Prolog at 50

Manuel Hermenegildo[1,2]

[1]T. U. of Madrid (UPM)
[2]IMDEA Software Institute

*Part of the contents of this talk appear in the recent TPLP paper "***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,
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written for Prolog's 50th anniversary and TPLP's 20th anniversary.

CILC'22 – Bologna, June 30, 2022

Prolog at 50 more?

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- Summer of 1972: Alain Colmerauer and his team in Marseille develop and implement the first version of Prolog.
- Together with both earlier and later collaborations with Bob Kowalski and colleagues in Edinburgh, this laid the practical and theoretical foundations for the Prolog and logic programming of today.
- We celebrate the 50th anniversary of these events through this
  "Year of Prolog"

  Organized by:
  The Association for Logic Programming and
  The Prolog Heritage Association
- Objectives:
  - Highlight the continuing significance of Prolog and LP for both symbolic, explainable AI, and computing more generally.
  - Inspire a new generation of students, by drawing their attention to the logic-based approach to computing.

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- So, Prolog is 50!
  - What, 50 years?!? Half a century?!?!
  - Is Prolog therefore now 'old'? Is Prolog now irrelevant?

- 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'.
  - A truly impressive body of research and scientific firsts.

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Early steps, ancestries, and milestones

Ancestors and birth

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  - See Kowalski (1988,2013), Cohen (1988), VanRoy (1994), Colmerauer (1996), Gupta et al. (2001), vanEmden (2006), McJones's archive, etc.

- Anyway, some highlights:
  - The AI language LISP (McCarthy 1962) → "very high-level languages."
  - Resolution inference rule (Robinson 1965).
    - Semi-decision procedure for first-order (FO-)logic.

  - Boyer and Moore: structure sharing.
  - Cordell Green (1969): extend resolution to automatically answer questions in FO-logic (a high point for Logic in AI).
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Approximate timeline of some early Prologs (up to ISO)

1972 Prolog 0

1973 Prolog I

1975 CDL-Prolog

1975 DEC-10 Prolog

1982 Prolog II

1982 C-Prolog, MU-Prolog

1983 **(WAM)**

1985 Quintus

1986 SICStus, &-Prolog (Ciao)

1986 CLP($\mathcal{R}$)

1986 SWI-Prolog

1987 SB Prolog

1988 CHIP

1992 wamcc

1992 BinProlog

1993 ECL^iPS^e

1993 Ciao Prolog

1994 XSB

1994 B-Prolog

1995 **(ISO Prolog)**

1995 GNU Prolog

Plus several others: Unix Prolog, Waterloo Prolog, UNSW Prolog, ...
Some early systems may not fit a modern definition of Prolog.
All this progressed in parallel with further advances in the theoretical underpinnings:

- Kowalski/van Emden (1976) linear res. for Horn clauses, no factoring rule, ...
- Clark (1978) correctness of NaF w.r.t. program completion.
- Reiter (1978) formalization of "Closed world assumption."
- Minker, Gallaire, Cohen, Lassez/Jaffar/Maher, DHD Warren, Tamaki/Sato, DS Warren, ...

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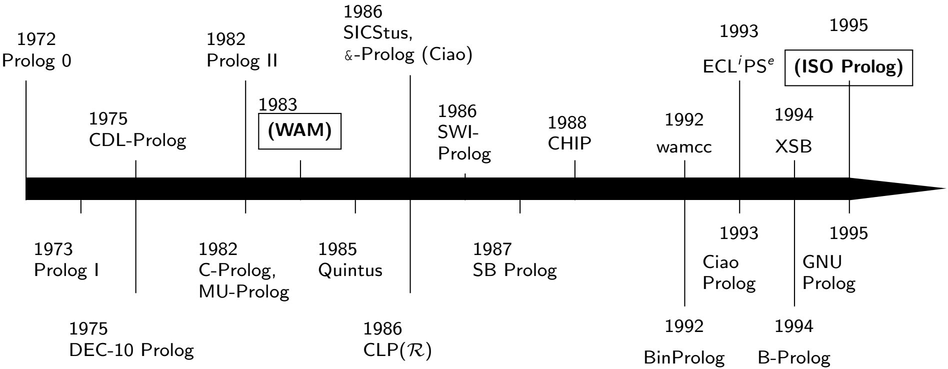

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Prolog 0

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Prolog I

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CDL-Prolog

1975
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1982
Prolog II

1982
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MU-Prolog

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Plus several others: Unix Prolog, Waterloo Prolog, UNSW Prolog, ...

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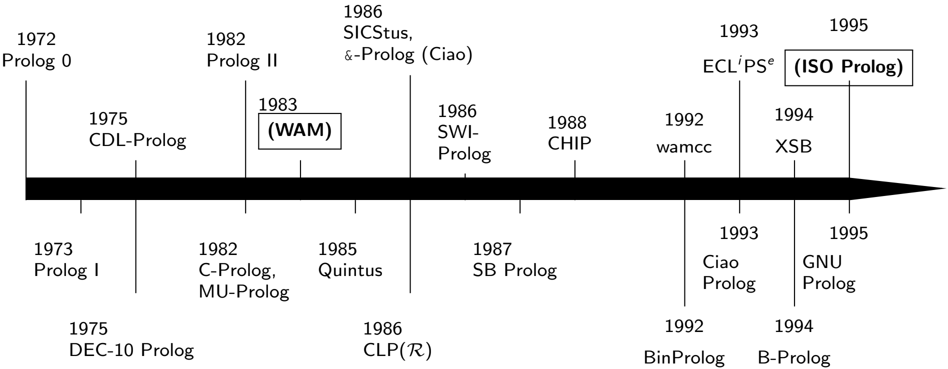

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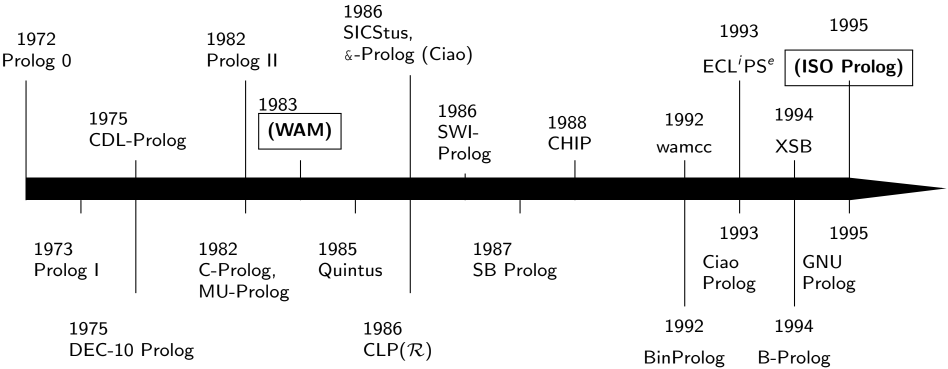

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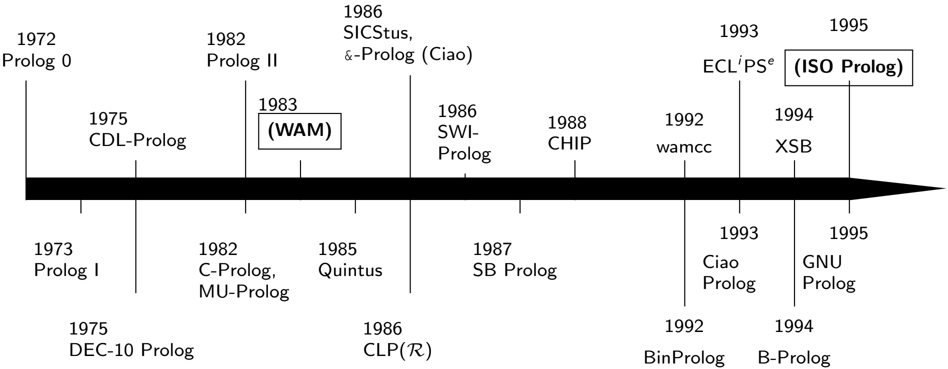

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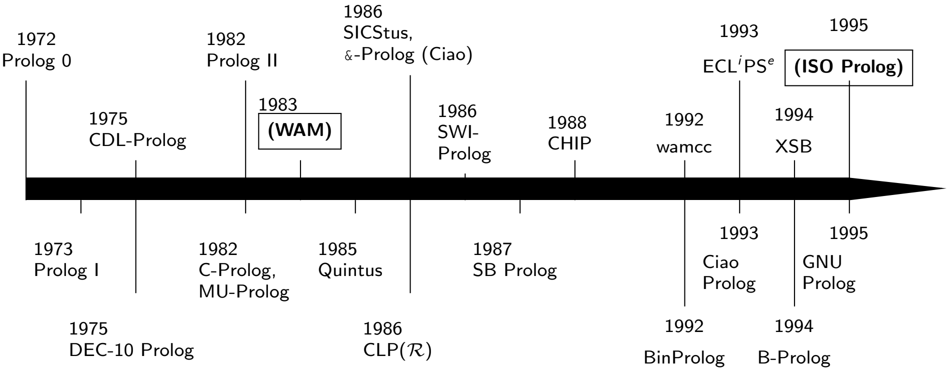

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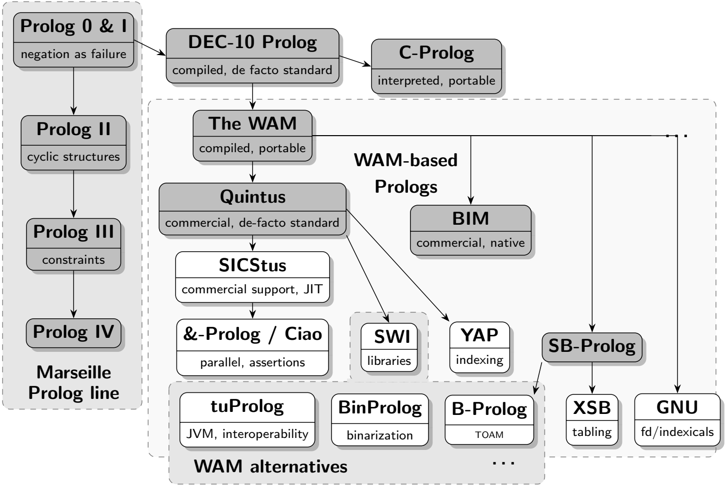

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negation as failure

Prolog II
cyclic structures

Prolog III
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Marseille Prolog line

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interpreted, portable

The WAM
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commercial, de-facto standard

BIM
commercial, native

SICStus
commercial support, JIT

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Arrows:	influences and inspiration.
White background:	currently active/supported systems.
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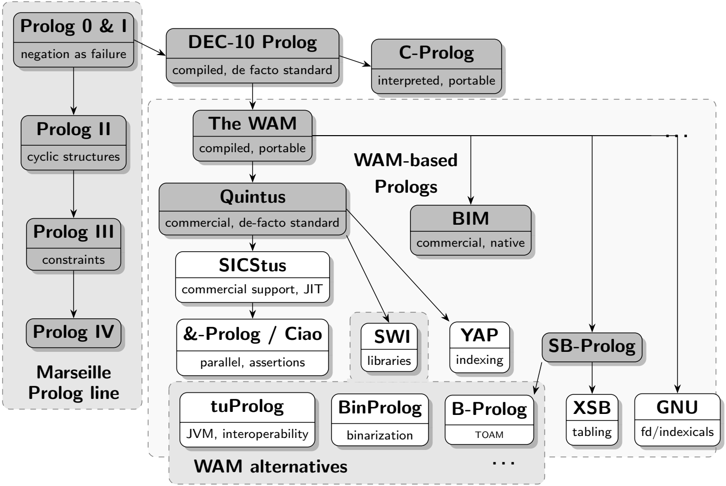

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  - Analysis (abstract interpretation).

→ Performance!

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An overview of current systems

Current systems: focus, some highlights

System	Some highlights
B-Prolog	Action rules, efficient CLP supporting many data structures.
Ciao	Multi-paradigm, module-level feature toggle, extensible language, static+dynamic verification of assertions (incl. types, modes), performance/scalabilty, language interfaces, HO, parallelism.
ECL^{i}PS^e	Focus on CLP, integration of MiniZinc and solvers, backward-compatible language evolution of Prolog.
GNU	Extensible CLP($\mathcal{FD}$) solver, lightweight compiled programs.
JIProlog	Interpreter in Java, embeddable, semantic intelligence / NLP applications.
Scryer	New Prolog in development, aims at full ISO conformance.
SICStus	Commercial Prolog, focus on performance and stability, sophisticated constraint system, advanced libraries, JIT compilation.
SWI	General-purpose, focus on multi-threaded programming and support of protocols (e.g., HTTP) and data formats (e.g., RDF, XML, JSON, etc.), slight divergence from ISO, compatibility with YAP, ECL^{i}PS^e and XSB.
tuProlog	Bi-directional multi-platform interoperability (JVM, .NET, Android, iOS), logic programming as a library.
XSB	Commercial interests, tabled resolution, additional concepts (e.g., SLG resolution, HiLog programming).
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- Core features:
  - Module system
  - Built-in data types
  - Foreign language interface
- Libraries and extensions:
  - Constraints/CHR
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  - Tabling
  - Parallelism
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  - Type and modes
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Support status for selected features - I

System	Open Src.	Modules	Non-Std. Data Types	Foreign Language Interfaces
B-Prolog	✗	✗	arrays, sets, hashtables	C, Java
Ciao	✓	✓	✗	C, Java, Python, JScrpt
ECLiPSe	✓	✓	arrays, strings	C, Java, Python, PHP
GNU Prolog	✓	✗	arrays	C, Java, PHP
JIProlog	✓	✓	✗	Java
SICStus	✗	✓	✗	C, Java, .NET, Tcl/Tk
SWI	✓	✓	dicts, strings	C, C++, Java
τProlog	✓	✓	✗	JavaScript
tuProlog	✓	✗	arrays	Java, .NET, Android, iOS
XSB	✓	✓	✗	C, Java, PERL
YAP	✓	✓	✗	C, Python, R

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XSB	✓	✓	✗	C, Java, PERL
YAP	✓	✓	✗	C, Python, R

Support status for selected features - II

System	CLP	CHR	Tabling	Parallelism	Indexing	Types/Modes
B-Prolog	$\mathcal{FD}$, $\mathcal{B}$, *Set*	✓	✓	✗	N-FA	✗
Ciao	$\mathcal{FD}$, $\mathcal{Q}$, $\mathcal{R}$	✓	✓	✓	FA, MA	✓
ECLiPSe	$\mathcal{FD}$, $\mathcal{Q}$, $\mathcal{R}$, *Set*	✓	✗	✓	most suitable	✗
GNU Prolog	$\mathcal{FD}$, $\mathcal{B}$	✗	✗	✗	FA	✗
JIProlog	✗	✗	✗	✗	undocumented	✗
SICStus	$\mathcal{FD}$, $\mathcal{B}$, $\mathcal{Q}$, $\mathcal{R}$	✓	✗	✗	FA	✗
SWI	$\mathcal{FD}$, $\mathcal{B}$, $\mathcal{Q}$, $\mathcal{R}$	✓	✓	✓	MA, deep, JIT	✗
τProlog	✗	✗	✗	✗	undocumented	✗
tuProlog	✗	✗	✗	✓	FA	✗
XSB	$\mathcal{R}$	✓	✓	✓	all, trie	✗
YAP	$\mathcal{FD}$, $\mathcal{Q}$, $\mathcal{R}$	✓	✓	✗	FA, MA, JIT	✗

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Ciao	$\mathcal{FD}$, $\mathcal{Q}$, $\mathcal{R}$	✓	✓	✓	FA, MA	✓
ECLiPSe	$\mathcal{FD}$, $\mathcal{Q}$, $\mathcal{R}$, Set	✓	✗	✓	most suitable	✗
GNU Prolog	$\mathcal{FD}$, $\mathcal{B}$	✗	✗	✗	FA	✗
JIProlog	✗	✗	✗	✗	undocumented	✗
SICStus	$\mathcal{FD}$, $\mathcal{B}$, $\mathcal{Q}$, $\mathcal{R}$	✓	✗	✗	FA	✗
SWI	$\mathcal{FD}$, $\mathcal{B}$, $\mathcal{Q}$, $\mathcal{R}$	✓	✓	✓	MA, deep, JIT	✗
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SWI	$\mathcal{FD}$, $\mathcal{B}$, $\mathcal{Q}$, $\mathcal{R}$	✓	✓	✓	MA, deep, JIT	✗
τProlog	✗	✗	✗	✗	undocumented	✗
tuProlog	✗	✗	✗	✓	FA	✗
XSB	$\mathcal{R}$	✓	✓	✓	all, trie	✗
YAP	$\mathcal{FD}$, $\mathcal{Q}$, $\mathcal{R}$	✓	✓	✗	FA, MA, JIT	✗

Support status for selected features - II

System	CLP	CHR	Tabling	Parallelism	Indexing	Types/Modes
B-Prolog	$\mathcal{FD}$, $\mathcal{B}$, *Set*	✓	✓	✗	N-FA	✗
Ciao	$\mathcal{FD}$, $\mathcal{Q}$, $\mathcal{R}$	✓	✓	✓	FA, MA	✓
ECLiPSe	$\mathcal{FD}$, $\mathcal{Q}$, $\mathcal{R}$, *Set*	✓	✗	✓	most suitable	✗
GNU Prolog	$\mathcal{FD}$, $\mathcal{B}$	✗	✗	✗	FA	✗
JIProlog	✗	✗	✗	✗	undocumented	✗
SICStus	$\mathcal{FD}$, $\mathcal{B}$, $\mathcal{Q}$, $\mathcal{R}$	✓	✗	✗	FA	✗
SWI	$\mathcal{FD}$, $\mathcal{B}$, $\mathcal{Q}$, $\mathcal{R}$	✓	✓	✓	MA, deep, JIT	✗
τProlog	✗	✗	✗	✗	undocumented	✗
tuProlog	✗	✗	✗	✓	FA	✗
XSB	$\mathcal{R}$	✓	✓	✓	all, trie	✗
YAP	$\mathcal{FD}$, $\mathcal{Q}$, $\mathcal{R}$	✓	✓	✗	FA, MA, JIT	✗

Support status for selected features - II

System	CLP	CHR	Tabling	Parallelism	Indexing	Types/Modes
B-Prolog	$\mathcal{FD}$, $\mathcal{B}$, *Set*	✓	✓	✗	N-FA	✗
Ciao	$\mathcal{FD}$, $\mathcal{Q}$, $\mathcal{R}$	✓	✓	✓	FA, MA	✓
ECLiPSe	$\mathcal{FD}$, $\mathcal{Q}$, $\mathcal{R}$, *Set*	✓	✗	✓	most suitable	✗
GNU Prolog	$\mathcal{FD}$, $\mathcal{B}$	✗	✗	✗	FA	✗
JIProlog	✗	✗	✗	✗	undocumented	✗
SICStus	$\mathcal{FD}$, $\mathcal{B}$, $\mathcal{Q}$, $\mathcal{R}$	✓	✗	✗	FA	✗
SWI	$\mathcal{FD}$, $\mathcal{B}$, $\mathcal{Q}$, $\mathcal{R}$	✓	✓	✓	MA, deep, JIT	✗
τProlog	✗	✗	✗	✗	undocumented	✗
tuProlog	✗	✗	✗	✓	FA	✗
XSB	$\mathcal{R}$	✓	✓	✓	all, trie	✗
YAP	$\mathcal{FD}$, $\mathcal{Q}$, $\mathcal{R}$	✓	✓	✗	FA, MA, JIT	✗

Support status for selected features - III

System	Coroutines	Testing	Debugger	Global Variables	Mutable Terms
B-Prolog	✓	✗	trace	✓	✗
Ciao	✓	✓	trace / source	✓	✓
ECLiPSe	✓	✓	trace	✓	✗
GNU Prolog	✗	✗	trace	✓	✓
JIProlog	✗	✗	trace	✗	✗
SICStus	✓	✓	trace / source	✗	✓
SWI	✓	✓	trace / graphical	✓	✓
τProlog	✗	✗	✗	✗	✗
tuProlog	✗	✗	spy	✗	✗
XSB	✓	✗	trace	✗	✗
YAP	✗	✗	trace	✓	✗

Support status for selected features - III

System	Coroutines	Testing	Debugger	Global Variables	Mutable Terms
B-Prolog	✓	✗	trace	✓	✗
Ciao	✓	✓	trace / source	✓	✓
ECLiPSe	✓	✓	trace	✓	✗
GNU Prolog	✗	✗	trace	✓	✓
JIProlog	✗	✗	trace	✗	✗
SICStus	✓	✓	trace / source	✗	✓
SWI	✓	✓	trace / graphical	✓	✓
τProlog	✗	✗	✗	✗	✗
tuProlog	✗	✗	spy	✗	✗
XSB	✓	✗	trace	✗	✗
YAP	✗	✗	trace	✓	✗

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XSB	✓	✗	trace	✗	✗
YAP	✗	✗	trace	✓	✗

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XSB	✓	✗	trace	✗	✗
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Summary

- ISO standard generally supported, however with minor differences.
- A good number of commonly available features:
  - module system
  - constraints
  - multi-threading (interfaces may differ)
  - tabling
  - co-routining

  Module pretty compatible but rest interfaces, domains may differ.
  CHR quite widespread.
- Type and mode annotations used for documentation but not enforced (except Ciao). Approaches:
  - Strong typing (Goedel, Mercury).
  - The Ciao model (now also known as "gradual typing").

Influences on Other Systems

Influence in other languages within LP and its extensions

- Datalog
- λ-Prolog
- Commited-choice languages
- Turbo Prolog
- Mercury
- Goedel
- Curry
- Assumptive LP
- ASP
- s(ASP) and s(CASP)
- CHR, CHRG
- HyProlog
- Co-inductive LP
- Probabilistic LP
- LogTalk
- Picat
- ...

Influence beyond LP

- Theorem proving technology.
- Java (abstract machine, specification, ...).
- Erlang.
- Many embeddings in other languages.
- Many others: C++, many compilers, ...
- Analyzers for other languages.
- ...

Analysis of the current situation and the way forward

Prolog strengths

- Clean, simple syntax and semantics.
- Immutable persistent data structures, with “declarative” pointers (logic variables).
- Arbitrary precision arithmetic.
- Safety (garbage collection, no NullPointer exceptions, ...).
- Tail-recursion and last-call optimization.
- Efficient inference, pattern matching, and unification; DCGs.
- Meta-programming, programs as data.
- Constraint solving.
- Independence of the selection rule (coroutines).
- Indexing, efficient tabling.
- Fast development, REPL (Read, Execute, Print, Loop), debugging, ...
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- Many books, courses, and learning materials.
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  - Program analysis (Abstr. Interp., Set-Based Anal., Datalog, energy, gas, ...).
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  - Explainable AI, verifiable AI.
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Dynamic vs. Static — An Almost Religious Argument!

Dynamic languages (Prolog, Lisp/Scheme, Python, Javascript, ...)

- Dynamic checking of types (and many other properties):
  - `..., A is B+C, ...`
    `B` and `C` checked to be `numexpr` by `is/2` at run time.
  - `..., arg(N,T,A), ...`
    `N` checked to be `nat` & $\leq$ `arity(T)` by `arg/3` (array bounds).
- Need to use tags (*boxing* of data) to identify type, var/nonvar, etc.
- Flexibility, compactness, rapid prototyping, scripting, ...

Static languages (ML, Haskell, Mercury, Gödel, ...)

- Compiler checks statically *types*.
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Solving the Dynamic vs. Static Dilemma

The Ciao Approach:

- Provide the flexibility of dynamic languages, but with
- *Guaranteed safety, reliability, and efficiency.*

- Use of *voluntary assertions* to express desired properties (incl. types).
  - Can be added up front, gradually, or not at all.
- Use of *advanced program analysis* (abstract interpretation) for:
  - Guaranteeing the properties as much as possible at compile-time.
  - Achieving high performance:
    - Eliminating run time checks at compile time.
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The Assertion Language

Assertions:

:- pred Pred [:Precond] [=> Postcond] [+ CompProps] .

Example:

```
:- pred quicksort(X,Y) : list(int) * var => sorted(Y) + (is_det,not_fails).
:- pred quicksort(X,Y) : var * list(int) => ground(X) + non_det.
```

- Optional, can be added at any time. Provide partial specification.
- Describe calls, success, and computational behavior/invariants.
- Each `pred` typically describes a “mode” of use; the set *covers all valid calls*.
- System makes it worthwhile for the programmer to use them: e.g., autodoc.

Inst vs. Compat:

- The **:** and => fileds describe *instantiation states* by default.
- Specifying “compatibility:”

```
:- pred quicksort/2 :: list(int) * list(int).
```

The Assertion Language (Contd.)

Properties:

```
:- regtype color := green | blue | red.
:- regtype list := [] | [_|list].
:- regtype list(X) := [] | [ X|list].          ≡   list(_,[]). list(X,[H|T]) :- X(H), list(X,T).
:- prop sorted := [] | [ _ ] | [X,Y|Z] :- X > Y, sorted([Y|Z]).
```

- Arbitrary predicates (but conditions on them: termination, steadfastness, ...)
- Many predefined in libs, some of them "native" to an analyzer.
  Can also be user-defined.
- Should be visible/imported and "runnable:" used also as run-time tests!
- *Types/shapes* are a special case of property (e.g., `regtype`s).
- But also, e.g., data sizes, instantiation states, aliasing, termination, determinacy, non-failure, time, memory, ...

The Assertion Language (Contd.)

Modes (essentially “property macros”):

```
:- pred qs(+,-).            ≡   :- pred qs(X,Y) :  (nonvar(X), var(Y)).
:- pred qs(?list,?list).    ≡   :- pred qs(X,Y) :: (list(X), list(Y)).
:- pred qs(+list,-list).    ≡   :- pred qs(X,Y) :  (list(X), var(Y)) => list(Y).
```

In fact, they are defined as macros:

```
:- modedef +(A) : nonvar(A).        :- modedef +(A,X) : X(A).
:- modedef -(A) : var(A).           :- modedef -(A,X) : var(A) => X(A).
```

Can include comments:

```
:- pred qs(+list,-list)   #   "Sorts."
:- pred qs(-list,+list)   #   "Generates permutations."
```

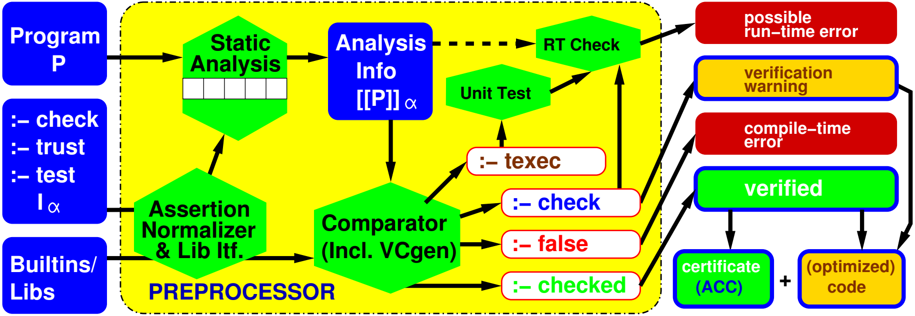
Program-point Assertions:

- Inlined with code: `..., check(( int(X), X>0 )), ....`

Assertion Status (so far “to be checked” – check status – default):

- Other: **trust** (guide analyzer), **true**/**false** (analysis output), **test**, etc.

The Ciao Integrated Approach to Specification, Debugging, Verification, Testing, and Optimization (Mostly Mid 90's!)



Discussion: Comparison with *Classical* Types

“Traditional” Types	**Ciao Assertion-based Model**
“Properties” limited by decidability	Much more general property language
May need to limit prog. lang.	No need to limit prog. lang.
“Untypable” programs rejected	Run-time checks introduced
(Almost) Decidable	Decidable + Undecidable (approximated)
Expressed in a different language	Expressed in the source language
Types must be defined	Types can be defined or inferred
Assertions are only of type “check”	“check”, “trust”, ...
Type signatures & assertions different	Type signatures *are* assertions

- But quite popular now: gradual typing, Racket, liquid Haskell, etc.
- Some key issues:
  Safe / Sound approximation *Suitable assertion language*
  Abstract Interpretation *Powerful abstract domains*
- Works best when properties and assertions can be expressed in the source language (i.e., source lang. supports *predicates*, *constraints*).

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Teaching (and preaching) Prolog

On teaching Prolog

- Prolog / LP / CLP *must* be taught in CS programs,
  - A CS graduate is simply not complete without knowledge of Prolog.

  (and maybe also in other majors and maybe in schools –cf. Prolog Year?)
- But it has to be done right!
  - The standard 'programming paradigms' approach is counter-productive.
  - Simply cannot be done in a couple of weeks emulating Prolog in Scheme.
    - What to do if that is the only slot available?
- On the way *dispel unfounded myths* about the language, and show how many of the shortcomings of early Prologs have been *addressed over the years*.

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- "Prolog gets into infinite loops."

  This is true –in fact, of any programming language or proof system. However, it is likely to discourage beginners if not explained well:

  - Use a system that can *alternatively and selectively* run in breadth-first, iterative deepening, tabling, etc.
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  - Then, explain the shape of the tree (solutions at finite depth, possible infinite failures, etc.), and thus why breadth-first works, and why depth-first sometimes may not.
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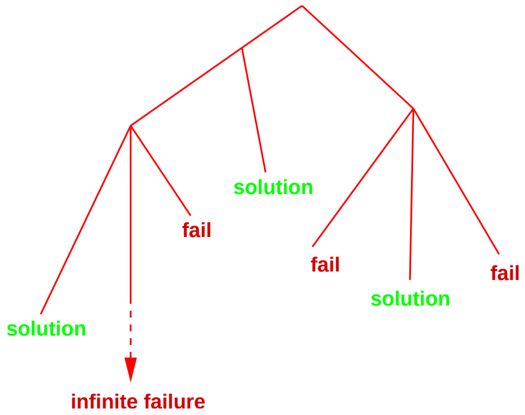
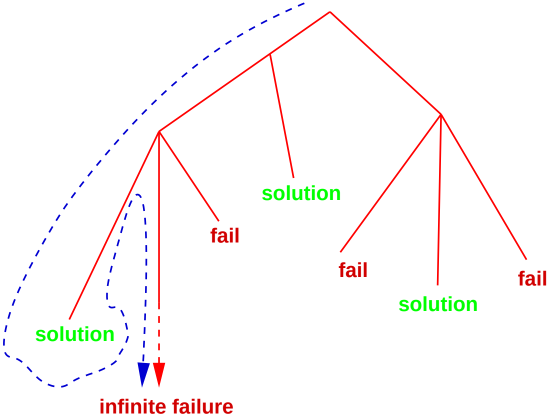
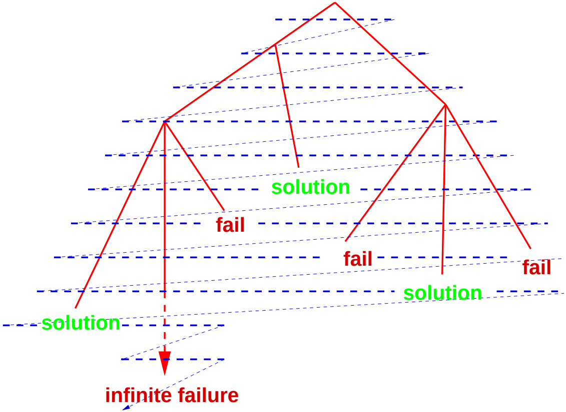
Characterization of the search tree



Depth-First Search



Breadth-First Search



On teaching Prolog

- "Arithmetic is not reversible."
  - Start with Peano arithmetic: beautiful but slow.
  - Then justify Prolog arithmetic for efficiency.
  - Then show (arithmetic) constraint domains: beautiful and efficient!
- "There is no occur check."
  - Explain why, and that there is a built-in for it.
  - Have a package (expansion) that calls it by default for all unifications.
  - Explain the existence of infinite tree unification (as a constraint domain).
- "Prolog is not pure (cut, assert, etc.)"
  - Have a pure mode in the implementation so that impure built-ins simply are not present.
  - Develop pure libraries (including monad-style).
  - Develop purer built-ins.

  and accept that impurity is necessary sometimes, but keep it encapsulated when possible.

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  - Show how logic programs are both logical theories (with declarative meaning) and procedural programs that can be debugged, followed step by step, etc.
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    - Otherwise not a programming language, just specification/KR – Prolog is both.
    - How otherwise to reason about complexity, memory consumption, etc.? To say that these things don't matter does not make sense in PL.
  - Show with examples (and benchmarking them) how you can go from executable specifications to efficient algorithms gradually, and as needed.
  - Show how unification is also a device for *constructing and matching complex data structures with (declarative) pointers*. Show it in the top level, giving "the data structures class."
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  - Show how logic programs are both logical theories (with declarative meaning) and procedural programs that can be debugged, followed step by step, etc.
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  - Show with examples (and benchmarking them) how you can go from executable specifications to efficient algorithms gradually, and as needed.
  - Show how unification is also a device for *constructing and matching complex data structures with (declarative) pointers*. Show it in the top level, giving "the data structures class."
  - Do use types (and properties in general): define them as predicates, show them used to check if something is in the type (dynamic checking), or "run backwards" to generate the "inhabitants"; property-based testing for free!

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  - Classical installation.
    Most appropriate for more advanced students / “real” use.
    Show serious, competitive language.
  - Playgrounds and notebooks (e.g., SWISH, Ciao Playgrounds/active manuals, τ-Prolog).
    - Server-based.
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Final thoughts

- The classical characteristics of Prolog are still unique and demanded.
- It is still one of the most interesting computing paradigms.
- Plus, it is also not 'your grandfather's Prolog' any more.
- Many (most?) of the initial shortcomings of the language have been addressed, even if by different systems.
- More relevant than ever at a time in need for explainable AI.

- Regarding system coordination: despite the intense evolution, differences between systems are not fundamental. To progress:
  - Create a forum (e.g., a web platform) to discuss proposals and gather pointers to solutions, in order to reach consensus on the most important extensions of current implementations.
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  - Take advantage of / build on existing mechanisms such as the ISO standard or (an updated version of) the Prolog Commons.
  - Involve implementors and users.
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