

Computational Logic:
(Constraint) Logic Programming
Theory, practice, and implementation

Program Analysis, Debugging, and Optimization

A Tour of `ciaopp`: The Ciao Prolog Preprocessor

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Introduction: The Ciao Program Development System

- 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.)

- 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.), ...

CiaoPP: The Ciao System Preprocessor

- 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].

Overview

- 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.

Properties and Assertions – I

- 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([]).                                       |
sorted([_]).                                     |
sorted([X,Y|Z]) :- X>Y, sorted([Y|Z]).          | peano_int(s(X)) :- peano_int(X).
```

Properties and Assertions – II

- 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.
```

Properties and Assertions – III

- 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}."
```

PART I: Analysis

- `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, ...

Inference of Complex Properties : Non-failure (Intuition)

- 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.

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`:
$$\text{Cost}_{\text{append}}(0, m) = 1 \text{ (boundary condition from first clause),}$$
$$\text{Cost}_{\text{append}}(n, m) = 1 + \text{Cost}_{\text{append}}(n - 1, m).$$
- Solution obtained: $\text{Cost}_{\text{append}}(n, m) = n + 1$.
- Based on also inferring argument size relationships (relative sizes).

“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!

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.

Validation Using Abstract Interpretation

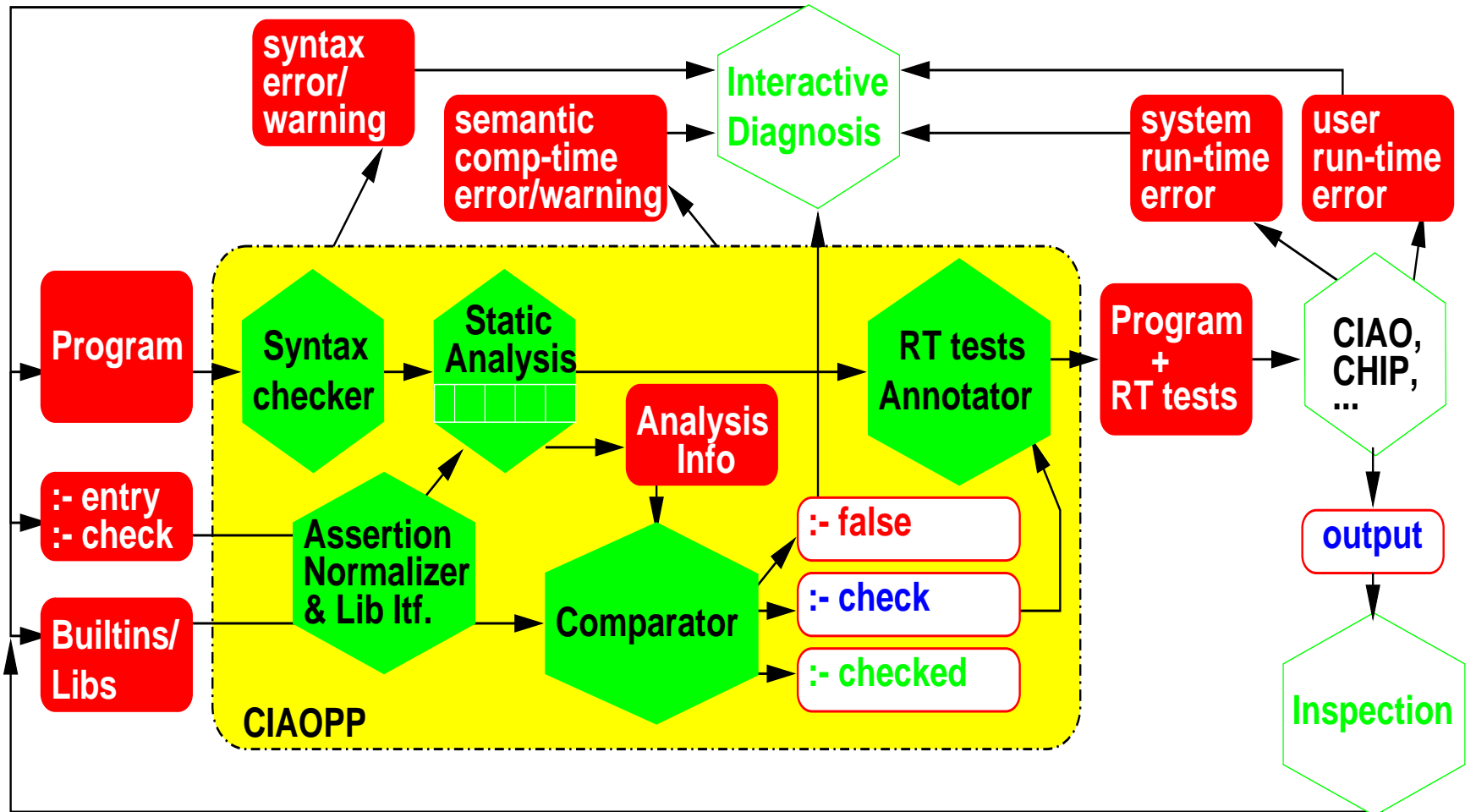
- Specification given as a semantic value $\mathcal{I}_\alpha \in D_\alpha$ and compared with $\llbracket P \rrbracket_\alpha$.

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

($\llbracket P \rrbracket_{\alpha^+}$ 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.”

Integrated Validation/Diagnosis in the Ciao Preprocessor



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.

Debugging with Global Analysis

- 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!

Finding Bugs with Global Analysis

- 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.

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

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!

(Multiple) Specialization

- Given the analysis output:

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

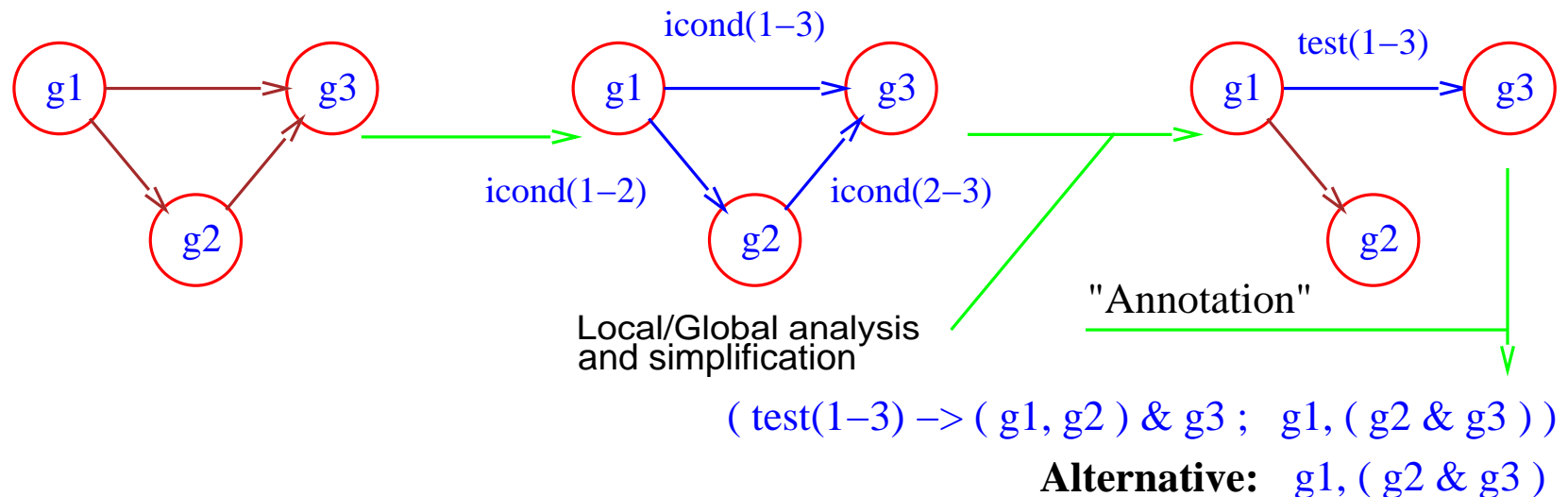
the `ground(X)` can be *abstractly executed* to `true`
and the whole conditional to `write(A)`.

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

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:

$g_1(\dots), g_2(\dots), g_3(\dots)$



Automatic Program Parallelization (Contd.)

- *Example:*

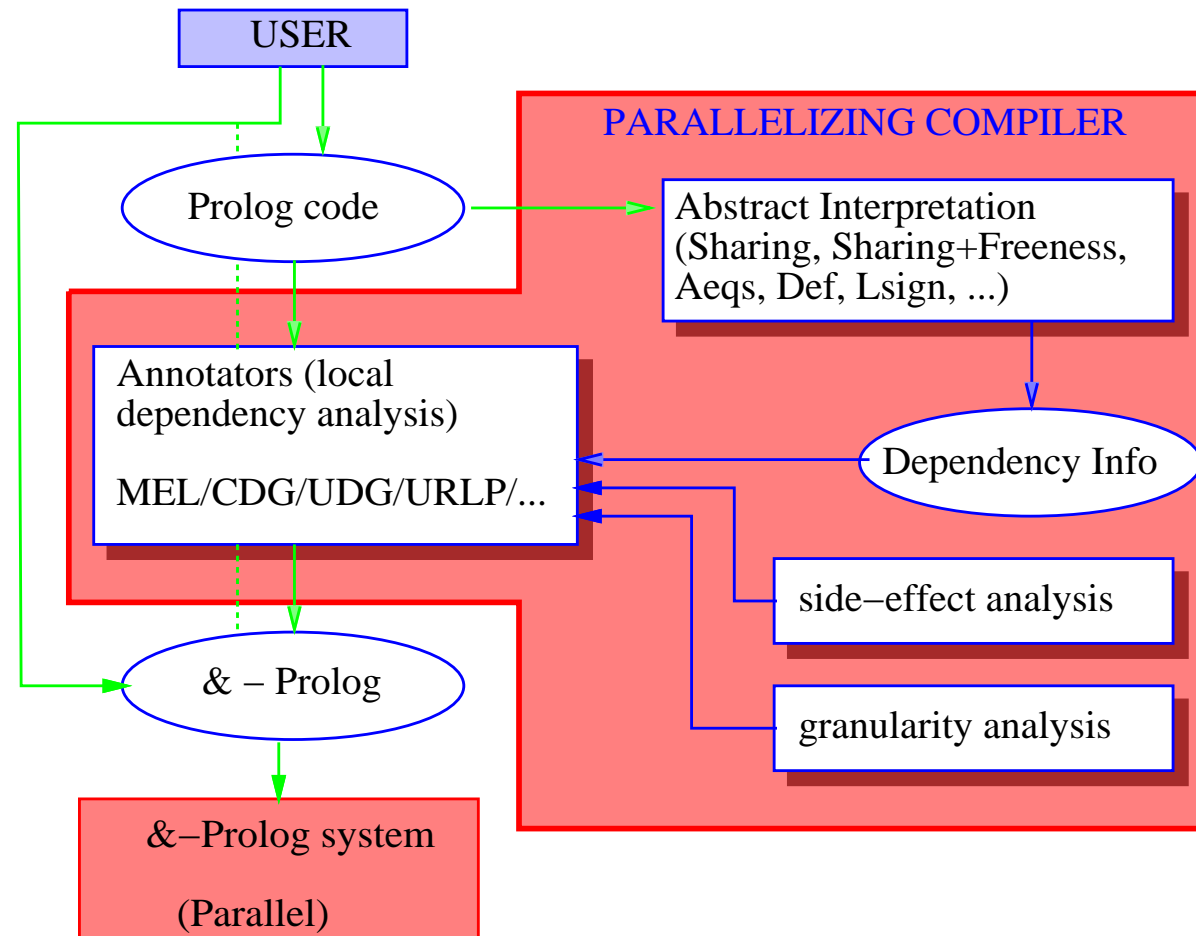
```
qs([X|L],R) :- part(L,X,L1,L2),  
               qs(L2,R2), qs(L1,R1),  
               app(R1,[X|R2],R).
```

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



Granularity Control

- Do not schedule tasks for parallel execution if they are too small.
- Cannot be done well completely at compile-time: work done by a call often depends on the size of its input:
 $q([], []).$
 $q([X|RX], [X1|RX1]) :- X1 \text{ is } X + 1, \quad q(RX, RX1).$
- Approach [12]:
 - ◇ generate at compile-time *functions* (to be evaluated at run-time) that efficiently approximate task size (upper and lower bounds),
 - ◇ transform programs to carry out run-time granularity control.
 - ◇ Note: size computations can be done on-the-fly [11].
- Example (with q above):
..., $q(X, Y) \ \& \ r(X), \dots$
Cost = $2 * \text{length}(X) + 1$ (cost function $2 * n + 1$). Assuming *threshold* is 4 units:
..., $\text{length}(X, LX), \text{Cost is } LX * 2 + 1, (\text{Cost} > 4 \rightarrow q(X, Y) \ \& \ r(Z)$
; $q(X, y), \ r(X)), \dots$

Granularity Control System Output

```
g_qsort([], []).
```

```
g_qsort([First|L1], L2) :-
```

```
  partition3o4o(First, L1, Ls, Lg, Size_Ls, Size_Lg),
```

```
  Size_Ls > 20 ->
```

```
    (Size_Lg > 20 -> g_qsort(Ls, Ls2) & g_qsort(Lg, Lg2);
```

```
                    g_qsort(Ls, Ls2), s_qsort(Lg, Lg2));
```

```
    (Size_Lg > 20 -> s_qsort(Ls, Ls2), g_qsort(Lg, Lg2);
```

```
                    s_qsort(Ls, Ls2), s_qsort(Lg, Lg2)),
```

```
  append(Ls2, [First|Lg2], L2).
```

```
partition3o4o(F, [], [], [], 0, 0).
```

```
partition3o4o(F, [X|Y], [X|Y1], Y2, SL, SG) :-
```

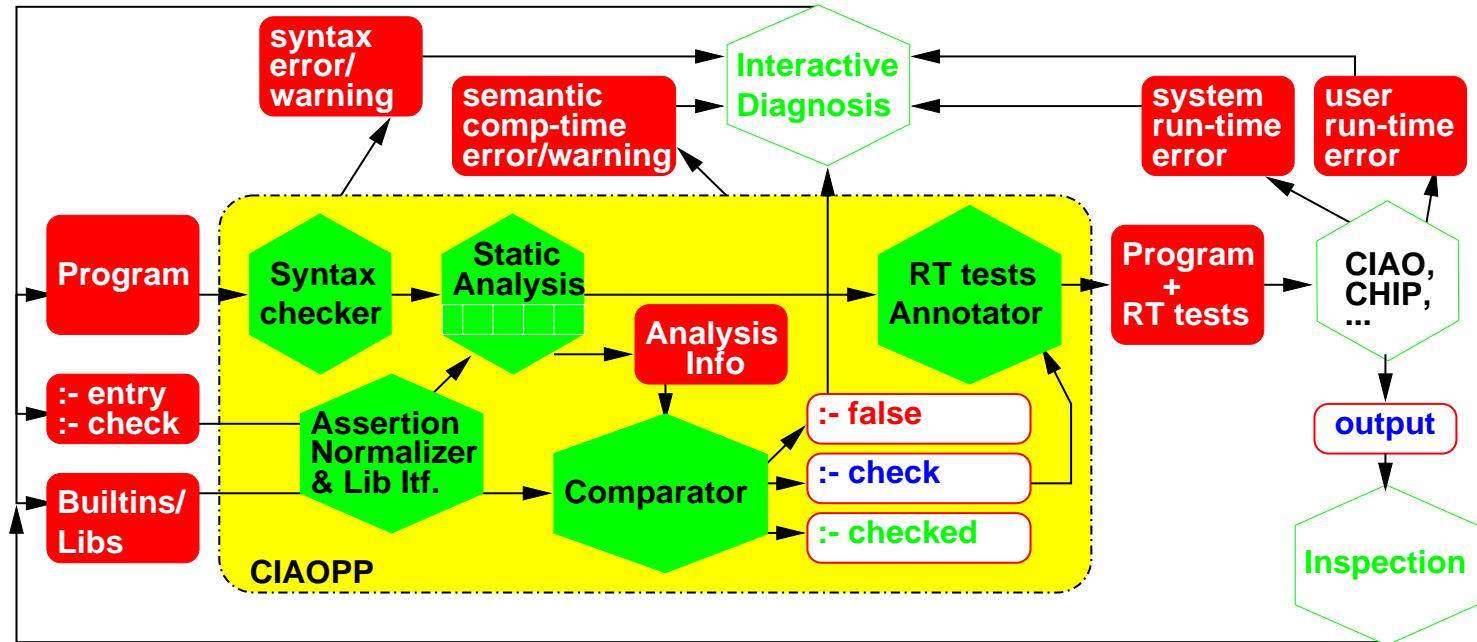
```
  X =< F, partition3o4o(F, Y, Y1, Y2, SL1, SG), SL is SL1 + 1.
```

```
partition3o4o(F, [X|Y], Y1, [X|Y2], SL, SG) :-
```

```
  X > F, partition3o4o(F, Y, Y1, Y2, SL, SG1), xSG is SG1 + 1.
```

- Note: when term sizes are compared directly with a threshold: not necessary to traverse all the terms involved, only to the point at which threshold is reached.

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.

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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