50 Years of Prolog and Beyond

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The Prolog Year
Prolog Day Symposium, November 10, 2022

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Part of the contents of this talk appear in the recent TPLP paper \textit{“50 years of Prolog and Beyond,”} by Philipp Körner, Michael Leuschel, João Barbosa, Vítor Santos Costa, Verónica Dahl, Manuel V. Hermenegildo, Jose F. Morales, Jan Wielemaker, Daniel Diaz, Salvador Abreu, and Giovanni Ciatto written for Prolog’s 50th anniversary and TPLP’s 20th anniversary.

Also big thanks to Bob Kowalski for historical input, feedback, and permanent inspiration.
So, then, Prolog is 50!
  ▶ What, 50 years?!? Half a century?!?!
  ▶ Is Prolog therefore now 'old'?

Actually... continued interest:
  ▶ Many active implementations, and more appearing continuously.
  ▶ TIOBE index of programming languages shows Prolog:
    ▶ In upper 10% of all languages tracked (270).
    ▶ Stable, even somewhat upward trend since 2012.
    ▶ One of only 13 languages that are tracked 'long term'.

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But, what is Prolog?
What is Prolog? Why is it important?

Prolog is an acronym of two words:

Programming
and
Logic

• What is the best way to program computers? I.e., how do we get them to solve problems and/or do what we need?

• How can logic help us in this task?
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- How can **logic** help us in this task?
A New View of Computing

- If we have an effective mechanical proof method.

~~> a new view of problem solving and computing is possible:

  ▶ First: program once and for all this deduction procedure in the computer,
  ▶ Then, for each problem we want to solve:
    - Find a suitable representation for the problem.
    - Then, to obtain solutions, ask questions and let deduction procedure do rest:
A New View of Computing

- If we have an effective mechanical proof method.

$\Rightarrow$ a new view of problem solving and computing is possible:

- First: program once and for all this deduction procedure in the computer,
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⇝ a new view of problem solving and computing is possible:
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→ a new view of problem solving and computing is possible:
  - First: program once and for all this *deduction procedure* in the computer,
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If we have an effective mechanical proof method.

→ a new view of problem solving and computing is possible:

- First: program once and for all this deduction procedure in the computer,
- Then, for each problem we want to solve:
  - Find a suitable representation for the problem.
  - Then, to obtain solutions, ask questions and let deduction procedure do rest:

![Diagram of problem-solving process with representation, deduction system, and correct answers/results.]
A New View of Computing

- If we have an effective mechanical proof method.

⇒ a new view of problem solving and computing is possible:

  ▶ First: program once and for all this deduction procedure in the computer,
  ▶ Then, for each problem we want to solve:
    - Find a suitable representation for the problem.
    - Then, to obtain solutions, ask questions and let deduction procedure do rest:

But then,
- No correctness proofs needed?
- Even no programming needed?
- Is this possible?
Prolog is the Materialization of this Dream!

- If we have an effective mechanical proof method.

$\Rightarrow$ a new view of problem solving and computing is possible:

- First: program once and for all this deduction procedure in the computer,
- Then, for each problem we want to solve:
  - Find a suitable representation for the problem.
  - Then, to obtain solutions, ask questions and let deduction procedure do rest:

\[\text{Prolog} \rightarrow \text{Questions} \rightarrow \text{SL-Resolution over Horn clauses} \rightarrow \text{(Correct) Answers / Results}\]

But then,
- No correctness proofs needed?
- Even no programming needed?
- Is this possible?
Family relations

Susan is the mother of Mary.
Susan is the mother of John.
Mary is the mother of Michael.
Family relations

\begin{verbatim}
mother_of(susan, mary).
mother_of(susan, john).
mother_of(mary, michael).
\end{verbatim}
Family relations

\[
\begin{align*}
\text{mother_of(susan, mary).} \\
\text{mother_of(susan, john).} \\
\text{mother_of(mary, michael).}
\end{align*}
\]

John is the father of David.
Family relations

mother_of(susan, mary).
mother_of(susan, john).
mother_of(mary, michael).
father_of(john, david).
Family relations

mother_of(susan, mary).
mother_of(susan, john).
mother_of(mary, michael).

father_of(john, david).

One is the grandmother of someone else if one is the mother of the mother (or father) of that other person.
Family relations

\[
\begin{align*}
\text{mother_of} & \ (\text{susan}, \ \text{mary}). \\
\text{mother_of} & \ (\text{susan}, \ \text{john}). \\
\text{mother_of} & \ (\text{mary}, \ \text{michael}). \\
\text{father_of} & \ (\text{john}, \ \text{david}). \\
\text{grandmother_of}(X,Y) & : \ = \\
& \quad \text{mother_of}(X,Z), \ \text{mother_of}(Z,Y). \\
\text{grandmother_of}(X,Y) & : \ = \\
& \quad \text{mother_of}(X,Z), \ \text{father_of}(Z,Y).
\end{align*}
\]
Family relations

mother_of(susan, mary).
mother_of(susan, john).
mother_of(mary, michael).

father_of(john, david).

grandmother_of(X, Y) :-
mother_of(X, Z), mother_of(Z, Y).

grandmother_of(X, Y) :-
mother_of(X, Z), father_of(Z, Y).

?- mother_of(susan, Y).
Family relations

mother_of(susan, mary).
mother_of(susan, john).
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Y = mary ? ;
Family relations

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grandmother_of(X,Y) :-
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?- mother_of(susan,Y).
Y = mary ? ;
Y = john ? ;
no
Family relations

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X = susan ? ;
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Y = mary ;
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X = susan,
Y = michael ;
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X = susan,
Y = michael ;
X = susan,
Y = david ;
no
Circuit topology

\[ \text{resistor(power,n1).} \]
\[ \text{resistor(power,n2).} \]
\[ \text{transistor(n2,ground,n1).} \]
\[ \text{transistor(n3,n4,n2).} \]
\[ \text{transistor(n5,ground,n4).} \]

\begin{verbatim}
inverter(Input,Output) :-
    transistor(Input,ground,Output), resistor(power,Output).
nand_gate(Input1,Input2,Output) :-
    transistor(Input1,X,Output), transistor(Input2,ground,X),
    resistor(power,Output).
and_gate(Input1,Input2,Output) :-
    nand_gate(Input1,Input2,X), inverter(X, Output).
\end{verbatim}

?- and_gate(In1,In2,Out)  \textcolor{green}{\Rightarrow}  \textcolor{red}{\text{In1=n3, In2=n5, Out=n1}}
Circuit topology

resistor(power,n1).
resistor(power,n2).
transistor(n2,ground,n1).
transistor(n3,n4,n2).
transistor(n5,ground,n4).

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?- and_gate(In1,In2,Out) ~⇒ In1=n3, In2=n5, Out=n1
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    resistor(power, Output).
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“Max is the maximum element of a set if there is no element in the set that is larger than it.”

\[
\text{max}(L, \text{Max}) \leftarrow \text{Max} \in L \land \not\exists E \mid E \in L \land E > \text{Max}
\]

\[
\text{max}(L,\text{Max}) :-
\text{member}(\text{Max},L),
\text{\+ (member}(E,L), E > \text{Max}).
\]
“Max is the maximum element of a set if there is no element in the set that is larger than it.”

$$\text{max}(L, \text{Max}) \leftarrow \text{Max} \in L \land \nexists E \mid E \in L \land E > \text{Max}$$

```prolog
max(L,Max) :-
    member(Max,L),
    + (member(E,L), E>Max).
?- max([3,5,2,8,1],Max).
Max = 8
```
“Max is the maximum element of a set if there is no element in the set that is larger than it.”

\[
\text{max}(L, \text{Max}) \leftarrow \text{Max} \in L \land \neg \exists E \mid E \in L \land E > \text{Max}
\]

```
max(L, Max) :-
    member(Max, L),
    \+ (member(E, L), E > Max).

?- max([3, 5, 2, 8, 1], Max).
Max = 8
```

```
max2([H|T], Max) :-
    max_(T, H, Max).

max_([], Max, Max).
max_([H|T], Tmax, Max) :-
    H > Tmax,
    max_(T, H, Max).
max_([H|T], Tmax, Max) :-
    H =< Tmax,
    max_(T, Tmax, Max).
```
“Max is the maximum element of a set if there is no element in the set that is larger than it.”

\[
\text{max}(L, \text{Max}) \leftarrow \text{Max} \in L \land \neg \exists E \mid E \in L \land E > \text{Max}
\]

\begin{align*}
\text{max}([3,5,2,8,1], \text{Max}) & : - \\
\text{Max} & = 8
\end{align*}
So, what is Prolog?

Procedure = Horn clause + Top-down reasoning (SL-resolution)

(Algorithm = Logic + Control)

So:

• Computational procedures can be given a logical form.
• Horn clause reasoning can be performed as efficiently as computation.
The birth of Prolog

(Sources: Colmerauer, Kowalski)

Colmerauer et al 1972. Prolog!
The birth of Prolog

Robinson, 1965
The resolution principle

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Colmerauer 1970
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Manuel Hermenegildo – 50 Years of Prolog and Beyond (The Prolog Year – Prolog Day Symposium, Nov. 10, 2022)
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Colmerauer et al 1972.
Prolog!

Summer 1972
Kowalski, 1972–1974
Predicate logic as programming language

(Sources: Colmerauer, Kowalski)
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Summer 1972

Green, 1969
Application of Theorem Proving to Problem Solving

Hewitt, 1969
PLANNER

Winograd, 1972
Understanding natural language

Hayes, 1971–1973
Computation and deduction

Foster and Elcock 1969, Absys 1

Colmerauer et al 1972. Prolog!

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Foster and Elcock 1969, Absys 1
The original Prolog

+Frere(*y,*z)-Pere(*x,*y)-Pere(*x,*z).

+Pere(Paul,Pierre)

+Mere(Marie,Jacques)

+Mari(Paul,Marie)

+Pere(*x,*y)-Mari(*x,*z)-Mere(*z,*y)

** CONCATENATION DE LISTES **

+CONC(*X,NIL,*X)
+CONC((*X,*Y),*Z,*X,*U) -CONC(*Y,*Z,*U)
+CONC(NIL,*X,*U) -CONC(*X,*U)
On peut représenter les descendants d’une clause $C_1$ de <données> sous forme d’un arbre:

$C_1$ → $C_2$ → $C_j$ → $C_i$ → $C_k$ → $C_1$
Some milestones (≈ up to ISO)

- First Prolog(s): all fundamental characteristics of the language already there!
Some milestones (≈ up to ISO)

- 1972: Prolog 0
- 1973: Prolog I
- 1975: DEC-10 Prolog

- Dec-10 Prolog: *compilation* (+ improved syntax, etc.)
  - performance (≈ lisp),
  - much more widespread use – but portability an issue.
Some milestones (≈ up to ISO)

- In parallel, many further advances in the theoretical underpinnings:
  - Kowalski and vanEmden (1976): minimal model and fixed-point semantics.
  - Clark (1978): correctness of NaF w.r.t. program completion.

Others: Minker, Gallaire, Cohen, Lassez/Jaffar/Maher, DHD Warren, Sato/Tamaki, DS Warren, ...
Some milestones (≈ up to ISO)

- 1972 Prolog 0
- 1975 DEC-10 Prolog
- 1975 CDL Prolog
- 1973 Prolog I
- 1982 C-Prolog, MU-Prolog

- CDL-Prolog, MU-Prolog, ...
- C-Prolog: portability (but interpreter).
Some milestones (≈ up to ISO)

- 1972: Prolog 0
- 1973: Prolog I
- 1975: DEC-10 Prolog
- 1975: CDL Prolog
- 1982: C-Prolog, MU-Prolog
- 1983: WAM

- The **WAM**: portability + speed... and implementation beauty.
Some milestones (≈ up to ISO)

- 1972: Prolog 0
- 1973: Prolog I
- 1975: DEC-10 Prolog
- 1975: CDL Prolog
- 1982: C-Prolog, MU-Prolog
- 1983: WAM

- FGCS ⇝ MCC ⇝ ECRC ⇝ ESPRIT ⇝ EU research programs, and others.
Some milestones (≈ up to ISO)

1972
Prolog 0
1975
Prolog I
1975
DEC-10
Prolog
1975
CDL
Prolog
1982
C-Prolog,
MU-Prolog
1983
WAM
1985
Quintus
1986 - SICStus

- First WAM-based systems: Quintus, SICStus, BIM, ...
  - Both commercial and public domain → more dissemination.
  - Many optimizations, GC, ... → more performance.
Some milestones (∼ up to ISO)

- 1972: Prolog 0
- 1973: Prolog I
- 1975: DEC-10 Prolog
- 1975: CDL Prolog
- 1982: WAM C-Prolog, MU-Prolog
- 1983: WAM &-Prolog (Ciao)
- 1985: Quintus
- 1986: SICStus

Or- and and-parallelism: Aurora, &-Prolog/Ciao, MUSE, DASWAM, IDIOM, Andorra, EAM, ...
Some milestones (≈ up to ISO)

1972
Prolog 0

1973
Prolog I

1975
DEC-10
Prolog

1975
CDL
Prolog

1982
C-Prolog,
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WAM

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Quintus

1986 - SICStus

&-Prolog (Ciao)

• Or- and and-parallelism: Aurora, &-Prolog/Ciao, MUSE, DASWAM, IDIOM, Andorra, EAM, ...

• Global analysis (abstract interpretation): Aquarius, &-Prolog/Ciao.
  (Independence, modes, types, determinacy, non-failure, cost, ...)

First practical compiler(s) using abstract interpretation?
Some milestones ($\approx$ up to ISO)

- 1972: Prolog 0
- 1975: DEC-10 Prolog
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- 1975: C-Prolog, MU-Prolog
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- 1983: &-Prolog (Ciao)
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- Or- and and-parallelism: Aurora, &-Prolog/Ciao, MUSE, DASWAM, IDIOM, Andorra, EAM, ...

- Global analysis (abstract interpretation): Aquarius, &-Prolog/Ciao. (Independence, modes, types, determinacy, non-failure, cost, ...)

  - First practical compiler(s) using abstract interpretation?

  $\rightsquigarrow$ Performance ($\approx$ imperative), auto-parallelization - real parallel speedups.
Some milestones (∼ up to ISO)

1972 Prolog 0
1973 Prolog I
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1983 WAM
1985 Quintus
1986 - SICStus &-Prolog (Ciao)
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- **Constraints** (Prolog II; CLP scheme and CLP(\(\mathcal{R}\)))
  - Allow many extensions to unification ("domains"), e.g., infinite terms.
  - Recover declarativity for Prolog arithmetic (now also reversible!).
Some milestones (≈ up to ISO)

- Constraints (Prolog II; CLP scheme and CLP(\(\mathcal{R}\)))
  - Allow many extensions to unification ("domains"), e.g., infinite terms.
  - Recover declarativity for Prolog arithmetic (now also reversible!).
  - Finite domains.
Some milestones ($\approx$ up to ISO)

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<thead>
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<th>Year</th>
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<td>ECLPS</td>
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Some milestones (≈ up to ISO)

- A different form of building the language:
  - Pure kernel, all built-ins are in libraries.
  - pure subsets of Prolog supported.
  - Many extensions: e.g., full higher-order and functional syntax support.
  (also λ-Prolog, HiLog, Hiord, ...).
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- Assertions: Types/modes, det, cost → verification, automatic. testing.
Some milestones (∼ up to ISO)

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  - CHIP
  - ECLIPS
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  - Quintus
  - SB Prolog
- **1988**
  - XSB
- **1992**
  - Ciao
  - BinProlog
  - wamcc
- **1993**
  - 1995
  - GNU
  - B-Prolog
  - Ciao
- **1994**
  - 1994
  - XSB
  - 1995

**Tabling (Early deduction, SLG-resolution, ...):**

- Much improved termination (bounded term size).
- Some nice complexity guarantees.
- Support for negation with well-founded semantics.
Some milestones (≈ up to ISO)

- The ISO standard brought much needed standardization; most systems followed (mostly).
Fast forward...

Let’s jump forward and take a look at the current state of things!
Prolog system heritage

Prolog 0 & I
- negation as failure

Prolog II
- cyclic structures

Prolog III
- constraints

Prolog IV
- Marseille Prolog line

DEC-10 Prolog
- compiled, de facto standard

C-Prolog
- interpreted, portable

The WAM
- compiled, portable

Quintus
- commercial, de-facto standard

BIM
- commercial, native

SICStus
- commercial support, JIT

&-Prolog / Ciao
- parallel, assertions

SWI
- libraries

YAP
- indexing

SB-Prolog

tuProlog
- JVM, interoperability

BinProlog
- binarization

B-Prolog
- TOAM

XSB
- tabling

GNU
- fd/indexicals

White background: currently active/supported systems.
Lower legends: just some highlight(s) (see later).
Arrows: influences and inspiration.

Again, more missing!: microProlog, LPA, ECL\textsuperscript{PS}, IBM, LIFE, Andorra-I, Scryer, Tau, ...

Manuel Hermenegildo – 50 Years of Prolog and Beyond (The Prolog Year – Prolog Day Symposium, Nov. 10, 2022)
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<th>Non-Std. Data Types</th>
<th>Foreign Language Interfaces</th>
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Manuel Hermenegildo – 50 Years of Prolog and Beyond (The Prolog Year – Prolog Day Symposium, Nov. 10, 2022)
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  - Applications of Prolog technology to other languages (analyzers, provers, ...).
Summary of current state

- Prolog systems have come a very long way!
  - As seen, a good number of features available on several systems:
    - Indexing, constraints/CHR, multi-threading, tabling, foreign interfaces, coroutining, global vars, mutables, testing, ...

- An issue is portability:
  - ISO standard generally supported (with only minor differences).
  - Basic module system pretty compatible.

However,
  - Interfaces and details of extensions often differ.
    - Can mostly be bridged (c.f., Paolo Moura’s work), but a real nuisance.
  - Some useful features still present in only a few systems:
    - e.g., types/modes/verification, functional syntax, s(CASP), ...

→ Work needed to improve portability.

- Also, better community infrastructure would be useful (see at the end).
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Prolog influences

• In other languages within LP and its extensions:
  ▶ Goedel, Mercury, Turbo-Prolog (static typing)
  ▶ λ-Prolog, Curry, Babel, HiLog (FP/HO)
  ▶ CP, GHC, Parlog, Erlang (committed choice)
  ▶ Datalog, ASP – Co-inductive LP, s(ASP) and s(CASP) (Prolog extensions)
  ▶ HyProlog (assumptions and abduction), Flora-2/ErgoAI, ...
  ▶ Probabilistic LP, ProbLog, ...
  ▶ ProGol, ILP (learning)
  ▶ LogTalk (objects), Picat (imperative syntax)
  ▶ CHR, CHRG, ...

• Beyond LP:
  ▶ Theorem proving technology
  ▶ Erlang
  ▶ Java (abstract machine, specification, ...)
  ▶ Many embeddings in other languages
  ▶ Many others: C++, many compilers, ...
  ▶ Many analyzers and verifiers for other languages
  ▶ ...

Manuel Hermenegildo – 50 Years of Prolog and Beyond  (The Prolog Year – Prolog Day Symposium, Nov. 10, 2022) 18
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Manuel Hermenegildo – 50 Years of Prolog and Beyond (The Prolog Year – Prolog Day Symposium, Nov. 10, 2022)
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- Comparatively small user base.
- Somewhat fragmented community.
- Active developer community with constant new implementations, features. (Good but possible further fragmentation of Prolog implementations.)
- New programming languages.
- The perception that it is an “old” language.
- Wrong image due to “shallow” teaching of the language.

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```
search tree:
solution
fail
solution
fail
fail
solution
fail
infinite failure
```
Depth-First Search
Breadth-First Search
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• Plus, it is also not 'your grandparents’s Prolog' any more.
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