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).
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:
  - 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).

```prolog
:- regtype list/1. | :- typedef list ::= [];[_|list].
list([]). | | | ________________________________
list([_|Y]) :- list(Y). | 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).
```
Properties and Assertions – II

• Basic assertions:

<table>
<thead>
<tr>
<th>Basic assertion</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>:- calls PredDesc : PreC</td>
<td></td>
</tr>
</tbody>
</table>

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):

<table>
<thead>
<tr>
<th>Compound assertion</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>:- pred PredDesc [ : PreC ] [ =&gt; PostC ][ + Comp ] .</td>
<td></td>
</tr>
</tbody>
</table>

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).

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

- **Program point assertions:**
  ```prolog
  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], ...**

  ```prolog
  :- 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:

\[
\begin{align*}
\text{abs}(X, Y) \leftarrow X \geq 0, \ Y \text{ is } X. \\
\text{abs}(X, Y) \leftarrow X < 0, \ Y \text{ is } -X.
\end{align*}
\]

- and a call to \textit{abs/2} with \(X\) bound to an \textit{integer} and \(Y\) free.
- The test of \textit{abs/2}, \(X \geq 0 \lor X < 0\), will succeed for this call.
- “The test of the predicate \textit{abs/2} covers the type of \(X\).”
- Since the rest of the body literals of \textit{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 $\text{append}/3$ with input lists of lengths $n$ and $m$.

- A difference equation can be set up for $\text{append}/3$:
  \[
  \begin{align*}
  \text{Cost}_{\text{append}}(0, m) &= 1 \text{ (boundary condition from first clause)}, \\
  \text{Cost}_{\text{append}}(n, m) &= 1 + \text{Cost}_{\text{append}}(n - 1, m).
  \end{align*}
  \]

- 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 $[P]$ vs. intended semantics $\mathcal{I}$ for $P$:
  - $P$ is partially correct w.r.t. $\mathcal{I}$ iff $[P] \subseteq \mathcal{I}$.
  - $P$ is complete w.r.t. $\mathcal{I}$ iff $\mathcal{I} \subseteq [P]$.
  - $P$ is incorrect w.r.t. $\mathcal{I}$ iff $[P] \nsubseteq \mathcal{I}$.
  - $P$ is incomplete w.r.t. $\mathcal{I}$ iff $\mathcal{I} \nsubseteq [P]$.

- $\mathcal{I}$ described via (check) assertions.

- Incorrectness and incompleteness indicate that diagnosis should be performed.

- Problems: difficulty in computing $[P]$ (+ $\mathcal{I}$ 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 $[P]_\alpha$.

<table>
<thead>
<tr>
<th>Property</th>
<th>Definition</th>
<th>Sufficient condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>P is partially correct w.r.t. $\mathcal{I}_\alpha$</td>
<td>$\alpha([P]) \subseteq \mathcal{I}_\alpha$</td>
<td>$[P]<em>{\alpha^+} \subseteq \mathcal{I}</em>\alpha$</td>
</tr>
<tr>
<td>P is complete w.r.t. $\mathcal{I}_\alpha$</td>
<td>$\mathcal{I}_\alpha \subseteq \alpha([P])$</td>
<td>$\mathcal{I}<em>\alpha \subseteq [P]</em>{\alpha^-}$</td>
</tr>
<tr>
<td>P is incorrect w.r.t. $\mathcal{I}_\alpha$</td>
<td>$\alpha([P]) \not\subseteq \mathcal{I}_\alpha$</td>
<td>$[P]<em>{\alpha^-} \not\subseteq \mathcal{I}</em>\alpha$, or $[P]<em>{\alpha^+} \cap \mathcal{I}</em>\alpha = \emptyset \land [P]_\alpha \neq \emptyset$</td>
</tr>
<tr>
<td>P is incomplete w.r.t. $\mathcal{I}_\alpha$</td>
<td>$\mathcal{I}_\alpha \not\subseteq \alpha([P])$</td>
<td>$\mathcal{I}<em>\alpha \not\subseteq [P]</em>{\alpha^+}$</td>
</tr>
</tbody>
</table>

($[P]_{\alpha^+}$ represents that $[P]_{\alpha} \supseteq \alpha([P])$ and $[P]_{\alpha^-}$ indicates that $[P]_\alpha \subseteq \alpha([P])$)

• 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

CIAOPP

- Syntax checker
- Static Analysis
- Comparator
- Analysis Info
- RT tests Annotator
- Interactive Diagnosis

Program

- Entry
- Check

Builtins/Libs

Builtins/Libs

Program + RT tests

CIAO, CHIP, ...

output

Inspection

- Syntax error/warning
- Semantic comp-time error/warning
- System run-time error
- User run-time error

...CHIP, CIAO,
A Program validation example

• Given:

```prolog
:- 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:

```prolog
:- 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, discontiguous, 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:
  \[ \text{main}(X,Y) : \text{- q}(X,N), \text{ Y is X+N.} \]

  \[ \text{q}(1,V). \]
  
  with, e.g., mode analysis an error is flagged: N is not ground.

• Checking program assertions:
  \[ \text{:- pred p(X,Y) : list(num) * var => list(num) * list(num) + no_fail.} \]

  \[ \text{p([],[]).} \]
  \[ \text{p([H|T],[NH|NT]) \text{- q}(H,NH), p(T,NT).} \]

  \[ \text{q(H,NH) \text{- H > 0, NH = H+1.}} \]
  \[ \text{q(H,NH) \text{- H < 0, NH = H-1.}} \]
  
  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,...):

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

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

- Key issues:

<table>
<thead>
<tr>
<th>Approximation</th>
<th>Suitable assertion language</th>
</tr>
</thead>
<tbody>
<tr>
<td>Abstract Interpretation</td>
<td>Relating approximations of actual and intended semantics</td>
</tr>
</tbody>
</table>
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:

```prolog
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.
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:
  \[ g_1(\ldots), g_2(\ldots), g_3(\ldots) \]

```
( test(1−3) ⇒ ( g1, g2 ) & g3 ; g1, ( g2 & g3 ) )
```

Alternative:
```
"Annotation"
```

Local/Global analysis and simplification

```python
( test(1−3) → ( g1, g2 ) & g3 ; g1, ( g2 & g3 ) )
```

Alternative: \[ g1, ( g2 & g3 ) \]
**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

USER

Ciao:
(C)LP, FP, (Java) ...

Abstract Interpretation
(Sharing, Sharing+Freeness, Aeqs, Def, Lsign, ...)

PARALLELIZING COMPILER (CiaoPP)

Annotators (local dependency analysis)
MEL/CDG/UDG/URLP/...

Dependency Info

side-effect analysis

Parallelized Code (&)

granularity analysis

Parallelized Code (&)

Ciao/&−Prolog Parallel RT system
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:
  \[
  q([],[]).
  q([X|RX],[X1|RX1]) :- X1 is X + 1, q(RX,RX1).
  \]

- **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):
  
  \[
  \ldots, q(X,Y) \& r(X), \ldots
  \]

  Cost = \( 2 \times \text{length}(X) + 1 \) (cost function \( 2 \times n + 1 \)). Assuming *threshold* is 4 units:

  \[
  \ldots, \text{length}(X,LX), \text{Cost is } LX \times 2 + 1, (\text{Cost} > 4 \rightarrow q(X,Y) \& r(Z)\text{ ; } q(X,y), r(X)), \ldots
  \]
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.
• 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
  - 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
Recent Bibliography on the ciaopp System Components


