

Logic and Problem Solving with Prolog

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Prolog at 50: Forever Young!

Prolog: Programming in Logic – a (very) short history

- originating in the late 70's, logic based alternative to LISP, ready for AI
- motivations for *Programming in Logic*:
 - Alain Colmerauer: programming grammars for NLP [4, 5]
 - Robert Kowalski: algorithms = logic + control [12, 10]
- from First Order Logic to Prolog in a nutshell:
 - shape of the general case, after elimination of quantifiers:
$$a ; b :- c, d, e.$$
 - restricted to a computationally well-behaved subset of predicate logic:
 - *Horn clauses*: $a :- b, c, d.$ all variables universally quantified
 - SLD-resolution, using Alan Robinson's unification algorithm
 - multiple answers returned: (improperly) called “non-deterministic” execution
- newer derivatives: Constraint Programming, SAT-solvers, Answer Set Programming: exploit fast execution of propositional logic
- a founding member of the “declarative programming” family
- more about history: 50 years of Prolog, [9], early years: [11]

Prolog: raising again, possibly as part of a new AI-Spring

Programming Language ratings - from the Tiobe index (June 2022)

- 1 Python 12.20 %
- 2 C 11.91 %
- 10 Swift 1.55 %
- 15 Go 1.02 %
- 20 Prolog **0.74** %
- 28 Julia % 0.52%
- 32 Lisp 0.35 %
- 34 Scala 0.30 %
- 38 Haskell 0.21 %
- 44 Scheme 0.19%
- 50 ML 0.17 %

a few years ago: Prolog not on the list (for being behind the first 50)

Prolog: the Basics

A quick Splash into Prolog, with a Graph Coloring Program

```
% color vertices with given colors Cs
color_graph([],_).
color_graph([e(CI,CJ)|Es],Cs) :-
    take_one_color(CI,Cs,OtherCs),
    take_one_color(CJ,OtherCs,_), % CJ is anything except CI
    color_graph(Es,Cs).

take_one_color(C, [C|Cs], Cs).
take_one_color(C, [Other|Cs1], [Other|Cs2]) :- take_one_color(C,Cs1,Cs2).

% test data: undirected graph as list of edges
go:- Edges=[  
    e(V1,V2), e(V2,V3), e(V1,V3), e(V3,V4), e(V4,V5),  
    e(V5,V6), e(V4,V6), e(V2,V5), e(V1,V6)  
,  
    Colors=[r,g,b],  
    color_graph(Edges,Colors),  
    writeln(Edges),  
    fail  
; writeln(done).
```

Running the Program (BTW, all the code for this tutorial is at <https://github.com/ptaraau/PrologTutorial>

```
/*
$ swipl
?- consult('cols.pro') .
...
?- go.
[e(r,g),e(g,b),e(r,b),e(b,r),e(r,b),e(b,g),e(r,g),e(g,b),e(r,g)]
[e(r,g),e(g,b),e(r,b),e(b,g),e(g,r),e(r,b),e(g,b),e(g,r),e(r,b)]
[e(r,b),e(b,g),e(r,g),e(g,r),e(r,g),e(g,b),e(r,b),e(b,g),e(r,b)]
[e(r,b),e(b,g),e(r,g),e(g,b),e(b,r),e(r,g),e(b,g),e(b,r),e(r,g)]
...
[e(b,g),e(g,r),e(b,r),e(r,g),e(g,b),e(b,r),e(g,r),e(g,b),e(b,r)]
[e(b,g),e(g,r),e(b,r),e(r,b),e(b,r),e(r,g),e(b,g),e(g,r),e(b,g)]
done
true.
*/
```

Prolog: unification, backtracking, clause selection

```
?- X=a, Y=X. % variables uppercase, constants lower
X = a, Y = a.

?- X=a, X=b.
false.

?- f(X,b)=f(a,Y). % compound terms unify recursively
X = a, Y = b.

% clauses
a(1). a(2). a(3).    % facts for a/1
b(2). b(3). b(4).    % facts for b/1

c(0).
c(X) :- a(X), b(X).   % a/1 and b/1 must agree on X

?- c(R).               % the goal at the Prolog REPL
R=0; R=2; R=3.         % the stream of answers
```

Propositional Logic: with pure Prolog and a few CUTs

- truth tables
- naive SAT algorithm
- naive tautology prover

```
truthTable(F) :- term_variables(F, Vs), eval(F, R), writeln(Vs:R), fail ; true.  
  
sat(X) :- eval(X, 1), !.  
  
taut(X) :- not(eval(X, 0)).  
  
eval(X, X) :- var(X), !, bit(X).  
eval(X, R) :- integer(X), !, R=X.  
...  
eval((A*B), R) :- eval(A, X), eval(B, Y), conj(X, Y, R).  
eval((A+B), R) :- eval(A, X), eval(B, Y), disj(X, Y, R).  
...  
bit(0).  
bit(1).
```

full code at: [https://github.com/ptarau/PrologTutorial/
blob/main/code/boolean_logic.pro](https://github.com/ptarau/PrologTutorial/blob/main/code/boolean_logic.pro)

Examples

```
?- truthTable(A->B->C) .  
[0, 0, 0]:1  
[0, 0, 1]:1  
[0, 1, 0]:1  
[0, 1, 1]:1  
[1, 0, 0]:1  
[1, 0, 1]:1  
[1, 1, 0]:0  
[1, 1, 1]:1  
true.  
  
?- sat(A * -B + B * -C + C * -A) .  
A = B, B = 0,  
C = 1.  
  
% Peirce's law  
?- taut( ( (X -> Y) -> X) -> X) .  
true.
```

A favorite Prolog Data Structure: Lists

full code at: <https://github.com/ptarau/PrologTutorial/blob/main/code/lists.pro>

```
% concatenate to lists
append_([], Ys, Ys).
append_([X|Xs], Ys, [X|Zs]) :- append_(Xs, Ys, Zs).

% member in terms of append
member_(X, Xs) :- append_(_, [X|_], Xs).

% generate subsets of a set
subset_of([], []).
subset_of([_|Xs], Ys) :- subset_of(Xs, Ys).
subset_of([X|Xs], [X|Ys]) :- subset_of(Xs, Ys).

% a simple quicksort predicate
qsort([], []).
qsort([X|Xs], Rs) :-
    findall(Y, (member(Y, Xs), Y < X), LittleOnes),
    findall(Y, (member(Y, Xs), Y >= X), BigOnes),
    qsort(LittleOnes, Firsts),
    qsort(BigOnes, Lasts),
    append(Firsts, [X|Lasts], Rs).
```

Examples

```
?- append_([1,X,3], [Y,5], [A,2,B,4,C]) .
```

```
X = 2,  
Y = 4,  
A = 1,  
B = 3,  
C = 5.
```

```
?- member_(_X, [1,2]) .
```

```
X = 1 ;  
X = 2.
```

```
?- subset_of([1,2,3],Xs) .
```

```
Xs = [] ;  
Xs = [3] ;  
Xs = [2] ;  
Xs = [2, 3] ;  
Xs = [1] ;  
Xs = [1, 3] ;  
Xs = [1, 2] ;  
Xs = [1, 2, 3].
```

```
?- qsort([3,2,1,5,3,6,6,2],Sorted) .
```

```
Sorted = [1, 2, 2, 3, 3, 5, 6, 6].
```

A Glimpse at how Prolog works, actually

Unification: key intuition and a few more examples

- Prolog terms: trees with function symbols or atoms labeling their nodes
- two terms unify if the corresponding trees overlap, when allowing variables to match subtrees
- but, this only happens if equality constraints hold: a variable cannot match two different subtrees!
- also, cycles are forbidden (see `unify_with_occurs_check`), but this is not enforced by default

```
% recursive descent to unify subterms
?- f(X,g(X,X))=f(h(Z,Z),U), Z=a.
X = h(a,a) ,
Z = a ,
U = g(h(a,a),h(a,a))

% the same variables can occur on both sides
?- [X,Y,Z]=[f(Y,Y),g(Z,Z),h(a,b)].
X = f(g(h(a,b),h(a,b)),g(h(a,b),h(a,b))) ,
Y = g(h(a,b),h(a,b)) ,
Z = h(a,b)
```

A stack-based unification algorithm

actually part of the **Minlog interpreter** at: <https://github.com/ptarau/PrologTutorial/blob/main/code/minlog/minlog.py>

```
def unify(x, y, trail):
    ustack = [y,x]
    while ustack:
        x1 = deref(ustack.pop())
        x2 = deref(ustack.pop())
        if x1 == x2: continue
        if isinstance(x1, Var): x1.bind(x2, trail)
        elif isinstance(x2, Var): x2.bind(x1, trail)
        elif not (isinstance(x1, tuple) and isinstance(x2, tuple)): return False
        else: # assuming x1,x2 are both tuples (i.e., compound terms)
            arity = len(x1)
            if len(x2) != arity: return False
            for i in range(arity - 1, -1, -1): # going right to left here!
                ustack.append(x2[i])
                ustack.append(x1[i])
    return True
```

deref(): dereferencing is just following variable-to-variable links until a nonvariable term or unbound variable is reached

Prolog: the two-clause meta-interpreter

The meta-interpreter `metaint/1` uses a (difference)-list view of prolog clauses.

```
metaint([]) .          % no more goals left, succeed
metaint([G|Gs]) :-      % unify the first goal with the head of a clause
    cls([G|Bs], Gs),   % build a new list of goals from the body of the
                      % clause extended with the remaining goals as tail
    metaint(Bs) .       % interpret the extended body
```

- clauses are represented as facts of the form `cls/2`
- the first argument representing the head of the clause + a list of body goals
- clauses are terminated with a variable, also the second argument of `cls/2`.

```
cls([ add(0,X,X)           |Tail], Tail) .
cls([ add(s(X),Y,s(Z)), add(X,Y,Z)     |Tail], Tail) .
cls([ goal(R), add(s(s(0)),s(s(0)),R) |Tail], Tail) .
```

```
?- metaint([goal(R)]).
R = s(s(s(s(0)))) .
```

Next: Just mimic the 2 clause metainterpreter in Python!

```
def interp(css, goal):
    def step(goals):
        """
        recursively applies unfolding to its goal stack
        backtracking is implemented using "yield"
        """
        def undo(trail):
            ... # unbinds variables on backtracking

        def unfold(g, gs):
            ... # tries to unify goal g with head of a clause

        trail = []
        if goals == []:
            yield goal
        else:
            g, gs = goals
            for newgoals in unfold(g, gs):
                yield from step(newgoals)
                undo(trail)

        yield from step(goal)
```

Fast Implementation: the Warren Abstract Machine (WAM)

- designed by D.H.D. Warren in the early 80'
- uses registers, two stacks (for goals and clause choices), heap and trail
- cited these days as [1], a very good tutorial introduction
- improvements over the years, but basic architecture unchanged
 - simplified WAM, using a transformation to binary clauses [16] [14]
 - alternative designs: stack frames based [19]
 - tabling, first-order semantics for HiLog [13], [3]
 - just-in-time indexing schemes of YAP [6] and SWI-Prolog [18]
- implemented both natively and as a software virtual machine
- an early overview of WAM derivatives: [17]
- a TPLP issue dedicated to Prolog system implementations:
[6, 2, 13, 8, 19, 14]
- overview of parallel implementations: [7]

Some Neat Language Constructs in Prolog

A Prolog source-level transformation: Definite Clause Grammars (DCGs)

Prolog's DCG preprocessor transforms a clause defined with “`-->`” like

```
a0 --> a1, a2, ..., an.
```

into a clause where predicates have two extra arguments expressing a chain of state changes as in

```
a0(S0, Sn) :- a1(S0, S1), a2(S1, S2), ..., an(Sn-1, Sn).
```

- they can be used to compose relations (functions in particular)
- with compound terms (e.g. lists) as arguments they form a Turing-complete embedded language

```
f --> g, h.  
f(In, Out) :- g(In, Temp), h(Temp, Out).
```

Some extra notation: { . . . } calls to Prolog, [. . .] wraps terminal symbols

Playing with DCGs - a generation example

```
dalle-->subject, verb, object.  
  
subject-->[a, cat] ; [a, dog].  
verb-->[sitting].  
adjective-->[golden] ; [shiny].  
object-->[on, the], adjective, location, [with, a], instrument.  
location-->[moon].  
instrument-->[violin] ; [trumpet].
```

```
go:-  
    dalle(Words, []), nl,  
    member(W, Words), write(W), write(' '), fail.  
go.
```

- pick any of the generated sentences
- paste it to: <https://www.craiyon.com/>
- the Dalle-mini program will paint it!

```
?- go.  
a cat sitting on the golden moon with a violin  
a cat sitting on the golden moon with a trumpet  
...  
a dog sitting on the shiny moon with a trumpet
```

The imperfect charm of our neuro-symbolic moonshot :-)



Procedural Constructs in Prolog

- Prolog's procedural language constructs are as old as the language itself (a reason some of them will feel a bit rusty)
- CUT ("!") is needed to control search and express if-the-else and case constructs
- asserta/1,assertz/1,retract/1,retractall/1,abolish/1,clause/2 create and update the "dynamic database" - basically supporting a self-modifying program
- setarg, nb_setarg support backtrackable or persistent array operations on compound terms playing the role of arrays
- we will not teach them to you, but as you will learn about them just because of that, the advice is to use them with moderation :-)
- but do not fear occasional impurity, especially in library development code (e.g., aggregates) if wrapped up into a declarative looking API

On Prolog Extensions, with a bias for “The Road Not Taken”

Prolog Extensions, with a common theme

the shared theme, at least at implementation level: some form of **coroutining**

- constraint programming: boolean, finite domains etc.
 - key to implementing them: coroutining via attributed variables
 - goals are suspended until unification triggers resumption
 - another application: lazy streams and in particular lazy lists
- tabling: avoiding re-execution of goals already seen, including with “well-behaved negation as failure” (SLDNF-resolution)
- parallel execution: AND-parallelism, OR-parallelism
- multi-threading, remote execution, coordination
- our next focus: a less well-known but critical extension to keep Prolog competitive with modern coroutining features now prevalent in popular languages: (Python, Javascript, C#, etc.,) **First-class Logic Engines**

Coroutining with First-class Logic Engines

we want full reflection of Prolog's multiple-answer generation (our 2-clause meta-interpreter "cheats" when it inherits that from the underlying Prolog)

- a *logic engine* is a Prolog language processor reflected through an API that allows its computations to be controlled interactively from another *logic engine*
- intuition: it is very much the same thing as a programmer controlling Prolog's interactive toplevel loop:
 - launch a new goal
 - ask for a new answer
 - interpret it
 - react to it
- logic engines can create other logic engines as well as external objects
- logic engines can be controlled cooperatively or preemptively

SWI-Prolog code at: <https://github.com/ptarau/PrologTutorial/blob/main/code/engines.pro>

Engines: new_engine/3

`new_engine(AnswerPattern, Goal, Engine):`

- creates a new instance of the Prolog interpreter, uniquely identified by Engine
- shares code with the currently running program
- initialized with Goal as a starting point
- AnswerPattern : answers returned by the engine will be instances of the pattern

Engines: ask/2, stop/1

ask(Engine, AnswerInstance):

- tries to harvest the answer computed from Goal, as an instance of AnswerPattern
- if an answer is found, it is returned as the (AnswerInstance), otherwise the atom no is returned
- it is used to retrieve successive answers generated by an Engine, on demand
- it is responsible for actually triggering computations in the engine
- one can see this as transforming Prolog's backtracking over all answers into a deterministic stream of lazily generated answers

stop(Engine):

- stops the Engine
- no is returned for new queries

The `yield` operation: a key co-routining primitive

`yield(Term)`

- will save the state of the engine and transfer *control* and a *result* Term to its client
- the client will receive a copy of Term simply by using its `get/2` operation
- an Engine returns control to its client either by calling `yield/1` or when a computed answer becomes available

A simple application example: throwing an exception

```
throw(E) :- yield(exception(E)).
```

SWI-Prolog implementation (also with more on “talking” to the engines) at:
<https://www.swi-prolog.org/pldoc/man?section=engines>

Typical use of the Engine API

- ① the *client* creates and initializes a new *engine*
- ② the client triggers a new computation in the *engine*:
 - the *client* passes some data and a new goal to the *engine* and issues a get operation that passes control to it
 - the *engine* starts a computation from its initial goal or the point where it has been suspended and runs (a copy of) the new goal received from its *client*
 - the *engine* returns (a copy of) the answer, then suspends and returns control to its *client*
- ③ the *client* interprets the answer and proceeds with its next computation step
- ④ the process is fully reentrant and the *client* may repeat it from an arbitrary point in its computation

What can we do with first-class engines?

- define the complete set of ISO-Prolog operations at source level
- in fact, one can define the engine operations in Horn clause Prolog - with a bit of black magic (e.g. splitting a term into two variant terms)
- implement (at source level) Erlang-style messaging - with millions of engines
- implement Prolog's dynamic database at source level
- build an algebra for composing engines and their answer streams
- implement “tabling” (a form of dynamic programming that avoids recomputation) at source level

NEW: first-class logic engines have been added to Natlog, a Prolog with a lighter syntax tightly integrated with Python: [15]

use pip3 install natlog to install it or get it from
<https://github.com/ptarau/minlog>

Source-level emulation of Prolog built-ins with engines

```
if(Cond, Then, Else) :-  
    new_engine(Cond, Cond, Engine),  
    ask(Engine, Answer), stop(Engine),  
    process_answer(Answer, Cond, Then, Else).  
  
process_answer(the(Cond), Cond, Then, _) :- call(Then).  
process_answer(no, _, _, Else) :- call(Else).  
  
not_(G) :- if(G, fail, true).  
once_(G) :- if(G, true, fail).  
var_(X) :- not_(not_(X=1)), not_(not_(X=2)).  
nonvar_(X) :- not_(var_(X)).  
  
copy_term_(T, CT) :- new_engine(T, true, E), ask(E, the(CT)), stop(E).  
  
findall_(X, G, Xs) :- new_engine(X, G, E), ask(E, Y), collect(E, Y, Xs).  
  
collect(_, no, []).  
collect(E, the(X), [X|Xs]) :- ask(E, Y), collect(E, Y, Xs).
```

Examples

- an infinite Fibonacci stream with yield

```
fibo(X) :- new_engine(_, slide_fibo(1, 1), E), repeat, ask(E, the(X)).  
  
slide_fibo(X, Y) :- Z is X+Y, yield(X), slide_fibo(Y, Z).
```

```
?- fibo(X).  
X = 1 ;  
X = 1 ;  
X = 2 ;  
X = 3 ;  
...  
  
?- findall_(X, member(X, [1, 2, 3]), Xs).  
Xs = [1, 2, 3].  
  
?- X=1, if(X=1, Y=2, Y=3).  
X = 1,  
Y = 2.  
  
?- X=1, if(X=10, Y=2, Y=3).  
X = 1,  
Y = 3.
```

Prolog as a Program Solving Tool

Sudoku (for kids): the board filled out with logic variables

```
s4x4([[ [S11, S12, S13, S14],  
        [S21, S22, S23, S24],  
  
        [S31, S32, S33, S34],  
        [S41, S42, S43, S44] ],  
      [ [S11, S21, S31, S41],  
        [S12, S22, S32, S42],  
  
        [S13, S23, S33, S43],  
        [S14, S24, S34, S44] ],  
      [ [S11, S12, S21, S22],  
        [S13, S14, S23, S24],  
  
        [S31, S32, S41, S42],  
        [S33, S34, S43, S44] ]]).
```

The program: just a maplist of maplists of permutations

```
sudoku (Xss) :-  
    s4x4 (Xsss), Xsss=[Xss|_],  
    maplist (maplist (permute ([1,2,3,4])), Xss) .  
  
permute ([] ,[]).  
permute ([X|Xs], Zs) :- permute (Xs, Ys), ins (X, Ys, Zs) .  
  
ins (X, Xs, [X|Xs]).  
ins (X, [Y|Xs], [Y|Ys]) :- ins (X, Xs, Ys) .  
  
go:- sudoku (Xss), nl, member (Xs, Xss), write (Xs), nl, fail ; nl.
```

```
?- go.  
[1,2,3,4]  
[3,4,1,2]  
[2,3,4,1]  
[4,1,2,3]  
...
```

code at <https://github.com/ptarau/PrologTutorial/blob/main/code/sudoku4kids.pro>

Sudoku, for ages 13 or more - with graph coloring

- the previous program is simple and declarative but very slow
- what can we do, with just Prolog and no constraints, SAT or ASP?
- sudoku on NxN grid is NP-complete ...
- NP-complete programs have P-time translation to other NP-complete programs, with possibly faster solvers for them (e.g., SAT)
- our solver candidate will be **graph coloring**
- we will constrain variables to have different colors than their neighbors on rows, columns or square blocks!
- a bit like the “all_different” global constraint propagator
- full code at:
[https://github.com/ptarau/PrologTutorial/blob/
main/code/sudoku_in_style.pro](https://github.com/ptarau/PrologTutorial/blob/main/code/sudoku_in_style.pro)
- moreover, we would like, as we are in Prolog, to either solve a given Problem or to generate (all) problems of a given size

Transforming Sudoku to a graph coloring problem

full code at: https://github.com/ptarau/PrologTutorial/blob/main/code/sudoku_in_style.pro

```
% build dif graph
to_dif_graph(B,Difs) :-
    functor(B,N),
    bagof(XDif,
          I^J^(index_pairs(N,I-J), to_a_dif_graph(N,B,I,J,XDif)), Difs).

% collects all difs for var at I,J in board
to_a_dif_graph(N,B,I,J,X-Difs) :- at(B,I-J,X),
    difs(row_dif,N,B,I,J,RowDifs),
    difs(col_dif,N,B,I,J,ColDifs),
    difs(bloc_dif,N,B,I,J,[BlocDifs]),
    app([RowDifs,ColDifs,BlocDifs],Difs).

% collects difs of a row, col or bloc generator
difs(Generator,N,B,I,J,Difs) :-
    bagof(V, call(Generator,N,B,I,J,V), Difs).
```

Once translated to graph coloring, Sudoku is just a maplist of color picks!

```
sudoku(B) :-  
    functor(B,_,N), % N is the size of the board B  
    to_dif_graph(B,Difs), % builds dif graph  
    maplist(pick(N),Difs). % constrains graph
```

- pick/2 finds a position X (seen as a “color”) such that X is not in the set Xs of its neighbors in rows, columns or blocks
- note that this set is trimmed down such that each neighbor (a logical variable or a “color” assigned to an integer) is represent only once

```
pick(N,X-Xs) :- between(1,N,X), \+ member_const(X,Xs).  
  
member_const(X, [Y|_]) :- nonvar(Y), X =:= Y, !.  
member_const(X, [_|Xs]) :- member_const(X,Xs).
```

- NOTE: more compact Sudoku solvers can be built using finite domain constraints or ASP-systems, but our point here is the fact that one can do it quite efficiently in plain Prolog

Solving a known to be hard Sudoku problem: “Escargot”

```
escargot([  
    [1, _, _, _, _, 7, _, 9, _],  
    [_ 3, _, _, 2, _, _, _, 8],  
    [_ _, 9, 6, _, _, 5, _, _],  
    [_ _, 5, 3, _, _, 9, _, _],  
    [_ 1, _, _, 8, _, _, _, 2],  
    [6, _, _, _, 4, _, _, _],  
    [3, _, _, _, _, _, 1, _],  
    [_ 4, _, _, _, _, _, 7],  
    [_ _, 7, _, _, 3, _, _]  
]).  
1 6 2 8 5 7 4 9 3  
5 3 4 1 2 9 6 7 8  
7 8 9 6 4 3 5 2 1  
4 7 5 3 1 2 9 8 6  
9 1 3 5 8 6 7 4 2  
6 2 8 7 9 4 1 3 5  
3 5 6 4 7 8 2 1 9  
2 4 1 9 3 5 8 6 7  
8 9 7 2 6 1 3 5 4
```

the program can solve or generate problems of given size (tested up to 16x16)

N-Queens as a pure Horn Clause program

- original idea due to Thom Frühwirth
- row, columns and diagonal constraints are expressed directly in term of the lists containing the positions of the queens, \Rightarrow no arithmetic involved!
- see proof of correctness in Wlodek Drabent's paper at ICLP'22

```
goal (Queens) :-queens ([1, 2, 3, 4, 5, 6, 7, 8, 9, 10], Queens) .
```

```
queens (Qs, Ps) :-gen_places (Qs, Ps), place_queens (Qs, Ps, _, _) .
```

```
gen_places ([], []) .
```

```
gen_places ([_|Qs], [_|Ps]) :-gen_places (Qs, Ps) .
```

```
% place_queen (Queen, Column, Updiagonal, Downdiagonal)
```

```
place_queen (I, [I|_], [I|_], [I|_]) .
```

```
place_queen (I, [_|Cs], [_|Us], [_|Ds]) :-place_queen (I, Cs, Us, Ds) .
```

```
place_queens ([], _, _, _) .
```

```
place_queens ([I|Is], Cs, Us, [_|Ds]) :-
```

```
    place_queens (Is, Cs, [_|Us], Ds),
```

```
    place_queen (I, Cs, Us, Ds) .
```

Examples

```
?- qs([a,b,c,d],Qs).
```

```
Qs = [b, d, a, c] ;
```

```
Qs = [c, a, d, b] .
```

```
?- numlist(1,24,Ns),qs(Ns,Qs).
```

```
Ns = [1, 2, 3, 4, 5, 6, 7, 8, 9|...],
```

```
Qs = [24,21,23,20,22,8,3,7,19,10,18,6,4,17,1,5,2,16,14,12,9,15,13,11].
```

- it is a pure Prolog program, no CUTs, no arithmetic
- the program simply states that the queens should be distinct on columns and diagonals, once row position is fixed
- input does not need to be numeric, the program can be seen simply as a **filter on the set of all permutations of given size**
- unusually fast for a pure Prolog program (e.g., N=24)
- still, not comparable with CLP-FD, SAT or ASP equivalents going up to sizes in the hundreds

The final round: a few harder things, done easily

λ -terms with de Bruijn Indices

- *de Bruijn Indices* provide a name-free representation of lambda terms
- terms that can be transformed by a renaming of variables (α -conversion) will share a unique representation
 - variables following lambda abstractions are omitted
 - their occurrences are marked with natural numbers *counting the number of lambdas until the one binding them* on the way up to the “root” of the term
- $(\lambda(a(s(0), \lambda(0))))$ represents α -equivalent terms (roughly, same up to a renaming of their variables) e.g.,
 - $\lambda z. \lambda y. (z(\lambda x. x))$
 - $\lambda z. \lambda y. (z(\lambda z. z))$
 - ...
- λ -terms are called *closed* if the de Bruijn counters do not reach outside the scope of the lambda binders, when counting one step up for each binder crossed
- otherwise they are called *open*

λ -terms of and their (simple) types

- λ -terms are binary-unary trees, with leaves in unary arithmetic marking distances to their lambda binders (de Bruijn notation)
- the constructors are
 - 1/1 = lambda node
 - a/2 = application node
 - s/1 = de Bruijn index counter (in successor arithmetic)
 - 0 = de Bruijn index zero
- the types of the lambda terms are binary trees:
 - type constructor \rightarrow
 - variables in leaf positions

code at https://github.com/ptarau/PrologTutorial/blob/main/code/type_inference.pro

Generating la λ -terms of a given size (possibly open)

- we use successor arithmetic: 0, $s(0), s(s(0)) \dots$
- possibly open term: de Bruijn indices might point higher than our lambda binders
- size definition: $a/2 = 2$ units, $l/1 = 1$ unit. $s/1 = 1$ unit, $0 = 0$ units

```
genLambda (s (S), X) :- genLambda (X, S, 0) .  
  
genLambda (X, N1, N2) :- nth_elem (X, N1, N2) .  
genLambda (l (A), s (N1), N2) :- genLambda (A, N1, N2) .  
genLambda (a (A, B), s (s (N1)), N3) :-  
    genLambda (A, N1, N2) ,  
    genLambda (B, N2, N3) .  
  
nth_elem (0, N, N) .  
nth_elem (s (X), s (N1), N2) :- nth_elem (X, N1, N2) .
```

Examples

```
?- genLambda(s(s(s(0))),Term).
```

```
Term = s(s(0)) ;
```

```
Term = l(s(0)) ;
```

```
Term = l(l(0)) ;
```

```
Term = a(0, 0) ;
```

```
false.
```

```
?- genLambda(s(s(s(s(0)))),Term).
```

```
Term = s(s(s(0))) ;
```

```
Term = l(s(s(0))) ;
```

```
Term = l(l(s(0))) ;
```

```
Term = l(l(l(0))) ;
```

```
Term = l(a(0, 0)) ;
```

```
Term = a(0, s(0)) ;
```

```
Term = a(0, l(0)) ;
```

```
Term = a(s(0), 0) ;
```

```
Term = a(l(0), 0) ;
```

```
false.
```

Generating closed terms

- a list, initially empty of variables is built
- each lambda binder pushes a variable to it
- each leaf is constrained to correspond, via its de Bruijn index to a variable
- we use the list to count binders - but it will later hold types that we infer

```
genClosed(s(S), X) :- genClosed(X, [], S, 0).  
  
genClosed(X, Vs, N1, N2) :- nth_elem_on(X, Vs, N1, N2).  
genClosed(l(A), Vs, s(N1), N2) :- genClosed(A, [ ] | Vs), N1, N2).  
genClosed(a(A, B), Vs, s(s(N1)), N3) :-  
    genClosed(A, Vs, N1, N2),  
    genClosed(B, Vs, N2, N3).  
  
nth_elem_on(0, [ ] | [ ], N, N).  
nth_elem_on(s(X), [ ] | Vs, s(N1), N2) :- nth_elem_on(X, Vs, N1, N2).
```

Example

```
?- genClosed(s(s(s(0))), Term).
```

```
Term = l(l(0)) .
```

```
?- genClosed(s(s(s(s(0)))), Term).
```

```
Term = l(l(s(0))) ;
```

```
Term = l(l(l(0))) ;
```

```
Term = l(a(0, 0)) .
```

```
?- genClosed(s(s(s(s(s(0))))), Term).
```

```
Term = l(l(l(s(0)))) ;
```

```
Term = l(l(l(l(0)))) ;
```

```
Term = l(l(a(0, 0))) ;
```

```
Term = l(a(0, l(0))) ;
```

```
Term = l(a(l(0), 0)) ;
```

```
Term = a(l(0), l(0)) .
```

Type Inference for λ -terms

- in an application ($a/2$ node): $X \rightarrow Y$ and X reduce to Y
- all variables of the lambda binder $l/1$ should have the same type
- $\Rightarrow \text{unify_with_occurs_check}$ will unify them, avoiding cycles!

```
type_of(X, T) :- type_of(X, T, []) .  
  
type_of(I, V, Vs) :-  
    nth_elem_of(I, Vs, V0),  
    unify_with_occurs_check(V, V0) .  
  
type_of(l(A), (X->Y), Vs) :-  
    type_of(A, Y, [X/Vs]) .  
  
type_of(a(A,B), Y, Vs) :-  
    type_of(A, (X->Y), Vs),  
    type_of(B, X, Vs) .  
  
nth_elem_of(0, [X|_], X) .  
nth_elem_of(s(I), [_|Xs], X) :- nth_elem_of(I, Xs, X) .
```

this is unusually easy in Prolog, but it might take a few hundred lines in your favorite other language ...

Generating simply-typable de Bruijn terms of a given size

- types mimic function application (i.e., β -reduction of lambda terms)
- we refine our program generating closed terms by imposing constraints on the variables introduced by lambda binders
- de Bruijn indices pointing to the same variable should agree on types
- unification with “occurs-check”: circular types are not allowed!

```
genTypable(s(S), X, T) :- genTypable(X, T, [], S, 0).
```

```
genTypable(X, V, Vs, N1, N2) :- genIndex(X, Vs, V, N1, N2).
```

```
genTypable(l(A), (X->Xs), Vs, s(N1), N2) :- genTypable(A, Xs, [X/Vs], N1, N2).
```

```
genTypable(a(A,B), Xs, Vs, s(s(N1)), N3) :-
```

```
    genTypable(A, (X->Xs), Vs, N1, N2),
```

```
    genTypable(B, X, Vs, N2, N3).
```

```
genIndex(0, [V|_], V0, N, N) :- unify_with_occurs_check(V0, V).
```

```
genIndex(s(X), [_/Vs], V, s(N1), N2) :- genIndex(X, Vs, V, N1, N2).
```

Examples

```
?- genTyped(4).
```

```
l(l(l(s(0))))
```

```
A->B->C->B
```

```
l(l(l(l(0))))
```

```
A->B->C->D->D
```

```
l(a(0,l(0)))
```

```
((A->A)->B)->B
```

```
l(a(l(0),0))
```

```
A->A
```

```
a(l(0),l(0))
```

```
A->A
```

Writing a theorem prover for Intuitionistic Propositional Logic

code at <https://github.com/ptarau/PrologTutorial/blob/main/code/prover.pro>

- intuitionistic logic is key to today's proof assistants
- there's a correspondence between computations and proofs: the *Curry-Howard isomorphism*
- in its simplest form, it connects the *implicational fragment of propositional intuitionistic logic* with types in the *simply typed lambda calculus*
- type inference computes the type of a λ -term (a theorem in IPC!)
- a theorem prover solves the harder (PSPACE-complete) inverse problem of finding a proof given a formula representing a type
- a simply-typed λ -term can be synthesized as a result of a successful proof for the implicational subset
- next we will implement a more general prover, covering all interesting IPC operators

Roy Dyckhoff's G4ip sequent calculus

termination ensured with “multiset ordering”, no loop checking is needed!

$$\Gamma, p \Rightarrow p \quad Ax \quad (p \text{ an atom})$$

$$\Gamma, \perp \Rightarrow \Delta \quad L\perp$$

$$\frac{\Gamma \Rightarrow \varphi \quad \Gamma \Rightarrow \psi}{\Gamma \Rightarrow \varphi \wedge \psi} \quad R\wedge$$

$$\frac{\Gamma, \varphi, \psi \Rightarrow \Delta}{\Gamma, \varphi \wedge \psi \Rightarrow \Delta} \quad L\wedge$$

$$\frac{}{\Gamma \Rightarrow \varphi_0 \vee \varphi_1} \quad R\vee \quad (i = 0, 1)$$

$$\frac{\Gamma, \varphi \Rightarrow \Delta \quad \Gamma, \psi \Rightarrow \Delta}{\Gamma, \varphi \vee \psi \Rightarrow \Delta} \quad L\vee$$

$$\frac{\Gamma, \varphi \Rightarrow \psi}{\Gamma \Rightarrow \varphi \rightarrow \psi} \quad R\rightarrow$$

$$\frac{\Gamma, p, \varphi \Rightarrow \Delta}{\Gamma, p, p \rightarrow \varphi \Rightarrow \Delta} \quad Lp\rightarrow \quad (p \text{ an atom})$$

$$\frac{\Gamma, \varphi \rightarrow (\psi \rightarrow \gamma) \Rightarrow \Delta}{\Gamma, \varphi \wedge \psi \rightarrow \gamma \Rightarrow \Delta} \quad L\wedge\rightarrow$$

$$\frac{\Gamma, \varphi \rightarrow \gamma, \psi \rightarrow \gamma \Rightarrow \Delta}{\Gamma, \varphi \vee \psi \rightarrow \gamma \Rightarrow \Delta} \quad L\vee\rightarrow$$

$$\frac{\Gamma, \psi \rightarrow \gamma \Rightarrow \varphi \rightarrow \psi \quad \gamma, \Gamma \Rightarrow \Delta}{\Gamma, (\varphi \rightarrow \psi) \rightarrow \gamma \Rightarrow \Delta} \quad L\rightarrow\rightarrow$$

The Theorem Prover for IPC

- we derive the prover directly from Roy Dyckhoff's G4ip calculus
- code at <https://github.com/ptarau/PrologTutorial/blob/main/code/prover.pro>

```
iprover(true,_) :-!.
iprover(A,Vs) :- memberchk(A,Vs), !.
iprover(_,Vs) :- memberchk(false,Vs), !.
iprover(~A,Vs) :- !, iprover(false,[A|Vs]) .
iprover(A<->B,Vs) :- !, iprover(B,[A|Vs]), iprover(A,[B|Vs]) .
iprover( (A->B), Vs) :- !, iprover(B,[A|Vs]) .
iprover( (B<-A), Vs) :- !, iprover(B,[A|Vs]) .
iprover(A & B, Vs) :- !, iprover(A,Vs), iprover(B,Vs) .
iprover(G,Vs1) :- % atomic or disj or false
    select(Red,Vs1,Vs2),
    iprover_reduce(Red,G,Vs2,Vs3),
    !,
    iprover(G,Vs3) .
iprover(A v B, Vs) :- (iprover(A,Vs) ; iprover(B,Vs)), !.
```

The Prover, continued

- we delegate details to helper predicates: `iprover_reduce/4` and `iprover_impl/4`.

```
iprover_reduce(true, _, Vs1, Vs2) :- !, iprover_impl(false, false, Vs1, Vs2) .  
iprover_reduce(~A, _, Vs1, Vs2) :- !, iprover_impl(A, false, Vs1, Vs2) .  
iprover_reduce((A->B), _, Vs1, Vs2) :- !, iprover_impl(A, B, Vs1, Vs2) .  
iprover_reduce((B<-A), _, Vs1, Vs2) :- !, iprover_impl(A, B, Vs1, Vs2) .  
iprover_reduce((A & B), _, Vs, [A, B/Vs]) :- !.  
iprover_reduce((A<->B), _, Vs, [(A->B), (B->A) /Vs]) :- !.  
iprover_reduce((A v B), G, Vs, [B/Vs]) :- iprover(G, [A/Vs]) .
```

```
iprover_impl(true, B, Vs, [B/Vs]) :- !.  
iprover_impl(~C, B, Vs, [B/Vs]) :- !, iprover((C->false), Vs) .  
iprover_impl((C->D), B, Vs, [B/Vs]) :- !, iprover((C->D), [(D->B) /Vs]) .  
iprover_impl((D<-C), B, Vs, [B/Vs]) :- !, iprover((C->D), [(D->B) /Vs]) .  
iprover_impl((C & D), B, Vs, [(C->(D->B)) /Vs]) :- !.  
iprover_impl((C v D), B, Vs, [(C->B), (D->B) /Vs]) :- !.  
iprover_impl((C<->D), B, Vs, [( (C->D) -> ( (D->C) ->B) ) /Vs]) :- !.  
iprover_impl(A, B, Vs, [B/Vs]) :- memberchk(A, Vs) .
```

- Classical Logic “for free”, via Glivenko’s theorem:

```
cprover(T) :- iprover(~ ~T) .
```



Examples

```
?- iprover(p v ~p).  
false.
```

```
?- cprover(p v ~p).  
true.
```

```
?- iprover(~ ~ ~ p <-> ~ p).  
true.
```

```
?- iprover(~ ~ p <-> p).  
false.
```

```
?- cprover(~ ~ p <-> p).  
true.
```

```
?- iprover( (h<-b<-c<-d) <-> (h<-b&c&d) ).  
true.
```

A simple Prolog-based Neuro-symbolic Computing Technique

On training Neural Networks as Theorem Provers

- we have used Prolog to derive a generator for lambda terms and their types
- we can generate a dataset for training neural networks, turning them into reliable theorem provers, for the **harder inverse problem**: given a formula implicational subset of IPC, find a proof term for it!
- an easier problem: restrict to the linear subset of implicational IPC
- **open problems, future work:**
 - can this be extended to full fragments of IPC or LL?
 - would the similar success rates apply to large, random generated formulas?
 - how would the NNs perform on larger, human-made formulas?

Machine Learning (ML) with Deep Neural Networks (NNs)

- the key ML concepts to watch for:
 - “honesty”: split the dataset into: **training**, **validation** and (independent) **test** sets
 - things to avoid:
 - overfitting (works on training, fails on validation and testing data)
 - unlikely to work well on random (high Kolmogorov complexity) data
- the key NN general concepts to watch for:
 - NNs are *trainable universal approximators* for a given function
 - $L_{t+1} = \sigma(A * L_t + b)$ where L_t is a layer at step t , A is a matrix containing trainable parameters, b is a bias vector and σ is a non-linear function (logistic sigmoid, tanh, $\text{RELU}(x)=\max(0,x)$, etc.)
 - differentiable functions, gradients computed on backpropagation
 - an intuition behind why deep NNs are needed: each layer abstracts away statistically relevant patterns that are fed to the next layer
 - often, to ensure generalization, information is deliberately lost

Training the Neural Networks as Theorem Provers via the Curry-Howard Isomorphism

- formulas/types and proofs/lambda terms are both trees
- ⇒ we can represent them as prefix strings
- what type of neural networks to use?
 - with trees as prefix string: ⇒ “seq2seq” recurrent NNs
 - LSTM (long short term memory) NNs : good to handle long distance dependencies in the prefix forms
 - transformers might be better, but they need very large amounts of data and heavy GPU training
- an interesting special case: linear implication with theorems corresponding to lambda terms in which every binder binds exactly one variable
- “ \rightarrow ” becomes “ \circ ” (the “lollipop”)

Formulas depicted as trees, together with their proof terms

formula:



$\lambda X. \lambda Y. (Y X)$



formula:



$\lambda X. X$



seq2seq Neural Networks

- sequence as input, train to guess sequence as output
- used originally for translation of natural languages, with training on large parallel corpora
- notable alternatives: *transformers*, trained to predict masked words in a sentence as well as predict next sentence in a text
- unsupervised* - just feeding them very large text data
- examples: BERT, GPT-3 - impressive performance on several NLP tasks (e.g., GPT-3 generating fake news)
- newer variants, possibly more interesting: **tree2tree**, **dag2dag** and several types of **graph neural networks** (e.g., convolutional, attention, spectral, torch geometric)

LSTM seq2seq Neural Networks

- recurrent neural networks keep track of dependencies within sequences
- feedback from values at time t is fed into computations at time $t + 1$
- long short-term memory (LSTM) is a recurrent neural network (RNN) architecture
- it can not only process single data points (such as images), but also entire sequences of data (such as text, speech or video)
- LSTM NNs have feedback connections \Rightarrow LSTM avoids vanishing or exploding gradient problems by also feeding *unchanged* values to the next layer

Evaluating the Performance of our Neural Networks as Theorem Provers

- the experiments with training the neural networks using the linear and intuitionistic theorem dataset are available at:
<https://github.com/ptarau/neuralgs>
- the $\langle formula, proof\ term \rangle$ generators are available at:
<https://github.com/ptarau/TypesAndProofs>
- the generated datasets are available at:
<http://www.cse.unt.edu/~tarau/datasets/>

next, we will illustrate with some plots that our seq2seq LSTM recurrent neural network trained on encodings of theorems and their proof-terms performs unusually well

Accuracy of the LSTM seq2seq neural network on our formula/proof term dataset for the linear logic subset

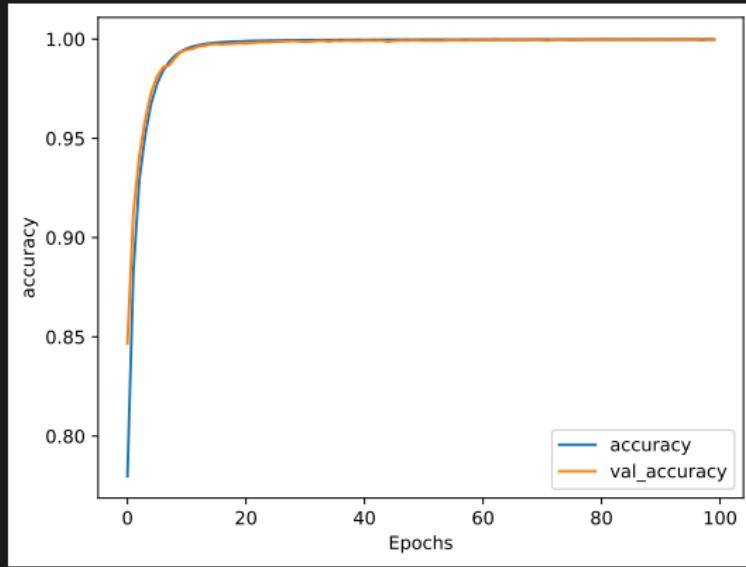


Figure: Accuracy curve for 100 epochs

Loss curve of the LSTM seq2seq neural network on our formula/proof term dataset for the linear logic subset

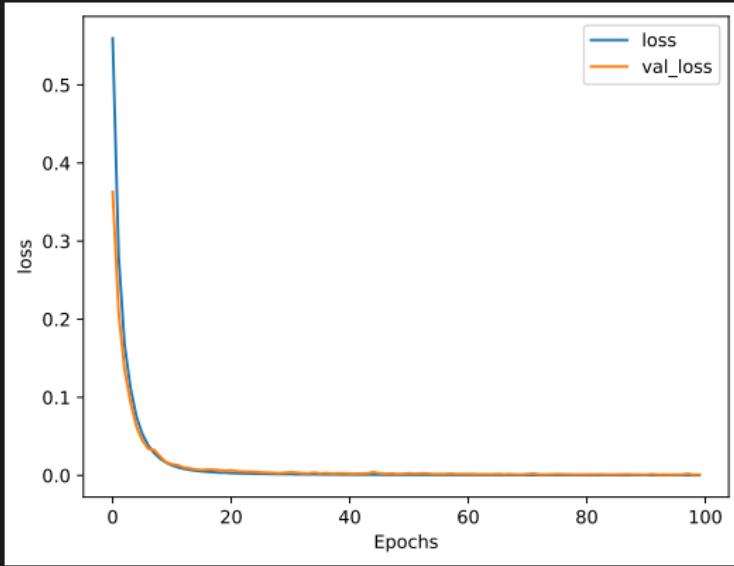


Figure: Loss curve for 100 epochs

Accuracy for linear subset + unprovable formulas

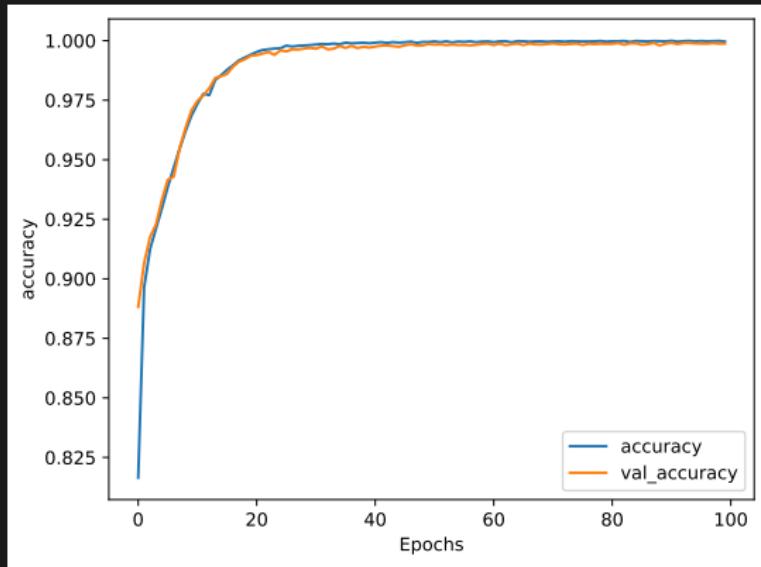


Figure: Accuracy curve for 100 epochs

Loss for linear subset + unprovable formulas

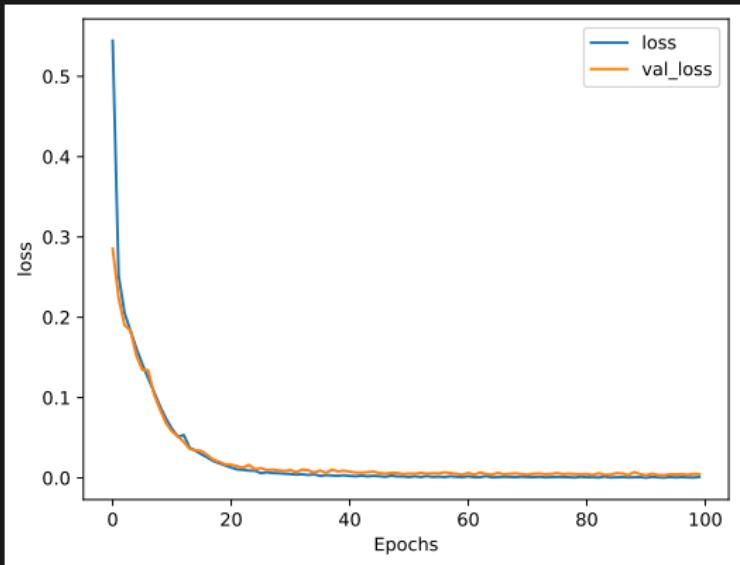


Figure: Loss curve for 100 epochs

Can we train Neural Network as
Provers for a PSPACE-complete
Logic?

Accuracy for implicational IPC

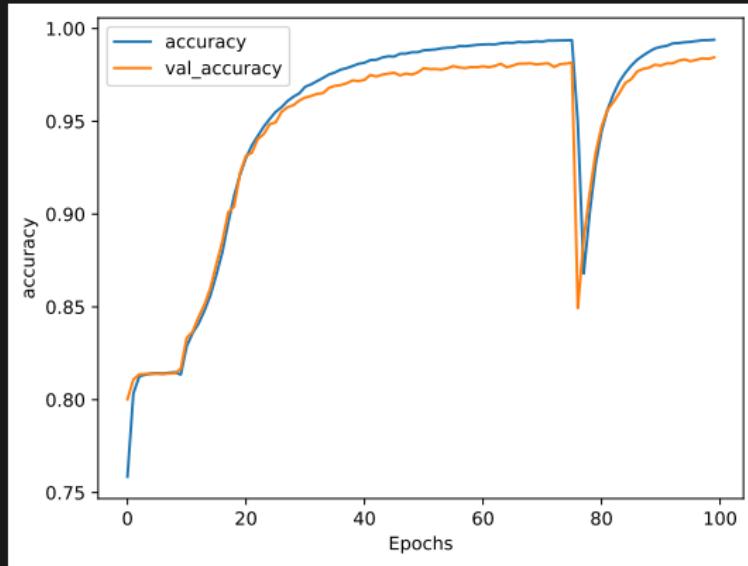


Figure: Accuracy curve for 100 epochs

Loss for implicational IPC

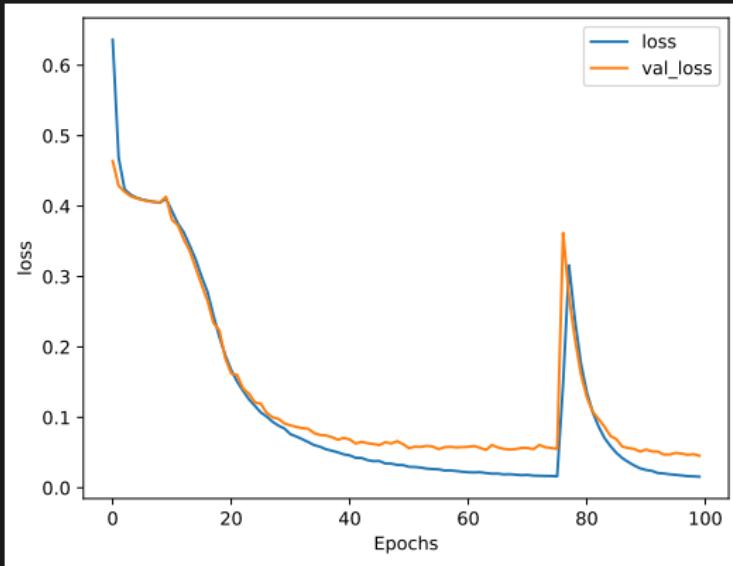


Figure: Loss curve for 100 epochs

Conclusions and Suggestions for Next Learning Steps

- we have overviewed some key strengths of Prolog with focus on problem solving while staying close to its pure, Horn Clause logic kernel
- a highlight: by starting from a two line meta-interpreter, we have captured the necessary step-by-step transformations that one needs to implement in a procedural language that mimics it
- suggested further explorations:
 - constraint solving extensions
 - tabling and its uses for elegant dynamic programming algorithms
 - probabilistic logic programming
- hot research topic: **neuro-symbolic** extensions to Prolog and synergies with ML in general and NLP in particular

Some Key Prolog Resources

- Marius Triska's excellent online Prolog book
<https://www.metalevel.at/prolog>
- The Art of Prolog, a great classic Prolog book: http://cliplab.org/~logalg/doc/The_Art_of_Prolog.pdf
- SWI-Prolog's excellent eco-system of libraries and extensions
<https://www.swi-prolog.org/>
- a solid, industrial strength commercial system:
<https://sicstus.sics.se/>
- some nice, open source Prolog Systems
 - Ciao Prolog: <https://ciao-lang.org/>
 - XSB Prolog: <http://xsb.sourceforge.net/>
 - ECLIPSe Prolog + CP system: <https://eclipseclp.org/>
 - GNU Prolog: <http://www.gprolog.org/>
- and much more: <https://en.wikipedia.org/wiki/Prolog>

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Questions?