channels.
For example, we might define the following function:

```
val selectRecv : ('a chan * ('a -> 'b)) list -> 'b
```

that takes a list of channels paired with actions and waits until a message is available on one of the channels.

Interprocess communication

In practice, it is often the case that

- interactions between processes involve multiple messages.
- processes need to interact with multiple partners (nondeterministic choice).

These two properties of IPC cause a conflict.

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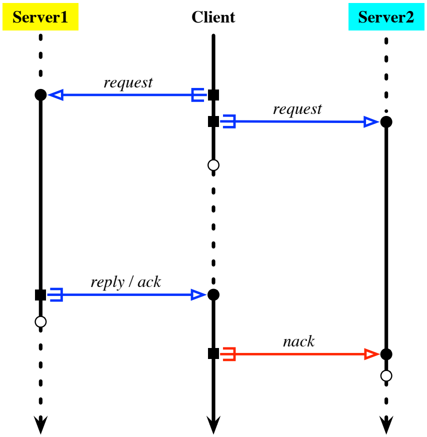
Interprocess communication *(continued ...)*

For example, consider a possible interaction between a client and two servers.



Interprocess communication *(continued ...)*

Without abstraction, the code is a mess.

```
let val replCh1 = channel() and nack1 = cvar()
    val replCh2 = channel() and nack2 = cvar()
in
   send (reqCh1, (req1, replCh1, nack1));
   send (reqCh2, (req2, replCh2, nack2));
   selectRecv [
      (replCh1, fn repl1 => ( set nack2;  act1 repl1 ),
      (replCh2, fn repl2 => ( set nack1;  act2 repl2 )
   ]
end
```

But traditional abstraction mechanisms do not support choice!

Concurrent ML

The conflict between choice and abstraction was the prime motivation behind the design of Concurrent ML.

- CML provides a uniform framework for synchronization: events.
- CML provides event combinators for constructing abstract protocols.
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Events

- We use event values to package up protocols as first-class abstractions.
- An event is an abstraction of a synchronous operation, such as receiving a message or a timeout.

```
type 'a event
```

- Base-event constructors create event values for communication primitives:

```
val recvEvt : 'a chan -> 'a event
val sendEvt : 'a chan * 'a -> unit event
```

Events *(continued ...)*

Event operations:

- Event wrappers for post-synchronization actions:

```
val wrap : ('a event * ('a -> 'b)) -> 'b event
```

- Event generators for pre-synchronization actions and cancellation:

```
val guard    : (unit -> 'a event) -> 'a event
val withNack : (unit event -> 'a event) -> 'a event
```

- Choice for managing multiple communications:

```
val choose : 'a event list -> 'a event
```

- Synchronization on an event value:

```
val sync : 'a event -> 'a
```

Example: Swap channels

A swap channel is an abstraction that allows two threads to swap values.

```
type 'a swap_chan

val swapChannel : unit -> 'a swap_chan
val swapEvt     : 'a swap_chan * 'a -> 'a event
```

Example: Swap channels *(continued ...)*

The basic implementation of swap channels is straightforward.

```
datatype 'a swap_chan = SC of ('a * 'a chan) chan

fun swapChannel () = SC(channel ())

fun swap (SC ch, vOut) = let
      val inCh = channel ()
      in
        select [
            wrap (recvEvt ch,
              fn (vIn, outCh) => (send(outCh, vOut); vIn)),
            wrap (sendEvt (ch, (vOut, inCh)),
              fn () => recv inCh)
          ]
      end
```

The `select` function is shorthand for `sync ∘ choose`.
Note that the `swap` function both offers to send and receive on the channel so as to avoid deadlock.

Making swap channels first class

We can also make the `swap` operation first class

```
val swapEvt : 'a swap_chan * 'a -> 'a event
```

by using the `guard` combinator to allocate the reply channel.

```
fun swapEvt (SC ch, vOut) = guard (fn () => let
      val inCh = channel ()
      in
        choose [
            wrap (recvEvt ch,
              fn (vIn, outCh) => (send(outCh, vOut); vIn)),
            wrap (sendEvt (ch, (vOut, inCh)),
              fn () => recv inCh)
          ]
      end)
```

Two-server interaction using events

Server abstraction:

```
type server
val rpcEvt : server * req -> repl event
```

The client code is no longer a mess.

```
select [
    wrap (rpcEvt server1, fn repl1 => act1 repl1 ),
    wrap (rpcEvt server2, fn repl2 => act2 repl2 )
  ]
```

Two-server interaction using events *(continued ...)*

The implementation of the server protocol is as before, but we can now package it up as an event-valued abstraction:

```
datatype server = SERVER of (req * repl chan * unit event) chan

fun rpcEvt (SERVER recCh, req) = withNack (fn nack => let
      val replCh = channel ()
      in
        send (reqCh, (req, replCh, nack));
        revcEvt replCh
      end)
```

Other abstractions

Events have been used to implement a wide range of abstractions in CML, including:

- Futures
- Promises (asynchronous RPC)
- Actors
- Join patterns

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Example — distributed tuple spaces

The *Linda* family of languages use *tuple spaces* to organize distributed computation.

A tuple space is a shared associative memory, with three operations:

- **output** adds a tuple.
- **input** removes a tuple from the tuple space. The tuple is selected by matching against a *template*.
- **read** reads a tuple from the tuple space, without removing it.

```
val output : (ts * tuple) -> unit
val input  : (ts * template) -> value list event
val read   : (ts * template) -> value list event
```

Distributed tuple spaces *(continued ...)*

There are two ways to implement a distributed tuple space:

- *Read-all, write-one*
- *Read-one, write-all*

We choose read-all, write-one. In this organization, a `write` operation goes to a single processor, while an `input` or `read` operation must query all processors.

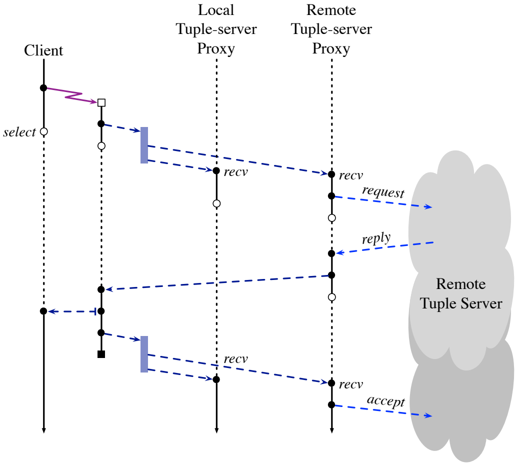
Distributed tuple spaces *(continued ...)*

The `input` protocol is complicated:

1. The reader broadcasts the query to all tuple-space servers.
2. Each server checks for a match; if it finds one, it places a hold on the tuple and sends it to the reader. Otherwise it remembers the request to check against subsequent `write` operations.
3. The reader waits for a matching tuple. When it receives a match, it sends an acknowledgement to the source, and cancellation messages to the others.
4. When a tuple server receives an acknowledgement, it removes the tuple; when it receives a cancellation it removes any hold or queued request.

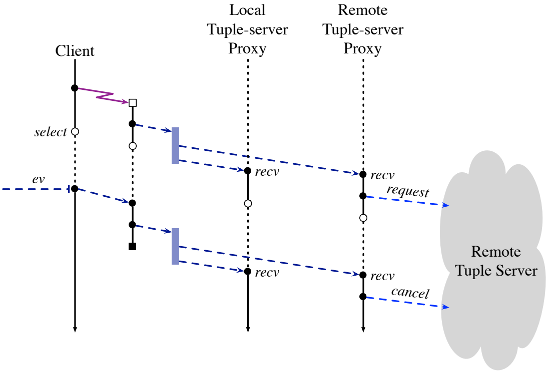
Distributed tuple spaces *(continued ...)*

Here is the message traffic for a successful `input` operation:



Distributed tuple spaces *(continued ...)*

We use negative acknowledgements to cancel requests when the client chooses some other event.



Note that we must confirm that a client accepts a tuple before sending out the acknowledgement.

Implementing concurrency in functional languages

- Functional languages can provide a platform for efficient implementations of concurrency features.
- This is especially true for languages that support first-class continuations.

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Continuations

Continuations are a semantic concept that captures the meaning of the "rest of the program."

In a functional language, we can apply the *continuation-passing-style* transformation to make continuations explicit.

For example, consider the expression "`(x+y)*z`." We can rewrite it as follows:

```
(fn k => k(x+y)) (fn v => v*z)
```

In this rewritten code, the variable `k` is bound to the continiation of the expression "`x+y`."

First-class continuations

Some languages make it possible to reify the implicit continuations. For example, SML/NJ provides the following interface to its first-class continuations:

```
type 'a cont

val callcc : ('a cont -> 'a) -> 'a
val throw  : 'a cont -> 'a -> 'b
```

First-class continuations can be used to implement many kinds of control-flow, including loops, back-tracking, exceptions, and various concurrency mechanisms.

Coroutines

Implementing a simple coroutine package using continuations is straightforward.

```
val fork : (unit -> unit) -> unit
val exit : unit -> 'a
val yield : unit -> unit
```

Coroutines *(continued ...)*

```
val rdyQ : unit cont Q.queue = Q.mkQueue()

fun dispatch () = throw (Q.dequeue rdyQ) ()

fun yield () = callcc (fn k => (
      Q.enqueue (rdyQ, k);
      dispatch ()))

fun exit () = dispatch ()

fun fork f = callcc (fn parentK => (
      Q.enqueue (rdyQ, parentK);
      (f ()) handle _ => ();
      exit ()))
```

Adding synchronization

To allow our threads to communicate, we will add support for *ivars*, which are write-once synchronous variables.

```
type 'a ivar

fun ivar : unit -> 'a ivar
val get : 'a ivar -> 'a
val put : 'a ivar * 'a -> unit
```

An ivar can either be empty (possibly with waiting threads) or full with a value, as reflected in the following representation:

```
datatype 'a ivar_state
  = EMPTY of 'a cont list
  | FULL of 'a

datatype 'a ivar = IV of 'a ivar_state ref
```

Ivars are created in the empty state:

```
fun ivar = ref(EMPTY[])
```

Adding syncronization *(continued ...)*

To get a value from an ivar, we check its state and block if it is empty.

```
fun get (IV r) = (case !r
       of EMPTY waiting => callcc (fn resumeK => (
            r := EMPTY(resumeK :: waiting);
            dispatch()))
        | FULL v => v)

fun put (IV r, v) = (case !r
       of EMPTY waiting => (
            r := FULL v;
            List.app (bindAndEnqueue v) waiting)
        | FULL v => raise Fail "already␣set")
```

The tricky part is the `bindAndEnqueue` function, which turns an `'a cont` into a `unit cont` and then enqueues it on the scheduling queue.

```
fun bindAndEnqueue (v : 'a) (k : 'a cont) : unit =
      Q.enqueue (rdyQ,
        callcc (fn k' => (
          callcc (fn unitK => throw k' unitK);
          throw k v)))
```

Preemption and parallelism

- We can add preemptive scheduling by representing timer interrupts as asynchronous operations that reify the program state as a continuation.
- Adding preemption does require a mechanism for masking interrupts.
- We can also extend this model to support multicore parallelism, but that requires low-level shared-memory synchronization mechanisms to prevent race conditions when accessing the scheduling queues, etc.

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