Logical Loops

Joachim Schimpf

ICLP 2002

Overview

- A general iteration construct for Prolog and Prolog-based (CLP) languages
- Definition via program transformation
- Comparison with alternatives
  - Recursion
  - Higher-order constructs
  - Bounded Quantifiers
- Expressive Power
- Experience

Motivation

Introduced in ECLiPSe to support

- **Prolog beginners**
  - Provide a familiar feature: loops
- **Application writers**
  - Improved productivity, code structure, maintainability
- **Constraint Problem Modellers**
  - Provide equivalent of bounded quantification

Iteration (over list elements)

- Replace this

```
write_list(List) :-
        write("List: "),
        write_list1(List).

write_list1([]).
write_list1([X|T]) :-
        write(X),
        write_list1(T).
```

- With this

```
write_list(List) :-
        write("List: "),
        ( foreach(X,List) do
              write(X)
        ).
```

Iteration (over range of numbers)

- Replace this

```
write_nat(N) :-
        write("Numbers: "),
        write_nat1(0,N).

write_nat1(N, N) :- !.
write_nat1(I0, N) :-
        I is I0+1,
        write(I),
        write_nat1(I, N).
```

- With this

```
write_nat(N) :-
      write("Numbers: "),
      ( for(I,1,N) do
            write(I)
      ).
```

Aggregation

- Replace this

```
sumlist(Xs, S) :-
      sumlist(Xs, 0, S).

sumlist([], S, S).
sumlist([X|Xs], S0, S) :-
      S1 is S0+X,
      sumlist(Xs, S1, S).
```

- With this

```
sumlist(Xs, S) :-
      (   foreach(X,Xs),
          fromto(0,S0,S1,S)
      do
          S1 is S0+X
      ).
```

iterate

aggregate

Mapping

- Replace this

```
map :- …,
      add_one(Xs, Ys), ….

add_one([], []).
add_one([X|Xs], [Y|Ys]) :-
      Y is X+1,
       add_one(Xs, Ys).
```

- With this

```
map :- …,
      (   foreach(X,Xs),
          foreach(Y,Ys)
      do
          Y is X+1,
      ), ….
```

iterate

construct

Programming idioms covered

Fully:

- **Iteration**
- **Aggregation**
- **Mapping**

Partly:

- **Filtering**
- **While-loop**

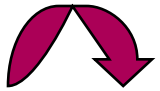
General Form

(*IterationSpecs* do *Body*)

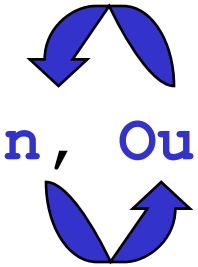
sequence of

foreach(Elem, List)	**list iterator / aggregator**
foreacharg(Arg, Structure)	**structure iterator**
count(I, Min, Max)	**integer iterator / aggregator**
for(I, Min, Max [,Step])	**numeric iterator**
param(X1, X2, …)	**constant iterator**
fromto(First, In, Out, Last)	**generic iterator / aggregator**

The generic fromto-iterator



```
( fromto(First, In, Out, Last) do … In→Out … )
```



```
( fromto(First, In, Out, Last) do … In→Out … )
```

```
( fromto(First, In, Out, Last) do … In→Out … )
```

Fromto can express all other iterators, e.g.

```
fromto(List, [X|Xs], Xs, [])   ⇔   foreach(X,List)
```

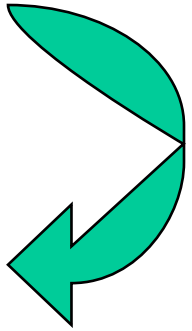
Transformation scheme

A goal

```
…,( IterationSpecifiers do Body ), …
```

Is replaced by

```
…, PreCallGoals, μ(CallArgs), …
```

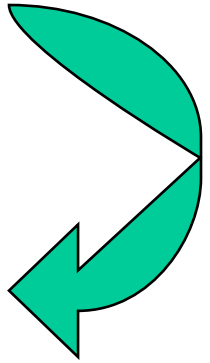


With an auxiliary predicate μ defined as

```
μ(BaseArgs) :- !.
μ(HeadArgs) :-
        PreBodyGoals,
        Body,
        μ(RecArgs).
```

Sample translation

```
?- ( foreach(X,List), count(I,N0,N), fromto(0,S0,S1,Sum) do
         S1 is S0+X
   ).
```



```
?-  From is N0-1,                          % PreCallGoals
    do_1(List, From, N, 0, Sum).           % Initial call

do_1([], _1, _1, _2, _2) :- !.             % Base clause
do_1([X|_1], _2, _3, S0, _4) :-            % Recursive clause head
       I is _2 + 1,                        % PreBodyGoals
       S1 is S0+X,                         % Body
       do_1(_1, I, _3, S1, _4).            % Recursive call
```

Loops vs. Recursion

- **Conciseness**
  - Auxiliary predicate and its arity are hidden.
- **Modifiability**
  - Add/remove single iteration specifier rather than argument(s) in 4 places.
- **Structure**
  - Nested loops can be clearer than a flat collection of predicates.
  - Iteration specifiers group related information together.
- **Abstraction**
  - Intention of iteration is explicit.
  - Fromto can help beginners understand the concept of accumulators.

Abstraction

```
reverse(L, R) :-
        (   fromto(L, [X|Ls], Ls, []),
        ;   fromto([], Rs, [X|Rs], R)
        do
            true
        ).
```

Symmetry

Single argument

Argument pair (accumulator)

```
reverse(L, R) :- do_2(L,[],R).

do_2([],R,R) :- !.

do_2([X|Ls],Rs,R) :- do_2(Ls,[X|Rs],R).
```

Loops vs. Higher-Order Constructs (1)

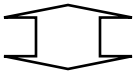
Higher-Order constructs for similar tasks:

```
map(plus(1),Xs,Ys)      ⟺  ( foreach(X,Xs), foreach(Y,Ys) do
                               plus(1, X, Y)
                           )

foldl(plus,Xs,0,Sum)    ⟺  ( foreach(X,Xs), fromto(0,S0,S1,Sum) do
                               plus(X,S0,S1)
                           )

filter(<(5),Xs,Ys)      ⟺  ( foreach(X,Xs), fromto(Ys,Ys1,Ys0,[]) do
                               ( X > 5 -> Ys1=[X|Ys0] ; Ys1=Ys0 )
                           )
```

Loops vs. Higher-Order Constructs (2)

More realistic comparison with a lambda-term syntax:

```
foldl(lambda([X,S0,S1], S1 is S0+X), Xs, 0, Sum)
```



```
foreach(X,Xs), fromto(0,S0,S1,Sum) do S1 is S0+X
```

Loop formulation has same size and better grouping

Loops vs Higher-Order Constructs (3)

Higher-Order map/fold/filter

- Data structure (list) specific
- Arbitrary traversal orders
- foldl / foldr symmetry
- Families needed: map/(2+N), fold/(2+2N), filter/(2+N)
- Combinations needed: map_foldl/5, …
- Higher-order-typed arguments

Do-loop

- Any data structure (fromto)
- Only iteration / tail recursion
- Only efficient foldl-equivalent
- Arbitrary number of iteration specifiers allowed
- Arbitrary combinations of iteration specifiers allowed
- Same typing as recursive form

Claim: Higher-order constructs are powerful, but not the best for iteration

Loops vs. Bounded Quantification

- **Quantification over finite sets**
  - Mathematical modelling languages (AMPL and others)
  - Extension to LP (Voronkov 90, Barklund et al 93/95, Apt 96)

```
pos_list(List) :- ∀ X ∈ List      X > 0.
pos_array(A,N) :- ∀ I ∈ 1..N   A[I] > 0.
```

- **But: mapping of lists is impossible**

```
add_one_to_all(Xs,Ys) :- ∀X∈Xs ∀Y∈Ys  Y is X+1.
```

  - Does not work: No concept of “corresponding elements”
  - Needs arrays to be useful !

- **But: aggregation operators**
  - E.g. minimum, maximum, sum, … must be introduced separately

```
sum_list(Xs,S) :- S=ΣX : X∈Xs.
```

Expressive Power of Loops (1)

- **We can write a while-loop, albeit awkwardly:**

```
(
     fromto(cont, _, Continue, stop)
do
     ( termination_condition(…) ->
          Continue = stop
     ;    Continue = cont
     ),
     …
)
```

Expressive Power of Loops (2)

A recursion-free meta-interpreter for pure Prolog:

```
solve(Q) :-
    ( fromto([Q], [G|C0], C1, []) do
        solve_step(G, C0, C1)
    ).

solve_step(true,  C, C).
solve_step((A,B), C, [A,B|C]).
solve_step( A,    C, [B|C]) :- clause(A, B).
```

Evaluation criteria

A language feature should

- **Fit with existing language concepts / user ideas**
  - **“Principle of least astonishment”**
- **Provide a clear advantage**
  - **Code size, elegance, maintainability, robustness, …**
- **Not have an overhead cost**
  - **Otherwise programmers will use lower-level methods**

Programmer Acceptance

Loops have been in ECLiPSe officially since 1998.

Analysis of commerical code developed with ECLiPSe:

- **Application A (1997-2001)**
  - **254 predicate in 24 modules**
  - **34 loops**
- **Application B (2000-2002)**
  - **528 predicates in 35 modules**
  - **210 loops**

Conclusion

- **Language extension with a minimum of new concepts**
  - no types, modes, arrays were needed
- **Efficiently implementable**
  - virtually no runtime overheads
- **Accepted by programmers**
  - this has always been a problem with higher-order constructs
- **Translation code available at**
  - http://www.icparc.ic.ac.uk/eclipse/software/loops/

Rejected Ideas

- **Nondeterministic iteration**
  - Once the termination conditions are met, the loop terminates.
  - Allowing more iterations on backtracking seems too error-prone.
- **Better support for while/until-loops**
  - Makes the semantics much more complex.
- **Clearly separate iterators and aggregators**
  - Would lose some multi-directionality, but a good idea with modes.
- **More/less iterator shorthands**
  - A matter of taste.

Loops and Arrays

Array notation makes loops even more useful:

```
…,
( for(I,1,N), param(Board,N) do
      ( for(J,I+1,N), param(Board,I) do
            Board[I] #\= Board[J],
            Board[I] #\= Board[J]+J-I,
            Board[I] #\= Board[J]+I-J
       )
 ).
```

Bounded Quantification

- **"*A priori*" Bounded Quantification**
  - **(Barklund and Bevemyr (Reform Prolog) 1993)**
  - **(Barklund and Hill (Gödel) 1995)**
  - **(Apt 1996)**
  - **Mathematical modelling languages**

  Quantification over finite sets:

```
pos_list(List) :- ∀ X ∈ List      X > 0.
pos_array(A,N) :- ∀ I ∈ 1..N   A[I] > 0.
```

- **Bounded Quantification (Voronkov 1990)**
  - **More powerful due to list-suffix quantifier**
  - **Termination can depend on quantified formula**
  - **Turing-complete**

Mapping with Bounded Quantifiers (BQ)

- **Mapping of lists is impossible with *a priori* BQ**

  `add_one_to_all(Xs,Ys) :- ∀X∈Xs ∀Y∈Ys  Y is X+1.`

  Does not work: No concept of "corresponding elements"

- ***A priori* BQ needs arrays**

  `add_one_to_all(A,B) :- ∀I∈1..N  B[I] is A[I]+1.`

  Indeed all authors introduce arrays into their proposed languages.

  But still cannot map a list to an array …

- **Voronkov's full BQ can express list mapping**

  However, very unintuitive

- **Loop solution:**

  We have a concept of implicitly ordered iteration steps

Aggregation with Bounded Quantifiers

- **Aggregation not covered by basic *a priori* BQ**
- **Specific aggregation operators must be introduced**

  e.g. minimum, maximum, sum, …

  ```
  sum_list(Xs,S) :- S=ΣX : X∈Xs.
  ```

- **Loop solution:**

  The fromto-specifier can function as iterator and aggregator.

  Any aggregation function can be expressed.