Implementing Coroutines with call/cc

Coroutines are a very handy generalization of subroutines. A coroutine may *suspend* its execution and later *resume* from the point of suspension. Unlike subroutines, coroutines do no have to complete their execution before they return.

Coroutines are useful for computation of long or infinite streams of data, where we wish to compute some data, use it, compute additional data, use it, etc.

Subroutines aren’t always able to handle this, as we may need to save a lot of internal state to resume with the correct next value.

Producer/Consumer using Coroutines

The example we will use is one of a consumer of a potentially infinite stream of data. The next integer in the stream (represented as an unbounded list) is read. Call this value n. Then the next n integers are read and summed together. The answer is printed, and the user is asked whether another sum is required. Since we don’t know in advance how many integers will be needed, we’ll use a coroutine to produce the data list in segments, requesting another segment as necessary.

```
(define (consumer)
  (next 0); reset next function
  (let loop ((data (moredata)))
    (let  (
     (sum+restoflist
       (sum-n-elems (car data)
           (cons 0 (cdr data)))))
      (display (car sum+restoflist))
      (newline)
      (display "more? ")
      (if (equal? (read) 'y)
        (if (= 1
            (length sum+restoflist))
         (loop (moredata))
         (loop (cdr sum+restoflist))
        )
        #t ; Normal completion
      )
    )
  )
)
```

Next, we’ll consider **`sum-n-elems`**, which adds the first element of list (a running sum) to the next n elements on the list. We’ll use **`moredata`** to extend the data list as needed.

```
(define (sum-n-elems n list)
  (cond
     ((= 0 n)   list)
     ((null? (cdr list))
      (sum-n-elems n
        (cons (car list)(moredata))))
     (else
      (sum-n-elems (- n 1)
        (cons (+ (car list)
                 (cadr list))
              (cddr list))))


   )
)
```

The function **`moredata`** is called whenever we need more data. Initially a **`producer`** function is called to get the initial segment of data. **`producer`** actually returns the next data segment *plus* a continuation (stored in **`producer-cc`**) used to resume execution of **`producer`** when the next data segment is required.

```
(define moredata
 (let ( (producer-cc  () ) )
   (lambda ()
     (let (
       (data+cont
         (if (null? producer-cc)
           (call/cc (lambda (here)
              (producer here)))
           (call/cc (lambda (here)
              (producer-cc here)))
         )
        ))
        (set! producer-cc
              (cdr data+cont))
        (car data+cont)
     )
   )
 )
)
```

Function (**`next z)`** returns the next **`z`** integers in an infinite sequence that starts at 1. A value **`z=0`** is a special flag indicating that the sequence should be reset to start at 1.

```
(define next
  (let ( (i 1))
    (lambda (z)
      (if (= 0 z)
        (set! i 1)
        (let loop
          ((cnt z) (val i) (ints () ))
            (if (> cnt 0)
                (loop (- cnt 1)
                      (+ val 1)
                      (append ints
                       (list val)))
                (begin
                   (set! i val)
                   ints
                )
            )
        )
) ) ) )
```

The function **`producer`** generates an infinite sequence of integers (1,2,3,...). It suspends every 5/10/15/25 elements and returns control to **`moredata`**.

```
(define (producer initial-return)
    (let  loop
        ( (return initial-return) )
      (set! return
          (call/cc (lambda (here)
            (return (cons (next 5)
                                here)))))
      (set! return
          (call/cc (lambda (here)
            (return (cons (next 10)
                                here)))))
      (set! return
          (call/cc (lambda (here)
            (return (cons (next 15)
                                here)))))
      (loop
          (call/cc (lambda (here)
            (return (cons (next 25)
                                here)))))
)    )
```

Reading Assignment

- MULTILISP: a language for concurrent symbolic computation,
  by Robert H. Halstead
  (linked from class web page)

Lazy Evaluation

Lazy evaluation is sometimes called "call by need." We do an evaluation when a value is used; not when it is defined.

Scheme provides for lazy evaluation:

`(delay expression)`

Evaluation of **`expression`** is delayed. The call returns a "promise" that is essentially a lambda expression.

`(force promise)`

A promise, created by a call to **`delay`**, is evaluated. If the promise has already been evaluated, the value computed by the first call to **`force`** is reused.

Example:

Though **`and`** is predefined, writing a correct implementation for it is a bit tricky.

The obvious program

```
(define (and A B)
  (if A
     B
     #f
  )
)
```

is incorrect since **`B`** is always evaluated whether it is needed or not. In a call like

```
(and (not (= i 0)) (> (/ j i) 10))
```

unnecessary evaluation might be fatal.

An argument to a function is *strict* if it is always used. Non-strict arguments may cause failure if evaluated unnecessarily.

With lazy evaluation, we can define a more robust **`and`** function:

```
(define (and A B)
  (if A
     (force B)
     #f
  )
)
```

This is called as:

```
(and (not (= i 0))
     (delay (> (/ j i) 10)))
```

Note that making the programmer remember to add a call to **`delay`** is unappealing.

Delayed evaluation also allows us a neat implementation of suspensions.

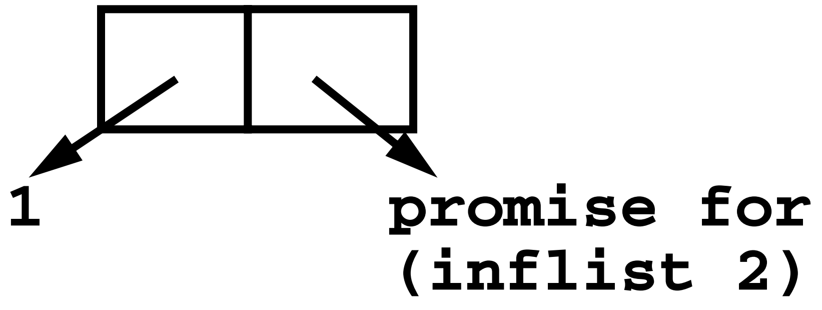
The following definition of an infinite list of integers clearly fails:

```
(define (inflist i)
   (cons i (inflist (+ i 1))))
```

But with use of delays we get the desired effect in finite time:

```
(define (inflist i)
   (cons i
     (delay (inflist (+ i 1)))))
```

Now a call like **`(inflist 1)`** creates



We need to slightly modify how we explore suspended infinite lists. We can't redefine `car` and `cdr` as these are far too fundamental to tamper with.

Instead we'll define `head` and `tail` to do much the same job:

```
(define head car)
(define (tail L)
   (force (cdr L)))
```

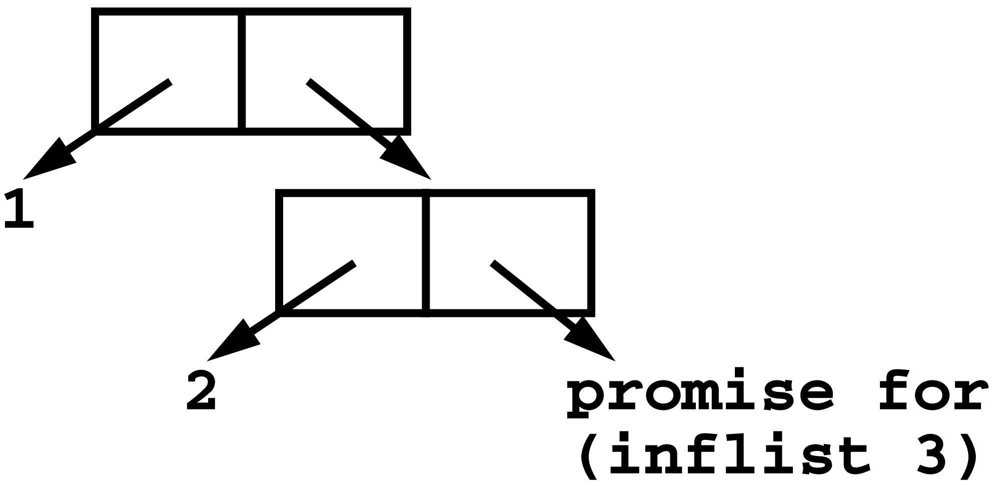
`head` looks at `car` values which are fully evaluated.

`tail` forces one level of evaluation of a delayed `cdr` and saves the evaluated value in place of the suspension (promise).

Given

`(define IL (inflist 1))`

`(head (tail IL))` returns **`2`** and expands **`IL`** into



Exploiting Parallelism

Conventional procedural programming languages are difficult to compile for multiprocessors.

Frequent assignments make it difficult to find independent computations.

Consider (in Fortran):

```
   do 10  I = 1,1000
      X(I) = 0
      A(I) = A(I+1)+1
      B(I) = B(I-1)-1
      C(I) = (C(I-2) + C(I+2))/2
10 continue
```

This loop defines 1000 values for arrays **X**, **A**, **B** and **C**.

Which computations can be done in parallel, partitioning parts of an array to several processors, each operating independently?

- `X(I) = 0`
  Assignments to `X` can be readily parallelized.
- `A(I) = A(I+1)+1`
  Each update of `A(I)` uses an `A(I+1)` value that is not yet changed. Thus a whole array of new `A` values can be computed from an array of "old" `A` values in parallel.
- `B(I) = B(I-1)-1`
  This is less obvious. Each `B(I)` uses `B(I-1)` which is defined in terms of `B(I-2)`, etc. Ultimately all new `B` values depend only on `B(0)` and `I`. That is, `B(I)` = `B(0) - I`. So this computation can be parallelized, but it takes a fair amount of insight to realize it.

- **`C(I) = (C(I-2) + C(I+2))/2`**
  It is clear that even and odd elements of **`C`** don’t interact. Hence two processors could compute even and odd elements of **`C`** in parallel. Beyond this, since both earlier and later **`C`** values are used in each computation of an element, no further means of parallel evaluation is evident. Serial evaluation will probably be needed for even or odd values.

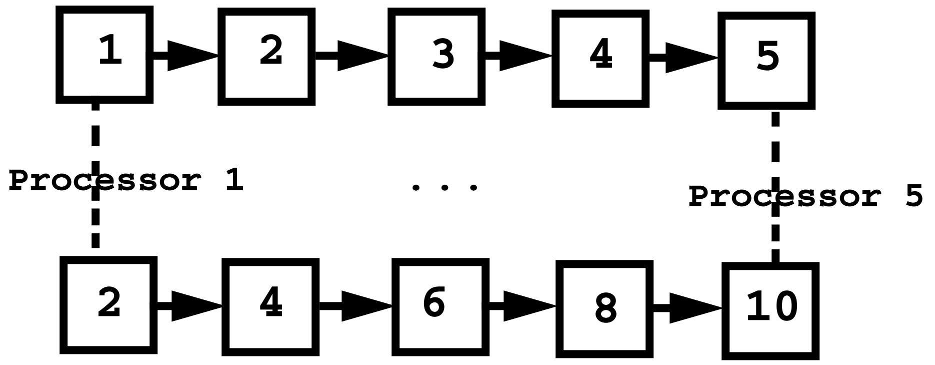
Exploiting Parallelism in Scheme

Assume we have a shared-memory multiprocessor. We might be able to assign different processors to evaluate various independent subexpressions.

For example, consider

```
(map (lambda(x) (* 2 x))
   '(1 2 3 4 5))
```

We might assign a processor to each list element and compute the lambda function on each concurrently:



How is Parallelism Found?

There are two approaches:

- We can use a “smart” compiler that is able to find parallelism in existing programs written in standard serial programming languages.
- We can add features to an existing programming language that allows a programmer to show where parallel evaluation is desired.

Concurrentization

Concurrentization (often called parallelization) is process of automatically finding potential concurrent execution in a serial program.

Automatically finding current execution is complicated by a number of factors:

- Data Dependence

  Not all expressions are independent. We may need to delay evaluation of an operator or subprogram until its operands are available.

  Thus in

  ```
  (+ (* x y) (* y z))
  ```

  we can't start the addition until both multiplications are done.

- Control Dependence

  Not all expressions need be (or should be) evaluated.

  In

  ```
  (if (= a 0)
           0
      (/  b a))
  ```

  we don’t want to do the division until we know **a** ≠ **0**.

- Side Effects

  If one expression can write a value that another expression might read, we probably will need to *serialize* their execution.

  Consider

  ```
  (define rand!
   (let ((seed 99))
     (lambda ()
      (set! seed
        (mod (* seed 1001) 101101))
      seed
  )) )
  ```

Now in

`(+ (f (rand!)) (g (rand!)))`

we can't evaluate **`(f (rand!))`** and **`(g (rand!))`** in parallel, because of the side effect of **`set!`** in **`rand!`**. In fact if we did, **`f`** and **`g`** might see *exactly* the same "random" number! (Why?)

- Granularity

  Evaluating an expression concurrently has an overhead (to setup a concurrent computation). Evaluating very simple expressions (like **`(car x)`** or **`(+ x 1)`**) in parallel isn't worth the overhead cost.

  Estimating where the "break even" threshold is may be tricky.

Utility of Concurrentization

Concurrentization has been most successful in engineering and scientific programs that are very regular in structure, evaluating large multidimensional arrays in simple nested loops. Many very complex simulations (weather, fluid dynamics, astrophysics) are run on multiprocessors after extensive concurrentization.

Concurrentization has been far less successful on non-scientific programs that don't use large arrays manipulated in nested for loops. A compiler, for example, is difficult to run (in parallel) on a multiprocessor.

Concurrentization within Processors

Concurrentization is used extensively within many modern uniprocessors. Pentium and PowerPC processors routinely execute several instructions in parallel if they are independent (e.g., read and write distinct registers). This are *superscalar* processors.

These processors also routinely *speculate* on execution paths, “guessing” that a branch will (or won’t) be taken even before the branch is executed! This allows for more concurrent execution than if strictly “in order” execution is done. These processors are called “out of order” processors.

Adding Parallel Features to Programming Languages.

It is common to take an existing serial programming language and add features that support concurrent or parallel execution. For example versions for Fortran (like HPF—High Performance Fortran) add a parallel do loop that executes individual iterations in parallel.

Java supports threads, which may be executed in parallel. Synchronization and mutual exclusion are provided to avoid unintended interactions.

Multilisp

Multilisp is a version of Scheme augmented with three parallel evaluation mechanisms:

- Pcall
  Arguments to a call are evaluated in parallel.
- Future
  Evaluation of an expression starts immediately. Rather than waiting for completion of the computation, a “future” is returned. This future will eventually transform itself into the result value (when the computation completes)
- Delay
  Evaluation is delayed until the result value is really needed.

The Pcall Mechanism

Pcall is an extension to Scheme's function call mechanism that causes the function and its arguments to be all computed in parallel.

Thus

```
(pcall F X Y Z)
```

causes **F**, **X**, **Y** and **Z** to all be evaluated in parallel. When all evaluations are done, **F** is called with **X**, **Y** and **Z** as its parameters (just as in ordinary Scheme).

Compare

```
(+ (* X Y) (* Y Z))
```

with

```
(pcall + (* X Y) (* Y Z))
```

It may not look like **`pcall`** can give you that much parallel execution, but in the context of recursive definitions, the effect can be dramatic.

Consider **`treemap`**, a version of **`map`** that operates on binary trees (S-expressions).

```
(define (treemap fct tree)
 (if (pair? tree)
  (pcall cons
     (treemap fct (car tree))
     (treemap fct (cdr tree))
  )
  (fct tree)
))
```

Look at the execution of **`treemap`** on the tree

```
  (((1 . 2) . (3 . 4)) .
   ((5 . 6) . (7 . 8)))
```

We start with one call that uses the whole tree. This splits into two parallel calls, one operating on

```
((1 . 2) . (3 . 4))
```

and the other operating on

```
((5 . 6) . (7 . 8))
```

Each of these calls splits into 2 calls, and finally we have 8 independent calls, each operating on the values **`1`** to **`8`**.