

An Overview of

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Introduction

Objective:

- Design best possible programming language and environment, for developing challenging (semantic :-)) applications rapidly.

Motivating context:

- “Heroic” programming: changes, adaptation, “STOP,” ...

Approach:

- Start from a small, but very *extensible* (LP-based) kernel –a language building language.
- Build gradually extensions on top of it.
- Support Prolog (as a library) but *go well beyond it*.
- Incorporate the *most useful features* from other prog. paradigms.
- Offer the *best of the dynamic and static* language approaches.
 - Provide the flexibility of dynamic languages, but with
 - *Guaranteed safety, reliability, and efficiency.*
 - Attaining *high performance* through optimization.
- Support the programmer with a *great environment*.

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A Modular Language Building Language

Ciao makes it very easy to build *syntactic and semantic extensions* in a flexible and scalable way.

- Addresses shortcomings of traditional Prolog `expand_term`, etc.:
 - Expansions defined for *semantic* points: goals, terms, heads, bodies, ... (not just a global `expand_term`) → *much easier coding*.
 - All operators, expansions, flags, etc. are *module-local*.
 - Dynamic and static code clearly separated, e.g.:
 - Syntax expansion code does not necessarily end up in executables.
 - Program syntax does not necessarily affect what is read.
 - Mechanisms for defining compositions of extensions.
 - New types of operators
 - Higher-order syntax (e.g., `X(a)`), ...

→ Any extensions can be *activated or deactivated on per-module basis*.

→ The concept of *packages*.

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A Modular Language Building Language (Contd.)

Fundamental enabler –Ciao's module/class system.

Allows also:

- Modular program devel., separate/incremental compilation.
 - Modular (scalable) global analysis for detecting errors and optimizing.
 - Also, building small, fast executables and embeddability (non-needed parts of the language and libraries are not included).
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- All these mechanisms are easily accessible to the programmer for building extensions, restrictions (language subsets), DSLs, etc.
 - Ciao is itself built in layers over a small (LP-based) *kernel*.
 - Built-ins are *in libraries* (and can be redefined or not loaded).
 - Same with all language features (loops, conditionals, functions, '...' ...).

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Logic Programming

Is it still a Prolog system?

- Yes, indistinguishable to the naked eye!
(Even won this year's Prolog programming competition! :-))
- As ISO-Prolog compliant as other popular Prologs.
- Quite compatible with de-facto standards (e.g., SICStus).
- Standard predicates, libraries, etc.

However, inside:

- No “builtins:” Prolog support is in libraries, which *can be unloaded*.
- All Prolog libraries loaded automatically for Prolog programs.

- This allows having, e.g., *pure LP* modules (no cut, no assert, ...).
- Also, other computation rules: breadth-first, iterative-deepening, Andorra, *tabling*, *fuzzy* rules, ASP, etc.

All through packages, loadable on a per-module basis.

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Supporting the Best Features of Other Paradigms

Multiparadigm:

- *Constraint programming*: clpr, clpq, Leuven CHR, fd, ...
- *Functional programming*:
 - Function definitions, function calls, functional syntax for predicates.
 - *Higher-order* and *lazyness* for functions and predicates.
- *Objects*: a naturally embedded notion of classes and objects.
- *Concurrency, parallelism, distributed execution*.
- *Imperative features*: mutables, assignment, loops, cases, arrays, etc.

+ many other packages:

- Records, named argument positions.
- Logical interface to databases. Persistence.
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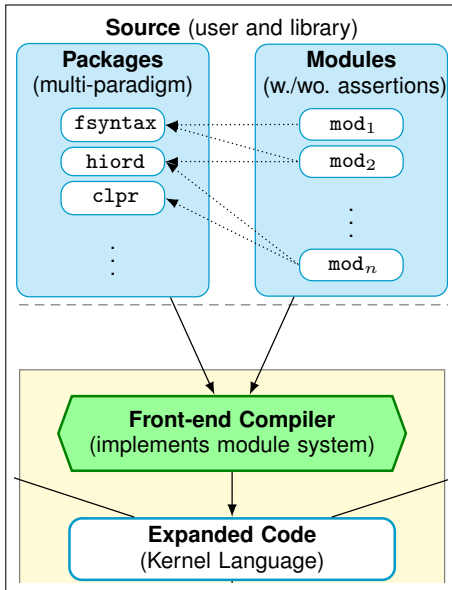
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Ciao Overview: Language Extensions



Dynamic vs. Static — An almost religious argument!

Dynamic languages

(Prolog, 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` & $\leq \text{arity}(T)$ 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, Java, ...)

- Compiler checks statically *types*.
- No dynamic checks needed for types.
- Safety guarantees (types), scalability, performance, large systems, ...
- Some languages (e.g., C) are neither:
 no checking of, e.g., array bounds at compile time or run time...

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Solving the Dynamic vs. Static Dilemma

The Ciao Approach:

- Provide the flexibility of dynamic languages, but with
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- 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.
 - Unboxing.
 - Specialization, slicing, ...
 - Automatic parallelization.
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- Integrated Approach to Specification, Debugging, Verification, Testing, and Optimization.

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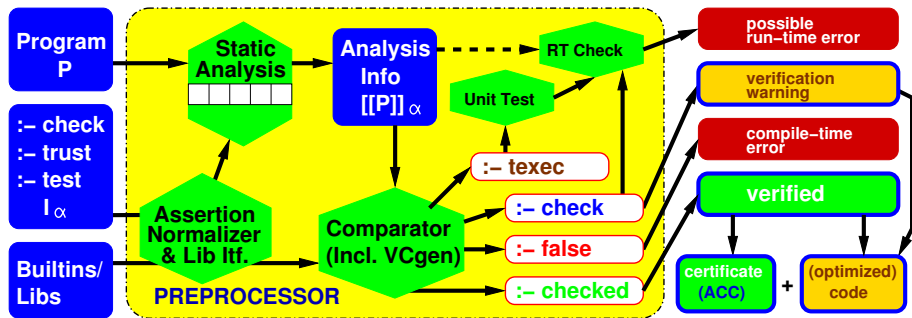
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Solving the Dynamic vs. Static Dilemma (Contd.)

Other aspects:

- Code can be interpreted or compiled. Scripting supported.
But also separate compilation, global analysis.
- Code can be added or modified dynamically
(but has to be marked as 'dynamic').
- Full reflection and meta-programming (but need to be declared).
- Interactive top level, embeddable source debugger.
But compiler also creates small executables for small programs.
- Executables can be static, dynamic, or lazy load.

Integrated Approach to Specification, Debugging, Verification, Testing, and Optimization



The Assertion Language

Assertions:

```
:- pred Pred [:Precond] [=> Postcond] [+ Comp-formula ] .
```

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., autdoc.

Inst vs. Compat:

- The `:` and `=>` fields 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., regtypes).
- 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."

```

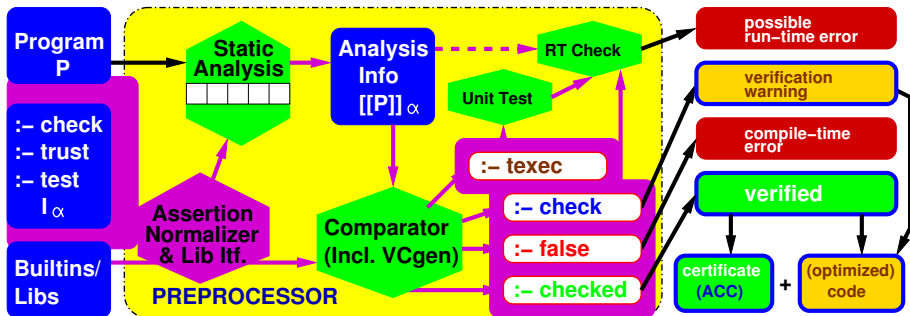
Program-point Assertions:

- 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 Assertion Language (Contd.)



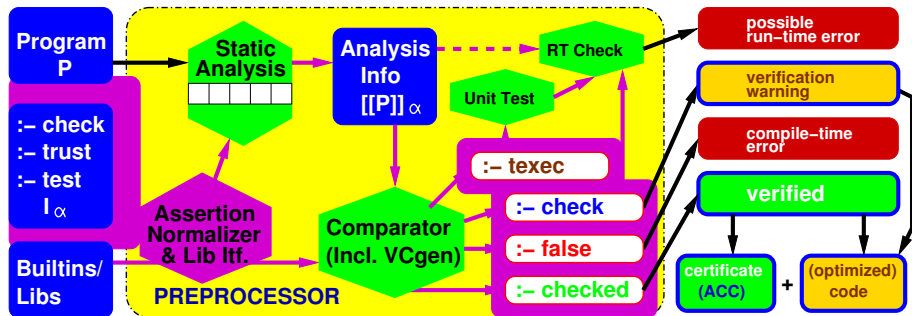
- Used everywhere, for many purposes!

- Simplest applications:

- Generation of run-time tests.
- Auto-documentation.

- Simple to extend also to testing.

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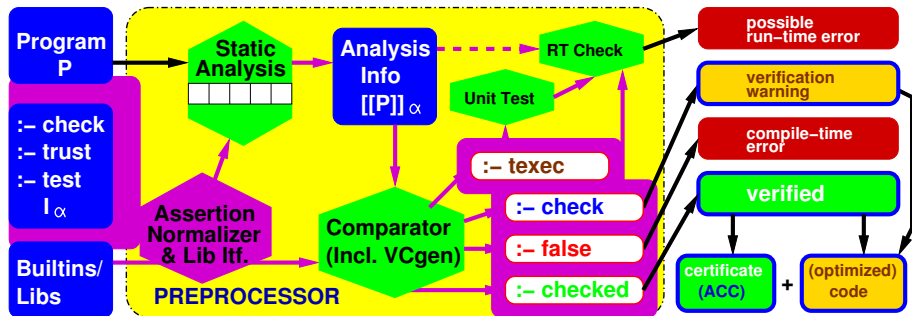


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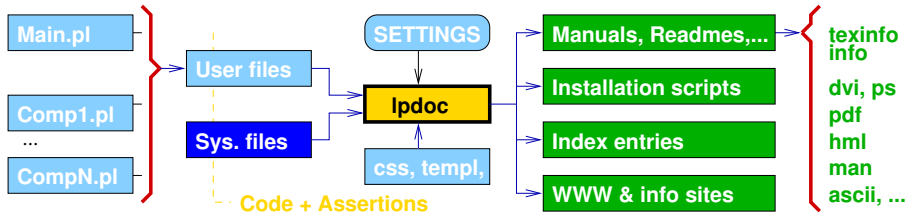
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Autodocumenter: LPdoc



- Uses:

- All the information that the compiler has.
- Assertions.
- Doc declarations (or active comments):


```
:- doc(title,"Complex numbers library").
:- doc(summary,"Provides an ADT for complex numbers.").
```

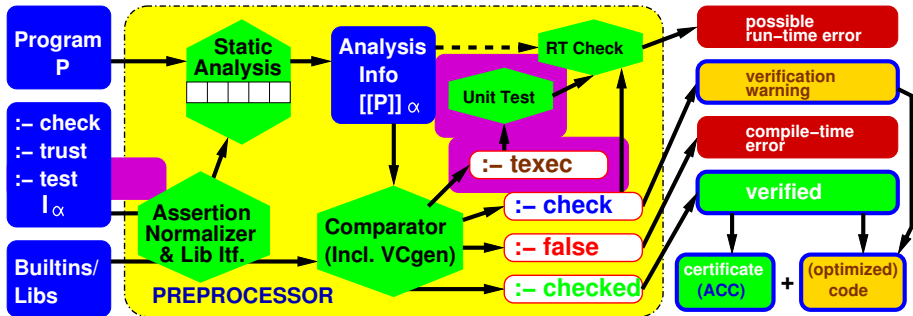
```
%! title: Complex numbers library
```

```
%! summary: Provides an ADT for complex numbers
```

- Markup language, close to \LaTeX /texinfo.

With indices, references, figures, ...

Assertion-based Testing



Assertion-based Testing

Assertion schema used:

```
:- test Pred[:Precond] [=>Postcond] [+CompExecProps] .
```

Such test assertions translate into:

What needs to be checked (normal assertions):

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

What test case needs to be run (test driver):

```
:- texec Pred [:Precond] [+Exec-Formula] .
```

Many interactions within the integrated framework:

- (Unit) tests are part of the assertion language.
- Parts of unit tests that can be verified at compile-time are deleted.
- Rest of unit testing uses the run-time assertion-checking machinery.
- Unit tests also provide test cases for run-time checks coming from assertions.
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Verification and Error Detection using Safe Approximations

- Need to compare actual semantics $\llbracket P \rrbracket$ with intended semantics \mathcal{I} :

P is <i>partially correct</i> w.r.t. \mathcal{I} iff	$\llbracket P \rrbracket \leq \mathcal{I}$
P is <i>complete</i> w.r.t. \mathcal{I} iff	$\mathcal{I} \leq \llbracket P \rrbracket$
P is <i>incorrect</i> w.r.t. \mathcal{I} iff	$\llbracket P \rrbracket \not\leq \mathcal{I}$
P is <i>incomplete</i> w.r.t. \mathcal{I} iff	$\mathcal{I} \not\leq \llbracket P \rrbracket$

Usually, partial descriptions of \mathcal{I} available, typically as *assertions*.

- Problem:** difficulty computing $\llbracket P \rrbracket$ w.r.t. **interesting observables**.
- Approach:* use a *safe approximation* of $\llbracket P \rrbracket \rightarrow$ i.e., $\llbracket P \rrbracket_{\alpha+}$ or $\llbracket P \rrbracket_{\alpha-}$
- Specially attractive if compiler computes (most of) $\llbracket P \rrbracket_{\alpha+}$ anyway.

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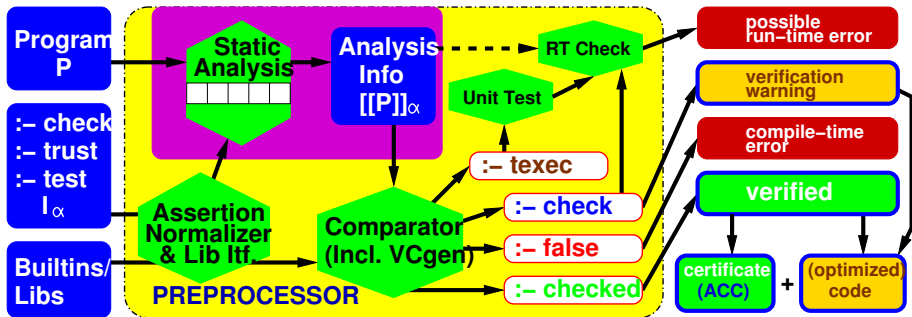
P is <i>partially correct</i> w.r.t. \mathcal{I} iff	$\llbracket P \rrbracket \leq \mathcal{I}$
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P is <i>incorrect</i> w.r.t. \mathcal{I} iff	$\llbracket P \rrbracket \not\leq \mathcal{I}$
P is <i>incomplete</i> w.r.t. \mathcal{I} iff	$\mathcal{I} \not\leq \llbracket P \rrbracket$

Usually, partial descriptions of \mathcal{I} available, typically as *assertions*.

- Problem*: difficulty computing $\llbracket P \rrbracket$ w.r.t. **interesting observables**.
- Approach*: use a *safe approximation* of $\llbracket P \rrbracket \rightarrow$ i.e., $\llbracket P \rrbracket_{\alpha^+}$ or $\llbracket P \rrbracket_{\alpha^-}$
- Specially attractive if compiler computes (most of) $\llbracket P \rrbracket_{\alpha^+}$ anyway.

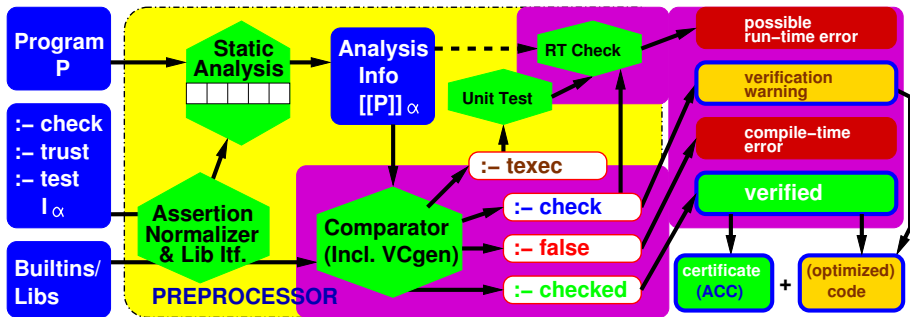
	Definition	Sufficient condition
P is prt. correct w.r.t. \mathcal{I}_α if	$\alpha(\llbracket P \rrbracket) \leq \mathcal{I}_\alpha$	$\llbracket P \rrbracket_{\alpha^+} \leq \mathcal{I}_\alpha$
P is complete w.r.t. \mathcal{I}_α if	$\mathcal{I}_\alpha \leq \alpha(\llbracket P \rrbracket)$	$\mathcal{I}_\alpha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

The Analyses



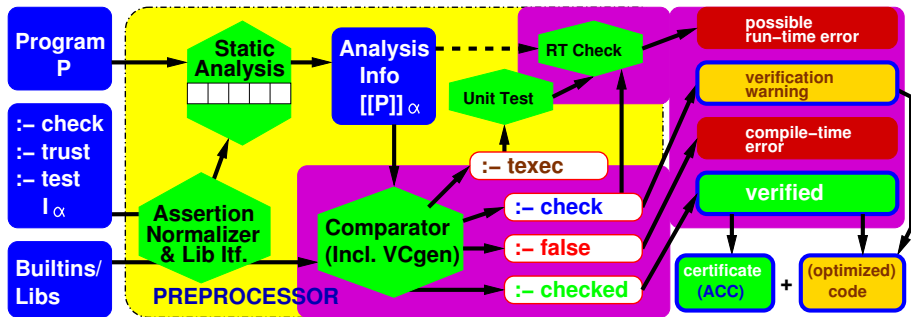
- Modular, parametric, polyvariant abstract interpretation.
- Accelerated, incremental fixpoint.
- Properties:
 - Shapes, data sizes, sharing/aliasing, CHA, determinacy, exceptions, termination, ...
 - Resources (time, memory, energy, ...), (user-defined) resources.

Integrated Static/Dynamic Debugging and Verification



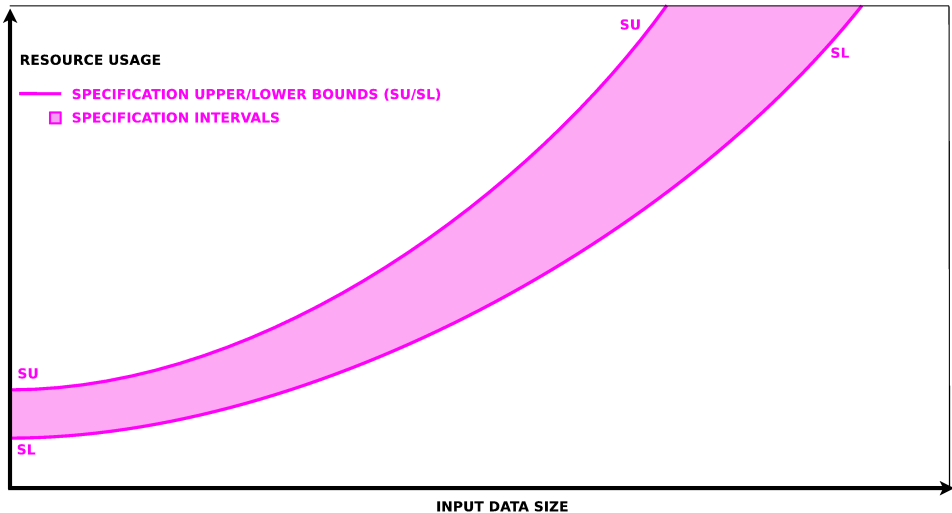
	Definition	Sufficient condition
P is prt. correct w.r.t. \mathcal{I}_α if	$\alpha([[P]]) \leq \mathcal{I}_\alpha$	$[[P]]_{\alpha^+} \leq \mathcal{I}_\alpha$
P is complete w.r.t. \mathcal{I}_α if	$\mathcal{I}_\alpha \leq \alpha([[P]])$	$\mathcal{I}_\alpha \leq [[P]]_{\alpha^=}$
P is incorrect w.r.t. \mathcal{I}_α if	$\alpha([[P]]) \not\leq \mathcal{I}_\alpha$	$[[P]]_{\alpha^=} \not\leq \mathcal{I}_\alpha$, or $[[P]]_{\alpha^+} \cap \mathcal{I}_\alpha = \emptyset \wedge [[P]]_\alpha \neq \emptyset$
P is incomplete w.r.t. \mathcal{I}_α if	$\mathcal{I}_\alpha \not\leq \alpha([[P]])$	$\mathcal{I}_\alpha \not\leq [[P]]_{\alpha^+}$

Integrated Static/Dynamic Debugging and Verification

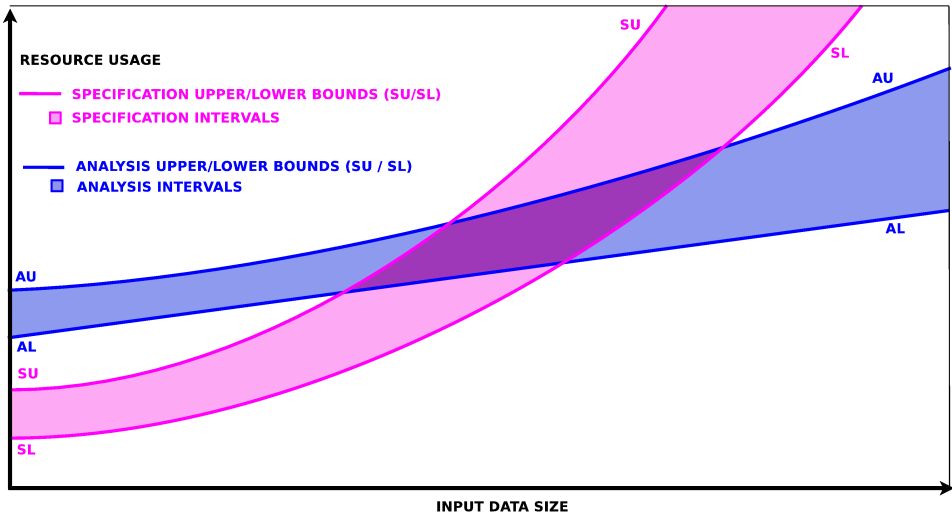


- Run-time checks generated for *parts* of assertions not verified statically.
- Diagnosis (for both static and dynamic errors).
- Comparison not always trivial: e.g., Resource Debugging/Certification
 - Need to compare functions.
 - “Segmented” answers.

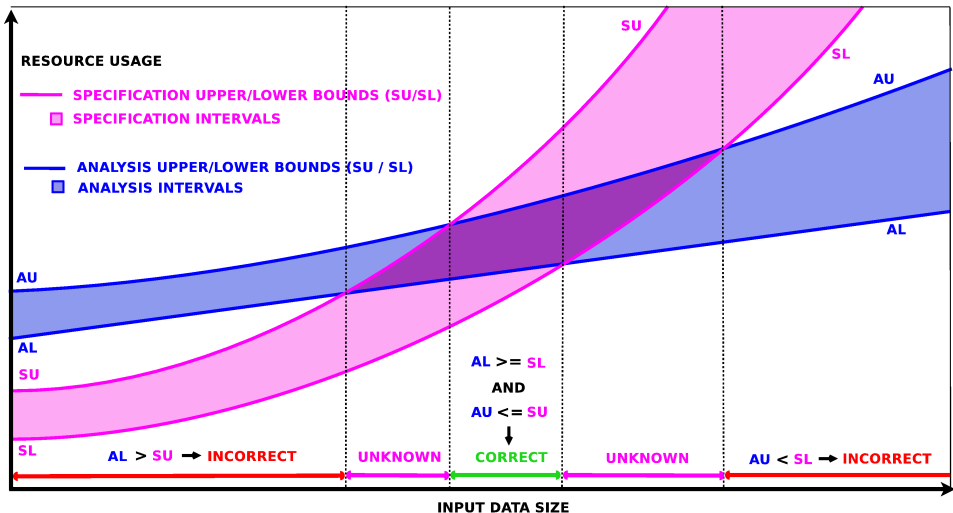
Resource Usage Verification (based on intervals)



Resource Usage Verification



Resource Usage Verification



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 <i>are</i> assertions

- Some key issues:

<i>Safe / Sound approximation</i>	<i>Suitable assertion language</i>
<i>Abstract Interpretation</i>	<i>Powerful abstract domains</i>
- Works best when properties and assertions can be expressed in the source language (i.e., source lang. supports *predicates, constraints*).

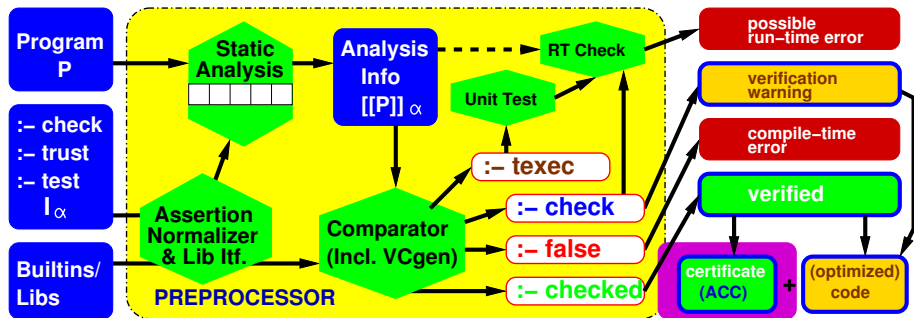
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Abstraction-based Certification, Abstraction-Carrying Code



PRODUCER

CONSUMER

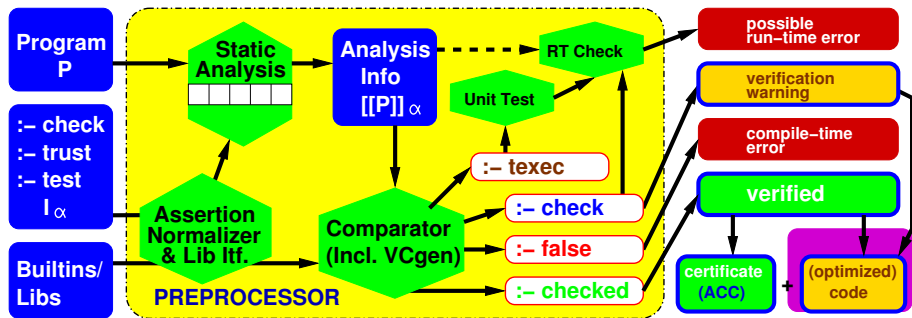
$$\llbracket P \rrbracket_\alpha = \text{Analysis} = \text{lfp}(\text{analysis_step})$$

Certificate $\subset \llbracket P \rrbracket_\alpha$
 Certificate
 Safety Policy

Checker = *analysis_step*

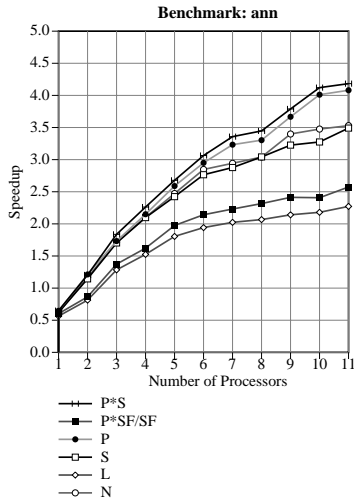
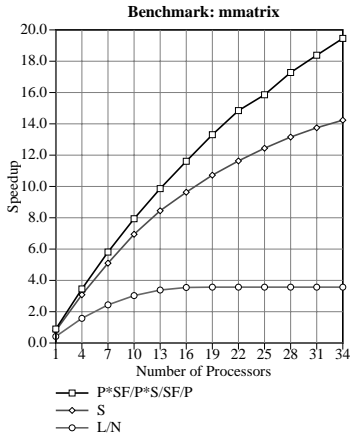
- Interesting extensions: reduced certificates, incrementality, ...

Optimization



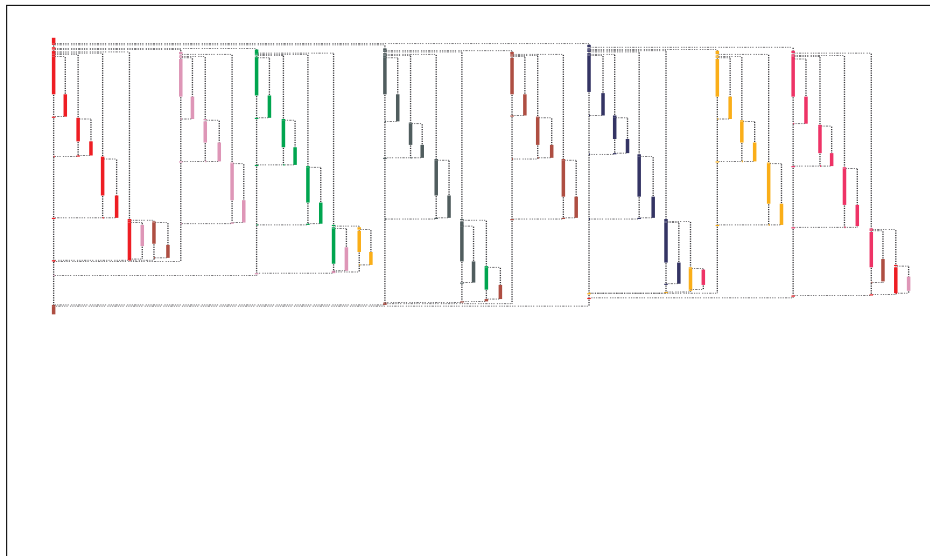
- Source-level optimizations:
 - Partial evaluation, (multiple) (abstract) specialization, ...
 - Low-level optimizations:
 - Dynamic check elimination, unboxing.
 - Use of specialized instructions.
 - Optimized native code generation.
- obtaining close-to-C performance for dynamic languages.
- Parallelization. Granularity control.

Some Speedups (Using Different Abstract Domains)



(ann: parallelizer parallelizing itself; 1-10 proc.: actual speedups on Sequant Symmetry; 10+ simulator projections from execution traces)

8 processors, with granularity control (same scale)



Other Relevant Ciao Features

- Extensive support for the Web:
 - PiLLOW, http(s), ODBC, XML, ZeroMQ, XPath, RDF, ...
- Extensive support for concurrency, reactivity:
 - Agents, condition-action rules, ...
- Recent applications to web services:
 - Sharing & resources for orchestration.
 - Interfaces, libraries, ...
- Compilation to javascript.

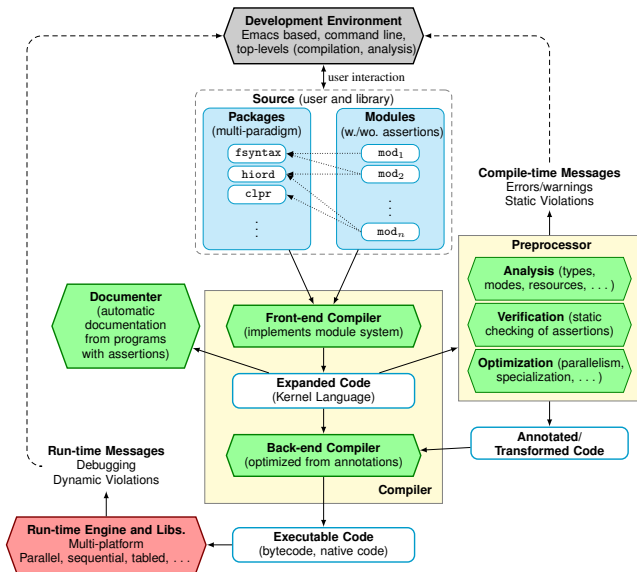
Very interested in collaborating with RuleML groups towards providing support for advanced RuleML needs!

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Ciao Overview



Discussion

- Approaches prior to Ciao had what we perceived as limitations:
 - limited the properties which may appear in specifications, or
 - checked specifications only at run-time or only at compile-time, or
 - were not automatic, or
 - required assertions for all predicates, ...
- The Ciao approach – solution to static/dynamic conundrum, which:
 - Integrates automatic compile-time and run-time checking of assertions.
 - Allows using assertions in only some parts of the program.
 - Deals *safely* with complex properties (beyond, e.g., traditional types).

Allows “modern” (agile/extreme/...) programming style:

- Develop program and specifications gradually, not necessarily in sync.
- Both can be incomplete (including types).
 - Temporarily use spec (including tests) as implementation.
- Go from types, to more complex assertions, to full specifications.
- Assertion language design is important: many roles, used throughout.
- Assertions, properties in source language; “seamless integration.”
- Performance through optimization, not language restriction.

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Some Members of The Ciao Forge

- Ciao is quite a distributed/collaborative effort:
 - Directly within the CLIP Group (UPM and IMDEA Software):
M. Hermenegildo, K. Muthukumar, M. García de la Banda, F. Bueno, G. Puebla, M. Carro, D. Cabeza, P. López-G., R. Haemmerlé, J. Morales, E. Mera, J. Navas, M. Méndez, A. Casas, J. Correas, D. Trallero, C. Ochoa, P. Chico, M.T. Trigo, P. Pietrzak, C. Vaucheret, E. Albert, P. Arenas, S. Genaim, ...
 - Plus lots of contributors worldwide:
G. Gupta (UT Dallas), E. Pontelli (NM State University), P. Stuckey and M. García de la Banda (Melbourne U.), K. Marriott (Monash U.), M. Bruynooghe, A. Mulkers, G. Janssens, and V. Dumortier (K.U. Leuven), S. Debray (U. of Arizona), J. Maluzynski and W. Drabent, (Linköping U.), P. Deransart (INRIA), J. Gallagher (Roskilde University), C. Holzbauer (Austrian Research Institute for AI), M. Codish (Beer-Sheva), SICS, ...

Downloading, etc.

<http://www.ciaohome.org>

Provides access to:

- Latest Ciao, CiaoPP, LPdoc, etc.
- Development versions.
- Documentation.
- Mailing lists.
- etc.

Please contact us for [SVN access](#).

Around 1,000,000 lines of (mostly Prolog) code.

Mostly **LGPL** (some packages have some variations).

All papers available on line at: <http://clip.dia.fi.upm.es/clippubsbyyear>
and <http://clip.dia.fi.upm.es/clippubsbytopic>

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