Declarative Programming Techniques

Accumulators (CTM 3.4.3)
Difference Lists (CTM 3.4.4)

Carlos Varela

RPI

Adapted with permission from:
Seif Haridi
KTH
Peter Van Roy
UCL

November 29, 2016
Accumulators

• *Accumulator programming* is a way to handle state in declarative programs. It is a programming technique that uses arguments to carry state, transform the state, and pass it to the next procedure.

• Assume that the state $S$ consists of a number of components to be transformed individually:

$S = (X, Y, Z, ...)$

• For each predicate $P$, each state component is made into a pair, the first component is the *input* state and the second component is the output state after $P$ has terminated

• $S$ is represented as

$(X_{in}, X_{out}, Y_{in}, Y_{out}, Z_{in}, Z_{out}, ...)$
A Trivial Example in Prolog

\[
\text{increment}(N0,N) :- \\
\quad \text{N is } N0 + 1.
\]
\[
\text{square}(N0,N) :- \\
\quad \text{N is } N0 \times N0.
\]
\[
\text{inc_square}(N0,N) :- \\
\quad \text{increment}(N0,N1), \\
\quad \text{square}(N1,N).
\]

\textbf{increment} takes \textit{N0} as the input and produces \textit{N} as the output by adding 1 to \textit{N0}.

\textbf{square} takes \textit{N0} as the input and produces \textit{N} as the output by multiplying \textit{N0} to itself.

\textbf{inc_square} takes \textit{N0} as the input and produces \textit{N} as the output by using an intermediate variable \textit{N1} to carry \textit{N0+1} (the output of \textbf{increment}) and passing it as input to \textbf{square}. The pairs \textit{N0-N1} and \textit{N1-N} are called \textit{accumulators}. 
A Trivial Example in Oz

\[
\begin{align*}
\text{proc} & \{\text{Increment} \ N0 \ N\} \\
& \quad N = N0 + 1 \\
\text{end} \\
\text{proc} & \{\text{Square} \ N0 \ N\} \\
& \quad N = N0 \times N0 \\
\text{end} \\
\text{proc} & \{\text{IncSquare} \ N0 \ N\} \\
& \quad \text{N1 in} \\
& \quad \{\text{Increment} \ N0 \ N1\} \\
& \quad \{\text{Square} \ N1 \ N\} \\
\text{end}
\end{align*}
\]

\textbf{Increment} takes \(N0\) as the input and produces \(N\) as the output by adding 1 to \(N0\).

\textbf{Square} takes \(N0\) as the input and produces \(N\) as the output by multiplying \(N0\) to itself.

\textbf{IncSquare} takes \(N0\) as the input and produces \(N\) as the output by using an intermediate variable \(N1\) to carry \(N0+1\) (the output of \textbf{Increment}) and passing it as input to \textbf{Square}. The pairs \(N0-N1\) and \(N1-N\) are called \textit{accumulators}. 
Accumulators

• Assume that the state $S$ consists of a number of components to be transformed individually:
  $$S = (X,Y,Z)$$

• Assume $P_1$ to $P_n$ are procedures in Oz

  ```plaintext
  proc \{P X_0 X Y_0 Y Z_0 Z\}
    \{P1 X_0 X_1 Y_0 Y_1 Z_0 Z_1\}
    \{P2 X_1 X_2 Y_1 Y_2 Z_1 Z_2\}
    \ldots
    \{Pn X_{n-1} X Y_{n-1} Y Z_{n-1} Z\}
  end
  ```

• The procedural syntax is easier to use if there is more than one accumulator

  The same concept applies to predicates in Prolog
MergeSort Example

• Consider a variant of MergeSort with accumulator

  proc \{MergeSort1 N S0 S Xs\}
  – \(N\) is an integer,
  – \(S0\) is an input list to be sorted
  – \(S\) is the remainder of \(S0\) after the first \(N\) elements are sorted
  – \(Xs\) is the sorted first \(N\) elements of \(S0\)

• The pair \((S0, S)\) is an accumulator

• The definition is in a procedural syntax in Oz because it
  has two outputs \(S\) and \(Xs\)
Example (2)

```plaintext
fun {MergeSort Xs}
    Ys in
    {MergeSort1 \{Length Xs\} Xs _ Ys}
    Ys
end

proc {MergeSort1 N S0 S Xs}
    if N==0 then S = S0 Xs = nil
    elseif N ==1 then X in X|S = S0 Xs=[X]
    else \%\% N > 1
        local S1 Xs1 Xs2 NL NR in
        NL = N div 2
        NR = N - NL
        {MergeSort1 NL S0 S1 Xs1}
        {MergeSort1 NR S1 S Xs2}
        Xs = \{Merge Xs1 Xs2\}
    end
end
```
MergeSort Example in Prolog

```prolog
mergesort(Xs, Ys) :-
    length(Xs, N),
    mergesort1(N, Xs, _, Ys).

mergesort1(0, S, S, []) :- !.
mergesort1(1, [X|S], S, [X]) :- !.
mergesort1(N, S0, S, Xs) :-
    NL is N // 2,
    NR is N - NL,
    mergesort1(NL, S0, S1, Xs1),
    mergesort1(NR, S1, S, Xs2),
    merge(Xs1, Xs2, Xs).
```

C. Varela; Adapted w/permission from S. Haridi and P. Van Roy
Multiple accumulators

- Consider a stack machine for evaluating arithmetic expressions
- Example: (1+4)-3
- The machine executes the following instructions
  push(1)
  push(4)
  plus
  push(3)
  minus

\[
\begin{array}{c}
4 \\
1 \\
\end{array} \rightarrow \begin{array}{c}
5 \\
\end{array} \rightarrow \begin{array}{c}
3 \\
5 \\
\end{array} \rightarrow \begin{array}{c}
2 \\
\end{array}
\]
Multiple accumulators (2)

- Example: \((1+4)-3\)
- The arithmetic expressions are represented as trees:
  \[
  \text{minus(plus(1 4) 3)}
  \]
- Write a procedure that takes arithmetic expressions represented as trees and output a list of stack machine instructions and counts the number of instructions

\[
\text{proc \{ExprCode Expr Cin Cout Nin Nout\}}
\]

- Cin: initial list of instructions
- Cout: final list of instructions
- Nin: initial count
- Nout: final count
Multiple accumulators (3)

proc {ExprCode Expr C0 C N0 N}
    case Expr
    of plus(Expr1 Expr2) then C1 N1 in
        C1 = plus|C0
        N1 = N0 + 1
        {SeqCode [Expr2 Expr1] C1 C N1 N}
    [] minus(Expr1 Expr2) then C1 N1 in
        C1 = minus|C0
        N1 = N0 + 1
        {SeqCode [Expr2 Expr1] C1 C N1 N}
    [] I andthen {IsInt I} then
        C = push(I)|C0
        N = N0 + 1
    end
end
Multiple accumulators (4)

\[
\text{proc } \{\text{ExprCode } \text{Expr } C0 \ C \ N0 \ N\}\n\]
\[
\text{case } \text{Expr} \n\]
\[
\text{of plus(Expr1 Expr2) then } C1 \ N1 \text{ in } C1 = \text{plus}\{C0 \n\]
\[
N1 = N0 + 1\n\]
\[
\{\text{SeqCode } [\text{Expr2 Expr1}] \ C1 \ C \ N1 \ N\}\n\]
\[
\text{minus(Expr1 Expr2) then } C1 \ N1 \text{ in } C1 = \text{minus}\{C0 \n\]
\[
N1 = N0 + 1\n\]
\[
\{\text{SeqCode } [\text{Expr2 Expr1}] \ C1 \ C \ N1 \ N\}\n\]
\[
[] \text{I andthen } \{\text{IsInt I}\} \text{ then } \n\]
\[
C = \text{push}\{I\}\{C0 \n\]
\[
N = N0 + 1\n\]
\]
\[
\text{end}\n\]
\[
\text{end}\n\]

\[
\text{proc } \{\text{SeqCode } \text{Es } C0 \ C \ N0 \ N\}\n\]
\[
\text{case } \text{Es} \n\]
\[
\text{of nil then } C = C0 \ N = N0 \n\]
\[
[] \text{E|Er then } N1 \ C1 \text{ in } \n\]
\[
\{\text{ExprCode } \text{E} \ C0 \ C1 \ N0 \ N1\} \n\]
\[
\{\text{SeqCode } \text{Er} \ C1 \ C \ N1 \ N\}\n\]
\[
\text{end}\n\]
\[
\text{end}\n\]
Shorter version (4)

proc \{ExprCode Expr C0 C N0 N\} 
  case Expr 
    of plus(Expr1 Expr2) then 
      \{SeqCode [Expr2 Expr1] plus|C0 C N0 + 1 N\} 
    [] minus(Expr1 Expr2) then 
      \{SeqCode [Expr2 Expr1] minus|C0 C N0 + 1 N\} 
    [] I andthen \{IsInt I\} then 
      C = push(I)|C0 
      N = N0 + 1 
  end 
end

proc \{SeqCode Es C0 C N0 N\} 
  case Es 
    of nil then C = C0 N = N0 
    [] E|Er then N1 C1 in 
      \{ExprCode E C0 C1 N0 N1\} 
      \{SeqCode Er C1 C N1 N\} 
    end 
  end
**Functional style (4)**

```plaintext
fun {ExprCode Expr t(C0 N0) }
  case Expr
  of plus(Expr1 Expr2) then
    {SeqCode [Expr2 Expr1] t(plus|C0 N0 + 1)}
  [] minus(Expr1 Expr2) then
    {SeqCode [Expr2 Expr1] t(minus|C0 N0 + 1)}
  [] I andthen {IsInt I} then
    t(push(I)|C0 N0 + 1)
  end
end
```

```plaintext
fun {SeqCode Es T}
  case Es
  of nil then T
  [] E|Er then
    T1 = {ExprCode E T} in
    {SeqCode Er T1}
  end
end
```
Difference lists in Oz

- A *difference list* is a pair of lists, each might have an unbound tail, with the invariant that one can get the second list by removing zero or more elements from the first list.

- $X \ # \ X$ % Represent the empty list
- nil $\ # \ nil$ % idem
- $[a] \ # \ [a]$ % idem
- $(a|b|c|X) \ # \ X$ % Represents $[a\ b\ c]\ X$
- $[a\ b\ c\ d]\ #\ [d]$ % idem
- $[a\ b\ c\ d|Y]\ #\ [d|Y]$ % idem
- $[a\ b\ c\ d|Y]\ #\ Y$ % Represents $[a\ b\ c\ d]$
Difference lists in Prolog

- A difference list is a pair of lists, each might have an unbound tail, with the invariant that one can get the second list by removing zero or more elements from the first list

- \( \text{X , X} \) % Represent the empty list
- \( [\] , [\] \) % idem
- \( [a] , [a] \) % idem
- \( [a,b,c|X] , X \) % Represents \([a,b,c]\)
- \( [a,b,c,d] , [d] \) % idem
- \( [a,b,c,d|Y] , [d|Y] \) % idem
- \( [a,b,c,d|Y] , Y \) % Represents \([a,b,c,d]\)
Difference lists in Oz (2)

• When the second list is unbound, an append operation with another difference list takes constant time

• fun {AppendD D1 D2}
  S1 # E1 = D1
  S2 # E2 = D2
  in
  E1 = S2
  S1 # E2
end

• local X Y in {Browse {AppendD (1|2|3|X)#X (4|5|Y)#Y}} end

• Displays (1|2|3|4|5|Y)#Y
Difference lists in Prolog (2)

• When the second list is unbound, an append operation with another difference list takes constant time

\[
\text{append_dl}(S_1,E_1, S_2,E_2, S_1,E_2) \iff E_1 = S_2.
\]

\[
?\text{- append_dl}([1,2,3|X],X, [4,5|Y],Y, S,E).
\]

Displays
\[
X = [4, 5|_G193] \\
Y = _G193 \\
S = [1, 2, 3, 4, 5|_G193] \\
E = _G193 \\
\]
A FIFO queue with difference lists (1)

- A *FIFO queue* is a sequence of elements with an insert and a delete operation.
  - Insert adds an element to the end and delete removes it from the beginning.
- Queues can be implemented with lists. If L represents the queue content, then deleting X can remove the head of the list matching X|T but inserting X requires traversing the list \{Append L [X]\} (insert element at the end).
  - *Insert is inefficient*: it takes time proportional to the number of queue elements.
- With difference lists we can implement a queue with *constant-time insert and delete operations*.
  - The queue content is represented as \(q(N \ S \ E)\), where \(N\) is the number of elements and \(S#E\) is a difference list representing the elements.
A FIFO queue
with difference lists (2)

- Inserting ‘b’:
  - In: q(1 a|T T)
  - Out: q(2 a|b|U U)

- Deleting X:
  - In: q(2 a|b|U U)
  - Out: q(1 b|U U) and X=a

- Difference list allows operations at both ends

- N is needed to keep track of the number of queue elements

```plaintext
fun {NewQueue} X in q(0 X X) end

fun {Insert Q X}
  case Q of q(N S E) then E1 in E=X|E1 q(N+1 S E1) end
end

fun {Delete Q X}
  case Q of q(N S E) then S1 in X|S1=S q(N-1 S1 E) end
end

fun {EmptyQueue Q} case Q of q(N S E) then N==0 end end
```
fun Flatten Xs
    case Xs
        of nil then nil
        [] X|Xr andthen \IsLeaf X\ then
            X|{Flatten Xr}
        [] X|Xr andthen \Not \IsLeaf X\} then
            {Append \Flatten X\ \{Flatten Xr\}}
    end
end

Flatten takes a list of elements and sub-lists and returns a list with only the elements, e.g.:

\{Flatten [1 [2] [[3]]]\} = [1 2 3]

Let us replace lists by difference lists and see what happens.
Flatten with difference lists (1)

- Flatten of nil is $X\#X$
- Flatten of a leaf $X|X_r$ is $(X|Y_1)#Y$
  - flatten of $X_r$ is $Y_1#Y$
- Flatten of $X|X_r$ is $Y_1#Y$ where
  - flatten of $X$ is $Y_1#Y_2$
  - flatten of $X_r$ is $Y_3#Y$
  - equate $Y_2$ and $Y_3$
Flatten with difference lists (2)

Here is the new program. It is much more efficient than the first version.

```
proc {FlattenD Xs Ds}
  case Xs
    of nil then Y in Ds = Y#Y
    [] X|Xr andthen {IsLeaf X} then Y1 Y in
      {FlattenD Xr Y1#Y2}
      Ds = (X|Y1)#Y
    [] X|Xr andthen {IsList X} then Y0 Y1 Y2 in
      {FlattenD X Y0#Y1}
      {FlattenD Xr Y1#Y2}
    end
  end

fun {Flatten Xs} Y in {FlattenD Xs Y#nil} Y end
```
Reverse

• Here is our recursive reverse:

\[
\text{fun } \{\text{Reverse } Xs\} \\
\text{case } Xs \\
\text{of } \text{nil then nil} \\
[] X|Xr \text{ then } \{\text{Append } \{\text{Reverse } Xr\} [X]\} \\
\text{end} \\
\text{end}
\]

• Rewrite this with difference lists:
  – Reverse of nil is X#X
  – Reverse of X|Xs is Y1#Y, where
    • reverse of Xs is Y1#Y2, and
    • equate Y2 and X|Y
Reverse with difference lists (1)

- The naive version takes time proportional to the square of the input length
- Using difference lists in the naive version makes it linear time
- We use two arguments $Y_1$ and $Y$ instead of $Y_1#Y$
- With a minor change we can make it iterative as well

```plaintext
fun {reverseD Xs}
proc {reverseD Xs Y1 Y}
    case Xs
    of nil then Y1=Y
    [] X|Xr then Y2 in
        {reverseD Xr Y1 Y2}
        Y2 = X|Y
    end
end
R in
{reverseD Xs R nil} R
end
```
Reverse with difference lists (2)

```
fun {ReverseD Xs}
proc {ReverseD Xs Y1 Y}
    case Xs
    of nil then Y1=Y
    [] X|Xr then
        {ReverseD Xr Y1 X|Y}
    end
end
R in
{ReverseD Xs R nil}
R
end
```
Difference lists: Summary

- Difference lists are a way to represent lists in the declarative model such that one append operation can be done in constant time
  - A function that builds a big list by concatenating together lots of little lists can usually be written efficiently with difference lists
  - The function can be written naively, using difference lists and append, and will be efficient when the append is expanded out
- Difference lists are declarative, yet have some of the power of destructive assignment
  - Because of the single-assignment property of dataflow variables
- Difference lists originated from Prolog and are used to implement, e.g., definite clause grammar rules for natural language parsing.
Exercises

91. Rewrite the Oz multiple accumulators example in Prolog.
92. Rewrite the Oz FIFO queue with difference lists in Prolog.
93. Draw the search trees for Prolog queries:
   - \texttt{append([1,2],[3],L)}.
   - \texttt{append(X,Y,[1,2,3]).}
   - \texttt{append_dl([1,2|\textbf{X}],X,[3|Y],Y,S,E)}.
94. CTM Exercise 3.10.11 (page 232)
95. CTM Exercise 3.10.14 (page 232)
96. CTM Exercise 3.10.15 (page 232)