

# Computational Logic: (Constraint) Logic Programming

*Theory, practice, and implementation*

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Program Analysis, Debugging, and Optimization

## A Tour of `ciaopp`: The Ciao Prolog Preprocessor

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## Introduction: The Ciao Program Development System

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- Ciao is a next-generation (C)LP programming environment – features:
  - ◇ Public domain (GNU license).
  - ◇ Pure kernel (*no “built-ins”*); subsumes ISO-Prolog (transparently) via *library*.
  - ◇ Designed to be extensible and analyzable.
  - ◇ Support for programming *in the large*:
    - \* robust module/object system, separate/incremental compilation, ...
    - \* “industry standard” performance.
    - \* (semi-automatic) interfaces to other languages, databases, etc.
    - \* assertion language, automatic static inference and checking, autodoc, ...
  - ◇ Support for programming *in the small*:
    - \* scripts, small (static/dynamic/lazy-load) executables, ...
  - ◇ Support for several paradigms:
    - \* functions, higher-order, objects, constraint domains, ...
    - \* concurrency, parallelism, distributed execution, ...
  - ◇ Advanced Emacs environment (with e.g., automatic access to documentation).

## Introduction: The Ciao Program Development System (Contd.)

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- Components of the environment (independent):
  - ciaosh: Standard top-level shell.
  - ciaoc: Standalone compiler.
  - ciaosi: Script interpreter.
  - lpdoc: Documentation Generator (info, ps, pdf, html, ...).
  - ciaopp: Preprocessor.
- + Many libraries:
  - ◇ Records (argument names).
  - ◇ Persistent predicates.
  - ◇ Transparent interface to databases.
  - ◇ Interfaces to C, Java, tcl-tk, etc.
  - ◇ Distributed execution.
  - ◇ Internet (PiLLOW: HTML, VRML, forms, http protocol, etc.), ...

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## CiaoPP: The Ciao System Preprocessor

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- A standalone preprocessor to the standard clause-level compiler [6].
- Performs source-to-source transformations:
  - ◇ Input: logic program (optionally w/assertions [15] & syntactic extensions).
  - ◇ Output: *error/warning messages + transformed logic program*, with
    - \* Results of analysis, as assertions (types, modes, sharing, non-failure, determinacy, term sizes, cost, ...).
    - \* Results of static checking of assertions [8, 14] (abstract verification).
    - \* Assertion run-time checking code.
    - \* Optimizations (specialization, parallelization, etc.).
- By design, a generic tool – can be applied to other systems (e.g., CHIP → CHIPRE).
- Underlying technology:
  - ◇ Modular polyvariant abstract interpretation [2, 10].
  - ◇ Modular abstract multiple specialization [17].

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## Overview

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- We demonstrate Ciaopp in use:
  - ◊ Inference of complex properties of programs.
  - ◊ Program debugging.
  - ◊ Program validation.
  - ◊ Program optimization (e.g., specialization, parallelization).
  - ◊ Program documentation.
- We discuss some practical issues:
  - ◊ The *assertion* language.
  - ◊ Dealing with built-ins and complex language features.
  - ◊ Modular analysis (including libraries).
  - ◊ Efficiency and incremental analysis (only reanalyze what is needed).
- We start by describing the Ciao assertion language, used throughout the demo.

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## Properties and Assertions – I

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- Assertion language [13] suitable for *multiple purposes* (see later).
- Assertions are typically *optional*.
- Properties (include *types* as a special case):
  - ◊ Arbitrary predicates, (generally) *written in the source language*.
  - ◊ Some predefined in system, some of them “native” to an analyzer.
  - ◊ Others user-defined.
  - ◊ Should be “runnable” (but property may be an approximation itself).

```
:- regtype list/1.                | :- typedef list ::= [];[_|list].
list([]).                        |
list( [_|Y] ) :- list(Y).        |
-----|
:- regtype int/1 + impl_defined. |
-----|
:- prop sorted/1.                |
sorted([]).                       | :- regtype peano_int/1.
sorted( [_] ).                    | peano_int(0).
sorted( [X,Y|Z] ) :- X>Y, sorted([Y|Z]). | peano_int(s(X)) :- peano_int(X).
```

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## Properties and Assertions – II

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- Basic assertions:

```
:- success PredDesc [ : PreC ] => PostC .
:- calls  PredDesc  : PreC .
:- comp   PredDesc [ : PreC ] + CompProps .
```

Examples:

```
:- success qsort(A,B) : list(A) => ground(B).
:- calls  qsort(A,B) : (list(A),var(B)).
:- comp   qsort(A,B) : (list(A,int),var(B)) + (det,succeeds).
```

- Compound assertion (syntactic sugar):

```
:- pred PredDesc [ : PreC ] [=> PostC] [+ Comp] .
```

Examples:

```
:- pred qsort(A,B) : (list(A,int),var(B)) => sorted(B) + (det,succeeds).
:- pred qsort(A,B) : (var(A),list(B,int)) => ground(A) + succeeds.
```

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## Properties and Assertions – III

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- Assertion *status*:

- ◇ check (default) – intended semantics, to be checked.
- ◇ true, false – actual semantics, output from compiler.
- ◇ trust – actual semantics, input from user (guiding compiler).
- ◇ checked – validation: a check that has been proved (same as a true).

```
:- trust pred is(X,Y) => (num(X),numexpr(Y)).
```

- Program point assertions:

```
main :- read(X), trust(int(X)), ...
```

- entry: equiv. to “trust calls” (but only describes calls *external* to a module).

- + much more syntactic sugar, mode macros, “compatibility” properties, fields for automatic documentation [7], ...

```
:- pred p/2 : list(int) * var => list(int) * int.
:- modedef +X : nonvar(X).
:- pred sortints(+L,-SL) :: list(int) * list(int) + sorted(SL)
    # "@var{SL} has same elements as @var{L}.".
```

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## PART I: Analysis

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- `ciaopp` includes two basic analyzers:
  - ◇ The PLAI generic, top-down analysis framework.
    - \* Several domains: modes (ground, free), independence, patterns, etc.
    - \* Incremental analysis, analysis of programs with delay, ...
  - ◇ Gallagher's bottom-up type analysis.
    - \* Adapted to infer *parametric types* (`list(int)`) and at the *literal level*.
  - ◇ Advanced analyzers (GraCos/CASLOG) for complex properties: non-failure, coverage, determinism, sizes, cost, ...
- Issues:
  - ◇ Reporting the results → “true” assertions.
  - ◇ Helping the analyzer → “entry/trust” assertions.
  - ◇ Dealing with builtins → “trust” assertions.
  - ◇ Incomplete programs → “trust” assertions.
  - ◇ Modular programs → “trust” assertions, interface (`.itf`, `.asr`) files.
  - ◇ Multivariance, incrementality, ...

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## Inference of Complex Properties : Non-failure (Intuition)

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- Based on the intuitively simple notion of a set of tests “covering” the type of the input variables.
- Clause: set of primitive tests followed by various unifications and body goals.
- The tests at the beginning determine whether the clause should be executed or not (may involve pattern matching, arithmetic tests, type tests, etc.)
- Consider the predicate:
$$abs(X, Y) \leftarrow X \geq 0, Y \text{ is } X.$$
$$abs(X, Y) \leftarrow X < 0, Y \text{ is } -X.$$
- and a call to `abs/2` with `X` bound to an *integer* and `Y` free.
- The test of `abs/2`,  $X \geq 0 \vee X < 0$ , will succeed for this call.
- “The test of the predicate `abs/2` covers the type of `X`.”
- Since the rest of the body literals of `abs/2` are guaranteed not to fail, at least one of the clauses will not fail, and thus the call will also not fail.

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## Inference of Complex Properties: Lower-Bounds on Cost (Intuition)

```
:- true pred append(A,B,C) : list * list * var.  
append([], L, L).  
append([H|L], L1, [H|R]) :- append(L, L1, R).
```

- Assuming:
  - ◇ Cost metric: number of resolution steps.
  - ◇ Argument size metric: list length.
  - ◇ Types, modes, covering, and non-failure info available.
- Let  $\text{Cost}_{\text{append}}(n, m)$ : cost of a call to `append/3` with input lists of lengths  $n$  and  $m$ .
- A difference equation can be set up for `append/3`:

$$\begin{aligned}\text{Cost}_{\text{append}}(0, m) &= 1 \text{ (boundary condition from first clause),} \\ \text{Cost}_{\text{append}}(n, m) &= 1 + \text{Cost}_{\text{append}}(n - 1, m).\end{aligned}$$

- Solution obtained:  $\text{Cost}_{\text{append}}(n, m) = n + 1$ .
- Based on also inferring argument size relationships (relative sizes).

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## “Resource awareness” example (Upper-Bounds Cost Analysis)

- Given:

```
:- entry inc_all : ground * var.
```

```
inc_all([], []).  
inc_all([H|T], [NH|NT]) :- NH is H+1, inc_all(T, NT).
```

- After running through `ciaopp` (cost analysis) we get:

```
:- entry inc_all : ground * var.
```

```
:- true pred inc_all(A,B) : (list(A,int), var(B))  
=> (list(A,int), list(B,int))  
+ upper_cost(2*length(A)+1).
```

```
inc_all([], []).  
inc_all([H|T], [NH|NT]) :- NH is H+1, inc_all(T, NT).
```

which is a program with a certificate of needed resources!

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## PART II: Program Validation and Diagnosis (Debugging)

- We compare actual semantics  $\llbracket P \rrbracket$  vs. intended semantics  $\mathcal{I}$  for  $P$ :
  - ◊  $P$  is *partially correct* w.r.t.  $\mathcal{I}$  iff  $\llbracket P \rrbracket \subseteq \mathcal{I}$ .
  - ◊  $P$  is *complete* w.r.t.  $\mathcal{I}$  iff  $\mathcal{I} \subseteq \llbracket P \rrbracket$ .
  - ◊  $P$  is *incorrect* w.r.t.  $\mathcal{I}$  iff  $\llbracket P \rrbracket \not\subseteq \mathcal{I}$ .
  - ◊  $P$  is *incomplete* w.r.t.  $\mathcal{I}$  iff  $\mathcal{I} \not\subseteq \llbracket P \rrbracket$ .
- $\mathcal{I}$  described via (check) assertions.
- Incorrectness and incompleteness indicate that diagnosis should be performed.
- *Problems*: difficulty in computing  $\llbracket P \rrbracket$  (+  $\mathcal{I}$  incomplete, i.e., *approximate*).
- *Approach*:
  - ◊ Use the abstract interpreter to infer properties of  $P$ .
  - ◊ Compare them to the assertions.
  - ◊ Generate run-time tests if anything remains to be tested.

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## Validation Using Abstract Interpretation

- Specification given as a semantic value  $\mathcal{I}_\alpha \in D_\alpha$  and compared with  $\llbracket P \rrbracket_\alpha$ .

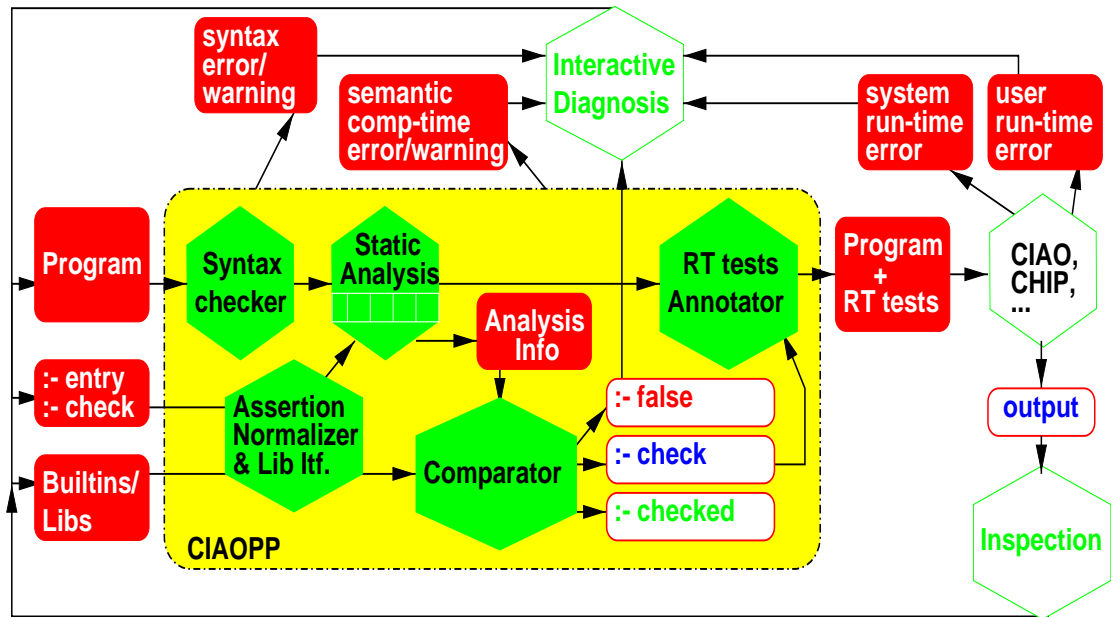
Property	Definition	Sufficient condition
P is partially correct w.r.t. $\mathcal{I}_\alpha$	$\alpha(\llbracket P \rrbracket) \subseteq \mathcal{I}_\alpha$	$\llbracket P \rrbracket_{\alpha^+} \subseteq \mathcal{I}_\alpha$
P is complete w.r.t. $\mathcal{I}_\alpha$	$\mathcal{I}_\alpha \subseteq \alpha(\llbracket P \rrbracket)$	$\mathcal{I}_\alpha \subseteq \llbracket P \rrbracket_{\alpha^-}$
P is incorrect w.r.t. $\mathcal{I}_\alpha$	$\alpha(\llbracket P \rrbracket) \not\subseteq \mathcal{I}_\alpha$	$\llbracket P \rrbracket_{\alpha^-} \not\subseteq \mathcal{I}_\alpha$ , or $\llbracket P \rrbracket_{\alpha^+} \cap \mathcal{I}_\alpha = \emptyset \wedge \llbracket P \rrbracket_\alpha \neq \emptyset$
P is incomplete w.r.t. $\mathcal{I}_\alpha$	$\mathcal{I}_\alpha \not\subseteq \alpha(\llbracket P \rrbracket)$	$\mathcal{I}_\alpha \not\subseteq \llbracket P \rrbracket_{\alpha^+}$

( $\llbracket P \rrbracket_{\alpha^+}$  represents that  $\llbracket P \rrbracket_\alpha \supseteq \alpha(\llbracket P \rrbracket)$  and  $\llbracket P \rrbracket_{\alpha^-}$  indicates that  $\llbracket P \rrbracket_\alpha \subseteq \alpha(\llbracket P \rrbracket)$ )

- Conclusions w.r.t. direct Galois insertions (i.e., over-approximation):
  - ◊ Suited for proving partial correctness and incompleteness w.r.t.  $\mathcal{I}$ .
  - ◊ It is also possible to prove incorrectness.
  - ◊ Completeness can only be proved if the abstraction is “precise.”
- Conclusion w.r.t. reversed Galois insertions (i.e., under-approximation):
  - ◊ Suited for proving completeness and incorrectness.
  - ◊ Partial correctness and incompleteness only if the abstraction is “precise.”

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## Integrated Validation/Diagnosis in the Ciao Preprocessor



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## A Program validation example

- Given:

```
:- check comp : list(int) * var + succeeds.
```

```
inc_all([], []).
```

```
inc_all([H|T], [NH|NT]) :- NH is H+1, inc_all(T, NT).
```

- After running through `ciaopp` (non-failure analysis) we get:

```
:- true comp : list(int) * var + succeeds.
```

```
inc_all([], []).
```

```
inc_all([H|T], [NH|NT]) :- NH is H+1, inc_all(T, NT).
```

which is a validated (certified) program.

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## Debugging with Global Analysis

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- Simple bugs:
  - ◇ Undefined predicates, discontinuous, multiple arity, ...
  - ◇ Cannot be done without global analysis & a robust module system.
- Checking programs against library interfaces:
  - ◇ System predicates (builtin and library predicates):
    - \* Intended behavior known in advance / usually assumed to be correct.
  - ◇ If interfaces of these predicates are available as *assertions*, we can:
    - \* automatically compare analysis results against these specs,
    - \* (+ avoid analyzing the libraries over and over again).
  - ◇ Detects many bugs with no user burden (no need to use assert. language).
  - ◇ Can also be done with user-defined libraries!
- We may be interested also in checking properties of our program.
  - ◇ Price: adding *assertions* describing what we want checked (can be partial).
  - ◇ Advantage: more errors detected and automatic documentation!

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## Finding Bugs with Global Analysis

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- Checking the calls to built-ins and libraries:

```
main(X,Y) :- q(X,N), Y is X+N.  
q(1,V).
```

with, e.g., mode analysis an error is flagged: N is not ground.
- Checking program assertions:

```
:- pred p(X,Y) : list(num) * var => list(num) * list(num) + no_fail.  
p([], []).  
p([H|T],[NH|NT]) :- q(H,NH), p(T,NT).  
  
q(H,NH) :- H > 0, NH = H+1.  
q(H,NH) :- H < 0, NH = H-1.
```

with, e.g., type analysis an error is flagged: Y is not a list of numbers (`is/2` should be used instead of `=/2`);  
with, e.g., non-failure analysis an error is flagged: `=/2` should be used.

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## Discussion: Comparison with “Classical” Types

- Global analysis w/approximations: important role also in program development.
- Allows going beyond straight-jacket of classical type systems (Gödel, Mercury,...):

“Traditional” Types	Properties
Compulsory (do not allow “any”)	Optional (allow “any”)
Expressed in a Special Language	Expressed in the Source Language
Limited Property Language	Much More General Property Language
Limit Programming Language	Do not Limit Programming Language
Untypable Programs Rejected	Run-time Checks Introduced
(Almost) Decidable	Approximated
“check”	“check” or “trust”

...without giving up much (types are included as just another kind of property).

- Key issues:

Approximation	Suitable assertion language
Abstract Interpretation	Relating approximations of actual and intended semantics

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## PART III: Using Analysis Results in Program Optimization

- Eliminating run-time work at compile-time.
  - ◊ Low-level optimization.
  - ◊ Abstract specialization/partial evaluation.  
Evaluating parts of the program based on abstract information.
  - ◊ Abstract multiple specialization.  
Ditto on (possibly) multiple versions of each predicate.
- Automatic program parallelization:  
strict and non-strict Independent And-Parallelism.
- Automatic task granularity control.
- Optimization of other control rules / languages (e.g., Andorra).
- Just for fun: generating documentation!

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## (Multiple) Specialization

- Given the analysis output:

```
main :-
    ...,
    true(int(X)),
    ( ground(X) -> write(a) ; write(b) ),
    ...
```

the `ground(X)` can be *abstractly executed* to `true` and the whole conditional to `write(A)`.

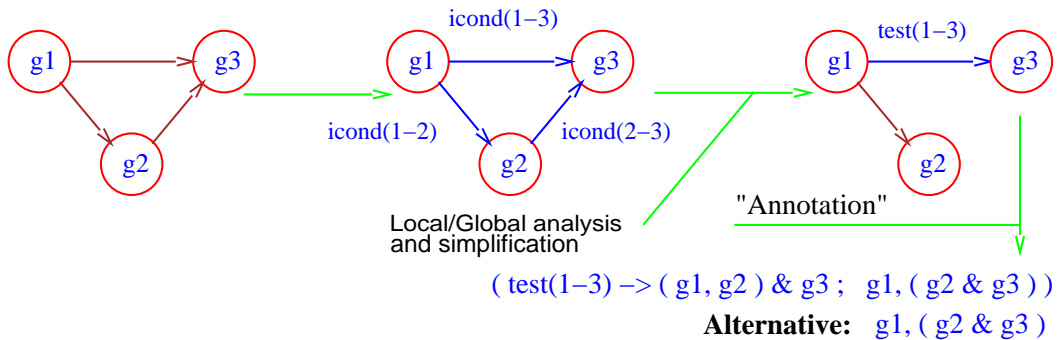
- Specializer is customizable, controlled by a table of “abstract executability”.
- Can subsume traditional “partial evaluation”:  
Given `true(X=list(a))`, then, e.g., `X=[a|Y] → X=[_ | Y]`  
(no need to test that first element is an `a`).
- Multiple specialization: creating multiple versions of predicates for different uses.

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## Automatic Program Parallelization

- Parallelization process [2] starts with dependency graph:
  - edges exist if there can be a dependency,
  - conditions label edges if the dependency can be removed.
- Global analysis: reduce number of checks in conditions (also to true and false).
- Annotation: encoding of parallelism in the target parallel language:

`g1(...), g2(...), g3(...)`



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## Automatic Program Parallelization (Contd.)

- *Example:*

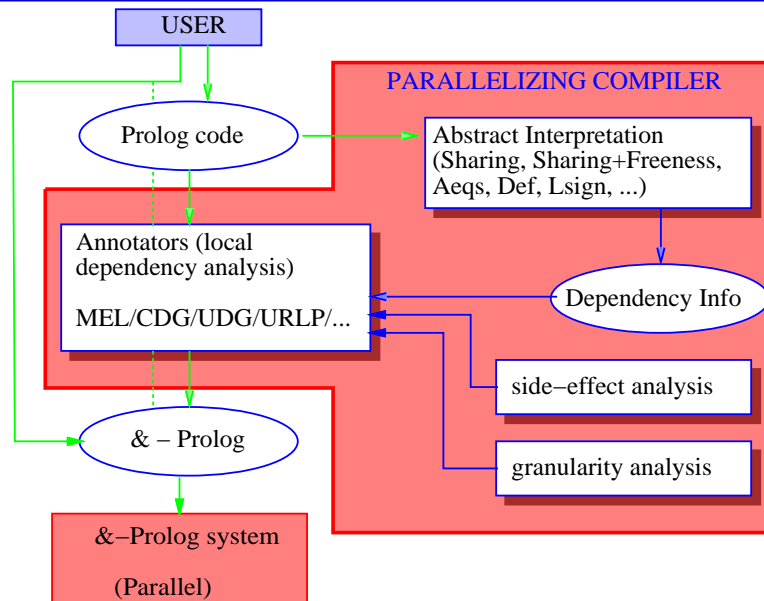
```
qs([X|L],R) :- part(L,X,L1,L2),
               qs(L2,R2), qs(L1,R1),
               app(R1,[X|R2],R).
```

Might be annotated in &-Prolog (or Ciao Prolog), using local analysis, as:

```
qs([X|L],R) :-
    part(L,X,L1,L2),
    ( indep(L1,L2) ->
      qs(L2,R2) & qs(L1,R1)
    ;   qs(L2,R2), qs(L1,R1) ),
    app(R1,[X|R2],R).
```

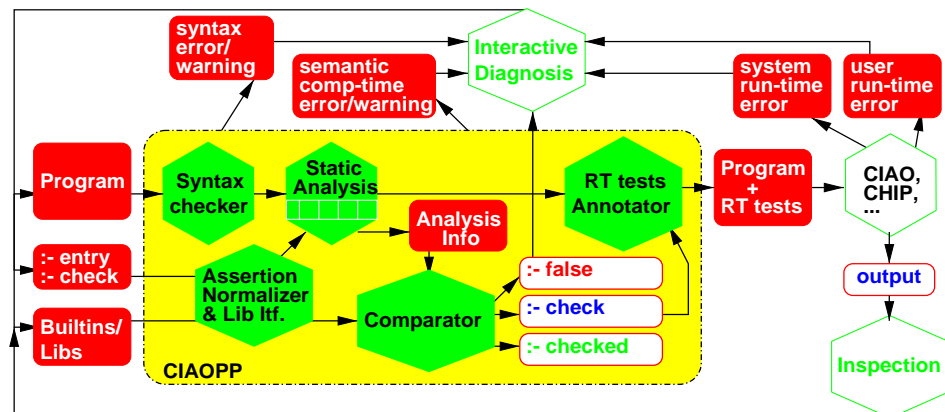
Global analysis would eliminate the `indep(L1,L2)` check.

## &-Prolog/Ciao parallelizer overview





## Genericity in the Ciao Preprocessor



- `ciaopp` is *generic*, i.e., it can be customized:
  - ◇ For a new language: giving assertions for its built-ins and libraries (+ syntax).
  - ◇ For new properties: adding a new *domain* to the analyzer.
- Example: `chipre`, preprocessor for CHIP.

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## Acknowledgements/Downloading the systems

- Ciao/`ciaopp` is a collaborative effort:
  - UPM, Melbourne/Monash (incremental analysis, ...), Arizona (cost analyses, ...), SICS (engine)
  - + Bristol, Linköping, NMSU, Leuven, Beer-Sheva, ...
- Downloading `ciao`, `ciaopp`, `ciaodoc/pl2texi`, and other CLIP software:
  - ◇ Standard distributions:
    - <http://www.clip.dia.fi.upm.es/Software>
  - ◇ Betas (in testing or completing documentation – ask webmaster for info):
    - <http://www.clip.dia.fi.upm.es/Software/Beta>
  - ◇ US Mirror: <http://www.cs.nmsu.edu/~clip/...> (in construction).
  - ◇ User's mailing list:
    - `ciao-users@clip.dia.fi.upm.es`
    - Subscribe by sending a message with only `subscribe` in the body to `ciao-users-request@clip.dia.fi.upm.es`

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