Programming Language Concepts, cs2104 Lecture 09 (2003-10-10)

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Reading Suggestions

- Chapter 4
  - Sections 4.1-4.3 [careful]
- And of course the handouts!

Organizational

- Assignment 3 deadline is extended (again) to October 13 (Monday)
- Consultation at October 11 (Saturday) from 11:00 – 13:00 at PC Lab2
- Check your marks for Assignment 1
- Finish correction of midterm exam soon

Concurrency

Concurrency

- First: declarative concurrency
- What is concurrency?
- How to make a program concurrent?
- How do concurrent programs execute?

The World Is Concurrent!

- Concurrent programs
  several activities execute simultaneously (concurrently)
- Most of the software you use is concurrent
  - operating system: IO, user interaction, many processes, …
  - web browser, Email client, Email server, …
  - telephony switches handling many calls
  - …

Why Should We Care?

- Software must be concurrent…
  … for many application areas
- Concurrency can be helpful for constructing programs
  - organize programs into independent parts
  - concurrency allows to make them independent with respect to how the execute
  - essential: how do concurrent programs interact?
- Concurrent programs can run faster on parallel machines (including clusters)

Concurrent Programming Is Difficult…

- This is the traditional belief
- The truth is: concurrency is very difficult…
  … if used with inappropriate tools and programming languages
- In particular troublesome: state and concurrency
  (see discussion end of Chapter 1)

Concurrent Programming Is Easy…

- Oz (as well as Erlang) has been designed to be very good at concurrency…
- Essential for concurrent programming here
  - data-flow variables
    very simple interaction between concurrent programs, mostly automatic
  - light-weight threads

Declarative Concurrent Programming

- What stays the same
  - the result of your program
  - concurrency does not change the result
- What changes
  - programs can compute incrementally
  - incremental input… (such as reading from a network connection)
    …is processed incrementally
  - the fun: much greater!

Our Schedule

- Programming with threads
  - data-driven concurrency
- Demand driven execution
  - …so that you can do the next assignment
- Abstract machine
  - explain the details, very simple!
  - next lecture

Threads

Our First Program

```
declare X0 X1 X2 X3
thread X1=1 + X0  end
thread X3=X1 + X2 end
{Browse [X0 X1 X2 X3]}
```

- Browser will show `[X0 X1 X2 X3]`
  - variables are not yet assigned

Our First Program

```
declare X0 X1 X2 X3
thread X1=1 + X0  end
thread X3=X1 + X2 end
{Browse [X0 X1 X2 X3]}
```

- Both threads suspend
  - `X1=1+X0` suspended
  - `X3=X1+X2` suspended

`X0` unassigned

`X1,X2` unassigned

Our First Program

```
declare X0 X1 X2 X3
thread X1=1 + X0  end
thread X3=X1 + X2 end
{Browse [X0 X1 X2 X3]}
```

- Feeding `X0=4`

Our First Program

```
declare X0 X1 X2 X3
thread X1=1 + X0  end
thread X3=X1 + X2 end
{Browse [X0 X1 X2 X3]}
```

- Feeding `X0=4`
  - first thread can execute, binds `X1` to `5`

Our First Program

```
declare X0 X1 X2 X3
thread X1=1 + X0  end
thread X3=X1 + X2 end
{Browse [X0 X1 X2 X3]}
```

- Feeding `X0=4`
  - first thread can execute, binds `X1` to `5`
  - Browser shows `[1 5 X2 X3]`

Our First Program

```
declare X0 X1 X2 X3
thread X1=1 + X0  end
thread X3=X1 + X2 end
{Browse [X0 X1 X2 X3]}
```

- Second thread is still suspending
  - variable `X2` still not assigned

Our First Program

```
declare X0 X1 X2 X3
thread X1=1 + X0  end
thread X3=X1 + X2 end
{Browse [X0 X1 X2 X3]}
```

- Feeding `X2=2`
  - second thread can execute, binds `X3` to `7`
  - Browser shows `[1 5 2 7]`

Threads

- A thread is created by the
  thread ⟨s⟩ **end**
  statement

- Threads compute
  - independently
  - as soon as their statement can execute
  - interact by binding variables in store

The Browser

- The Browser is also implemented in Oz
- It runs in a thread of its own
- It also is run whenever browsed variables are bound
- It uses some extra functionality to look to unbound variables

The sequential model

Statements are executed sequentially from a single semantic stack

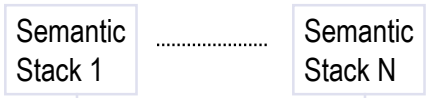
Semantic Stack

Single-assignment store

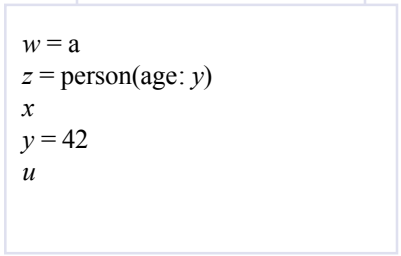
$w = \text{a}$
$z = \text{person(age: } y\text{)}$
x
$y = 42$
u

The concurrent model

Multiple semantic stacks (threads)



Single-assignment store

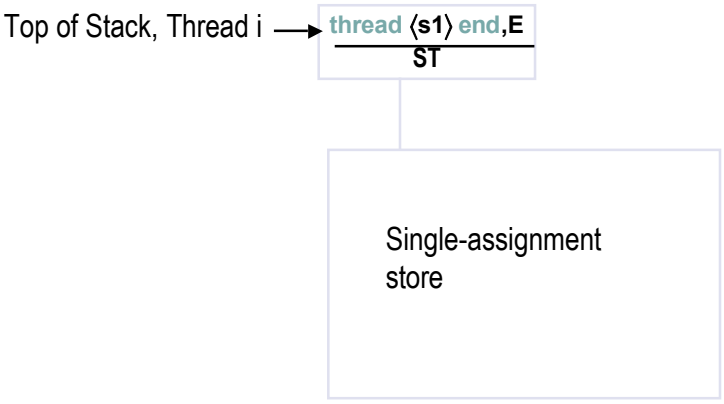


Concurrent declarative model

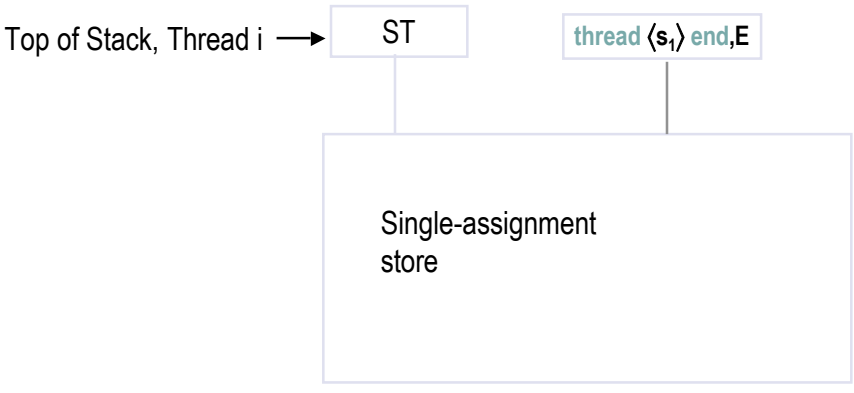
The following defines the syntax of a statement, ⟨s⟩ denotes a statement

⟨s⟩ ::=	skip	*empty statement*
|	⟨x⟩ = ⟨y⟩	*variable-variable binding*
|	⟨x⟩ = ⟨v⟩	*variable-value binding*
|	⟨s_1⟩ ⟨s_2⟩	*sequential composition*
|	local ⟨x⟩ in ⟨s_1⟩ end	*declaration*
|	proc {⟨x⟩ ⟨y_1⟩ … ⟨y_n⟩} ⟨s_1⟩ end	*procedure introduction*
|	if ⟨x⟩ then ⟨s_1⟩ else ⟨s_2⟩ end	*conditional*
|	{ ⟨x⟩ ⟨y_1⟩ … ⟨y_n⟩ }	*procedure application*
|	case ⟨x⟩ of ⟨pattern⟩ then ⟨s_1⟩ else ⟨s_2⟩ end	*pattern matching*
|	**thread ⟨s_1⟩ end**	***thread creation***

The concurrent model



The concurrent model



Basic Concepts

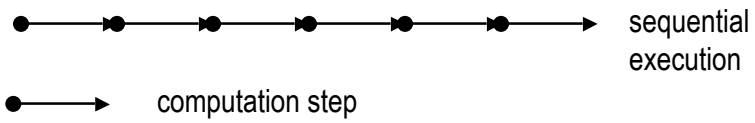
- The model allows multiple statements to execute ”at the same time” ?
- Imagine that these threads really execute in parallel, each has its own processor, but share the same memory
- Reading and writing different variables can be done simultaneously by different threads
- Reading the same variable can be done simultaneously
- Writing the same variable is done sequentially

Causal order

- In a sequential program all execution states are totally ordered
- In a concurrent program all execution states of a given thread is totally ordered
- The execution state of the concurrent program as a whole is **partially ordered**

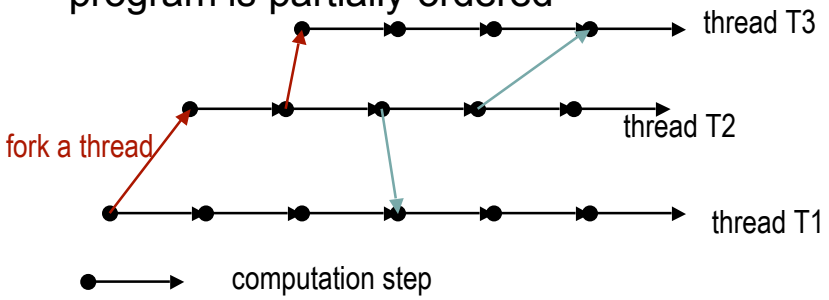
Total order

- In a sequential program all execution states are totally ordered

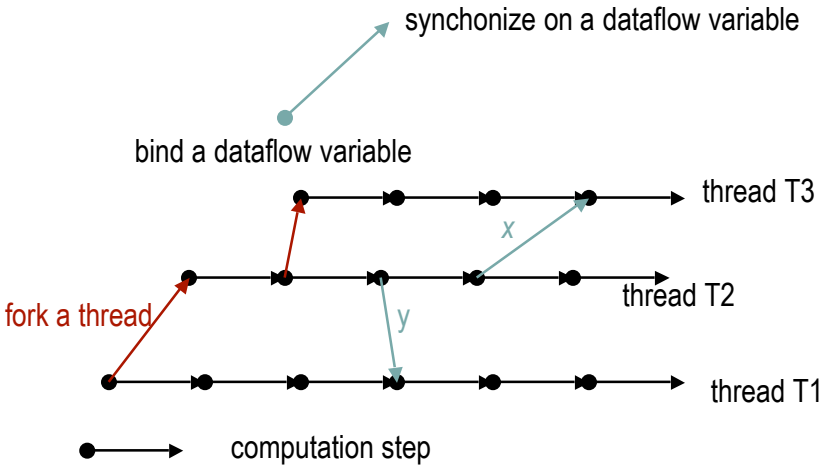


Causal order in the declarative model

- In a concurrent program all execution states of a given thread is totally ordered
- The execution state of the concurrent program is partially ordered



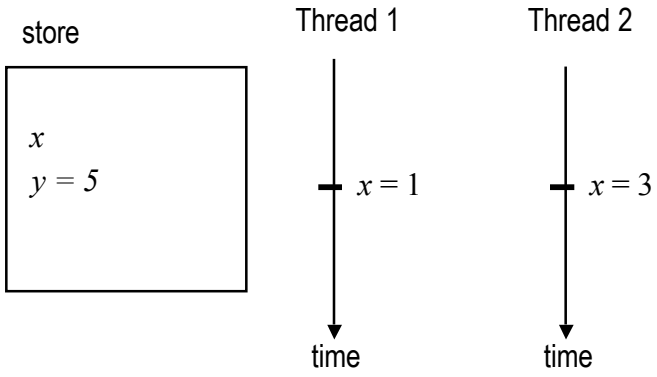
Causal order in the declarative model



Nondeterminism

- An execution is nondeterministic if there is a computation step in which there is a choice what to do next
- Nondeterminism appears naturally when there are multiple concurrent states

Example of nondeterminism



The thread that binds x first will continue, the other thread will raise an exception

Nondeterminism

- In the concurrent declarative model when there is only one binder for each dataflow variable, the nondeterminism is not observable on the store (i.e. the store develops to the same final results)
- This means for correctness we can ignore the concurrency
- Declarative concurrency

Scheduling

- The choice of which thread to execute next and for how long is done by a part of the system called the *scheduler*
- A thread is *runnable* if its next statement to execute is not blocked on a dataflow variable, otherwise the thread is *suspended*

Scheduling

- A scheduler is fair if it does not starve a runnable thread
  - All runnable thread execute eventually
- Fair scheduling make it easy to reason about programs
- Otherwise some prefectly runnable program will never get its share

Example of runnable thread

```
thread
   for I in 1..10000 do {Show 1} end
end
thread
   for I in 1..10000 do {Show 2} end
end
```


Example of runnable thread

```
thread
   for I in 1..10000 do {Show 1} end
end
thread
   for I in 1..10000 do {Show 2} end
end
```

- This program will interleave the execution of two thread, one printing 1, and the other printing 2
- fair scheduler

Dataflow computation

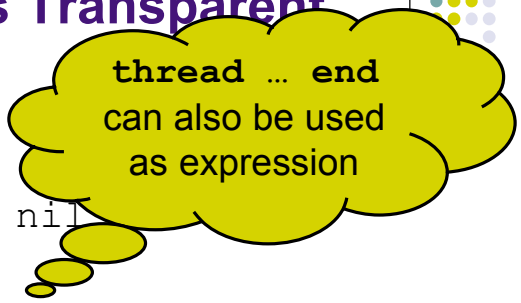
- Threads suspend of data availability in dataflow variables
- The **{Delay X}** primitive makes the thread suspends for X milliseconds, after that the thread is runnable

```
declare X
{Browse X}
local Y in
   thread {Delay 1000} Y = 10*10 end
   X = Y + 100*100
end
```


Concurrency Is Transparent

```
fun {CMap Xs F}
   case Xs
   of nil  then nil
   [] X|Xr then
      thread {F X} end|{CMap Xr F}
   end
end
```

Concurrency Is Transparent




```
fun {CMap Xs F}
   case Xs
   of nil  then nil
   [] X|Xr then
      thread {F X} end|{CMap Xr F}
   end
end
```


Concurrency Is Transparent

```
fun {CMap Xs F}
   case Xs
   of nil  then nil
   [] X|Xr then
      thread {F X} end|{CMap Xr F}
   end
end
```

- What happens:

```
declare F
{Browse {CMap [1 2 3 4] F}}
```

Concurrency Is Transparent

```
fun {CMap Xs F}
   case Xs
   of nil  then nil
   [] X|Xr then
      thread {F X} end|{CMap Xr F}
   end
end
```

- Browser shows `[_ _ _ _]`
  - `CMap` computes the list skeleton
  - newly created threads suspend until `F` bound

Concurrency Is Transparent

```
fun {CMap Xs F}
   case Xs
   of nil  then nil
   [] X|Xr then
      thread {F X} end|{CMap Xr F}
   end
end
```

- What happens:

```
F = fun {$ X} X+1 end
```

Concurrency Is Transparent

```
fun {CMap Xs F}
   case Xs
   of nil  then nil
   [] X|Xr then
      thread {F X} end|{CMap Xr F}
   end
end
```

- Browser shows `[2 3 4 5]`

Cheap concurrency and dataflow

- Declarative programs can easily be made concurrent
- Just use the thread statement where concurrent is needed

Cheap concurrency and dataflow

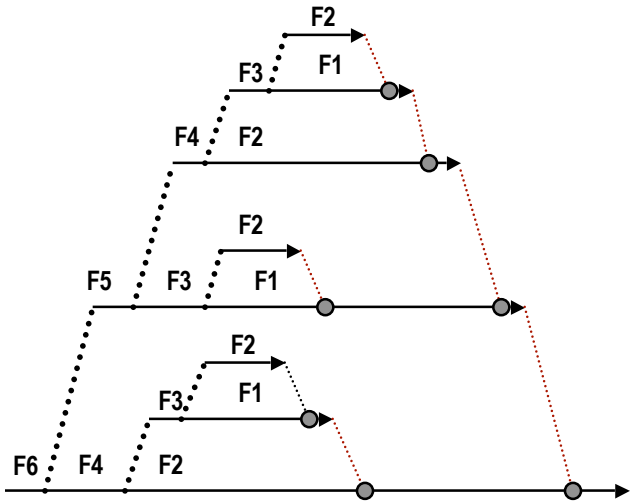
```
fun {Fib X}
   if X==0 then 0
    elseif X==1 then 1
   else
      thread {Fib X-1} end + {Fib X-2}
   end
end
```


Understanding why

```
fun {Fib X}
   if … then 0 elseif … then 1
   else  F1 F2 in
      F1  =  thread {Fib X-1} end
      F2  =  {Fib X-2}
      F1  + F2
   end
end
```

Dataflow dependency

Execution of {Fib 6}

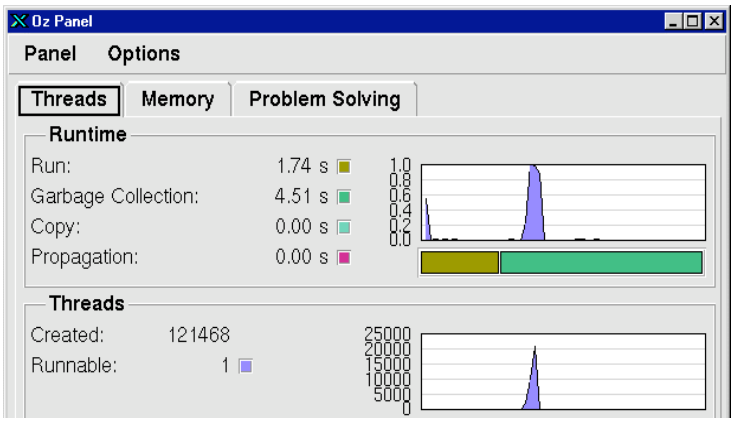


Fork a thread

Synchronize on result

Running thread

Fib



Producer ⇔ Consumer

```
thread X={Produce} end
thread {Consume X} end
```

- Typically, what is produced will be put on a list that never ends (without `nil`)

  stream

- Consumer consumes as soon as producer produces

Example: Producer ⇔ Consumer

```
fun {Produce N}
   N|{Produce N+1}
end
proc {Consume Xs}
   case Xs of X|Xr then
      if X mod 1000 == 0 then
         {Browse X}
      end
      {Consume Xr}
   end
end
```

Stream Transducer

```
thread Xs={Produce}        end
thread Ys={Transduce Xs}   end
thread {Consume Ys}        end
```

- Transducer
  - reads input stream
  - computes output stream
- Can be: filtering, mapping, …

Concurrent Streams

- Often used for simulation
  - analog circuits
  - digital circuits
- Lab assignment 4
  - streams used for simulation of analog circuits
  - simple circuits
  - lazy streams

Client ⇔ Server

- Similar to producer ⇔ consumer

- Typical scenario:
  - more clients than servers
  - server has a fixed identity
  - clients send messages to server
  - server replies

- Later: message sending

Fairness

- Essential that even though producer can always produce, consumer also gets a chance to run

- Threads are scheduled with **fairness**
  - if a thread is runnable, it eventually will run

Thread Scheduling

- More guarantees than just fairness
- Threads are given a time slice to run
  - approximately 10ms
  - when time slice is over: thread is **preempted**
  - next runnable thread is **scheduled**
- Can be even influenced by priorities
  - controls relative size of time slice [see book]

Summary

- Threads
  - suspend and resume automatically
  - controlled by variables
  - reminder: **data-flow variables**
  - cheap
  - execute fairly according to time-slice
- Pattern
  - producer ⇔ transducer ⇔ consumer

Demand Driven Execution

How to Control Producers?

- Producer should not produce more than needed
- Make consumer the stream producer
  - consumer produces skeleton, producer fills skeleton
  - difficult
- Use lazy streams: producer runs on request

Needed Variables

- Idea: start execution, when value for variable needed

  short: **variable needed**

- Value for variable needed…

  …a thread suspends on variable!

Triggers

- By-need triggers
  - a variable `X`
  - a zero-argument function `F`
- Trigger creation

```
X={ByNeed F}
```

The By-Need Protocol

- Suppose `(X,F)` is a by-need trigger
- If `X` is needed,
  execute `thread X=F end`
  delete trigger, `X` becomes a normal variable

Example: ByNeed

```
X={ByNeed fun {$} 4 end}
```

- Executing `{Browse X}`
  - shows `<Future>` (meaning not yet triggered)
  - Browser does not need variables!
- Executing `Z=X+1`
  - `X` is needed
  - thread `T` blocks (`X` is not yet bound)
  - new thread created that binds `X` to `4`
  - thread `T` resumes and binds `Z` to `5`

Lazy Functions

```
fun lazy {Produce N}
   N|{Produce N+1}
end
```

abbreviates

```
fun {Produce N}
   {ByNeed fun {$} N|{Produce N+1} end}
end
```


Lazy Production

```
fun lazy {Produce N}
   N|{Produce N+1}
end
```

- Intuitive understanding: function executes only, if its output is needed

Example: Lazy Production

```
fun lazy {Produce N}
   N|{Produce N+1}
end
declare Ns={Produce 0}
{Browse Ns}
```

- Shows again `<Future>`
  - Remember: the Browser does not need variables

Example: Lazy Production

```
fun lazy {Produce N}
   N|{Produce N+1}
end
declare Ns={Produce 0}
```

- Execute `_=Ns.1`
  - needs the variable `Ns`
  - Browser now shows `0|<Future>`

Example: Lazy Production

```
fun lazy {Produce N}
   N|{Produce N+1}
end
declare Ns={Produce 0}
```

- Execute `_=Ns.2.2.1`
  - needs the variable `Ns.2.2`
  - Browser now shows `0|1|2|<Future>`

Everything Lazy!

- Not only producers, but also transducers can be made lazy
- Sketch
  - consumer needs variable
  - transducer is triggered, needs variable
  - producer is triggered

Lazy Example

```
fun lazy {Inc Xs}
   case Xs
   of X|Xr then X+1|{Inc Xr}
   end
end

declare Xs={Inc {Inc {Produce N}}}
```


Your Lab Assignment 4

- Producer
  - produce currencies — stream of current values
- Transducer
  - amplify streams — lazy transducer that scales stream values

Summary

- Demand-driven execution
  - execute computation, if variable needed
  - need is suspension by a thread
  - requested computation is run in new thread
- By-Need triggers
- Lazy functions

Outlook

- How can we capture threads in abstract machine?
  - have multiple semantic stacks
  - semantic stack = thread
- How about by-need?
  - have a store that contains trigger
  - rest is as we have sketched it

Important

- You must try the examples and go to the tutorial
- Things are simple and fun

Demand Driven Execution

Demand-driven Execution

- Let computations drive other computations
  - producer driven by consumer/transducer
  - module loader by thread needing module
- Variables control “demand” or “need”
  - variable needed: thread suspends on variable
  - by-need trigger:
    - variable
    - nullary function describing value to be computed
  - execution by newly created thread

Needed Variables

- Idea: start execution, when value for variable needed

  short: **variable needed**
- Value for variable needed…

  …a thread suspends on variable!

Triggers

- By-need triggers
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```
X={ByNeed F}
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- Suppose `(X,F)` is a by-need trigger
- If `X` is needed,
  execute **`thread`** `X={F}` **`end`**
  delete trigger, `X` becomes a normal variable

Lazy Functions

```
fun lazy {Produce N}
   N|{Produce N+1}
end
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abbreviates

```
fun {Produce N}
   {ByNeed fun {$} N|{Produce N+1} end}
end
```


Summary

- Demand-driven execution
  - execute computation, if variable needed
  - need is suspension by a thread
  - requested computation is run in new thread
- By-Need triggers
- Lazy functions

See You In Two Weeks!

See You Next Week!

Have a Nice Weekend