



Logic Programming and Prolog

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Slides at <https://github.com/mvolkmann/talks/>

Thanks!

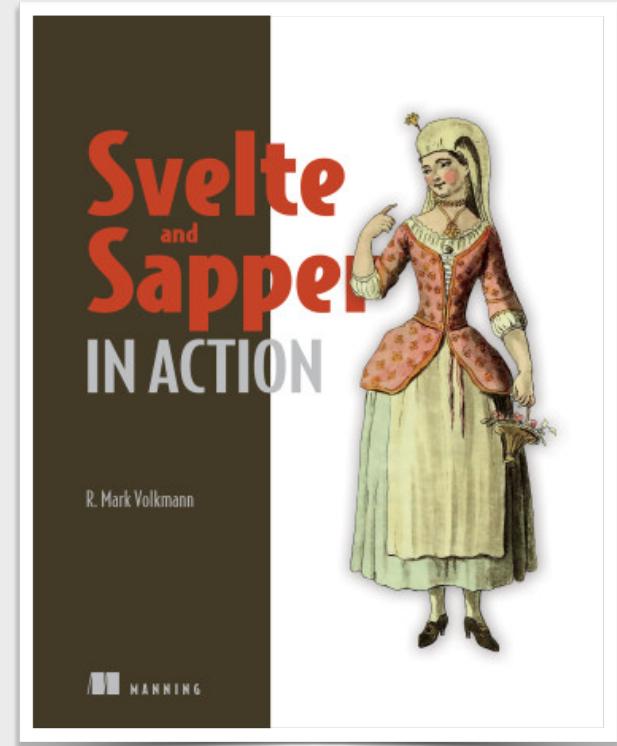
- Many thanks to **Dr. Markus Triska** for taking the time to provide detailed answers to my many questions
- Professor at Vienna University of Technology, Austria
 - Vienna Center for Logic and Algorithms (VCLA)
- <https://www.metalevel.at/>
- **The Power of Prolog**
 - <https://www.metalevel.at/prolog>
- **The Power of Prolog: Videos**
 - <https://www.metalevel.at/prolog/videos/>



About Me



- Partner and Distinguished Software Engineer at Object Computing, Inc. in St. Louis, Missouri USA
- 43 years of professional software development experience
- Writer and teacher
- Blog at <https://mvolkmann.github.io/blog/>
- Author of Manning book “Svelte ... in Action”



Logic Programming



- Very different from imperative, functional, and object-oriented programming
- Focuses on describing **what** is true, not **how** to do something
- Examples include **Prolog**, **Datalog**, **Logtalk**, and **Answer Set Programming** (ASP)
- Use cases
 - explainable AI (as opposed to approaches like neural networks), Natural Language Processing (NLP), parsing, problem solving, rule-based systems, and more

Datalog and Logtalk
are based on Prolog.

NLP includes automatic translation from one human language to another. It also includes translating human language to direct a computer and possibly generate a human language response (ex. Alexa and Siri).

Prolog Overview

- Name is contraction of “Programming in Logic”
- Provides a search engine over facts and rules
- Initially developed by Alain Colmerauer and Philippe Roussel in 1972
- Two dialects
 - Edinburgh Prolog - 1972
 - ISO Prolog - 1995
- Many current implementations strive to conform to the ISO standard, but also add features



Popular Implementations

- **Scryer Prolog** - <https://www.scryer.pl/>
 - implemented in Rust (64%) and Prolog (36%)
- **SICStus Prolog** - <https://sicstus.sics.se/>
 - high-performance, commercial implementation
- **GNU Prolog** - <http://www.gprolog.org/>
 - implemented in C (84%) and Prolog (15%)
- **SWI-Prolog** - <https://www.swi-prolog.org/>
 - implemented in C (48%) and Prolog (39%)
- **Ciao** - <https://ciao-lang.org>
 - implemented in Prolog (72%) and C (23%)
- **Tau Prolog** - <http://tau-prolog.org/>
 - implemented in JavaScript (95%) and Prolog (5%)



Scryer Prolog places all non-ISO predicates in libraries that must be explicitly included.



There are MANY MORE implementations!

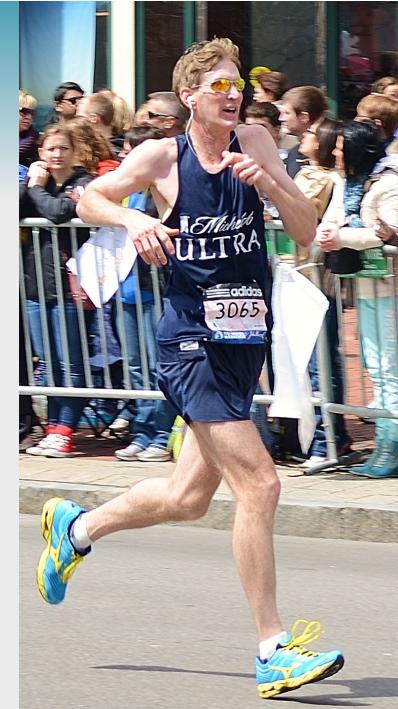
Why Challenging?

- Different way of thinking
- Lots of terminology to learn
- Large number of built-in predicates and operators
 - learning and becoming proficient takes a considerable amount of practice
- Many implementations to choose from
 - choose one that conforms to ISO standard
 - use standard features for more portability



Running

- Can feed a Prolog source file to a command-line tool that typically provides a “**top level**” (REPL) where compiler directives and queries can be entered
 - in Scryer Prolog, enter `scry [file-name.pl]` `scry` is an alias you can define
 - to load source file into top level, enter `[f].` or `consult(f).` `f` is file name or file path in quotes
 - to reload a source file after modifying it, load again
 - in SWI-Prolog, can enter `make.` to reload all loaded source files
 - enter queries terminated by a period
 - to exit, press `ctrl-d` or enter `halt.`
- Can compile to abstract machine code and execute in a virtual machine
 - many implementations use the Warren Abstract Machine (WAM) instruction set



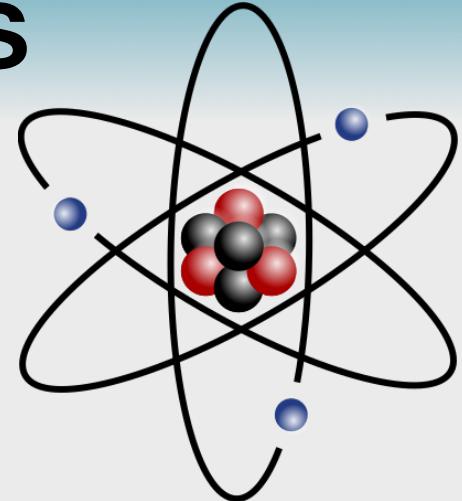
Comments

- Single-line comments
 - begin with % and extend to end of line
- Multi-line comments
 - surrounded by /* and */



Atoms and Variables

- **Atoms** - symbols treated like string constants
 - start with lowercase letter **OR** any text wrapped in single quotes
 - ex. `a`, `apple`, or `'I like apples!'` (not typically used)
- **Variables** - represent a value to be determined
 - start with uppercase letter or underscore (ex. `Fruit` or `_fruit`)
 - often a single letter or followed by `s` for plural (ex. `c` or `cs`)
when meaning is clear from context



Predicates: Facts and Rules

- **Facts** state things that are always true (hold)

```
female(amanda).  
female(tami).  
  
male(clarence).  
male(jeremy).  
male(mark).  
male(richard).  
  
father(clarence, tami).  
father(richard, mark).  
father(mark, amanda).  
father(mark, jeremy).  
  
mother(tami, amanda).  
mother(tami, jeremy).
```

Each line here is a “clause”.

Functor names are `female`, `male`, `father`, `mother`, and `grandfather`.

Functor names are usually followed by a list of **arguments** in parentheses.

Facts, rules, and queries all **end with a period**.

A functor name is also referred to as a “**principal functor**”.

- **Rules** state things that are conditionally true
- **Rules** have a head and body separated by `:-` read as “if”
- **Rules** “relate” their LHS to RHS

```
grandfather(X, Y) :-  
    male(X),  
    father(X, Z),  
    (father(Z, Y); mother(Z, Y)).
```

Comma operator forms a **conjunction** and is read as “and”.
Semicolon operator forms a **disjunction** and is read as “or”.

Facts can be written as rules that have the body `:- true`.

Queries - aka Questions

- Use to **test**, **complete**, or **generate** solutions
 - referred to as “working in multiple directions” or having “multiple usage modes”

```
% Test
?- grandfather(clarence, amanda).
true.

?- grandfather(mark, jeremy).
false.

% Complete
?- grandfather(X, jeremy).
X = clarence ;
X = richard ;
false. ← means no more
          solutions were found
?- grandfather(richard, X).
X = amanda ;
X = jeremy ;
false. ←
```

```
% Generate
?- grandfather(X, Y).
X = clarence,
Y = amanda ;
X = clarence,
Y = jeremy ;
X = richard,
Y = amanda ;
X = richard,
Y = jeremy ;
false.
```

Solutions are generated **lazily**, one at a time.
Press **semicolon** key or **spacebar** to see next solution.
Press **period** key to stop searching.



Unification

- Process of finding variable values that cause goals to hold
 - can use = and #= operator

`#=` is a CLP operator

`x = 7` is unification not assignment; `7 = x` is the same

`x #= y * 2, y in 1..5, label([x, y]).` `y * 2 #= x` is same
 - can use single predicate with variables
 - ex. `grandfather(X, Y)`
 - can use conjunction of predicates with variables
 - ex. `grandfather(X, jeremy), father(X, Y)`
 - finds `X = clarence, Y = tami` and `X = richard, Y = mark`
- Default search strategy is “depth-first with chronological backtracking”



Yu-Gi-Oh! card

Choicepoints

- Occur when multiple clauses of a predicate match
 - ex. `mother(tami, Child)` matches multiple values for `Child`
- Prolog selects first match, marks it as a choicepoint, and continues evaluating subsequent goals
- After finding a solution or failing to find a solution, if there are remaining clauses to select then Prolog **backtracks**
 - changes choicepoint to next matching clause after current choicepoint
 - evaluates subsequent goals using that selection



Characteristics of Good Rules

- Finds all valid solutions and does not find any invalid solutions
- Always terminates when there is not an infinite number of solutions
- Never leaves choicepoints after last solution is found
 - recognizes when last solution is found
- Supports “most general query”
 - means invoking with all arguments being variables
 - generates solutions

Pure Monotonic Core

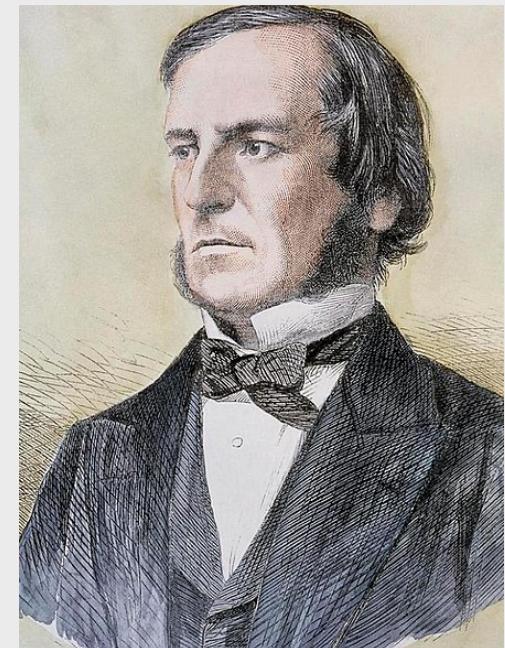
- When first learning Prolog it is recommended to only use parts that are
 - **pure**
 - no side-effects like mutating data or performing I/O
 - no extra-logical predicates
 - **monotonic**
 - adding constraints or conjunctions to a rule can only decrease possible solutions
 - adding clauses or disjunctions can only increase possible solutions
- **Goal** is to deeply learn about
 - **termination** - don't search forever when there are a finite number of solutions
 - **choicepoints** - recognize when last solution has been found
 - supporting **most general queries** - all arguments are variables

The definition of which parts
are in the pure monotonic core
is a little fuzzy.



Primitive Types ...

- **Boolean**
 - represented by built-in predicates `true` and `false`
- **Number**
 - supports integers and floating point numbers, optionally using exponential notation



George Boole
creator of Boolean Algebra

... Primitive Types



- **String**

- three representations: atom, list of character atoms, or list of ASCII codes
- delimiters
 - **single quotes** -> atom
 - **double quotes** -> depends on `double_quotes` compiler flag

use list predicates to operate on these lists

- **atom**: "apple" becomes atom `apple`
- **chars**: "apple" becomes list of character atoms `[a,p,p,l,e]` recommended setting;
default in Scryer Prolog
- **codes**: "apple" becomes list of ASCII codes `[97,112,122,108,101]`
- **string**: "apple" remains string "apple" (SWI-Prolog-only) non-standard
- **backticks** -> list of ASCII codes (SWI-Prolog-only) non-standard

Structure

- Named collection of values
 - ex.

```
fruit(apple, red)
fruit(banana, yellow)
```
 - can think of **fruit** as the structure type

- Can nest

- ex.

```
person(
    name("Mark", "Volkmann"),
    address(
        "123 Some Street",
        "Somewhere", "MO", 12345
    )
)
```

Collections - List

- List of values of any type inside square brackets
 - example: `Fruits = [apple, banana, cherry]`
- Can **destructure** into head and tail
 - using = operator
`[H|T] = Fruits`
 - in rule argument
`write_all([]).`
`write_all([H|T]) :- write(H), nl, write_all(T).`
- Some implementations place list predicates in a **module**
 - `:- use_module(library(lists)).`



List append

- **append** is a built-in predicate, but we could write it
- Note all the usage modes



```
% Appending an empty list to  
% any list gives the second list.  
append([], L, L).  
  
% Appending two lists is the same as  
% appending head of first list (H)  
% to result of  
% appending tail of first list (L1)  
% to second list (L2).  
append([H|L1], L2, [H|L3]) :-  
    append(L1, L2, L3).
```

```
% Is the result of appending  
% two lists a given result list?  
?- append([1, 2], [3, 4], [1, 2, 3, 4]).  
true.  
  
% What is the result of  
% appending two lists?  
?- append([1, 2], [3, 4], X).  
X = [1, 2, 3, 4].  
  
% What list must be appended to a  
% given list to obtain a given result?  
?- append([1, 2], X, [1, 2, 3, 4]).  
X = [3, 4].  
  
% What list must be prepended to a  
% given list to obtain a given result?  
?- append(X, [3, 4], [1, 2, 3, 4]).  
X = [1, 2]
```

```
% What lists can be appended  
% to obtain a given result?  
?- append(X, Y, [1, 2, 3, 4]).  
X = [],  
Y = [1, 2, 3, 4] ;  
X = [1],  
Y = [2, 3, 4] ;  
X = [1, 2],  
Y = [3, 4] ;  
X = [1, 2, 3],  
Y = [4] ;  
X = [1, 2, 3, 4],  
Y = [] ;  
false.
```

More Built-in List Predicates



- **findall** - collects all solutions in a list
- **foldl** - like **reduce** in JavaScript
- **length** - relates a list to its length
- **list_max** and **list_min**
- **maplist** - like **map** in JavaScript
- **member** - like **includes** in JavaScript
- **nth0** and **nth1** - relates an index to corresponding list element
- **reverse** - relates a list to its reverse
- **select** - relates a list to another with first instance of an element removed
- **sort** - relates a list to a sorted version
- **sum_list** - relates a list of numbers to its sum

Meta-predicates are predicates that take another as an argument.
Examples include **foldl** and **maplist**.

```
findall(X, grandfather(richard, X), L).  
% L = [amanda, jeremy]  
  
add(A, B, C) :- C #= A + B.  
foldl(add, Numbers, 0, Sum). % Sum = 6  
  
length(Numbers, Len). % Len = 3  
  
list_max(Numbers, Max). % Max = 3  
  
list_min(Numbers, Min). % Min = 1  
  
Fruits = ["apple", "banana", "cherry"],  
maplist(length, Fruits, Ls). % Ls = [5, 6, 6]  
  
nth0(1, Fruits, E). % E = "banana"  
Indexes start from zero.  
To start from one, use nth1.  
  
reverse(Numbers, R). % R = [3, 2, 1]  
  
select(2, Numbers, L). % L = [1, 3]  
  
sort([foo, bar, baz], Sorted). % Sorted = [bar, baz, foo]  
  
sum_list(Numbers, Sum). % Sum = 6
```

Also see **memberd_t**, **tfilter** and **tpartition** predicates in **reif** library.

Collections - Pair



- Key and value separated by a dash
- **pairs** library provides predicates that operate on pairs

```
:-
    :- use_module(library(pairs)) .
```

list of pairs

```

pairs_keys([a-apple, b-banana, c-cherry], Ks) .
% Ks = [a, b, c]).
```

```

pairs_values([a-apple, b-banana, c-cherry], Vs) .
% Vs = [apple, banana, cherry]).
```

```

pairs_keys_values([a-apple, b-banana, c-cherry], Ks, Vs) .
% Ks = [a, b, c]), Vs = [apple, banana, cherry]).
```

```

% The pairs must be sorted on their keys.
```

```

group_pairs_by_key([a-apple, a-ape, b-banana, b-bear], Gs) .
% Gs = [a-[apple,ape], b-[banana,bear]]).
```

```

first_letter(Atom, Letter) :- atom_chars(Atom, [Letter|_]) .
```

```

map_list_to_pairs(first_letter, [apple, banana, cherry], Ps) .
% Ps = [a-apple, b-banana, c-cherry]).
```



ASSOC

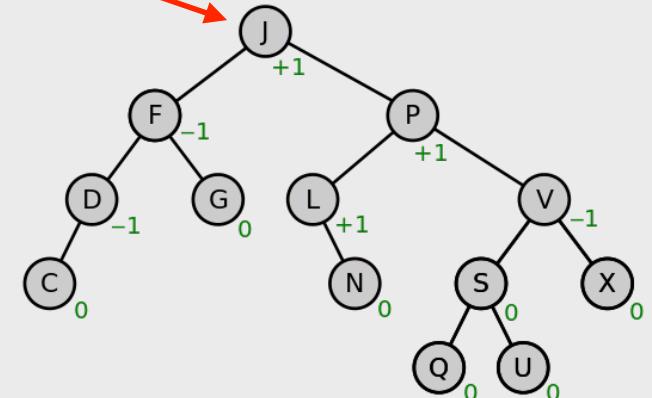


- Key/value pairs implemented as an AVL tree (balanced, binary) hash map alternative
- Supported by **assoc** library, not ISO standard
 - <https://www.scryer.pl/assoc.html>
- Highlights

```
:- use_module(library(assoc)).  
  
demo :-  
    empty_assoc(A0),  
    put_assoc(name, A0, 'Mark', A1),  
    get_assoc(name, A1, Name),  
    write(Name), nl, % Mark  
    del_assoc(name, A1, _, A2). % A2 does not contain name key.
```

It is a convention to end variable names that represent an **initial state** with zero.

The third argument can be a variable that gets set to value of key/value pair that is deleted.



The green numbers below each node are **balance factors** which are used to keep the tree balanced. They represent the depth of the right subtree minus the depth of the left subtree.

More Terminology

- **term** - a number, atom, variable, or compound term
- **compound term** - combination of basic terms (aka **structure**); arguments can be compound terms to nest them
- **goal** - compound term that appears in a rule body or query
- **clause** - a single fact or rule
- **predicate** - defined by collection of clauses (logical alternatives) that all have same **principal functor** (name)
- **knowledge base** - collection of facts and rules (aka database)



Predicate Names

- Should **describe a relationship rather than an imperative action** and **indicate the arguments they take and their order**

- Example

- using the name `sort` for a predicate that can generate a sorted list from an unsorted one is imperative and does not describe its arguments
 - better name is `listAscending` because it

- indicates there are two arguments
 - indicates order of arguments which is unsorted list followed by sorted list
 - does not favor a specific direction

Built-in predicate examples include
`atom_chars`, `atom_codes`,
`atom_length`, `atom_prefix`,
`number_chars`, and `number_codes`

- Only predicates with side effects should have imperative names

- ex. producing output

Built-in predicate examples include
`asserta`, `assertz`,
`retract`, `retractall`, `write`,
`write_canonical`, and `write_term`



Help

- In SWI-Prolog
 - for basic help on all predicates that contain given text in their name or description, enter `apropos (text)` .
 - for more detailed help on a specific predicate, enter `help (name)` .
 - for listing of all defined predicates, enter `listing` .
 - for listing of clauses for a given predicate name, enter `listing (name)` .



Functors

- Way to refer to a predicate using its **functor name** and **arity** (number of arguments) separated by a slash
- For example, earlier we saw these functors
 - `female/1`
 - `male/1`
 - `father/2`
 - `mother/2`
 - `grandfather/2`
- Functors often appear in documentation and error messages



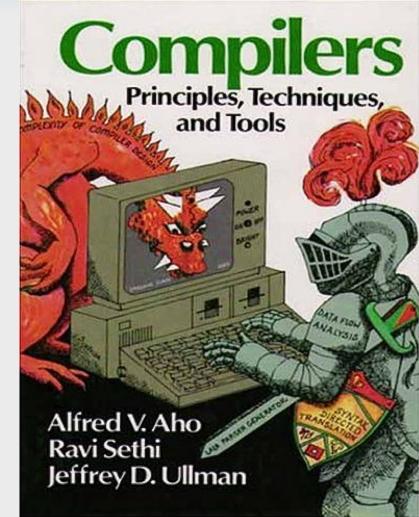
Supported Notations

- **Function notation:** `functor-name(arg1, arg2)`
 - ex. `father(F, jeremy)`
 - **List notation:** `[element1, element2, element3]`
 - shorthand for using period functor (aka list constructor)
 - ex. `.(element1, .(element2, .(element3, [])))`
 - **Operator notation**
 - operators can be prefix, infix, or postfix
 - common arithmetic operators are infix
 - ex. `y = 3, x is Y * 2.` is same as `y = 3, x is *(Y, 2).`
- custom operators
can be defined
- operator notation
- function notation

Compiler Directives



- Several uses, all starting with :- prefix operator
- **Set flag** that tells compiler to interpret code differently
 - ex. :- `set_prolog_flag(double_quotes, chars).`
- **Include another source file**
 - ex. :- `include(util).` includes contents of file `util.pl`
- **Import a library**, making its predicates and operators available
 - ex. :- `use_module(library(name)).`
- **Evaluate goals when file is loaded**
 - ex. :- `initialization(some-goal)`



Debugging Options



- Experiment with predicates in top level
- Write unit tests
- Step through each goal evaluation
 - enter `trace`.
 - enter a query
 - press spacebar after each output
- Use `format` predicate for print-style debugging
 - ex. `format('~w has ~w points.~n', [Name, Score]).`
 - remember [] around values!
 - many more supported placeholders, but `~w` and `~n` are most common

Unit Tests

- SWI-Prolog supports unit tests
- Convention is to use `.plt` file extension
- Run with `swipl family-name.plt`

I wrote my own light-weight test library that works with Scryer Prolog at https://github.com/mvolkmann/prolog-modules/blob/main/unit_test.pl. See example `.plt` files in the same repository.

```
family.pl
facts omitted

grandfather(X, Y) :-  
    male(X),  
    father(X, Z),  
    (father(Z, Y); mother(Z, Y)).  
  
is_father(X) :- father(X, _).  
  
is_mother(X) :- mother(X, _).  
  
is_son(X) :- male(X), (father(_, X); mother(_, X)).  
  
sibling(X, Y) :-  
    dif(X, Y), % can't be sibling of self  
    father(F, X), father(F, Y),  
    mother(M, X), mother(M, Y).  
  
sister(X, Y) :-  
    dif(X, Y), % can't be sister of self  
    female(X), sibling(X, Y).
```



```
family.plt
:- consult(family).
:- begin_tests(family).

test(grandfather) :-
    grandfather(clarence, jeremy),
    grandfather(clarence, amanda),
    grandfather(richard, jeremy),
    grandfather(richard, amanda), !.

test(is_father) :-
    is_father(clarence),
    is_father(richard),
    is_father(mark), !.

test(is_mother) :-
    is_mother(gerri),
    is_mother(judi),
    is_mother(tami), !.

test(is_son) :-
    is_son(jeremy),
    is_son(mark), !.

test(sibling) :-
    sibling(amanda, jeremy).

test(sister) :-
    sister(amanda, jeremy),
    \+ sister(amanda, amanda).

:- end_tests(family).
:- run_tests.
:- halt.
```

Cuts prevent warning "Test succeeded with choicepoint".

Knowledge Base Changes ...



- Can modify knowledge base clauses
- To **enable changes** to a given functor, use **dynamic (functor)**
ex. `dynamic(father/2).`
- To add a clause **before** all for same functor, use **asserta (clause)**
ex. `asserta(father(richard, laura)).`
- To add a clause **after** all for same functor, use **assertz (clause)**
ex. `assertz(father(richard, pam)).`
- To **remove** a clause, use **retract (clause)**
ex. `retract(father(richard, mark)).`
- To **remove all** clauses for a functor, use **retractall (head)**
ex. `retractall(father(richard, _)).`

To change knowledge base from top level, an alternative is to enter `[user] .`, enter clauses, and press `ctrl-d` to return to top level.



... Knowledge Base Changes

```

fruit(apple).
fruit(banana).

person_height(mark, 74).
person_height(tami, 65).

tall(N) :-
    person_height(N, H),
    H >= 72.

add_predicates :-
    % Dynamically add a fruit fact.
    dynamic(fruit/1),
    assertz(fruit(cherry)),

    % Dynamically add a tall fact.
    dynamic(tall/1),
    assertz(tall(giraffe)),

    % Dynamically add a rule.
    dynamic(sum/3),
    assertz(sum(X, Y, Z) :- Z is X + Y).

```

Rules succeed or fail.
They do not return a value.

There is no reason to add this particular rule dynamically, but this demonstrates that it is possible.

```

report(Thing) :-
    ( tall(Thing) ->
        report_(Thing, 'tall')
    ; report_(Thing, 'not tall')
    ).

```

Auxiliary rule names often end in an underscore by convention.

```

report_(Thing, X) :-
    format('~w is ~w.~n', [Thing, X]).

```

```

:- initialization(
    add_predicates,

```

```

    findall(F, fruit(F), Fruits),
    write(Fruits), nl,

```

[apple,banana,cherry]

findall gathers all solutions into a list

```

Things = [mark, tami, giraffe],
maplist(report, Things),

```

mark is tall.
tami is not tall.
giraffe is tall.

```

sum(2, 3, S),
write(S), nl,
halt.

```

Input



- By default, input is read from stdin
- Can specify input stream associated with file or network connection
- Stream aliases
 - `user_input` and `current_input` can change default bindings
- Many predicates read input
 - `read(Term)` - reads any Prolog term; user must end with period AND press return
 - `read_term(Term, Options)` - like read, but configurable
 - `read_line_to_string(Stream, S)` - reads any text; user can just press return SWI-Prolog-only
 - `get_line_to_chars(Stream, S)` - similar to above; defined in Scryer `charsio` library Scryer Prolog-only
 - a few others not defined by ISO standard

Output



- By default, output is written to stdout
- Can specify output stream associated with file or network connection
- Stream aliases
 - `user_output`, `user_error`, and `current_output` can change default bindings
- Many predicates write output
 - `write(Term)` - writes a Prolog term
 - `nl` - writes a newline character
 - `writeln(Term)` - combines `write` and `nl`; SWI-Prolog-only
 - `format(Format, Arguments)` - `format('~w, ~w!~n', ['Hello', 'World'])`
 - and a few more



Many placeholders other than `~w` and `~n` are supported, but these are the most useful.

Constraint Logic Programming (CLP)



- Uses constraint propagation to solve problems in specific domains
- Different library for each supported domain
 - integers (`clpfd`) in Scryer Prolog, use `clpz` library
 - booleans (`clpb`)
 - rational numbers (`clpq`)
 - floating point numbers (`clpr`)
- Each library provides additional Prolog operators and predicates
- Include with directive like

```
: - use_module(library(clpfd)).
```



CLP Operators

- CLP operators include
 - equal #=, not equal #\=
 - greater #>, greater or equal #>=
 - less #<, less or equal #=<
 - **in** (single value), **ins** (list of values) constrain variables to a given range
- CLP operators support multiple usage modes
 - for example, with **is** operator, RHS variables must be instantiated
 - #= operator does not have this restriction

```
N = 3, N in 1..5. % N = 3 (success)
L = [2, 4, 7], L ins 1..5. % false
```

```
add1(A, B, C) :- C is A + B.
```

```
add2(A, B, C) :- C #= A + B.
```



CLP Predicate Highlights

There are many more CLP predicates not described here.

- Enumeration
 - `labeling` and `label` (examples on next slide)
 - `label` is the same as `labeling` with no options
- Constraint predicates
 - `all_distinct` - all elements in a list have distinct values

```
L = [2, 4, 2],  
all_distinct(L). % false
```

- `global_cardinality` - relates a list to a list of pairs
 - in each pair, the key is a value from the list and its value is a count
 - both arguments must be instantiated

```
vs = [2, 4, 2, 3, 2, 4],  
global_cardinality(vs, [2-3, 3-1, 4-2]). % true
```

CLP Labeling



- Finds concrete solutions for abstract solutions

```
x in 5..10, Y in 7..14, X #> Y.  
% Without labeling, this outputs the following  
% without giving specific values for X and Y.  
% X in 8..10,  
% Y in 7..9  
  
x in 5..10, Y in 7..14, X #> Y., label([X, Y]).  
% With labeling, this gives  
% specific combinations of X and Y values.  
% X = 8, Y = 7 ;  
% X = 9, Y = 7 ;  
% X = 9, Y = 8 ;  
% X = 10, Y = 7 ;  
% X = 10, Y = 8 ;  
% X = 10, Y = 9.
```



Definite Clause Grammar (DCG)

- Set of grammar rules of form **GRHead** --> **GRBody**
- Not yet part of ISO standard, but may be added
- Enabled with `:– use_module(library(dcgs)).`
 - enabled by default in SWI-Prolog
- Name in head typically describes allowed sequences
- Body uses
 - , operator for concatenation - read as “and then” or “followed by”
 - | operator for alternatives - read as “or”
 - { *prolog-predicates* } - switches from DCG syntax to standard Prolog syntax and can set variables used in containing DCG rule

DCGs in Scryer Prolog

- Parse lines like “Player Gretzky wears number 99.”
- Extract player name and number

```
player(Name, Number) -->
  "Player ",
  seq(Name),
  " wears number ",
  % seq(Number),
  integer(Number),
  ". ".
```

gets Number
as a string

```
?- once(phrase(
  player(Name, Number),
  "Player Gretzky wears number 99."
)).
Name = "Gretzky", Number = 99
```

once stops searching
after first solution is found

```
% This matches any single digit.
digit(D) --> [D], { char_type(D, decimal_digit) }.

% This matches any non-empty list of digits.
digits([D|Ds]) --> digit(D), digits_(Ds).

% This matches any list of digits including an empty list.
digits_([D|Ds]) --> digit(D), digits_(Ds).
digits_([]) --> [].

% This matches any non-empty list of digits
% AND converts it to an integer.
integer(I) --> digits(Ds), { number_chars(I, Ds) }.
```

DCG rule bodies contain lists, DCG operators, and DCG predicates like **seq**.

seq, **seqq**, and ... are defined in the Scryer library **dcg**.
char_type is defined in the Scryer library **charsio**.

Unfair Enumeration

- Some queries have an infinite number of solutions
- In an unfair enumeration there are solutions that will never be output
- The **length** predicate can be used to advance multiple parts of a DCG rule body together rather than one at a time
 - called “**iterative deepening**”
- Example

```
as --> "a", as_.
as_ --> [] | as.

bs --> "b", bs_.
bs_ --> [] | bs.

as_and_bs --> as, bs.
```

```
?- phrase(as_and_bs, Cs).
   Cs = "ab"
;  Cs = "abb"
;  Cs = "abbb"
% and more!
```

will never output
solutions beginning
with more than one a

```
?- length(Cs, _), phrase(as_and_bs, Cs).
   Cs = "ab"
;  Cs = "abb"
;  Cs = "aab"
;  Cs = "abbb"
;  Cs = "aabb"
;  Cs = "aaab"
;  Cs = "abbbb"
% and more!
```

outputs all solutions
of a given length
before outputting
solutions with the
next larger length

Jugs Problem ...

- Have three jugs labeled **a**, **b**, and **c** with capacities 4, 3, and 7
- Start with **a** empty, **b** empty, and **c** full
- Can pour water from any non-empty jug to any non-full jug
- When we do, we must pour as much as possible
- Goal: find sequence of pours that result in a jug containing exactly 2 units
- **jug** structure arguments are label, capacity, and current level
- **from_to** structure arguments are from and to jug labels (a, b, and c)
- Solution is list of **from_to** structures



Die Hard With A Vengeance

Solution requires 4 moves.
Starting state is 0, 0, 7.
Pour from c to b. 0, 3, 4
Pour from b to a. 3, 0, 4
Pour from c to b. 3, 3, 1
Pour from b to a. 4, **2**, 1

... Jugs Problem

```

:- use_module(library(clpz)).
:- use_module(library(dcgs)).
:- use_module(library(format)).
:- use module(library(lists)).

```

Jugs is a list of three jug structures.
A solution has been found when any jug contains 2 units.

```
pours(Jugs) --> { member(jug(_, _, 2), Jugs) }.
```

```
pours(Jugs0) --> [from_to(From, To)],
```

Jugs0 is a list of three jug structures in no particular order.
This generates a list of from_to structures that describe a solution.

```
{
  select(jug(From, FromCapacity, FromFill0), Jugs0, Jugs1),
  select(jug(To, ToCapacity, ToFill0), Jugs1, Other),
```

% Calculate units that can be moved from From jug to To jug.
Amount #= min(FromFill0, ToCapacity - ToFill0),

% Calculate new amount in From jug.
FromFill #= FromFill0 - Amount,

```
% Calculate new amount in To jug.  
ToFill #= ToFill0 + Amount
},
% Generate a list of more from to structures
% starting from this new state.
pours([
  jug(From, FromCapacity, FromFill),
  jug(To, ToCapacity, ToFill) | Other
]).
```

list containing a single jug structure

The Prolog search engine will try all possible combinations of **From** and **To** values which are a to b, a to c, b to a, b to c, c to a, and c to b.

This finds the jug that is not the **From** or **To** jug by creating a list **Jugs1** that does not contain **From** and then creating another list **other** that does not contain **To**.
Other is used below as the tail of a new list.

This is where pours from a jug to itself are filtered out.
If **From** and **To** are both set to the same jug label then the first **select** will succeed, but the second will fail.

```

print_move(from_to(F, T)) :-  
  format("Pour from ~w to ~w.~n", [F, T]).  
  
:- initialization(  
  length(Moves, _), % for iterative deepening  
  phrase(moves([jug(a,4,0), jug(b,3,0), jug(c,7,7)]), Moves),  
  maplist(print_move, Moves),  
  halt  
).).
```

starting state

DCGs for Compiling

- DCGs can be used to implement a parser for a programming language
- Let's create one that can ...
 - use single-line comments
 - evaluate basic math expressions
 - assign to variables
 - define and call functions that return a value
 - print values
- Variable values are stored in a stack of hash maps
 - top scope and one per current function scope

```
# This function adds two integers.  
fn add(n1, n2)  
    sum = n1 + n2  
    return sum  
end  
  
# This function multiplies two integers.  
fn multiply(n1, n2)  
    return n1 * n2  
end  
  
v = add(2, 3) + multiply(3, 4)  
print v # 17  
  
print add(2, 3) + multiply(3, 4) # 17
```

This is code in my made-up programming language.

code at <https://github.com/mvolkmann/prolog-ast>

Abstract Syntax Tree (AST)

- Nested Prolog structures can be used to represent an AST as a single Prolog term
- DCGs can be used to parse custom syntax and generate such an AST
- A Prolog “compiler” program can parse custom syntax and write AST to a text file on a single line

Key:

- a** = assignment
- c** = function call
- f** = function definition
- k** = constant
- m** = math expression
- p** = print
- pr** = program
- r** = return

```
pr([  
    f(add, [n1,n2], [  
        a(sum, m(+,n1,n2)),  
        r(sum)  
    ]),  
    f(multiply, [n1,n2], [  
        r(m(*,n1,n2))  
    ]),  
    a(v, m(+,  
        c(add,[k(2),k(3)]),  
        c(multiply,[k(3),k(4)])  
    )),  
    p(v),  
    p(m(+,  
        c(add,[k(2),k(3)]),  
        c(multiply,[k(3),k(4)])  
    ))  
]).
```

pr argument is a list of statements
Spaces and newlines were added manually to make this more readable.

DCG AST Generator

```

assign(a(I, V)) --> id(I), ws, "=", ws, value2(V).
comment([]) --> "#", to_eol(_).
constant(k(V)) --> integer(V).
fn_call(c(Name, Args)) --> id(Name), "(", call_args(Args), ")".
fn_def(f(Name, Args, Stmtns)) -->
    "fn ", id(Name), "(", def_args(Args), ")",
    ws, eol,
    statements(Statements), ws, "end".
math(m(Op, V1, V2)) --> value1(V1), ws, operator(Op), ws, value1(V2).
print(p(V)) --> "print", ws, value2(V).
program(pr(Stmtns)) --> statements(Stmtns). ← start here!
return(r(V)) --> "return ", value2(V).

```

highlights of code from
lim_compile_scryer.pl

An important **feature** that is missing in this simple implementation is outputting **good error messages** when the input code contains syntax errors.

```

statement(S) --> assign(S) | comment(S) | fn_call(S) | fn_def(S) | print(S) | return(S).
statement_line([]) --> ws, eol.
statement_line(S) --> ws, statement(S), ws, eol.
statements(Stmtns) -->
    statement_line(S),
    matches when there is only one statement
    % This avoids including empty lists from comments and blank lines.
    { S == [] -> Stmtns = [], Stmtns = [S] }.
statements(Stmtns) -->
    statement_line(S), statements(Ss),
    matches when there are multiple statements
    % This avoids including empty lists from comments and blank lines.
    { S == [] -> Stmtns = Ss; Stmtns = [S|Ss] }.

```

DCG AST Runner

highlights of code from
lim_run_scryer.pl

```
% Skip empty statements from blank lines and comments.
eval([]).

% This assigns a value to a variable.
eval(a(Name, Value)) :- lookup(Value, V), vtables_put(Name, V).

% This calls a function, but does not use its return value.
eval(c(Name, Args)) :- process_call(Name, Args).

% This stores a function definition in the current vtable.
eval(f(Name, Params, Stmtts)) :- vtables_put(Name, [Params, Stmtts]).

% This evaluates all the statements in a program.
eval(pr(Stmtts)) :- maplist(eval, Stmtts). ← start here!

% This prints a value to stdout.
eval(p(Value)) :- lookup(Value, V), write(V), nl.

% This stores a value being returned from a function
% so the caller can find it. See "lookup(c...)" below.
eval(r(Value)) :-
    lookup(Value, V),
    % Store the return value so caller can retrieve it.
    bb_put(return_, V).
```

```
% This calls a function and uses its return value.
lookup(c(Name, Args), V) :-
    process_call(Name, Args),
    bb_get(return_, V).

% This gets the value of a constant.
lookup(k(Value), Value).

% This evaluates a math expression.
lookup(m(Operator, LHS, RHS), Result) :-
    lookup(LHS, L),
    lookup(RHS, R),
    ( Operator == (+) ->
        Result is L + R
    ; Operator == (-) ->
        Result is L - R
    ; Operator == (*) ->
        Result is L * R
    ; Operator == (/) ->
        Result is L / R
    ; write('lookup math: Operator not matched'),
        nl, fail
    ).

% This gets a value from the vtables.
lookup(Name, Value) :- vtables_get(Name, Value).
```

process_call
manages stack of vtables

Sudoku ...

5	3		7					
6		1	9	5				
9	8				6			
8			6			3		
4		8	3			1		
7		2			6			
6				2	8			
	4	1	9			5		
	8			7	9			

Goal is to find numbers such that:

- all cells contain number 1 through 9
- values in each row are unique
- values in each column are unique
- values in each 3x3 block are unique

```

:- use_module(library(clpz)).
:- use_module(library(format)).
:- use_module(library(lists)).

sudoku(Rows) :-
    % Verify that Rows is a list with 9 elements.
    length(Rows, 9),

    % Verify that all elements are lists
    % with the same length as Rows which is 9.
    maplist(same_length(Rows), Rows),

    % Create a flattened list of all the values (Vs),
    % and verify that all elements in Vs
    % are a number in the range 1 to 9.
    append(Rows, Vs), Vs ins 1..9,

    % Verify that all element values in all rows
    % are unique within their row.
    maplist(all_distinct, Rows),

    % Create a list of lists that represent the columns.
    transpose(Rows, Columns),

    % Verify that all element values in all columns
    % are unique within their column.
    maplist(all_distinct, Columns),

    % Assign a variable name to each of the 9 rows.
    [R1, R2, R3, R4, R5, R6, R7, R8, R9] = Rows,

    % Verify that the element values in every 3x3 block
    % are unique within their block.
    blocks(R1, R2, R3),
    blocks(R4, R5, R6),
    blocks(R7, R8, R9).

```





... Sudoku

```
% When a block is empty, its element values
% (which are none) can be considered unique.
blocks([], [], []).

% When a block is not empty, get its 9 values
% and verify that they are unique.
blocks(
    [R1C1,R1C2,R1C3|T1],
    [R2C1,R2C2,R2C3|T2],
    [R3C1,R3C2,R3C3|T3]) :-  

    all_distinct([R1C1, R1C2, R1C3, R2C1, R2C2,
    R2C3, R3C1, R3C2, R3C3]),
    blocks(T1, T2, T3).

% When there are no more rows, stop printing.
print_rows([]).

% When there are more rows, print the first row.
print_rows([H|T]) :-
    print_row(H),
    print_rows(T).

% When the last element of a row
% has been printed, print a newline.
print_row([]) :- nl.

% When there are more row elements,
% print the first one followed by a space.
print_row([H|T]) :-
    format("~w ", [H]),
    print_row(T).
```

```
% Each puzzle must contain at least 17 clues.
problem(1,
    [[_, _, _, _, _, _, _, _, _],
     [_, _, _, _, 3, _, 8, 5],
     [_, 1, _, 2, _, _, _, _],
     [_, _, _, 5, _, 7, _, _, _],
     [_, _, 4, _, _, 1, _, _, _],
     [_, 9, _, _, _, _, _, _],
     [5, _, _, _, _, _, 7, 3],
     [_, _, 2, _, 1, _, _, _, 1],
     [_, _, _, _, 4, _, _, _, 9]]).

[_,_,_,_,_,_,_,_,_]).

:- initialization((
    problem(1, Rows),
    sudoku(Rows),
    print_rows(Rows),
    halt
)).
```

Scryer Prolog From Other Languages

- **Rust**
 - ongoing work to enable this is described at
<https://github.com/mthom/scryer-prolog/pull/1880>
- **HTTP Server**
 - library at https://www.scryer.pl/http/http_server.html
 - example at https://github.com/mvolkmann/prolog-examples/blob/main/http_server_scryerp.pl

SWI-Prolog From Other Languages



- **C**
 - SWI-Prolog provides a “Foreign Language Interface” that allows C to call Prolog and Prolog to call C
 - <https://www.swi-prolog.org/pldoc/man?section=calling-prolog-from-c>
- **JavaScript**
 - use npm package `swipl`, to call Prolog from JavaScript
 - see `swipl.call` and `swipl.query`
- **HTTP Server**
 - SWI-Prolog has built-in predicates that
 - start an HTTP server
 - load predicates from Prolog source files
 - register routes
 - respond to HTTP GET requests with HTML generated from query results

described further in my Prolog blog page

Wrap Up

- Prolog **requires thinking about problems differently**, describing what is true instead of how to do things
- Prolog is **not a fit for most applications**, but it is ideal for certain kinds of problems
- Prolog can be **used for specific portions of an application**, while using other programming languages for the remainder



Resources

- Read “**The Power of Prolog**”
by Markus Triska from Vienna, Austria
at <https://www.metalevel.at/prolog>
- Watch corresponding **YouTube videos**
at <https://www.metalevel.at/prolog/videos/>
- Read **my Prolog blog page** at
<https://mvolkmann.github.io/blog/>
 - select “Prolog” in hamburger menu