Lecture 5: Arithmetic

- Theory
  - Introduce Prolog`s built-in abilities for performing **arithmetic**
  - Apply these to simple list processing problems, using **accumulators**
  - Look at **tail-recursive** predicates and explain why they are more efficient than predicates that are not tail-recursive

- Exercises
  - Exercises of LPN: 5.1, 5.2, 5.3
  - Practical work

Arithmetic in Prolog

- Prolog provides a number of basic arithmetic tools
- Integer and real numbers

Arithmetic	Prolog
2 + 3 = 5	?- 5 is 2+3.
3 x 4 = 12	?- 12 is 3*4.
5 – 3 = 2	?- 2 is 5-3.
3 – 5 = -2	?- -2 is 3-5.
4 : 2 = 2	?- 2 is 4/2.
1 is the remainder when 7 is divided by 2	?- 1 is mod(7,2).

Example queries

```
?- 10 is 5+5.
yes

?- 4 is 2+3.
no

?- X is 3 * 4.
X=12
yes

?- R is mod(7,2).
R=1
yes
```

Defining predicates with arithmetic

```
addThreeAndDouble(X, Y):-
    Y is (X+3) * 2.
```

Defining predicates with arithmetic

```
addThreeAndDouble(X, Y):-
    Y is (X+3) * 2.
```

```
?- addThreeAndDouble(1,X).
X=8
yes

?- addThreeAndDouble(2,X).
X=10
yes
```

A closer look

- It is important to know that +, -, / and * do not carry out any arithmetic
- Expressions such as 3+2, 4-7, 5/5 are ordinary Prolog terms
  - Functor: +, -, /, *
  - Arity: 2
  - Arguments: integers

A closer look

```
?- X = 3 + 2.
```

A closer look

```
?- X = 3 + 2.
X = 3+2
yes

?-
```

A closer look

```
?- X = 3 + 2.
X = 3+2
yes

?- 3 + 2 = X.
```

A closer look

```
?- X = 3 + 2.
X = 3+2
yes

?- 3 + 2 = X.
X = 3+2
yes

?-
```

The is/2 predicate

- To force Prolog to actually evaluate arithmetic expressions, we have to use

  is

  just as we did in the other examples
- This is an instruction for Prolog to carry out calculations
- Because this is not an ordinary Prolog predicate, there are some restrictions

The is/2 predicate

```
?- X is 3 + 2.
```

The is/2 predicate

```
?- X is 3 + 2.
X = 5
yes

?-
```

The is/2 predicate

```
?- X is 3 + 2.
X = 5
yes

?- 3 + 2 is X.
```

The is/2 predicate

```
?- X is 3 + 2.
X = 5
yes

?- 3 + 2 is X.
ERROR: is/2: Arguments are not sufficiently instantiated

?-
```

The is/2 predicate

```
?- X is 3 + 2.
X = 5
yes

?- 3 + 2 is X.
ERROR: is/2: Arguments are not sufficiently instantiated

?- Result is 2+2+2+2+2.
```

The is/2 predicate

```
?- X is 3 + 2.
X = 5
yes

?- 3 + 2 is X.
ERROR: is/2: Arguments are not sufficiently instantiated

?- Result is 2+2+2+2+2.
Result = 10
yes

?-
```

Restrictions on use of is/2

- We are free to use variables on the right hand side of the **is** predicate
- But when Prolog actually carries out the evaluation, the variables must be instantiated with a variable-free Prolog term
- This Prolog term must be an arithmetic expression

Notation

- Two final remarks on arithmetic expressions
  - 3+2, 4/2, 4-5 are just ordinary Prolog terms in a user-friendly notation:
    3+2 is really **+(3,2)** and so on.
  - Also the **is** predicate is a two-place Prolog predicate

Notation

- Two final remarks on arithmetic expressions
  - 3+2, 4/2, 4-5 are just ordinary Prolog terms in a user-friendly notation:
    3+2 is really **+(3,2)** and so on.
  - Also the **is** predicate is a two-place Prolog predicate

```
?- is(X,+(3,2)).
X = 5
yes
```

Arithmetic and Lists

- How long is a list?
  - The empty list has length: zero;
  - A non-empty list has length: one plus length of its tail.

Length of a list in Prolog

```
len([],0).
len([_|L],N):-
    len(L,X),
    N is X + 1.
```

```
?-
```

Length of a list in Prolog

```
len([],0).
len([_|L],N):-
    len(L,X),
    N is X + 1.
```

```
?- len([a,b,c,d,e,[a,x],t],X).
```

Length of a list in Prolog

```
len([],0).
len([_|L],N):-
    len(L,X),
    N is X + 1.
```

```
?- len([a,b,c,d,e,[a,x],t],X).
X=7
yes
?-
```

Accumulators

- This is quite a good program
  - Easy to understand
  - Relatively efficient
- But there is another method of finding the length of a list
  - Introduce the idea of accumulators
  - Accumulators are variables that hold intermediate results

Defining acclen/3

- The predicate acclen/3 has three arguments
  - The list whose length we want to find
  - The length of the list, an integer
  - An accumulator, keeping track of the intermediate values for the length

Defining acclen/3

- The accumulator of acclen/3
  - Initial value of the accumulator is 0
  - Add 1 to accumulator each time we can recursively take the head of a list
  - When we reach the empty list, the accumulator contains the length of the list

Length of a list in Prolog

```
acclen([],Acc,Length):-
    Length = Acc.

acclen([_|L],OldAcc,Length):-
    NewAcc is OldAcc + 1,
    acclen(L,NewAcc,Length).
```

```
?-
```

Length of a list in Prolog

```
acclen([],Acc,Length):-
    Length = Acc.

acclen([_|L],OldAcc,Length):-
    NewAcc is OldAcc + 1,
    acclen(L,NewAcc,Length).
```

add 1 to the accumulator each time we take off a head from the list

```
?-
```

Length of a list in Prolog

```
acclen([],Acc,Length):-
    Length = Acc.

acclen([_|L],OldAcc,Length):-
    NewAcc is OldAcc + 1,
    acclen(L,NewAcc,Length).
```

when we reach the empty list, the accumulator contains the length of the list

```
?-
```

Length of a list in Prolog

```
acclen([],Acc,Acc).

acclen([_|L],OldAcc,Length):-
     NewAcc is OldAcc + 1,
     acclen(L,NewAcc,Length).
```

```
?-
```

Length of a list in Prolog

```
acclen([],Acc,Acc).

acclen([_|L],OldAcc,Length):-
     NewAcc is OldAcc + 1,
     acclen(L,NewAcc,Length).
```

```
?-acclen([a,b,c],0,Len).
Len=3
yes

?-
```

Search tree for acclen/3


```
?- acclen([a,b,c],0,Len).
```

```
acclen([ ],Acc,Acc).

acclen([_|L],OldAcc,Length):-
    NewAcc is OldAcc + 1,
    acclen(L,NewAcc,Length).
```

Search tree for acclen/3

```
?- acclen([a,b,c],0,Len).
       /                    \
```

```
acclen([ ],Acc,Acc).

acclen([_|L],OldAcc,Length):-
    NewAcc is OldAcc + 1,
    acclen(L,NewAcc,Length).
```

Search tree for acclen/3

```
?- acclen([a,b,c],0,Len).
      /                    \
  no          ?- acclen([b,c],1,Len).
                   /                        \
```

```
acclen([ ],Acc,Acc).

acclen([_|L],OldAcc,Length):-
    NewAcc is OldAcc + 1,
    acclen(L,NewAcc,Length).
```

Search tree for acclen/3

```
acclen([ ],Acc,Acc).

acclen([_|L],OldAcc,Length):-
    NewAcc is OldAcc + 1,
    acclen(L,NewAcc,Length).
```

```
?- acclen([a,b,c],0,Len).
     /              \
   no         ?- acclen([b,c],1,Len).
                  /                 \
                no          ?- acclen([c],2,Len).
                               /                   \
```

Search tree for acclen/3

```
?- acclen([a,b,c],0,Len).
      /              \
   no          ?- acclen([b,c],1,Len).
                    /                \
                 no          ?- acclen([c],2,Len).
                                  /                    \
                               no               ?- acclen([],3,Len).
                                                      /               \
```

```
acclen([ ],Acc,Acc).

acclen([_|L],OldAcc,Length):-
     NewAcc is OldAcc + 1,
     acclen(L,NewAcc,Length).
```

Search tree for acclen/3

```
?- acclen([a,b,c],0,Len).
    /            \
  no        ?- acclen([b,c],1,Len).
              /            \
            no        ?- acclen([c],2,Len).
                        /            \
                      no        ?- acclen([],3,Len).
                                  /            \
                                Len=3          no
```

```
acclen([ ],Acc,Acc).

acclen([_|L],OldAcc,Length):-
    NewAcc is OldAcc + 1,
    acclen(L,NewAcc,Length).
```

Adding a wrapper predicate

```
acclen([ ],Acc,Acc).

acclen([ _|L],OldAcc,Length):-
    NewAcc is OldAcc + 1,
    acclen(L,NewAcc,Length).

length(List,Length):-
     acclen(List,0,Length).
```

```
?-length([a,b,c], X).
X=3
yes
```

Tail recursion

- Why is acclen/3 better than len/2 ?
  - acclen/3 is tail-recursive, and len/2 is not

- Difference:
  - In tail recursive predicates the results is fully calculated once we reach the base clause
  - In recursive predicates that are not tail recursive, there are still goals on the stack when we reach the base clause

Comparison

Not tail-recursive

```
len([],0).
len([_|L],NewLength):-
    len(L,Length),
    NewLength is Length + 1.
```

Tail-recursive

```
acclen([],Acc,Acc).
acclen([_|L],OldAcc,Length):-
    NewAcc is OldAcc + 1,
    acclen(L,NewAcc,Length).
```

Search tree for len/2

?- len([a,b,c], Len).

```
len([],0).
len([_|L],NewLength):-
    len(L,Length),
    NewLength is Length + 1.
```

Search tree for len/2

```
?- len([a,b,c], Len).
     /             \
   no    ?- len([b,c],Len1),
            Len is Len1 + 1.
```

```
len([],0).
len([_|L],NewLength):-
    len(L,Length),
    NewLength is Length + 1.
```

Search tree for len/2

```
?- len([a,b,c], Len).
      /               \
   no    ?- len([b,c],Len1),
             Len is Len1 + 1.
             /                 \
         no         ?- len([c], Len2),
                        Len1 is Len2+1,
                        Len is Len1+1.
```

```
len([],0).
len([_|L],NewLength):-
    len(L,Length),
    NewLength is Length + 1.
```

Search tree for len/2

```
?- len([a,b,c], Len).
    /              \
  no    ?- len([b,c],Len1),
             Len is Len1 + 1.
            /                 \
        no          ?- len([c], Len2),
                         Len1 is Len2+1,
                         Len is Len1+1.
                        /                \
                  no            ?- len([], Len3),
                                    Len2 is Len3+1,
                                    Len1 is Len2+1,
                                    Len is Len1 + 1.
```

```
len([],0).
len([_|L],NewLength):-
    len(L,Length),
    NewLength is Length + 1.
```

Search tree for len/2

```
?- len([a,b,c], Len).
    /              \
 no    ?- len([b,c],Len1),
           Len is Len1 + 1.
          /                 \
        no        ?- len([c], Len2),
                     Len1 is Len2+1,
                     Len is Len1+1.
                    /              \
                  no       ?- len([], Len3),
                              Len2 is Len3+1,
                              Len1 is Len2+1,
                              Len is Len1 + 1.
                             /                  \
        Len3=0, Len2=1,                          no
        Len1=2, Len=3
```

```
len([],0).
len([_|L],NewLength):-
   len(L,Length),
   NewLength is Length + 1.
```

Search tree for acclen/3

```
acclen([ ],Acc,Acc).

acclen([_|L],OldAcc,Length):-
    NewAcc is OldAcc + 1,
    acclen(L,NewAcc,Length).
```

```
?- acclen([a,b,c],0,Len).
     /              \
   no        ?- acclen([b,c],1,Len).
                 /                 \
               no          ?- acclen([c],2,Len).
                               /                   \
                             no            ?- acclen([],3,Len).
                                               /                \
                                            Len=3               no
```

Exercises

- Exercise 5.1
- Exercise 5.2
- Exercise 5.3

Comparing Integers

- Some Prolog arithmetic predicates actually do carry out arithmetic by themselves
- These are the operators that compare integers

Comparing Integers

Arithmetic	Prolog
$x < y$	`X < Y`
$x \leq y$	`X =< Y`
$x = y$	`X =:= Y`
$x \neq y$	`X =\= Y`
$x \geq y$	`X >= Y`
$x > y$	`X > Y`

Comparison Operators

- Have the obvious meaning
- Force both left and right hand argument to be evaluated

```
?- 2 < 4+1.
yes

?- 4+3 > 5+5.
no
```

Comparison Operators

- Have the obvious meaning
- Force both left and right hand argument to be evaluated

```
?- 4 = 4.
yes

?- 2+2 = 4.
no

?- 2+2 =:= 4.
yes
```

Comparing numbers

- We are going to define a predicate that takes two arguments, and is true when:
  - The first argument is a list of integers
  - The second argument is the highest integer in the list
- Basic idea
  - We will use an accumulator
  - The accumulator keeps track of the highest value encountered so far
  - If we find a higher value, the accumulator will be updated

Definition of accMax/3

```
accMax([H|T],A,Max):-
    H > A,
    accMax(T,H,Max).

accMax([H|T],A,Max):-
    H =< A,
    accMax(T,A,Max).

accMax([],A,A).
```

```
?- accMax([1,0,5,4],0,Max).
Max=5
yes
```

Adding a wrapper max/2

```
accMax([H|T],A,Max):-
    H > A,
    accMax(T,H,Max).

accMax([H|T],A,Max):-
    H =< A,
    accMax(T,A,Max).

accMax([],A,A).

max([H|T],Max):-
    accMax(T,H,Max).
```

```
?- max([1,0,5,4], Max).
Max=5
yes

?- max([-3, -1, -5, -4], Max).
Max= -1
yes

?-
```

Summary of this lecture

- In this lecture we showed how Prolog does **arithmetic**
- We demonstrated the difference between **tail-recursive** predicates and predicates that are not tail-recursive
- We introduced the programming technique of using **accumulators**
- We also introduced the idea of using **wrapper** predicates

Next lecture

- Yes, more lists!
  - Defining the append/3, a predicate that concatenates two lists
  - Discuss the idea of reversing a list, first naively using append/3, then with a more efficient way using accumulators