

## Transitive Relations

```
parent(sally,jane). parent(bob,jane).
parent(sally,john). parent(bob,john).
parent(mary,sally). parent(al,sally).
parent(ann,bob). parent(mike,bob).
parent(jean,al). parent(joe,al).
parent(ruth,mary). parent(jim,mary).
parent(esther,ruth). parent(mick,ruth).

grandparent(X,Y) :- parent(X,Z), parent(Z,Y).
ancestor(X,Y) :- parent(X,Y).
ancestor(X,Y) :- parent(X,Z), ancestor(Z,Y).
```

```
?- grandparent(Y,jane).
Y = mary ;
Y = al ;
Y = ann ;
Y = mike ;
No
?- ancestor(X,jane).
X = sally ;
X = bob ;
X = mary ;
X = al ;
X = ann ;
X = mike ;
X = jean ;
X = joe ;
X = ruth ;
X = jim ;
X = esther ;
X = mick ;
No
```

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## Steps to a Recursive Predicate

- 1. Predicate Form:**
  - Choose a predicate name appropriate for something that is true or false.
  - Choose mnemonic argument names.
- 2. Spec:** Write the specification in this form:  
*pred* succeeds iff ...
- 3. Base Cases:**
  - When is it so easy to tell the predicate is true that you needn't check any further?
  - Write these base case(s).
- 4. Recursive Cases:**
  - When it's not trivial, what do you need to know is true before you can be sure the predicate is true?
  - This is the antecedent of your rule.
  - There may be several non-trivial cases, each needing a rule.

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## Lists in Prolog

Two ways to describe a list:

1. [ *elements-with-commas* ]

```
Egs: [a, b, c]
[]
[a, [b, c], d, [], e]
[a, X, c, d]
```

2. [ *first* | *rest* ] (*rest* must be a list)

```
Egs: [a | [b, c]]
[a | Rest]
```

**Question:** Why use the second form with |?

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## Unifying Lists

```
?- [X, Y, Z] = [john, likes, fish].
```

```
?- [cat] = [X|Y].
```

```
?- [1,2] = [X|Y].
```

```
?- [a,b,c] = [X|Y].
```

```
?- [a,b|Z]=[X|Y].
```

```
?- [X,abc,Y]=[X,abc|Y].
```

```
?- [[the|Y]|Z] = [[X,hare] | [is,here]].
```

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## Let's Write Some List Predicates

1. member(X, List).
2. append(List1, List2, Result).
3. swapFirstTwo(List1, List2).
4. length(List).

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## List Membership

Definition of member...

```
?- member(a, [a,b]).
Yes
?- member(a, [b,c]).
No
?- member(X, [a,b,c]).
X=a ;
X=b ;
X=c ;
No
?- member(a, [c,b,X]).
X=a ;
No
?- member(X,Y).
X=_G72, Y=[_G72|_G73] ;
X=_G74, Y=[_G72,_G74|_G75] ;
X=_G76, Y=[_G72,_G74,_G76|_G77] ;
...
```

Lazy evaluation of potentially infinite data structures

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## Trace of Member

```
[trace] ?- member(c, [a,b,c,d]).
Call: (7) lists:member(c, [a, b, c, d]) ? creep
Call: (8) lists:member(c, [b, c, d]) ? creep
Call: (9) lists:member(c, [c, d]) ? creep
Exit: (9) lists:member(c, [c, d]) ? creep
Exit: (8) lists:member(c, [b, c, d]) ? creep
Exit: (7) lists:member(c, [a, b, c, d]) ? creep
```

Yes

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## A4 Digression

We're going to skip ahead to slides 59-63 and cover **Negation as Failure** which you will need in A4. We'll return to our list predicate examples after we cover these slides.

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## Append - More than "appending"

Definition of append

```
Build a list:
?- append([a],[b],Y).
Y=[a,b]
Yes
```

```
Break a list up:
?- append(X,[b],[a,b]).
X=[a]
Yes
?- append([a],Y,[a,b]).
Y=[b]
Yes
```

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## Append (cont.)

```
?- append(X,Y,[a,b]).
X=[],Y=[a,b];
X=[a],Y=[b];
X=[a,b],Y=[];
No
Generate lists:
?- append(X,[b],Z).
X=[],Z=[b];
X=[_G98],Z=[_G98,b];
X=[_G98,_G102],Z=[_G98,_G102,b];
...
```

```
Trace:
[trace] ?- append([a,b,c],[p,q,r],L).
Call: (7) lists:append([a, b, c], [p, q, r], _G303) ? creep
Call: (8) lists:append([b, c], [p, q, r], _G426) ? creep
Call: (9) lists:append([c], [p, q, r], _G429) ? creep
Call: (10) lists:append([], [p, q, r], _G432) ? creep
Exit: (10) lists:append([], [p, q, r], [p, q, r]) ? creep
Exit: (9) lists:append([c], [p, q, r], [c, p, q, r]) ? creep
Exit: (8) lists:append([b, c], [p, q, r], [b, c, p, q, r]) ? creep
Exit: (7) lists:append
([a, b, c], [p, q, r], [a, b, c, p, q, r]) ? creep
```

L = [a, b, c, p, q, r];

No

Try some other traces!

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## Computing the Length of a List

Definition of length...

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

```
?- length([],L).
L = 0
```

```
?- length(X,3).
X = [_G66,_G68,_G70]
```

```
?- length(X,0).
X = []
```

NOTE: Use built-in length function!!

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## Trace of Length:

Observe why this doesn't work!

```
xlength([],0).
xlength([_Y],N) :- xlength(Y,N-1).

[trace] ?- xlength([a,b,c,d],X).
Call: (7) xlength([a, b, c, d], _G296) ? creep
Call: (8) xlength([b, c, d], _G296-1) ? creep
Call: (9) xlength([c, d], _G296-1-1) ? creep
Call: (10) xlength([d], _G296-1-1-1) ? creep
Call: (11) xlength([], _G296-1-1-1-1) ? creep
Fail: (11) xlength([], _G296-1-1-1-1) ? creep
Fail: (10) xlength([d], _G296-1-1-1) ? creep
Fail: (9) xlength([c, d], _G296-1-1) ? creep
Fail: (8) xlength([b, c, d], _G296-1) ? creep
Fail: (7) xlength([a, b, c, d], _G296) ? creep
No
```

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## Trace of Length (cont)

But this does work

```
mylength([],0).
mylength([_Y],N) :- mylength2(Y,M), N is M+1.
```

```
[trace] ?- mylength([a,b,c,d],X).
Call: (7) mylength([a, b, c, d], _G296) ? creep
Call: (8) mylength([b, c, d], _L206) ? creep
Call: (9) mylength([c, d], _L225) ? creep
Call: (10) mylength([d], _L244) ? creep
Call: (11) mylength([], _L263) ? creep
Exit: (11) mylength([], 0) ? creep
^ Call: (11) _L244 is 0+1 ? creep
^ Exit: (11) 1 is 0+1 ? creep
Exit: (10) mylength([d], 1) ? creep
^ Call: (10) _L225 is 1+1 ? creep
^ Exit: (10) 2 is 1+1 ? creep
Exit: (9) mylength([c, d], 2) ? creep
^ Call: (9) _L206 is 2+1 ? creep
^ Exit: (9) 3 is 2+1 ? creep
Exit: (8) mylength([b, c, d], 3) ? creep
^ Call: (8) _G296 is 3+1 ? creep
^ Exit: (8) 4 is 3+1 ? creep
Exit: (7) mylength([a, b, c, d], 4) ? creep
X = 4
Yes
```

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## Accessing More Than One Initial Element

Definition of swap\_first.two...

```
?- swap_first_two([a,b], [b,a]).
Yes
?- swap_first_two([a,b], [b,c]).
No
?- swap_first_two([a,b,c], [b,a,c]).
Yes
?- swap_first_two([a,b,c], [b,a,d]).
No
?- swap_first_two([a,b,c], X).
X = [b,a,c];
No
?- swap_first_two([a,b|Y], X).
Y = [_56, X = [b,a|_56];
No
?- swap_first_two([],X).
No
?- swap_first_two([a],X).
No
?- swap_first_two([a,b],X).
X = [b,a];
No
```

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## Lists of a Specified Length

Definition of list\_of\_elem...

```
?- list_elem(X,b,3).
X = [b,b,b];
ERROR: Out of global stack
?- list_of_elem(X,Y,2).
X = [_50,_50]
Y = _50;
ERROR: Out of global stack
```

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## Lists of a Specified Length

New definition of list\_of\_elem...

```
?- working_list_elem(X,b,3).
X = [b,b,b];
No
?- working_list_elem(X,Y,2).
X = [_50,_50]
Y = _50;
No
```

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## Beyond Horn Logic

- So far, we have studied what is known as *pure* logic programming, in which all the rules are Horn.
- For some applications, however, we need to go beyond this.
- For instance, we often need
  - Arithmetic
  - Negation
- Fortunately, these can easily be accommodated by simple extensions to the logic-programming framework,

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## Arithmetic in Prolog

What is the result of these queries:

?- X = 97-65, Y = 32-0, X = Y.

?- X = 97-65, Y = 67, Z = 95-Y, X = Z.

To get an expression evaluated, use

*X is expression*

where *expression*

- is an arithmetic expression, and
- is fully instantiated.

Examples:

?- X is 10+17.

?- Y is 7, Z is 3+4, Y=Z.

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## Let's Write Some Predicates with Arithmetic

1. factorial(N, Ans).
2. sumlist(List, Total).

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## Factorial

factorial(0,1).

```
factorial(X,Y) :- W is X-1,
                factorial(W,Z),
                Y is Z*X.
```

What are the preconditions for factorial?

### Factorial with an Accumulator:

factorial2(0,X,X).

```
factorial2(N,A,F) :-
    N > 0,
    A1 is N*A,
    N1 is N -1,
    factorial2(N1,A1,F).
```

What are the preconditions?

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## Trace of Factorial

```
[trace] ?- factorial(3,X).
  Call: (7) factorial(3, _G284) ? creep
  ^ Call: (8) _L205 is 3-1 ? creep
  ^ Exit: (8) 2 is 3-1 ? creep
  Call: (8) factorial(2, _L206) ? creep
  ^ Call: (9) _L224 is 2-1 ? creep
  ^ Exit: (9) 1 is 2-1 ? creep
  Call: (9) factorial(1, _L225) ? creep
  ^ Call: (10) _L243 is 1-1 ? creep
  ^ Exit: (10) 0 is 1-1 ? creep
  Call: (10) factorial(0, _L244) ? creep
  ^ Exit: (10) factorial(0, 1) ? creep
  ^ Call: (10) _L225 is 1*1 ? creep
  ^ Exit: (10) 1 is 1*1 ? creep
  ^ Exit: (9) factorial(1, 1) ? creep
  ^ Call: (9) _L206 is 1*2 ? creep
  ^ Exit: (9) 2 is 1*2 ? creep
  ^ Exit: (8) factorial(2, 2) ? creep
  ^ Call: (8) _G284 is 2*3 ? creep
  ^ Exit: (8) 6 is 2*3 ? creep
  ^ Exit: (7) factorial(3, 6) ? creep
X = 6
Yes
```

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## Trace of Factorial w/ an Accumulator

```
[trace] ?- factorial2(3,1,2).
  Call: (8) factorial2(3, 1, _G288) ? creep
  ^ Call: (9) 3>0 ? creep
  ^ Exit: (9) 3>0 ? creep
  ^ Call: (9) _L206 is 3*1 ? creep
  ^ Exit: (9) 3 is 3*1 ? creep
  ^ Call: (9) _L207 is 3-1 ? creep
  ^ Exit: (9) 2 is 3-1 ? creep
  ^ Call: (9) factorial2(2, 3, _G288) ? creep
  ^ Call: (10) 2>0 ? creep
  ^ Exit: (10) 2>0 ? creep
  ^ Call: (10) _L226 is 2*3 ? creep
  ^ Exit: (10) 6 is 2*3 ? creep
  ^ Call: (10) _L227 is 2-1 ? creep
  ^ Exit: (10) 1 is 2-1 ? creep
  ^ Call: (10) factorial2(1, 6, _G288) ? creep
  ^ Call: (11) 1>0 ? creep
  ^ Exit: (11) 1>0 ? creep
  ^ Call: (11) _L246 is 1*6 ? creep
  ^ Exit: (11) 6 is 1*6 ? creep
  ^ Call: (11) _L247 is 1-1 ? creep
  ^ Exit: (11) 0 is 1-1 ? creep
  ^ Call: (11) factorial2(0, 6, _G288) ? creep
  ^ Exit: (11) factorial2(0, 6, 6) ? creep
  ^ Exit: (10) factorial2(1, 6, 6) ? creep
  ^ Exit: (9) factorial2(2, 3, 6) ? creep
  ^ Exit: (8) factorial2(3, 1, 6) ? creep
Z = 6
Yes
```

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## Sum of List

sumlist([],0).

```
sumlist([X|Rest],Ans) :- sumlist(Rest,Partial),
                        Ans is Partial+X.
```

Trace:

```
[trace] ?- sumlist([5,10,3],Y).
  Call: (7) sumlist([5, 10, 3], _G293) ? creep
  Call: (8) sumlist([10, 3], _L207) ? creep
  Call: (9) sumlist([3], _L247) ? creep
  Call: (10) sumlist([], _L227) ? creep
  ^ Exit: (10) sumlist([], 0) ? creep
  ^ Call: (10) _L227 is 0+3 ? creep
  ^ Exit: (10) 3 is 0+3 ? creep
  ^ Exit: (9) sumlist([3], 3) ? creep
  ^ Call: (9) _L207 is 3+10 ? creep
  ^ Exit: (9) 13 is 3+10 ? creep
  ^ Exit: (8) sumlist([10, 3], 13) ? creep
  ^ Call: (8) _G293 is 13+5 ? creep
  ^ Exit: (8) 18 is 13+5 ? creep
  ^ Exit: (7) sumlist([5, 10, 3], 18) ? creep
```

Y = 18

Yes

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## Arithmetic Predicates may not be Invertible

We may not be able to "invert" a predicate that involves arithmetic.

That is, we may not be able to put a variable in a different place.

**Tip:** Every time you write *is*, you must be sure the expression will be fully instantiated. If necessary, put a precondition on your predicate.

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## Negation as Failure

No equivalent of logical not in Prolog:

- Prolog can only assert that something is true.
- Prolog **cannot** assert that something is false.
- Prolog can assert that the given facts and rules do not allow something to be proven true.

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## Negation as Failure

Assuming that something unprovable is false is called **negation as failure**.

(Based on a **closed world assumption**.)

The goal `\+(G)` succeeds whenever the goal `G` fails.

```
?- member(b,[a,b,c]).
Yes
?- \+(member(b,[a,b,c])).
No
?- \+(member(b,[a,c])).
yes
```

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## Example: Disjoint Sets

```
overlap(S1,S2) :- member(X,S1),member(X,S2).
```

```
disjoint(S1,S2) :- \+(overlap(S1,S2)).
```

```
?- overlap([a,b,c],[c,d,e]).
Yes
?- overlap([a,b,c],[d,e,f]).
No
?- disjoint([a,b,c],[c,d,e]).
No
?- disjoint([a,b,c],[d,e,f]).
Yes
?- disjoint([a,b,c],X).
No %<-----Not what we wanted
```

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## Example: Disjoint Sets (cont.)

```
overlap(S1,S2) :- member(X,S1),member(X,S2).
```

```
disjoint(S1,S2) :- \+(overlap(S1,S2)).
```

```
?- disjoint([a,b,c],X).
No %<-----Not what we wanted
```

```
[trace] ?- disjoint([a,b,c],X).
Call: (7) disjoint([a, b, c], _G293) ? creep
Call: (8) overlap([a, b, c], _G293) ? creep
Call: (9) lists:member(_L230, [a, b, c]) ? creep
Exit: (9) lists:member(a, [a, b, c]) ? creep
Call: (9) lists:member(a, _G293) ? creep
Exit: (9) lists:member(a, [a|_G352]) ? creep
Exit: (8) overlap([a, b, c], [a|_G352]) ? creep
Fail: (7) disjoint([a, b, c], _G293) ? creep
```

No

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## Safety

### Proper use of Negation as Failure

`\+(G)` works properly only in the following cases:

1. When `G` is fully instantiated at the time prolog processes the goal `\+(G)`.

(In this case, `\+(G)` is interpreted to mean "goal `G` does not succeed".)

2. When all variables in `G` are unique to `G`, i.e., they don't appear elsewhere in the same clause.

(In this case, `\+(G(X))` is interpreted to mean "There is no value of `X` that will make `G(X)` succeed".)

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Consider the following rule:

```
(*) hates(tom,X) :- not loves(tom,X).
```

This may NOT be what we want, for several reasons:

- The answer is *infinite*, since for any person `p` not mentioned in the database, we cannot infer `loves(tom,p)`, so we must infer `hates(tom,p)`.

Rule (\*) is therefore said to be unsafe.

- The rule does not require `X` to be a person. *e.g.*, since we cannot infer

```
loves(tom,hammer)
loves(tom,verbs)
loves(tom,green)
loves(tom,abc)
```

we must infer that tom hates all these things.

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## Safety (Cont'd)

To avoid these problems, rules with negation should be guarded:

```
hates(tom,X) :- vegetable(x), green(X),
                not loves(tom,X).
```

*i.e.*, Tom hates every green vegetable that he does not love.

Here, `vegetable` and `green` are called guard literals. They guard against safety problems by binding `x` to specific values in the database.

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