25 Years of Ciao

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LOPSTR'18 — Frankfurt, Sep 6, 2018

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Going back to the beginning...

- Context, early 90's: **many languages/systems, each with one extension**.
  - Parallelism/concurrency: &-Prolog, MUSE, Andorra, GHC, CC, ...
  - Equations, functions, CLP(X), HO unification, ...
  - Control rules: Andorra, iterative deepening, tabling, ...

But systems typically only good at that one thing.

- Key observation: no need for a whole separate system for each extension.
  - E.g., if you have stack sets, microtasks, goal queues, etc. you can implement any concurrency/parallelism model.
  - E.g., if you have attributed variables: CLP(Q)/CLP(R) (Holzbaur), delays, ...

Ciao principles I: **Language definition/extension is library-based.**

- Start: small, very *extensible* LP kernel – a language-building language.
- Build gradually extensions in layers on top of it.
- Bring in the *most useful features* from the different programming paradigms.

- Much development within the ACCLAIM project (same as, e.g., Oz).
- This approach is also taken nowadays by, e.g., Racket.

[TPLP'12, PADL'13, LOPSTR'11, DCG-PhD'04, NovaSci'99, ILPS'95, PPCP'94, CL'00, ENTCS'00]
[PADL'12, ICLP'11, ICLP'08, EuroPar'96, NGC'91, NGC'89, ICPP'88, ICLP'87, ICLP'86]

- Context, early 90's:
  A tendency to restrict languages (generally for performance).
  - Elimination of unification: Mercury, GHC, CC, Erlang, ...
  - Elimination of non-determinism/search: GHC, CC, Erlang, ...

  Static languages, strong typing:
  - ML, Haskell | Gödel, Mercury.

- At the same time:
  Abstract interpretation-based global analysis becoming practical.
  - Motivated by auto-parallelization and other optimizations (*dynamic language*).
  - Efficient fixpoint (PLAI), with techniques for dealing with dynamic languages, interactive development (e.g., incremental analysis).
  - Powerful domains (sharing/aliasing, cost, convex hulls, polyhedra, CLP).
  - Global analysis supported by module system.
  - Already using assertions (`entry`, `trust`, `true`) to communicate w/analyzer.

Ciao principles II: **High performance via optimization, not language restriction.**

- No need to eliminate unification or tabling or backtracking or constraints, etc.

Ciao principles III: **Combine the best of the dynamic and static language approaches.**

- Provide the flexibility of dynamic languages:
  - Dynamic typing, dynamic load, dynamic program modification, meta-programming, top level, call (eval), scripts, ...
- But with *guaranteed safety and efficiency.*

Enablers:

- **Optimization** via analysis, partial evaluation, parallelization, profiling, separate/incr. compilation, small executables, embeddability, ...
- **AbsInt-based checking of optional assertions** – safe approximations – The Ciao assertions model

[ICLP'09, LPAR'06, SCP'05, SAS'03, PBH00a, LOPSTR'99, LNCS'99, AADEBUG'97]

Ciao principles II: **High performance via optimization, not language restriction.**

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- Approach not particularly in line with the trends at the time!
  - Strong typing was a religion, dynamic languages a **bad** thing.
  - Reflected in the languages developed: ML, Haskell | Goedel, Mercury.

→ "Ciao: (first?) dynamic language with safety assurances, trying to survive in a world dominated by strong typing."

- However, idea quite popular now: gradual typing, Racket, liquid Haskell, etc.

[ICLP'09, LPAR'06, SCP'05, SAS'03, PBH00a, LOPSTR'99, LNCS'99, AADEBUG'97]

Outline

Part I The Ciao language

Part II The Ciao assertions model

Part III Using CiaoPP as a multi-language analyzer/verifier

Part IV Conclusion and some recent work

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Part I The Ciao language

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Part III Using CiaoPP as a multi-language analyzer/verifier

Part IV Conclusion and some recent work

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`) $\rightarrow$ *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)`), ...

$\rightarrow$ Any extensions can be *activated* or *deactivated on per-module basis*.
$\rightarrow$ The concept of *packages*.

[TPLP'12, PADL'13, LOPSTR'11, CL'00, ENTCS'00, CiaoManual'18, DCG-PhD'04, NovaSci'99, ILPS'95, PPCP'94]

A Modular Language-Building Language (Contd.)

Fundamental enabler –Ciao's module/class system.

Allows also:

- Modular program development, 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).

- 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, ',' ...).

[TPLP'12, PADL'13, LOPSTR'11, CL'00, ENTCS'00, DCG-PhD'04, CiaoManual'18, NovaSci'99, ILPS'95, PPCP'94]

Supporting Traditional Logic Programming

Is it still a Prolog system?

- Yes, indistinguishable to the naked eye!
- 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 the mechanism of packages, loadable on a per-module basis:

```
:- module(_,exports).             % All traditional built-ins available
:- module(_,exports,[]).          % Just the pure kernel
:- module(_,exports,[packages]).  % Kernel+packages
:- module(_,exports,[iso]).       % Pure ISO
```

[ICLP'18, TR'95, CiaoManual'18, PPDP'16, FLOPS'12, ICLP'10, ICLP'09, PADL'09, PADL'08]

Supporting the Best Features of Other Paradigms

Multi-paradigm:

- *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.
- *Concurrency, parallelism, distributed execution*.
- *Imperative features*: mutables, assignment, loops, cases, arrays, etc.
- *Objects:* a naturally embedded notion of classes and objects.

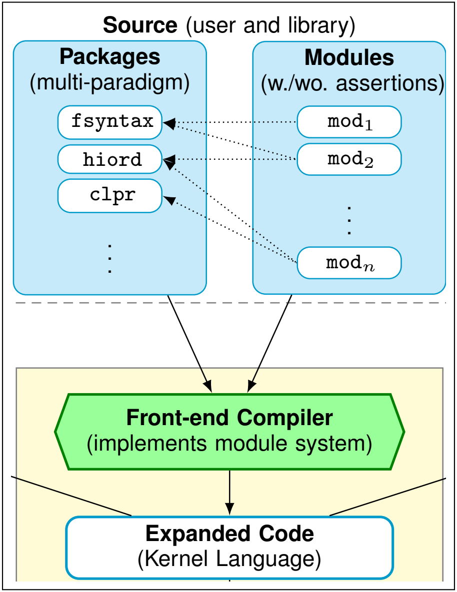
+ many other packages:

- Records, named argument positions.
- Logical interface to databases. Persistence.

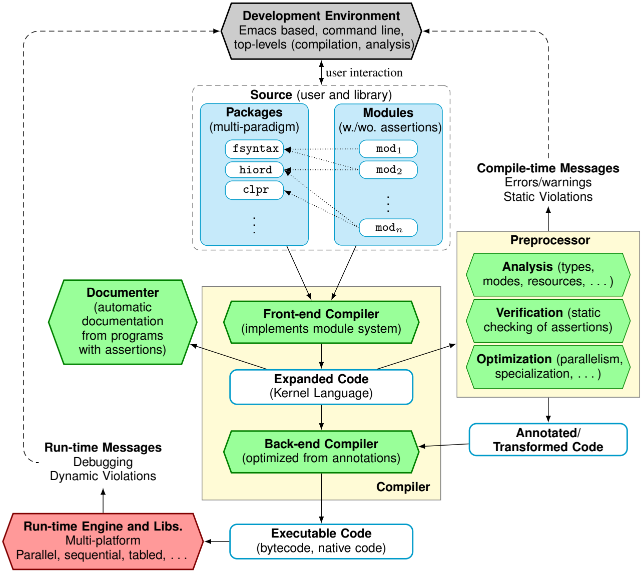
...

[PPDP'14, FLOPS'06, ASIAN'04, EuroPar'04, ICLP'02, CICLOPS'02, ICLP'99, ICLP'95, ProDe'96, CLNet'95, PPCP'94, ALP'94, CICLOPS'12]

Ciao Overview: Language Extensions



Ciao Architecture Overview



Demo: properties, types, predicates, functions, higher order, constraints,

breadth-first search, tabling, ...

Outline

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*.
- No dynamic checks needed for types.
- Safety guarantees (types), scalability, performance, large systems, ...

- Some languages (e.g., C) are neither (even if still very useful!):
  no checking of, e.g., array bounds at compile time or run time...

[AADEBUG'97, LNCS'99, LOPSTR'99, PBH00a, SAS'03, SCP'05, LPAR'06, ICLP'09]

Solving the Dynamic vs. Static Dilemma

The Ciao Approach:

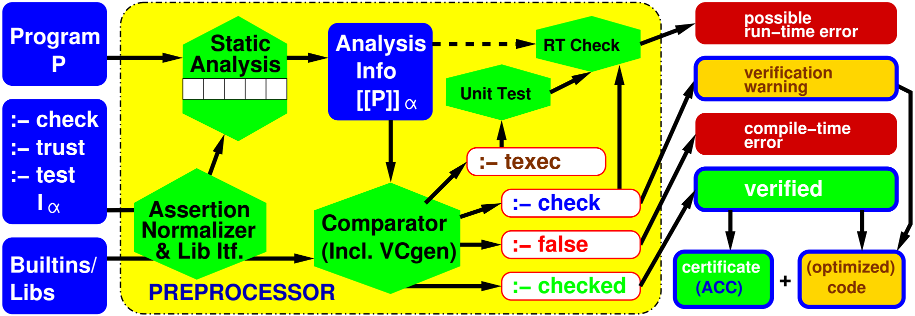
- Provide the flexibility of dynamic languages, but with
- *Guaranteed safety, reliability, and efficiency.*

- 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.
    - Unboxing.
    - Specialization, slicing, ...
    - Automatic parallelization.

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

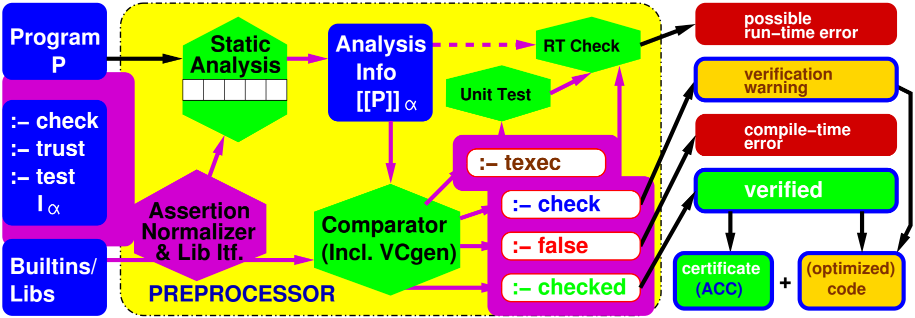
[AADEBUG'97, LNCS'99, LOPSTR'99, PBH00a, SAS'03, SCP'05, LPAR'06, ICLP'09]

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



[AADEBUG'97, LNCS'99, ICLP'99, LOPSTR'99, PBH00a, SAS'03, LPAR'04, ICLP'09, TPLP'18, FOPARA'12, ICLP'10]

The Assertion Language



- Assertions optional, can be added at any time. Provide partial spec.
- *Sets* of pre/post/global triples (+ "status" field, documentation, ...).
- Used everywhere, for many purposes (incl. doc gen., foreign itf).
- System makes it worthwhile for the programmer to include them.
- Part of the programming language and "runnable."

[ESOP'96, AADEBUG'97, ILPS-WS'97, LNCS'00, ICLP'09, PPDP'14, LOPSTR-Informal'18]

The Assertion Language (Subset)

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

Each typically a "mode" of use; the set *covers the valid calls*.

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

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

Properties; from libraries or user defined (in the source language):

:- regtype color := green | blue | red.
:- 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]).

Types/shapes, cost, data sizes, aliasing, termination, determinacy, non-failure, ...

Program-point Assertions:

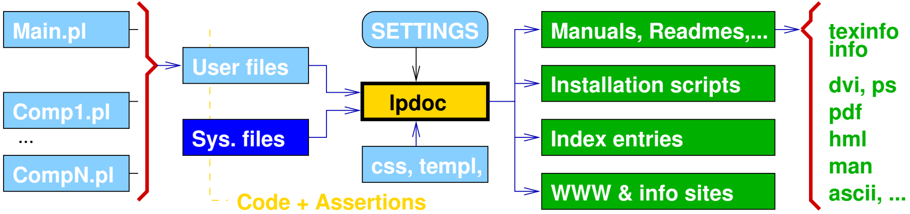
- Inlined with code: `..., check( int(X), X>0, mshare([[X]]) ), ....`

Assertion Status (so far "to be checked" – check status – default)

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

[ESOP'96, AADEBUG'97, ILPS-WS'97, LNCS'00, ICLP'09, PPDP'14, LOPSTR-Informal'18]

Autodocumenter: LPdoc



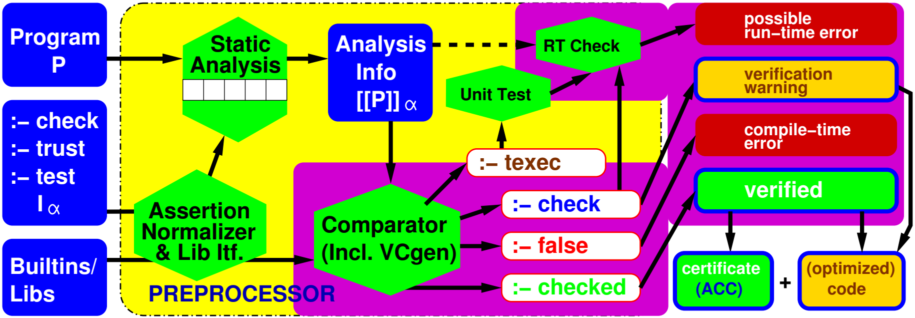
- Uses:
  - All the information that the compiler has.
  - **Assertions.**
  - Doc declarations and "active comments:"

```
:- 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) + markdown.
  - All Ciao manuals, tutorials, and sites generated with LPdoc.

[CL2000]

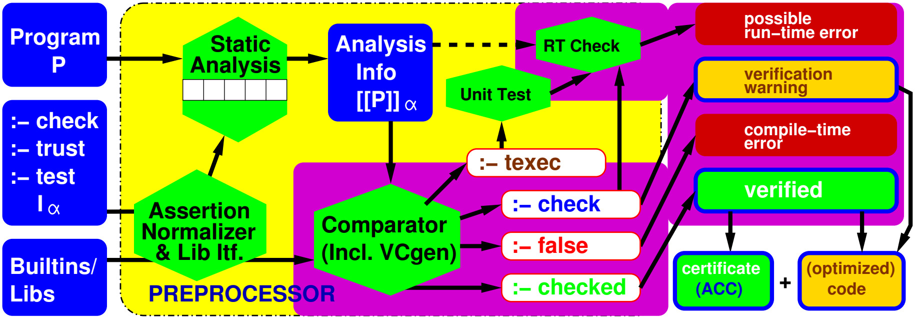
Integrated Static/Dynamic Debugging and Verification



	Definition	Sufficient condition
P is prt. correct w.r.t. $\mathcal{I}_\alpha$ if	$\alpha([\![P]\!]) \leq \mathcal{I}_\alpha$	$[\![P]\!]_{\alpha^+} \leq \mathcal{I}_\alpha$
P is complete w.r.t. $\mathcal{I}_\alpha$ if	$\mathcal{I}_\alpha \leq \alpha([\![P]\!])$	$\mathcal{I}_\alpha \leq [\![P]\!]_{\alpha^=}$
P is incorrect w.r.t. $\mathcal{I}_\alpha$ 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. $\mathcal{I}_\alpha$ if	$\mathcal{I}_\alpha \not\leq \alpha([\![P]\!])$	$\mathcal{I}_\alpha \not\leq [\![P]\!]_{\alpha^+}$

[AADEBUG'97, LNCS'99, LOPSTR'99, PBH00a, SAS'03, PPDP'05, LPAR'06, PEPM'08, ICLP'09]

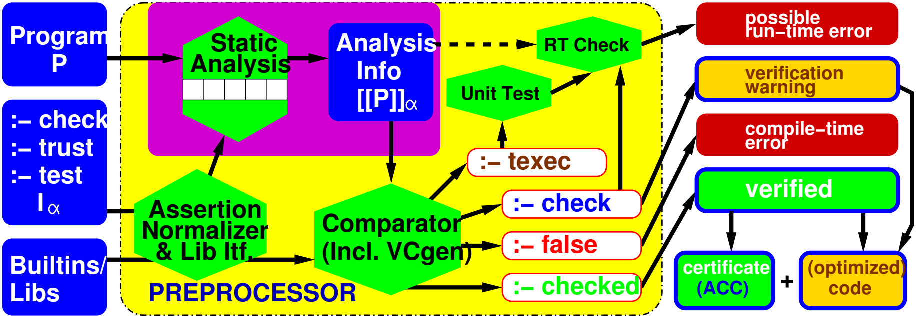
Integrated Static/Dynamic Debugging and Verification



- Based throughout on the notion of *safe approximation* (abstraction).
- Run-time checks generated for *parts* of asserts. 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.

[AADEBUG'97, LNCS'99, LOPSTR'99, PBH00a, SAS'03, PPDP'05, LPAR'06, PEPM'08, ICLP'09]

The Analyses



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

[LOPSTR'07] [JLP'92, TOPLAS'99, SAS'96, TOPLAS'00, FTfJP'07, LOPSTR-Informal'18, ICLP'18]
[POPL'94, ESOP'96, ENTCS'00, JLP'97, TOPLAS'96, TOPLAS'95, LOPSTR'01, LPAR'06, PEPM'08]
[ICLP'88, NACLP'89, ICLP'91, ICLP'97, SAS'02, FLOPS'04, LOPSTR'04, PADL'06, ICLP'08]
[VMCAI'08, LCPC'08, PASTE'08, CC'08, ISMM'09, NGC'10, LCPC'08] [PLDI'90, PASCO'94, JSC'96, SAS'94, ILPS'97]
[CLEI'06, ICLP'07, PPDP'08, NASA FM'08, Bytecode'09, ICLP'10, ICLP'13, LOPSTR'13, TPLP'14, ICLP'16, FLOPS'16]

Demo: assertions, static errors (types, data sizes, procedure cost, non-determinacy, ...), run-time check generation, certification, unit tests...

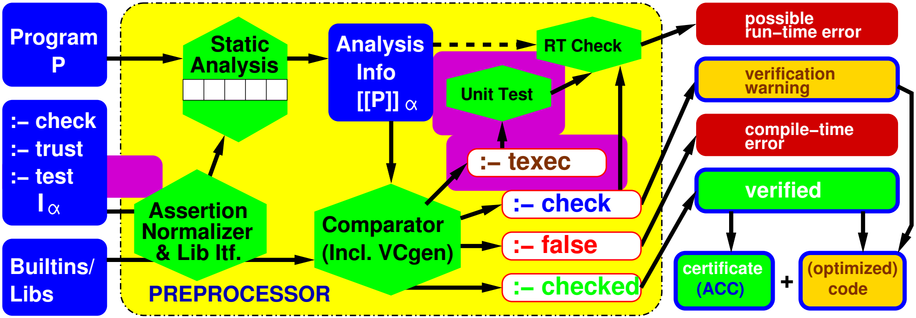
Discussion: Comparison with *Classical* Types

"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*).

[AADEBUG'97, LNCS'99, ICLP'99, LOPSTR'99, PBH00a, SAS'03, SCP'05, LPAR'06, ICLP'09]

Integration of Testing

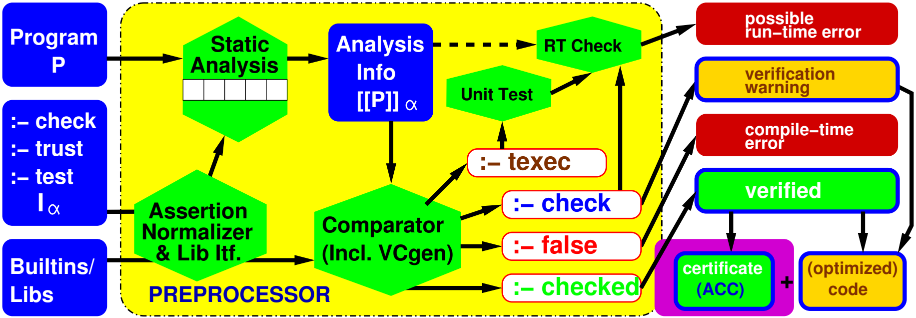


Many interactions within the integrated framework:

- (Unit) tests are part of the assertion language:
  `:- test Pred [:Precond] [=>Postcond] [+CompExecProps].`
- Parts of unit tests that can be verified at compile-time are deleted.
- Unit testing uses the run time assertion-checking machinery.
- Unit tests also provide test cases for the run-time checks.
  - Assertions checked by unit testing, even if not conceived as tests.

[ICLP'09]

Abstraction-based Certification, Abstraction-Carrying Code



PRODUCER

$[\![P]\!]_\alpha$ = Analysis = **lfp**(*analysis_step*)

Certificate $\subset [\![P]\!]_\alpha$
Certificate $\rightarrow$ Safety Policy

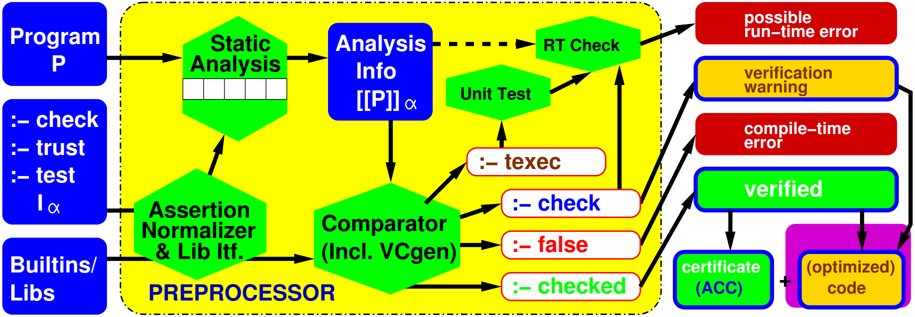
CONSUMER

Checker = *analysis_step*

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

[LPAR'04, COCV'04, PPDP'05, TPLP'12]

Optimization



- Source-level optimizations:
  - Partial evaluation, (multiple) (abstract) specialization, ...
- Low-level optimizations (e.g., dynamic check elimination, unboxing):
  - Use of specialized instructions.
  - Optimized native code generation.

$\rightarrow$ obtaining close-to-C performance for dynamic languages.

- Parallelization. Granularity control.

[PADL'04, CASES'06] [TPLP'11, SAS'06, PPDP'06, LOPSTR'05, PEPM'03, PLILP'91, PEPM'99, JLP'99] [TCS'09, LOPSTR'07, TOPLAS'00] [TOPLAS'99, JLP'99, PLILP'96, CompLangJ'96, JLP'95, SAS'94, ICLP'91, NGC'91, ?] [DAMP'07, JSC'96, PASCO'94, PLDI'90]

Partial Evaluation

CiaoPP includes a state-of-the-art partial evaluator

- Partial *deduction* (i.e., fold/unfold), poly-controlled, efficient, slicing, conjunctive, ...
- Polyvariant, modular **abstract** specialization (i.e., specialization w.r.t. abstract values).

→ Fully interleaved **integration of partial evaluation within abstract interpreter** ("Abstract Interpretation with Specialized Definitions").

Shown strictly more powerful than any separate analysis/peval approach.

- Applied together with lower-level optimizations to parallelization, run-time check optimization, etc.

[TPLP'11, SAS'06, PPDP'06, LOPSTR'05, PEPM'03, PEPM'99, JLP'99, PLILP'91]

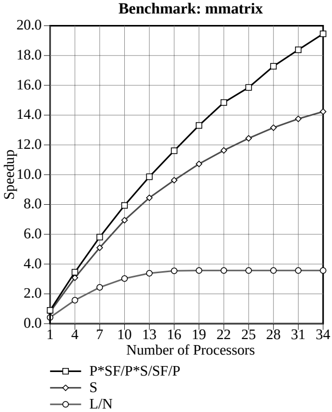
Optimizing Compilation

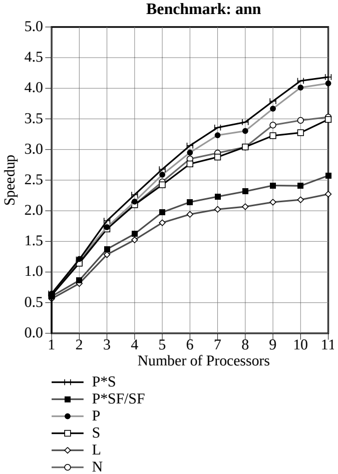
- Combine high-level instantiation, regular types, determinism, non-failure analyses with low-level analyses (choice-point analysis, heap usage, liveness, etc.).
  Used in multiple optimizations [PADL'04]:
  - Specialized unification, builtins, control structures; unboxing of argument and local variables (e.g., untagged int).
  - Same mechanism useful to reproduce hand-made instruction specializations in the bytecode emulator (reconstructed from a reduced set of unoptimized instructions) [TPLP'16, LOPSTR'06] $\rightarrow$ automatic generation of specialized emulators (e.g., with no non-determinism if not used).
- Emulator written in Ciao dialect [LOPSTR'06], multiple backends (e.g., Javascript [ICLP'12]).
- Case study for small devices (sound spatializer) [CASES'06]:

Compilation mode	**Non-Specialized**	**Specialized**
Bytecode	25.64	14.00
N.C. via C	21.59	11.99
Id. + semidet	19.59	11.53
Id. + mode/type	19.19	11.08
Id. + unboxing	6.97	**3.62**

[TPLP'16, LOPSTR'15, ICLP'12, PPDP'08, LOPSTR'06, CASES'06, ICLP'05, PADL'04]

Some Speedups (Using Different Abstract Domains)



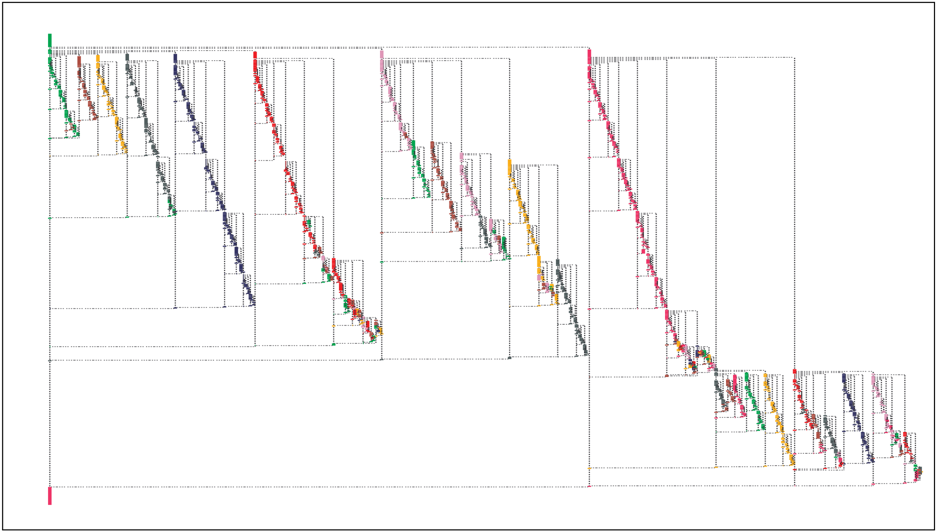


(ann: parallelizer parallelizing itself; 1-10 proc.: actual speedups on Sequent Symmetry; 10+ simulator projections from execution traces)

[TCS'09, LOPSTR'07, EuroPar'07, TOPLAS'00, TOPLAS'99, JLP'99, JLP'99, PLILP'96, CompLangJ'96, JLP'95, SAS'94]

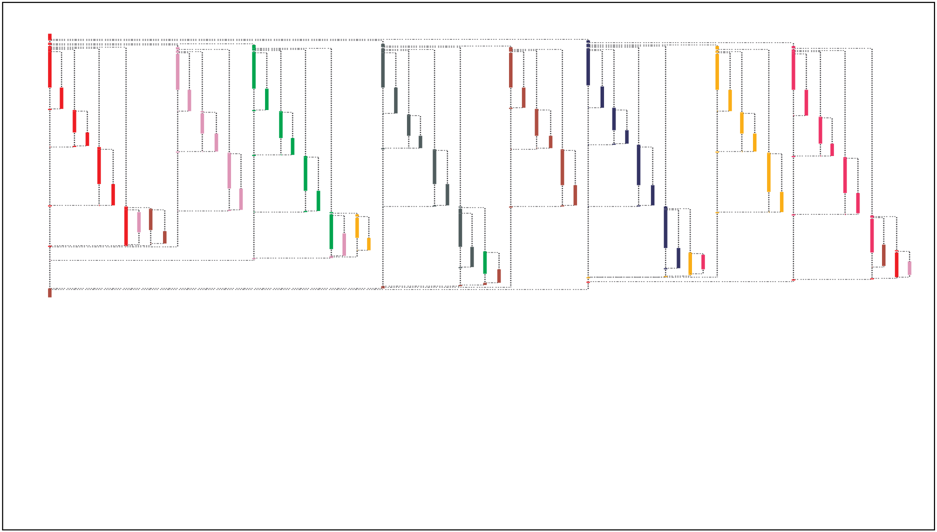
[ICLP'91, PLILP'91, NGC'91, ICLP'90, NACLP'89]

8 Processors



[DAMP'07, JSC'96, ICLP'95, PASCO'94, PLDI'90]

8 Processors, with Granularity Control (Same Scale)



[DAMP'07, JSC'96, ICLP'95, PASCO'94, PLDI'90]

Outline

Early 2000's

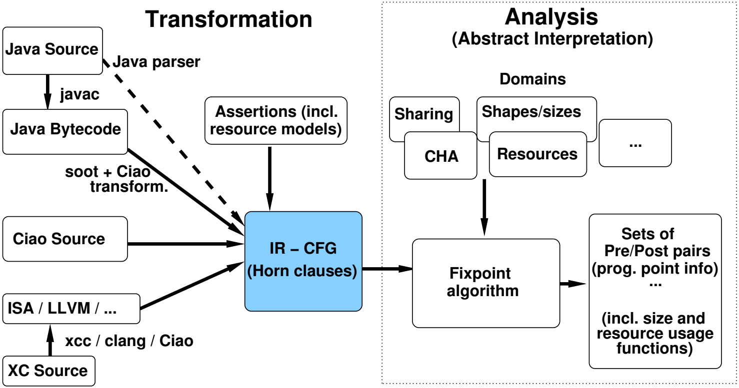
- Generalization of Ciao assertions model / CiaoPP to
  analyzing/verifying different languages by translation to Horn clauses. [LOPSTR'07]
  - Also allows analyzing/verifying multi-language applications.
  - First Constraint Horn Clause-based analyzer for non-logic languages?
- Extension to other properties (timing, energy).

→ Using CiaoPP as a general-purpose analysis and verification tool.

- The technique was already used early on (in our MA3 analyzer): we called it "abstract compilation" [ICLP'88].
- Approach quite popular now!

[LOPSTR'07, ICLP'88]

CiaoPP Intermediate Repr.: (Constraint) Horn Clauses



- Transformation:
  - Source: Program P in L_P + (possibly abstract) Semantics of L_P
  - Target: A (C) Horn Clause program capturing $[\![P]\!]$ (or, possibly, $[\![P]\!]^{\alpha}$)
- Block-based CFG. Each block represented as a *Horn clause*.
- Used for all analyses: aliasing, CHA/shape/types, data sizes, resources, etc.
- Allows supporting multiple languages.

[LOPSTR'07, ICLP'88]

Transformation Example - Java Source

Multiplying numbers from 1 to n (factorial)

source

```java
public static int r(int n)
{
  int ans=1;
  while(n>0)
  {
    ans*=n;
    n-=1;
  }
  return ans;
}
```

Horn clause IR

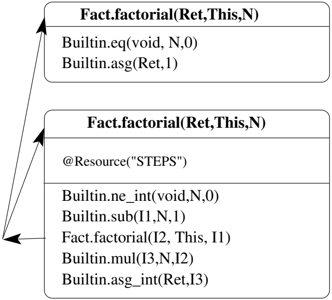
```prolog
:- pred r/2 : num * var.

r(N,Ret) :-
        Ans .=. 1,
        r_1(N, Ans, Ret).

r_1(N, Ans, Ret) :-
        N .>. 0,
        mul(Ans, N, Ans1),
        N1 .=. N - 1,
        r_1(N1, Ans1, Ret).
r_1(N, Ans, Ret):-
        N .=<. 0,
        Ret .=. Ans.
```

The HC IR:

- Reduces everything to recursions, which simplifies analysis.
- Makes the semantics of loops, recursions, etc. precise: all variables, increments/decrements, scoping, etc. are explicit.
- Allows “small-step” and “big-step” variants.

[LOPSTR’07, ICLP’88, VMCAI’08, FTfJP’07, Bytecode’07, Bytecode’09]

Transformation Example - Java Bytecode



→

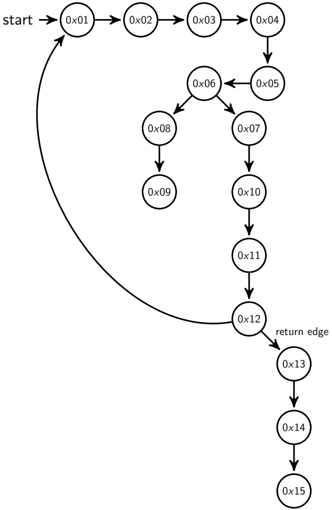
```
:- entry 'Fact.factorial'/3:var*atm*num.

'Fact.factorial'(Ret, This, N):-
        eq_int(void,N,int,0,int),
        asg_int(Ret,int,1,int).

'Fact.factorial'(Ret, This, N):-
        ne_int(void,N,int,0,int),
        sub(I1,int,N,int,1,int),
        Fact.factorial(I2,This,I1),
        mul(I3, int,N,int,I2,int),
        asg_int(Ret,int,I3,int).
```

[LOPSTR'07, ICLP'88, Bytecode'09, VMCAI'08, FTfJP'07, Bytecode'07, Bytecode'09, NASA FM'08]

Transformation example - binaries

Xcore ISA Example: Control Flow Graph (CFG)

```
<fact>:
0x01: entsp (u6)    0x2
0x02: stw   (ru6)   r0, sp[0x1]
0x03: ldw   (ru6)   r1, sp[0x1]
0x04: ldc   (ru6)   r0, 0x0
0x05: lss   (3r)    r0, r0, r1
0x06: bf    (ru6)   r0, 0x1 <0x08>
0x07: bu    (u6)    0x2 <0x10>
0x08: mkmsk (rus)   r0, 0x1
0x09: retsp (u6)    0x2
0x10: ldw   (ru6)   r0, sp[0x1]
0x11: sub   (2rus)  r0, r0, 0x1
0x12: bl    (u10)   -0xc <fact>
0x13: ldw   (ru6)   r1, sp[0x1]
0x14: mul   (l3r)   r0, r1, r0
0x15: retsp (u6)    0x2
```

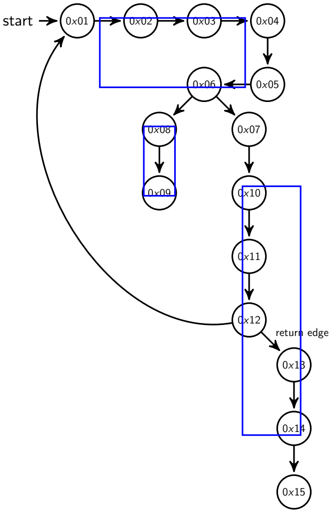


[LOPSTR'07, ICLP'88, TPLP'18, FOPARA'15, HIP3ES'15, LOPSTR'13]

Transformation example - binaries

Xcore ISA Example: Block Representation

```
<fact>
0x01: entsp (u6)    0x2
0x02: stw  (ru6)    r0, sp[0x1]
0x03: ldw  (ru6)    r1, sp[0x1]
0x04: ldc  (ru6)    r0, 0x0
0x05: lss  (3r)     r0, r0, r1
0x06: bf  (ru6)     r0, 0x1 <0x08>

0x07: bu  (u6)      0x2 <0x10>
0x10: ldw  (ru6)    r0, sp[0x1]
0x11: sub  (2rus)   r0, r0, 0x1
0x12: bl  (u10)     -0xc <fact>
0x13: ldw  (ru6)    r1, sp[0x1]
0x14: mul  (l3r)    r0, r1, r0
0x15: retsp (u6)    0x2

0x08: mkmsk  (rus)  r0, 0x1
0x09: retsp (u6)    0x2
```

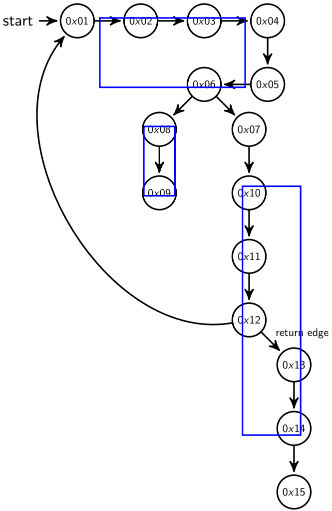


[LOPSTR'07, ICLP'88, TPLP'18, FOPARA'15, HIP3ES'15, LOPSTR'13]

Transformation example - binaries

Xcore ISA Example: Constrained Horn Clauses IR

```
:- entry fact/2.
fact(R0,R0_3):-
      entsp(_),
      stw(R0,Sp0x1),
      ldw(R1,Sp0x1),
      ldc(R0_1,0x0),
      lss(R0_2,R0_1,R1),
      bf(R0_2,_),
      bf01(R0_2,Sp0x1,R0_3,R1_1).

bf01(1,Sp0x1,R0_4,R1):-
      bu(_),
      ldw(R0_1,Sp0x1),
      sub(R0_2,R0_1,0x1),
      bl(_),
      fact(R0_2,R0_3),
      ldw(R1,Sp0x1),
      mul(R0_4,R1,R0_3),
      retsp(_).

bf01(0,Sp0x1,R0,R1):-
      mkmsk(R0,0x1),
      retsp(_).
```



[LOPSTR'07, ICLP'88, TPLP'18, FOPARA'15, HIP3ES'15, LOPSTR'13]

Generating the Intermediate Representation

- Typical tasks:
  - Generation of block-based CFG.
  - SSA transformation (e.g., splitting of input/output param).
  - Conversion of loops into recursions among blocks.
  - Branching, cases, dynamic dispatch → blocks w/same signature.
- Some specifics for Java bytecode:
  - Elimination of stack variables.
  - Conversion to three-address statements.
  - Explicit representation of this and ret as extra block parameters.
- Some specifics for binaries:
  - Control flow graph is constructed from ISA or LLVM IR representation.
  - Inferring block parameters.
  - Resolving branching to predicates with multiple clauses.
- Can be done via:
  - **partial evaluation of an interpreter** (implementing the semantics of the low-level code) w.r.t. the concrete low-level program or
  - **directly** (cf. Futamura projections).

[LOPSTR'07, ICLP'88, NASA FM'08, VMCAI'08, Bytecode'09, FOPARA'15, LOPSTR'13, HIP3ES'15, TPLP'18]

User-Definable Resources: Some Results (Java Bytecode)

Program	Resource(s)	t	Resource Usage Func. (*) / Metric	
BST	Heap usage	367	$O(2^n)$	$n \equiv$ tree depth
CellPhone	SMS monetary cost	386	$O(n^2)$	$n \equiv$ packets length
Client	Bytes received and	527	$O(n)$	$n \equiv$ stream length
	Bandwidth required		$O(1)$	—
Dhrystone	Energy consumption	759	$O(n)$	$n \equiv$ int value
Divbytwo	Stack usage	219	$O(log_2(n))$	$n \equiv$ int value
Files	Files left open and	649	$O(n)$	$n \equiv$ number of files
	Data stored		$O(n \times m)$	$m \equiv$ stream length
Join	DB accesses	460	$O(n \times m)$	$n, m \equiv$ table records
Screen	Screen width	536	$O(n)$	$n \equiv$ stream length

- Different cost/complexity functions, resources, size metrics, types of loops/recursion, etc.

(*) We represent just order for brevity (but full upper and lower bounds inferred).

[Bytecode'09, VMCAI'08, LOPSTR'07, FTfJP'07]

Time Bound Function Analysis

Cost model: cost assertions with the (WAM) bytecode instruction execution costs:

Examples

```
:- trust pred unify_variable(A, B) : int(A), int(B)
   + ( cost(ub, exectime, 667.07),
       cost(lb, exectime, 667.07) ).

:- trust pred unify_variable(A, B) : var(A), gnd(B)
   + ( cost(ub, exectime, 233.3),
       cost(lb, exectime, 233.3) ).

:- trust pred unify_variable(A, B): list(A), list(B)
   + cost(ub, exectime, 271.58+284.34*length(A) ).
...
```

- Automatically generated in a one-time profiling phase (regression).
- Made available to static cost analyzer, which uses it to infer timing bound functions for any program.

[PPDP'08, PADL'07, ICLP'07]

Observed and Estimated Execution Time (Intel)

Pr. No.	Cost. App.	Est.	Prf.	Intel (μs) Obs.	D. %	Pr.D. %
1	E	110	110	113	-2.4	-2.4
2	E	69	69	71	-2.3	-2.3
3	E	1525	1525	1576	-3.3	-3.3
4	E	1501	1501	1589	-5.7	-5.7
5	E	2569	2569	2638	-2.7	-2.7
6	E	1875	1875	2027	-7.8	-7.8
7	E	1868	1868	1931	-3.3	-3.3
8	L	43	68	81	-67.2	-17.8
	U	3414	3569	3640	-6.4	-2.0
9	L	54	79	91	-54.6	-14.8
	U	3414	3694	4011	-16.2	-8.2
10	L	135	142	124	8.6	13.7
	U	7922	2937	2858	120.6	2.7
11	L	216	138	111	72.3	22.5
	U	226	216	162	34.0	29.5

[PPDP'08, PADL'07, ICLP'07]

Energy Consumption Analysis – Approach

Requires low-level modeling – approach: [NASA FM'08]

- Specialize our parametric resource analysis with instruction-level models:
  - Provide energy and data size assertions for each individual instruction. (Energy and data sizes can be constants or *functions*.)
- CiaoPP then generates statically safe upper- and lower-bound energy consumption functions.

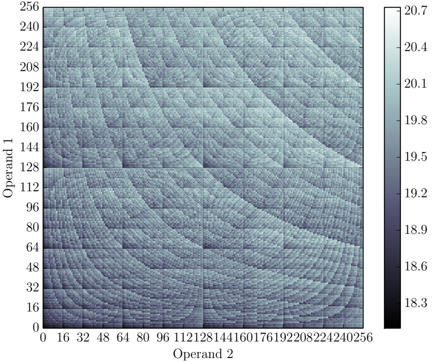
⇒ Addressed recently:

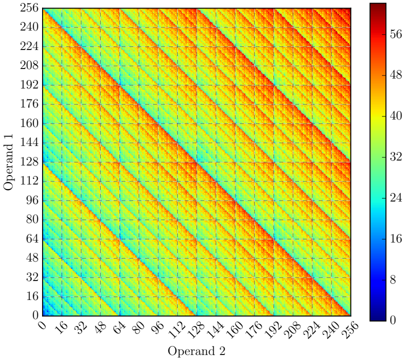
- Analysis of (embedded) programs written in XC, on XMOS processors.
- Using more sophisticated *ISA- and LLVM-level energy models* for XMOS XS1 (Bristol & XMOS).
- Comparing to measured energy consumption.

[NASA FM'08, LOPSTR'13, HIP3ES'15, FOPARA'15, HIP3ES'16, TPLP'18]

Low-level ISA Characterization – Operand Size

Obtaining the Cost Model: Energy Consumption/Instruction; Operand Size.

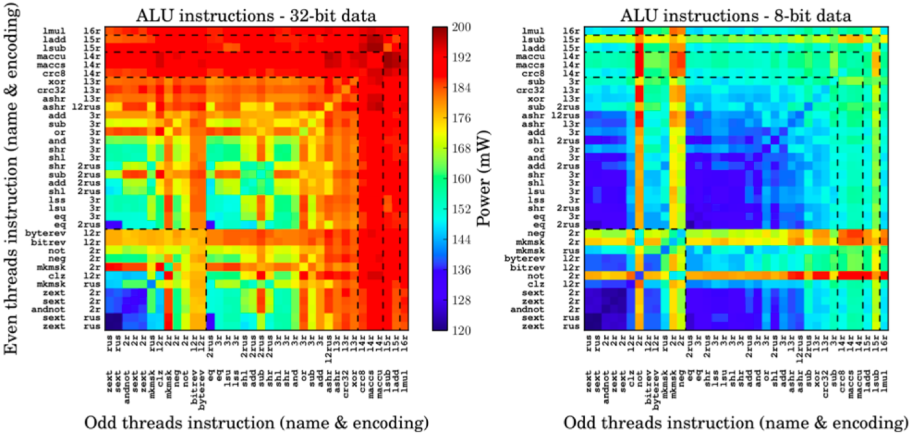




Eder, Kerrison – Bristol U / XMOS.

Low-level ISA Characterization – Interference

Obtaining the Cost Model: Energy Consumption/Instruction; Interference.



Eder, Kerrison – Bristol U / XMOS.

Energy Model, Expressed in the Ciao Assertion Language

energy.pl

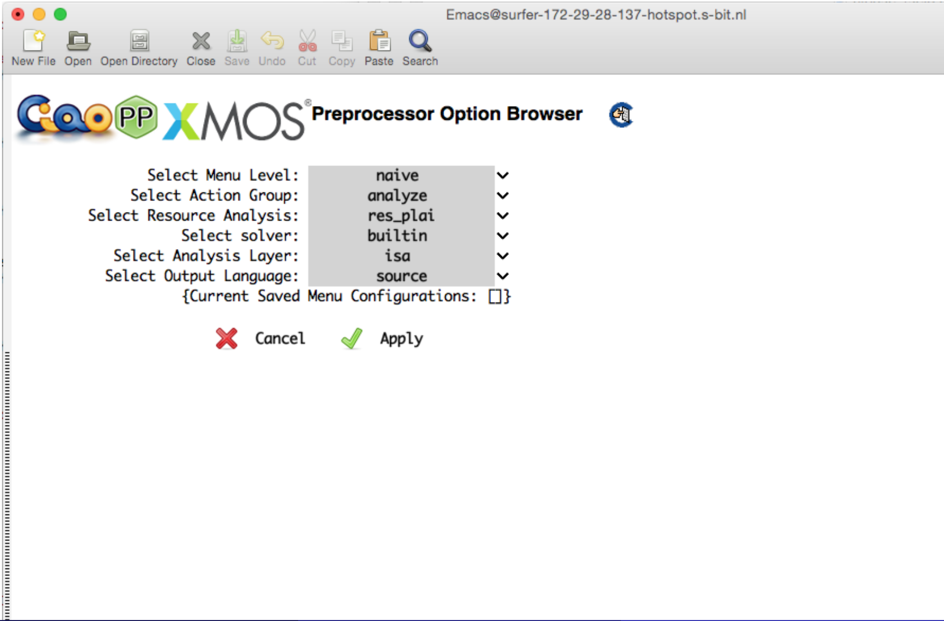
```
:- package(energy).
:- use_package(library(resources(definition))).
:- load_resource_definition(ciaopp(xcore(model(res_energy)))).

:- trust pred mkmsk_rus2(X)
       : var(X) => (num(X), rsize(X,num(A,B)))
       + ( resource(energy, 1112656, 1112656) ).

:- trust pred add_2rus2(X)
       : var(X) => (num(X), rsize(X,num(A,B)))
       + ( resource(energy, 1147788, 1147788) ).

:- trust pred add_3r2(X)
       : var(X) => (num(X), rsize(X,num(A,B)))
       + ( resource(energy, 1215439, 1215439 )).

:- trust pred sub_2rus2(X)
       : var(X) => (num(X), rsize(X, num(A,B)))
       + ( resource(energy, 1150574, 1150574)).

:- trust pred sub_3r2(X)
       : var(X) => (num(X), rsize(X,num(A,B)))
       + ( resource(energy, 1210759, 1210759 )).

:- trust pred ashr_l2rus2(X)
       : var(X) => (num(X), rsize(X,num(A,B)))
       + ( resource(energy, 1219682, 1219682) ).
```

--:--- energy.pl Top L1 (Ciao)--

Very simple model depicted (constant cost) but real models can include:

- Data properties: operand sizes or other (e.g., number of 1's, bits changing, ...).
- External parameters (voltage, clock, ...).
- List of previous instructions, pipeline state, cache state, etc.

CiaoPP Menu


Emacs@surfer-172-29-28-137-hotspot.s-bit.nl
New File
Open
Open Directory
Close
Save
Undo
Cut
Copy
Paste
Search
Preprocessor Option Browser
Select Menu Level: naive
Select Action Group: analyze
Select Resource Analysis: res_plai
Select solver: builtin
Select Analysis Layer: isa
Select Output Language: source
{Current Saved Menu Configurations: []}
Cancel
Apply

Analysis Results

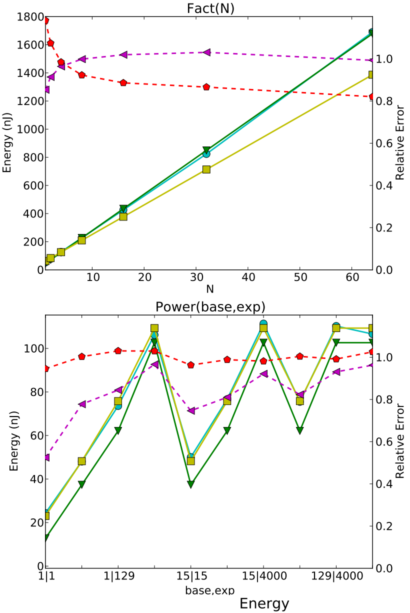
fact_results.pl

```
:- module(_,[fact/2],[ciaopp(xcore(model(instructions))),ciaopp(xcore(model(energy))),assertions]).

:- true pred fact(X,Y)
         : ( num(X), var(Y) )
        => ( num(X), num(Y), rsize(X,num(A,B)), rsize(Y,num('Factorial'(A),'Factorial'(B))) )
         + ( resource(energy, 6439360, 21469718 * B + 16420396) ).

fact(X,Y) :-
        entsp_u62(_3459),
        _3467 is X,
        stw_ru62(_3476),
        _3484 is X,
        stw_ru62(_3493),
        _3501 is _3467,
        ldw_ru62(_3510),
        _3518 is 0,
        ldc_ru62(_3527),
        _3518<_3501,
        lss_3r2(_3544),
        bt_ru62(_3552),
        1\=0,
        _3569 is _3467,
        ldw_ru62(_3578),
        _3586 is _3569-1,
        sub_2rus2(_3598),
        _3606 is _3569,
        stw_ru62(_3615),
        _3623 is _3586+0,
--:---  fact_results.pl    Top L11    (Ciao)-------------------------------------------
```

Analysis Output

```
#include "fact.h"

#pragma true fact(A) ==> (energy <= 2845229*A+1940746)

int fact(int i) {
  if(i<=0)  return 1;
  return i*fact(i-1);
}
```

Some Results [LOPSTR'13]



XC Analysis Results (FIR Filter, LLVM IR Level) [FOPARA'15]

```
#pragma true fir(xn, coeffs, state, N) :
            (3347178*N + 13967829 <= energy &&
             energy <= 3347178*N + 14417829)
```

```
int fir(int xn, int coeffs[], int state[], int ELEMENTS)
{
  unsigned int ynl; int ynh;
  ynl = (1<<23); ynh = 0;
  for(int j=ELEMENTS-1; j!=0; j--) {
      state[j] = state[j-1];
      {ynh, ynl} = macs(coeffs[j], state[j], ynh, ynl);
  }
  state[0] = xn;
  {ynh, ynl} = macs(coeffs[0], xn, ynh, ynl);
  if (sext(ynh,24) == ynh) {
      ynh = (ynh << 8) | (((unsigned) ynl) >> 24);}
  else if (ynh < 0) { ynh = 0x80000000; }
  else { ynh = 0x7fffffff; }
  return ynh;
}
```

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  }
  state[0] = xn;
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  if (sext(ynh,24) == ynh) {
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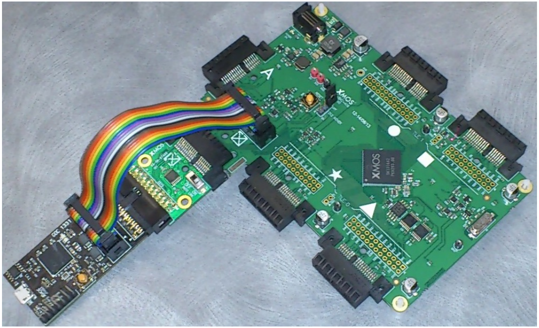
  else if (ynh < 0) { ynh = 0x80000000; }
  else { ynh = 0x7fffffff; }
  return ynh;
}
```

Measuring Power Consumption on the Hardware

- XMOS XTAG3 measurement circuit.
- Plugs into XMOS XS1 board.



We compare these HW measurements with:

- Static Resource Analysis (SRA).
- Instruction Set Simulation (ISS).

Accuracy vs. HW measurements (ISA and LLVM IR) [FOPARA'15]

Program	Error vs. HW		ISA/LLVMIR
	isa	llvmir	
fact(N)	2.86%	4.50%	0.94
fibonacci(N)	5.41%	11.94%	0.92
sqr(N)	1.49%	9.31%	0.91
power_of_two(N)	4.26%	11.15%	0.93
Average	**3.50%**	**9.20%**	**0.92**
reverse(N,M)	N/A	2.18%	N/A
concat(N,M)	N/A	8.71%	N/A
mat_mult(N,M)	N/A	1.47%	N/A
sum_facts(N,M)	N/A	2.42%	N/A
fir(N)	N/A	0.63%	N/A
biquad(N)	N/A	2.34%	N/A
Average	**N/A**	**3.0%**	**N/A**
Gobal Avg.	**3.50%**	**5.48%**	**0.92**

Accuracy vs. HW measurements (ISA and LLVM IR) [FOPARA'15]

Program	Error vs. HW		ISA/LLVMIR
	isa	llvmir	
fact(N)	2.86%	4.50%	0.94
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sqr(N)	1.49%	9.31%	0.91
power_of_two(N)	4.26%	11.15%	0.93
biquad(N)	N/A	2.34%	N/A
Average	**N/A**	**3.0%**	**N/A**
Gobal Avg.	**3.50%**	**5.48%**	**0.92**

- ISA analysis estimations are reasonably accurate.
- ISA estimations are more accurate than LLVM estimations.
- LLVM estimations are close to ISA estimations.
- Some programs cannot be analysed at the ISA level but can be analyzed at the LLVM level.

XC Program (FIR Filter) w/Energy Specification [HIP3ES'15, TPLP'18]

```
#pragma check fir(xn, coeffs, state, N) :
            (1 <= N) ==> (energy <= 416079189)

#pragma true fir(xn, coeffs, state, N) :
               (3347178*N + 13967829 <= energy &&
                energy <= 3347178*N + 14417829)

#pragma checked fir(xn, coeffs, state, N) :
               (1 <= N && N <= 120) ==> (energy <= 416079189)

#pragma false fir(xn, coeffs, state, N) :
               (121 <= N) ==> (energy <= 416079189)

int fir(int xn, int coeffs[], int state[], int ELEMENTS)
{
  unsigned int ynl; int ynh;
  ynl = (1<<23); ynh = 0;
  for(int j=ELEMENTS-1; j!=0; j--) {
      state[j] = state[j-1];
      {ynh, ynl} = macs(coeffs[j], state[j], ynh, ynl);
  }
  state[0] = xn;
  {ynh, ynl} = macs(coeffs[0], xn, ynh, ynl);
  if (sext(ynh,24) == ynh) {
      ynh = (ynh << 8) | (((unsigned) ynl) >> 24);}
  else if (ynh < 0) { ynh = 0x80000000; }
  else { ynh = 0x7fffffff; }
  return ynh;
}
```

XC Program (FIR Filter) w/Energy Specification [HIP3ES'15, TPLP'18]

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#pragma true fir(xn, coeffs, state, N) :
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             (121 <= N) ==> (energy <= 416079189)

int fir(int xn, int coeffs[], int state[], int ELEMENTS)
{
  unsigned int ynl; int ynh;
  ynl = (1<<23); ynh = 0;
  for(int j=ELEMENTS-1; j!=0; j--) {
      state[j] = state[j-1];
      {ynh, ynl} = macs(coeffs[j], state[j], ynh, ynl);
  }
  state[0] = xn;
  {ynh, ynl} = macs(coeffs[0], xn, ynh, ynl);
  if (sext(ynh,24) == ynh) {
      ynh = (ynh << 8) | (((unsigned) ynl) >> 24);}
  else if (ynh < 0) { ynh = 0x80000000; }
  else { ynh = 0x7fffffff; }
  return ynh;
}
```
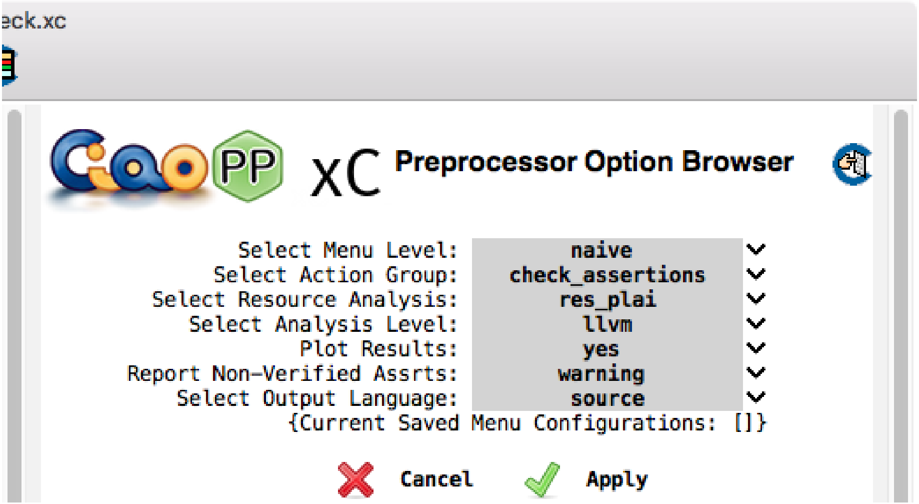
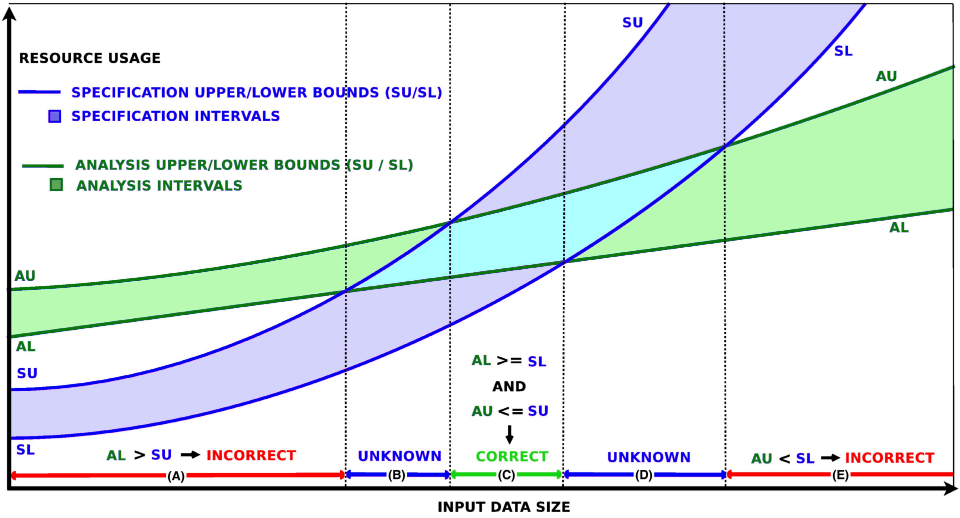

CiaoPP Menu


eck.xc
xC Preprocessor Option Browser
Select Menu Level: naive
Select Action Group: check_assertions
Select Resource Analysis: res_plai
Select Analysis Level: llvm
Plot Results: yes
Report Non-Verified Assrts: warning
Select Output Language: source
{Current Saved Menu Configurations: []}
Cancel
Apply

Resource Usage Verification



[TPLP'18, FOPARA'12, ICLP'10] [AADEBUG'97, LNCS'99, PBH00a, SCP'05, ICLP'09]

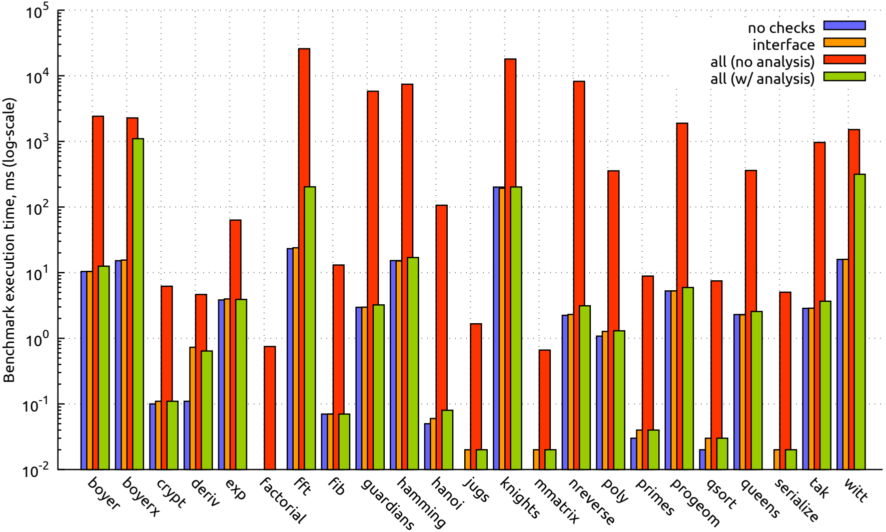
Outline

Dynamic Checking of Assertions: Optimizations

- Checking complex properties (like shape of terms) may incur significant performance penalty and can often even change program complexity.
- Same problem observed in the context of gradual typing for functional programs.
- Contributed several solutions:
  - Simplify assertions (based on static analysis) to remove checks.
  - Cache checks at run time (exploit immutable data and monotonous updates).
  - Restrict symbol visibility (when possible) to enforce stronger data invariants.

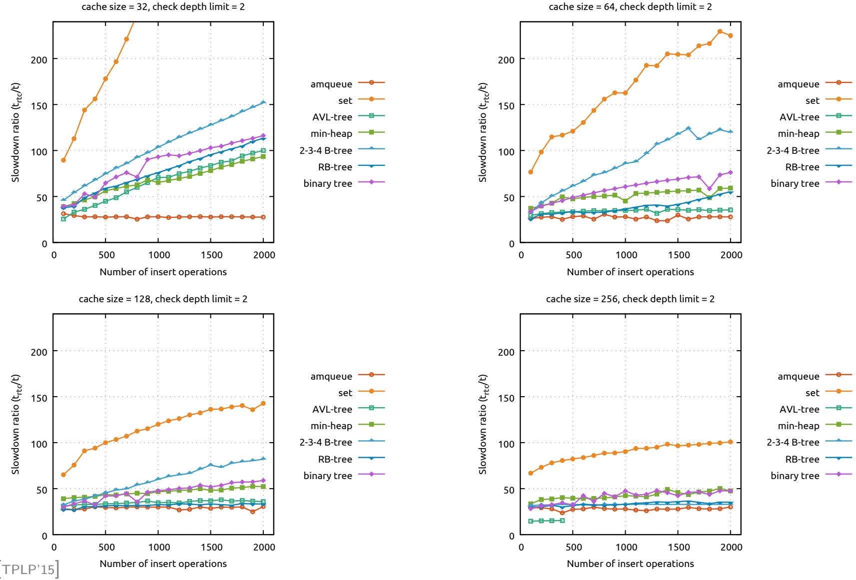
[PPDP'18, PADL'18, PPDP'16, TPLP'15]

Dynamic Checking of Assertions: Optimizations



[PPDP'18]

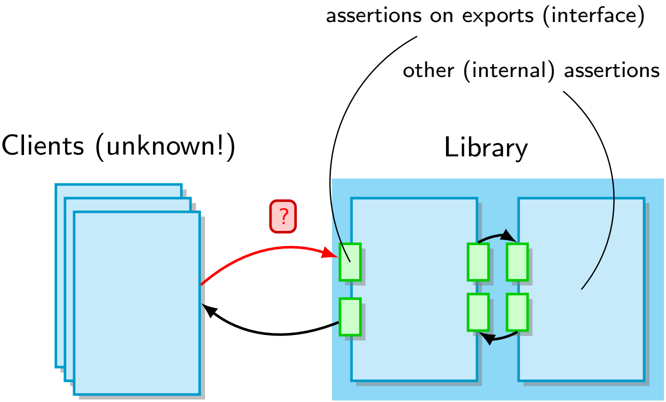
Dynamic Checking of Assertions: Optimizations



[TPLP'15]

Dynamic Checking of Assertions: Optimizations

Shallow run-time checking




```
:- hide e/0. :- hide t/3. % hidden functors
tree(e).      tree(t(L,X,R)) :- tree(L), int(X), tree(R).
% (auto-computed) =======>
tree#(e).     tree#(t(_,_,_)). % shallow property
```

[PADL'18]

More expressive higher-order assertions [?]

More powerful description of meta-arguments – we introduce:

- anonymous assertions.
- predprops (predicate properties).

Can apply all the assertion to meta-arguments.

```
:- comparator(Cmp) {
  :- pred Cmp(Res,M,N) : num(M), num(N)
                       => between(-1,1,Res). }.

:- pred my_min(X,Y,Cmp,Min) : comparator(Cmp).

my_min(X,Y,P,Min) :-
     P(R,X,Y), (R < 0 -> Min = X ; Min = Y).

test_min :- my_min(4,2,compA,2).

compI( 0,A,B) :- A = B.     compA(=,A,B) :- A = B.
compI(-1,A,B) :- A < B.     compA(<,A,B) :- A < B.
compI( 1,A,B) :- A > B.     compA(>,A,B) :- A > B.
```

[PPDP'14]

Semantic Search

Main idea:

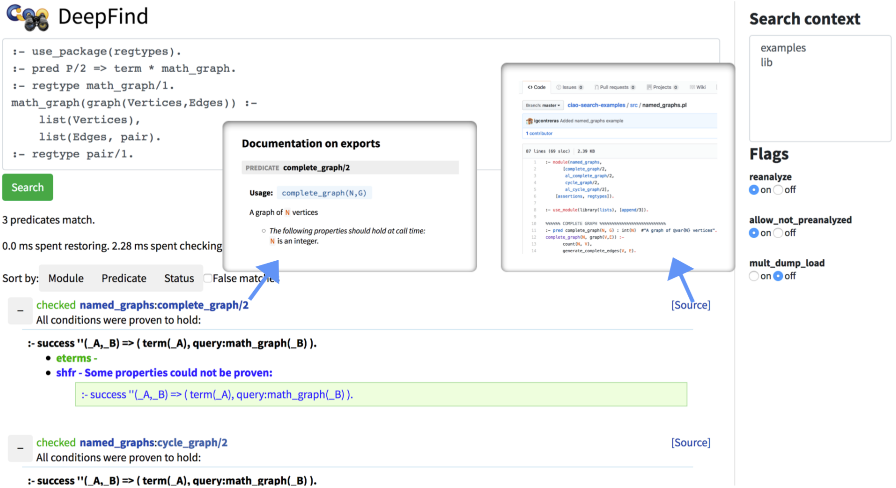
1. A **set of modules** is specified within which code is to be found.
2. A **static pre-analysis** made to infer semantic properties in one or more abstract domains.
   - E.g.: shapes/types, variable sharing, inst. modes, polyhedra, ...
3. User specifies **semantic properties** in a query, using a new kind of assertions that we call **query assertions**:
   - Example: `:- pred P(X,Y) : list(X) => sorted(Y).`
4. System looks for predicates that meet those properties, by comparing the query to the inferred information.

This method:

- Ensures that the code found **behaves correctly**.
- Reasons with **relations** between **(user-definable) properties** (implication, abstraction).
- Is **independent from the documentation**.

[ICLP'16]

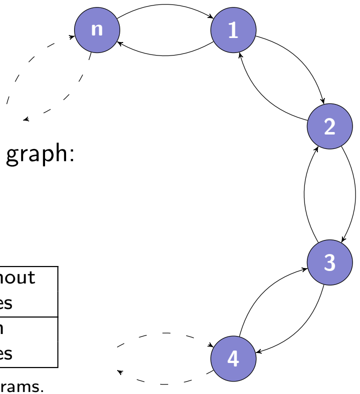
Semantic Search – Tool snapshot



[ICLP'16]

Tabling and TCLP

- **Tabling**: Detect loops, avoid recomputation.
- **TCLP**: Combine tabling with CLP (Reduce search).



- Example: Bounded-length traversal of cyclic graph:
  Can I go from **1** to **n** in less than **k** steps?

	LP	Tabling	CLP	TCLP	
Right rec.	✓	✓	✓	✓	Without cycles
Left rec.	×	✓	×	✓	
Right rec.	×	×	✓	✓	With cycles
Left rec.	×	×	×	✓	

Termination properties of equivalent, simple, logically correct programs.

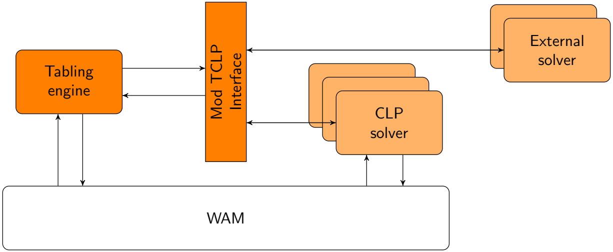
[PPDP'16, PADL'13, FLOPS'12, ICLP'10, ICLP'09, PADL'09, PADL'08]

Modular TCLP

- Different problems require different constraint domains / solvers.
- Connecting constraint solvers and tabling not straightforward.

Ciao provides

- A **simple** interface to perform this connection (Modular TCLP).
- An **answer management strategy** to discard / remove repeated answers.
- The TCLP interfaces for **several constraint domains**, e.g., CLP(Q/R).



Top-down Answer Set Programming – s(CASP)

- Is a top down Constraint Answer Set Programming interpreter.
- Avoids the grounding phase (range of constrained variables may be infinite).
- Each answer provides the mgu of a successful derivation, its justification tree, and the relevant (partial) stable model.
- Retains variables and constraints during the execution and in the model.

s(CASP)

=

ASP

+

Constraints

-

Grounding

[ICLP'18]

Top-down Answer Set Programming - s(CASP) - Example

```
duration(load,25).
duration(shoot,D):- D #> 5, D #< 15/2.
duration(wait,36).
spoiled(T_Armed):- T_Armed #> 35.
prohibited(shoot,Time):-
    Time #< 35, gun(unloaded).

holds(0, State, []):- …it(State).
holds(F_Time, … ):-
    F_Time #> 0,
    F_Time #= P_Time + Duration,
    duration(Action, Duration),
    not prohibited(Action, F_Time),
    trans(Ac…on, P_State, F_State),
    hol… .

init(st(alive,Gun,0)) :- gun(Gun).

trans(load, st(alive,_,_),
            st(alive,loaded,0)).
… ,Gun,P_Armed),
… Gun,F_Armed)):-
… med + Duration,
    duration(wait,Duration).
trans(shoot, st(alive,loaded,T_Armed),
             st(dead,unloaded,0)):-
    not spoiled(T_Armed).
… (alive,loaded,T_Armed),
… live,unloaded,0)):-
… rmed).

gun(loaded) :- not s_gun(loaded).
s_gun(loaded) :- not gun(loaded).
gun(unloaded) :- not gun(loaded).
s_gun(unloaded) :- not s_gun(loaded).
```

Interval in a dense domain

Restriction

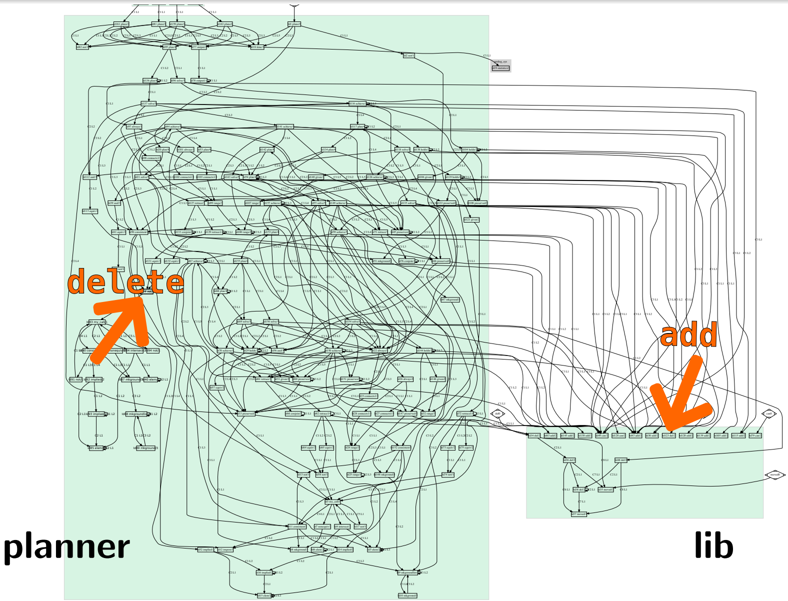
Negation

Two possible worlds

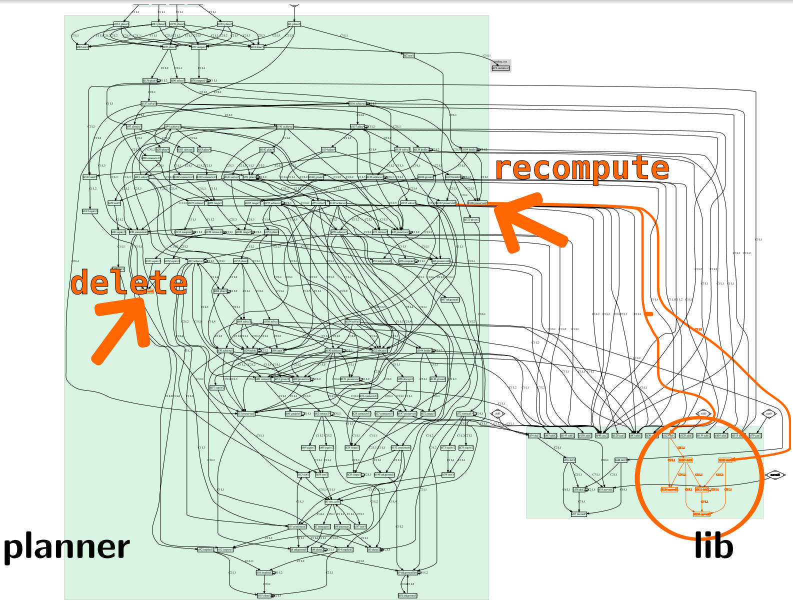
s(CASP) code for the extended and updated Yale Shooting problem.

[ICLP'18]

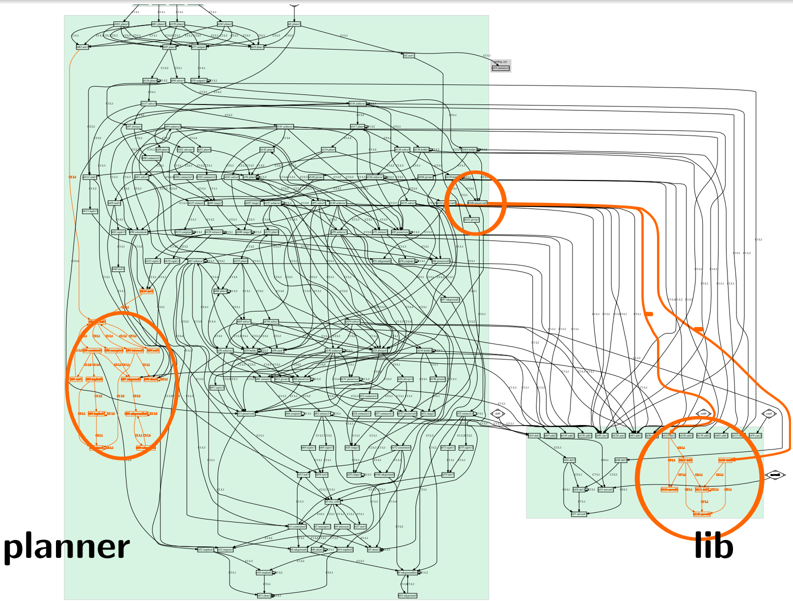
Modular, incremental, context-sensitive analysis



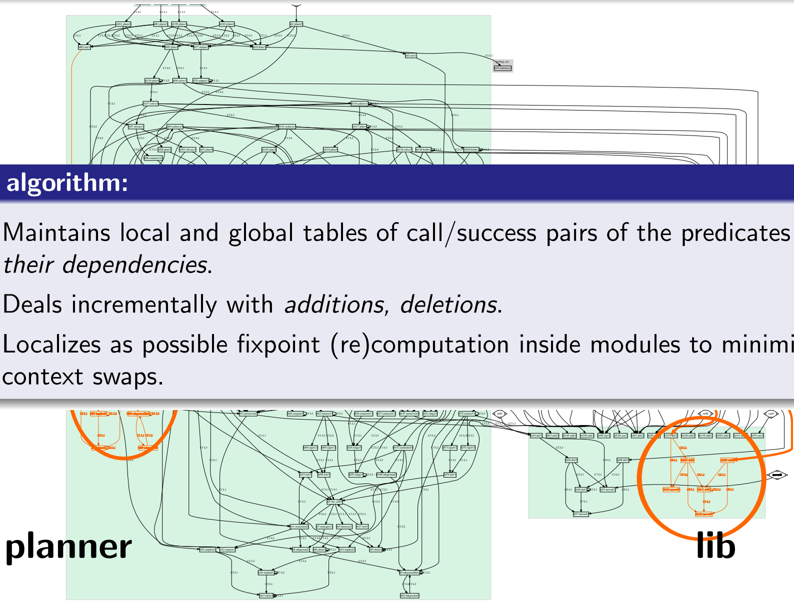
Modular, incremental, context-sensitive analysis



Modular, incremental, context-sensitive analysis



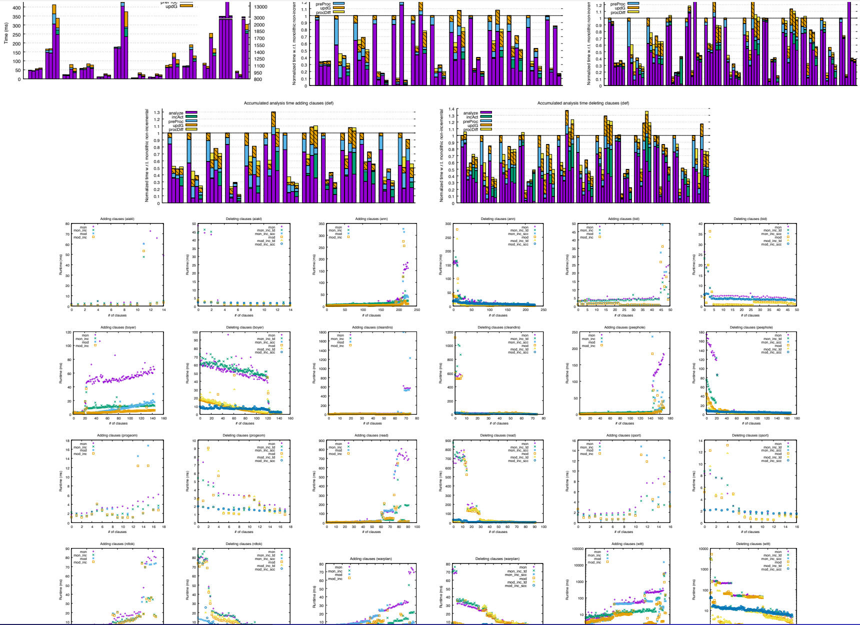
Modular, incremental, context-sensitive analysis



The algorithm:

- Maintains local and global tables of call/success pairs of the predicates *and their dependencies*.
- Deals incrementally with *additions, deletions*.
- Localizes as possible fixpoint (re)computation inside modules to minimize context swaps.

Experimental results



Experimental results

To take home:

- *Modular Incremental analysis works!* – Up to 60× speedup.
- *Modular analysis* from scratch is *improved* (up to 9×).
- Keeping structures for incrementality produces *small overhead*.
- Using the analyzer *interactively* becomes quite feasible, even for complex abstract domains.

Other features and recent developments

- Other interesting Ciao features:
  - *Modular* [LOPSTR'11] and *reversible* [PADL'13] extensions.
  - Compilation to Javascript [ICLP'12].
  - Test generation from properties.
- Other applications of CiaoPP:
  - Java bytecode analysis / verification [VMCAI'08, FTfJP'07, Bytecode'07, Bytecode'09]
  - MiniZinc, Services [Computing'13, MZN'11, ICSOC'11, ICSOC'10]
- Other related work:
  - Shapes, Sharing, and Parallelization in Imperative Languages [ISMM'09, LCPC'08, CC'08, PASTE'08, PASTE'07]

Some other recent work:

- Static performance guarantees for programs with run-time checks [PPDP'18].
- Guiding the analyzer with assertions [LOPSTR-Informal'18].
- Combining the incremental and the modular fixpoints [ICLP'18].

Why is the system called "Ciao"?

- It stems originally from an acronym:
  - *CIAO*: **C**onstraint Programming with **I**ndependent **A**nd + **O**r parallelism.
- But the name also represents the *spirit* of the system:
  - Ciao is an interesting word that means *both Hello* and *Goodbye*.
  - "Ciao Prolog:"
    - is aimed at introducing programmers to Prolog and LP/CLP – the "Hello Prolog" part,
    - but it also represents really a new-generation programming language and environment (with FP, HO, assertions, global analysis, objects, ...) – the "Goodbye Prolog" part.

`http://www.ciao-lang.org`

- Ciao, CiaoPP, LPdoc, etc.
- Documentation.
- Mailing lists.
- **Bundles**.
- etc.

Around 1,3 million lines of Ciao/Prolog code (+166K of C, 67K of Java, ...).

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

Continuous integration, etc.

Also on GitHub (including many **bundles**):

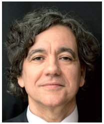
`https://github.com/ciao-lang`

Playground:

`http://play.ciao-lang.org`

The Current Ciao/CiaoPP Team


Manuel Carro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Christian Holzbaur	Kim Marriott	Enrico Pontelli	Ángel Pineda

Milestones / tools / timeline (partial)

'83-90	Parallel abstract machines: task stealing, micro tasks, (cactus) stack sets → motivation: auto-parallelization.
'88	**MA3 analyzer**: memo tables (cf. OLDT resolution), practicality established.
'89	**PLAI analyzer**: accelerated "top-down" fixpoint, abstract domains as plugins. Sharing, side-effect analysis → automatic parallelization / real speedups (on shmem).
90's	Incremental analysis, concurrency (dynamic scheduling), automatic domain combinations, scalability, auto-parallelization, extension to constraints.
'93	**GraCoS** (Granularity Control System): fully automatic cost analysis (upper bounds), and automatic parallelization with task granularity control (with optimizations).
mid 90's	**The Ciao/CiaoPP model: Library-based language features, Integrated verification/debugging/optimization w/assertions.**
'91-'06	Combined **abstract interpretation and partial evaluation**.
late 90's	**Lower bounds** cost analysis, **divide-and-conquer**. No-fail (no exceptions), determinacy.
'01	**Verification of cost properties**, additional resources, ...
'01-05	Modularity/scalability. Diagnosis (locating origin of assrt. violations). New shape/type domains, widenings. Polyhedra, convex hulls.
'03	**Abstraction carrying code**, reduced certificates.
'04-'07	Verification/debugging/optimization of **user-defined resources**.
'05	**Multi-language support using CLP (CHC) as IR**: Java, C# (shapes, resources, ...).
'06-'08	**Probabilistic** cost, verification of execution **time**, **energy** (Java), heap models, ...
'12-18	(X)C program energy analysis/verification, ISA-level energy models.
'13-18	**Cost analysis as Abstract Interpretation** Sized shapes. LLVM. **Static Profiling**.
'15-17	Optimized dynamic property checking (run-time tests).
'16	Sematic code search, Improved CLP+Tabling.
'18	Top-down **ASP**, fixpoint guidance, analysis scalability, rt check cost assurances, ...

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