Principles of Concurrency and Parallelism

Lecture 2: Coroutines

1/12/12

Expressivity

- A concurrent program provides no fundamental computability advantages over a sequential program
  - Any computation that can be expressed using a multitape Turing machine can be expressed using a single-tape Turing machine
- Why have it, then?
  - Performance: parallelism
  - Responsiveness:
    - web servers
    - operating systems
  - Flexibility
    - Algorithms, data structures, etc.
  - Expressivity

Starting Point: Control

- How do we represent or capture the notion of simultaneity?
- Example:
  - A generator:

```
x = 0;
proc f() = {  r := x;
              x := x + 1;
              return r }
f();   yields 0
f();   yields 1
```

Generators

- Suppose instead of incrementing a counter, we returned the elements of an array

```
i := 0

proc f(a) = { if i < Array.length(a)
                  then { r := A[i];
                         i := i + 1;
                         return r }
                  else raise ArrayOutofBoundsExn }
```

- A bit more complicated, but generation can still be expressed using updates on the array index

Generators

- What happens if generation is not so apparent?
- Example:
  - Generate all the elements of a tree
  - How do we write a getNextTreeElt routine?
    - We need to record and remember the next position in the tree for subsequent calls to the generator
    - We want to keep things modular and abstract, and not expose how the tree is traversed to clients
    - Want to write something like:

```
foreach node in Tree do { ... }
```

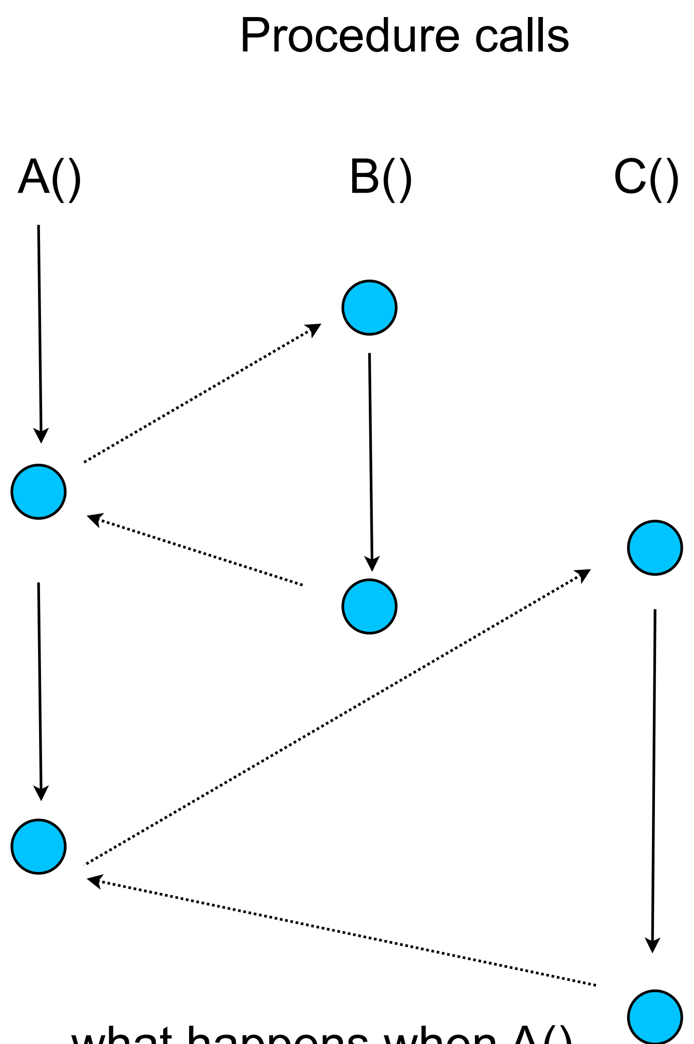
Generators

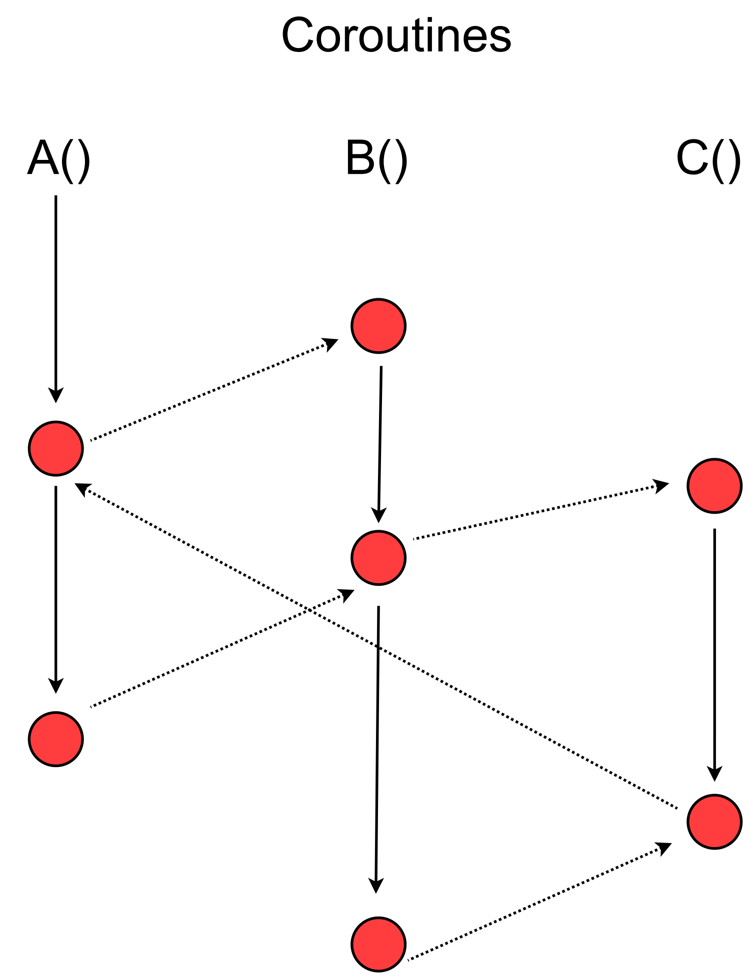
- How do we implement foreach?
  - It is meant to be a generator that yields the next leaf in the tree (according to some traversal policy) every time it is invoked
  - Must preserve the state of the traversal internally
  - How should this state be kept?

Iterators and Coroutines

- Iterators are a special case of generators
  - Found in C++, Java, Python, Lua, etc.
  - Enables enumeration of the elements of a datatype
- Key questions:
  - How do we maintain local state implicitly?
  - Can we build a general iteration framework without having to provide specialized versions for each datatype?
- Idea:
  - Imagine a procedure that "remembers" its state across calls

Coroutine





what happens when A() calls B() again?

When a coroutine returns, it remembers its program state. Why is this useful?

Generators and Coroutines

- Procedures:
  - single operation: call
  - single stack, stack frame popped upon return
- Generators:
  - two operations: suspend and resume
    - assymetric: generator suspends, caller resumes it
  - single stack, generator is an "object" that maintains local state variables
  - single entry point
- Coroutines:
  - one operation: transfer
    - fully symmetric
  - When A transfers to B it acts like a:
    - generator suspend wrt A
    - generator resume wrt B
  - transfer names who gets control next
    - non stack-like

Coroutines and Concurrency

- How would you implement coroutines?
  - Typically, implementations of procedures and procedure calls involving pushing and popping "activation frames" on the stack
  - These frames hold the arguments and local variables for the call.
  - The frame is popped when the procedure is returned.
- How do we preserve the state that will be used when we make the next call?
  - Keep multiple stacks, one for each coroutine
  - Essential feature of threads

Continuations

- A reified representation of a program's control stack.
- Example:

```
proc f(x) = { ...
              g(y);
              ... ;   A
            }

proc h(y) = { ...
              f(...);
              ... ;   B
            }
```

When g is called, the program stack retains enough information to "remember" that ***A*** must be executed and then ***B***.

The stack captures the "rest of the computation" - it is the *continuation* of the call to g().

If the computation were preempted immediately after the call to g() returns, its resumption would entail execution of the continuation

Continuations

- Can we reify this notion into a source language?
  - result is a continuation, a reified representation

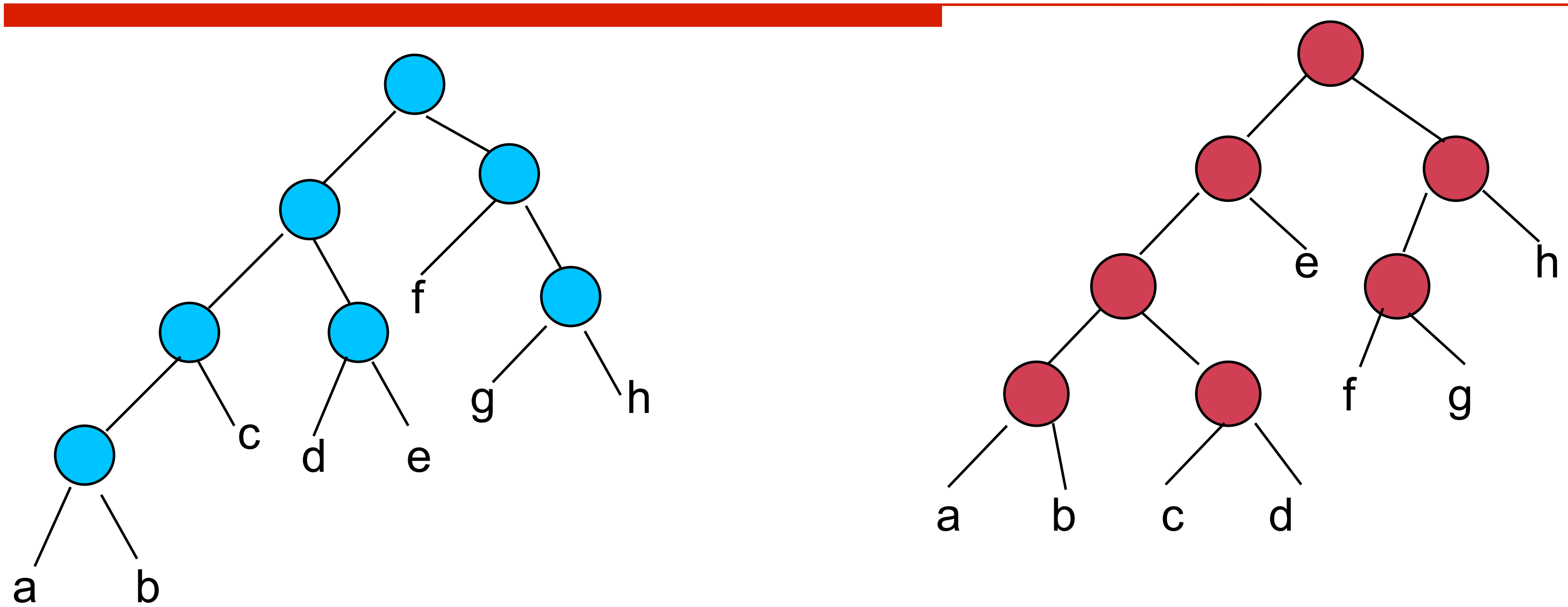
    (in the form of an abstraction) of a program control-stack.
  - Define a primitive operation called call/cc:
    - call-with-current-continuation
    - callcc (fn k => e)
      - captures the current continuation, binds to k, and evaluate e
      - the notation fn k => e defines an anonymous function that takes k as an argument
    - throw k x
      - apply continuation k with argument x

Example

```
call/cc (fn k => (throw k 3) + 2) + 1 → 4

let f = call/cc (fn k => fn x => throw k (fn y => x + y))
in f 6 →  12
```

Example: Samefringe



- Two binary trees have the same fringe if they have exactly the same leaves reading left to right

Samefringe

- Simple strategy:
  - Collect leaves of both trees into two lists, and compare elements

    frontier t1 = *collect all leaves of tree* t1
    frontier t2 = *collect all leaves of tree* t2

    samefringe (t1,t2) = *compare the frontiers of* t1 *and* t2 *pairwise*

  - What's wrong with this approach?

Samefringe Using Coroutines

- Rather than collecting all leaves or transforming tree eagerly, generate leaf values for two trees lazily
- Create generators for the two trees that yield the next leaf when invoked, and return control back to the caller, remembering where they are

```
fun samefringe(t1,t2) =
     let val g1 = makeGenerator(t1)
          val g2 = makeGenerator(t2)

          fun loop() = let val l1 = g1()
                                  val l2 = g2()
                             in case (l1,l2) of
                                    (Empty,Empty) => true
                                  | (Leaf(x),Leaf(y)) => (x = y) andalso loop()
                                  | _ => false
                              end
      in loop ()
      end
```

- How do we write these generators?

What have we achieved?

- Call/cc gives us a way to capture the remaining part of a computation at any given program point.
- If we capture a continuation and store it, we have a handle on a program state. This is what is necessary to suspend a co-routine.
- If we invoke a captured continuation, we effectively resume a computation (or co-routine) at the point where its continuation was saved.

Generators (revisited)

- How should we generate the leaves for samefringe?
- Need to:
  - save state and suspend after each new leaf is found
  - resume caller once state is saved
- Use continuations for state saving
  - If continuations are “first-class” they can be stored into locations for later use

Generators (revisited)

```
cont caller;
proc generate-num;

proc generate-numbers () = {
  loop (i=0) (i++)
    {
         call/cc (fn (genrest) =>
                   { generate-num := proc () = throw genrest ();
                     throw caller i }
    }

generate-num := generate-numbers;
proc make-generator () = {
   fn () => call/cc (fn (k) => {
                                 caller := k;
                                 generate-num()
                              })
  }
```

Analysis

- Continuations saved at two points in the generator definition:
  - To save state associated with the generator loop itself
  - To save the callers state, so that it can be resumed with the next generated value
- How might we implement this functionality in the absence of explicit continuations?

Manifestation

- Several languages provide explicit support for continuation-capture
  - Scheme, ML, Haskell, ...
- Here's how we might write a generator in ML:

```
fun makeGenerator i =
    let val caller = ref NONE
        val generateNumRef = ref (fn () => ())
        fun generateNums () =
            let fun loop (i) =
                let val _ = callcc (fn genrest =>
                                  ((generateNumRef := (fn ()=> throw genrest ()));
                                   throw (valOf(!caller)) (SOME i)))
              in loop (i+1)
              end
            in loop (i)
            end
        val _ = (generateNumRef := generateNums)
    in fn () =>
        callcc (fn k =>   (caller := SOME k;
                          (!generateNumRef)();
                          NONE))
    end
```

What next?

- Being able to save and restore control state is at the heart of any implementation of concurrency
- Using continuations, we can build our own threading system
  - schedulers
    - cooperative
    - preemptive
- Not quite so simple though ...
  - exceptions and aborting; interrupts
  - asynchrony

Further Reading

Essentials of Programming Languages, Friedman, Wand, Haynes (2001)

Continuation-based Multiprocessing, Wand (1980)

Continuations and Threads: Expressing Machine Concurrency Directly in Advanced Languages (1997)

Continuations and Concurrency, Hieb and Dybvig (1990)