On-the-fly Verification
via (Incremental, Interactive) Abstract Interpretation with CiaoPP and Verifly

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[3]Spanish Research Council (CSIC)

Introduction / overview

- **Objective:** Analyze/Verify software projects interactively, during development:
  - Detect bugs, verify assertions on-the-fly, in the editor (also at commit, etc.).
- **Problem:** Precision (e.g., context-sensitivity, complex domains, ...) can be expensive.

In our tool (CiaoPP) we address this challenge through:

- Efficient, context/path-sensitive fixpoint (the "top-down algorithm," PLAI) [NACLP'89, MCC'90]
- Fine-grain (clause-level) incremental analysis (originally not exploiting module structure). [SAS'96, TOPLAS'00]
- Extending incremental analysis to exploit much better modular structure. [ICLP'18, LOPSTR'19, TPLP'21c]
- IDE integration → our `VeriFly` "on-the-fly" verification tool. [NASA-FIDE21, TPLP'21b]

All while:

- Supporting multiple languages via translation to CHCs (a.k.a. Prolog/CLP). [LOPSTR'07, TPLP'18, VPT'20, TPLP'21a]
- Covering both functional and non-functional properties (types, pointers, shapes, intervals, ... time, memory, energy, gas, ...) [PLDI'90] ... [SAS'20]

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Brief Introduction to the CiaoPP Framework

90's: mostly statically-typed languages: ML, Haskell — Gödel, Mercury

⇝ Developed the Ciao Prolog language, to provide:
Of course, an excellent Prolog, but, in addition:

- the flexibility / fast prototyping of dynamic languages,
- with the guarantees of static / strongly typed languages.

- Objective: bridge the gap between dynamic and static languages.
(First?) dynamic language with safety assurances.

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Keys:

- Assertions rather than (traditional) types, and optional.
- Do not restrict the properties $\rightarrow$ accept undecidability.
- Use safe approximations $\rightsquigarrow$ abstract interpretation-based 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 $[\![P]\!]_{\alpha^+} \cap \mathcal{I}_\alpha = \emptyset \wedge [\![P]\!]_\alpha \neq \emptyset$
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PLAI (CiaoPP's Generic AI Framework)

- Generic framework: given P (as a set of CHCs) and abstract domain(s), computes $\mathrm{lfp}(S_P^{\alpha}) = [\![P]\!]_{\alpha}$, s.t. $[\![P]\!]_{\alpha}$ safely approximates $[\![P]\!]$.

$\rightarrow$ Essentially efficient, incremental, abstract OLDT resolution algo. for CHC's. It is the original "top-down" algorithm! [NACLP'89]

- It maintains and computes as a result (simplified):
  - **A call-answer table**: with (multiple) entries $\{block : \lambda_{in} \mapsto \lambda_{out}\}$.
    - Exit states for calls to *block* satisfying precond λ_{in} meet postcond λ_{out}.
  - **A dependency arc table**: $\{A : \lambda_{inA} \Rightarrow B : \lambda_{inB}\}$.
    - Answers for call $A : \lambda_{inA}$ depend on the answers for $B : \lambda_{inB}$: (if exit for $B : \lambda_{inB}$ changes, exit for $A : \lambda_{inA}$ possibly also changes).
- Characteristics:
  - **Precision:** context-/path-sensitivity (multivariance), prog. point info, ...
  - **Efficiency:** memoization, dependency tracking, SCCs, base cases, ...
  - **Genericity:** abstract domains are plugins, configurable, widenings, ...
  - Handles mutually recursive methods, library calls, externals, ...
  - Can be **guided** with assertions (*trust* run-time checks, external proofs, etc.)
  - **Modular** (reduced working set) and **incremental** (reuse past analyses).

[NACLP'89, MCC'90, JLP'92, POPL'94, SAS'96, TOPLAS'00, ENTCS'00, FTfJP'07, ICLP'18]

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  - Handles mutually recursive methods, library calls, externals, ...
  - Can be **guided** with assertions (*trust* run-time checks, external proofs, etc.)
  - **Modular** (reduced working set) and **incremental** (reuse past analyses).

[NACLP'89, MCC'90, JLP'92, POPL'94, SAS'96, TOPLAS'00, ENTCS'00, FTfJP'07, ICLP'18]

PLAI (CiaoPP's Generic AI Framework)

- Generic framework: given P (as a set of CHCs) and abstract domain(s), computes $\mathrm{lfp}(S_P^\alpha) = [\![P]\!]_\alpha$, s.t. $[\![P]\!]_\alpha$ safely approximates $[\![P]\!]$.

$\rightarrow$ Essentially efficient, incremental, abstract OLDT resolution algo. for CHC's. It is the original "top-down" algorithm! [NACLP'89]

- It maintains and computes as a result (simplified):
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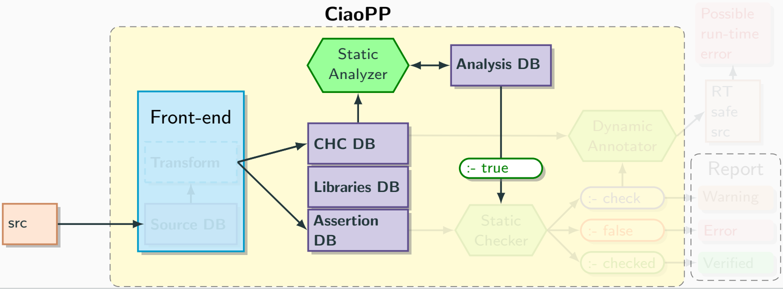
Brief Introduction to the CiaoPP Framework



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Abstract Interpretation-based, parametric on properties/domains: recursive types/shapes, pointer aliasing, constraints, determinacy, non-failure/exception, cost, sizes, termination, ...

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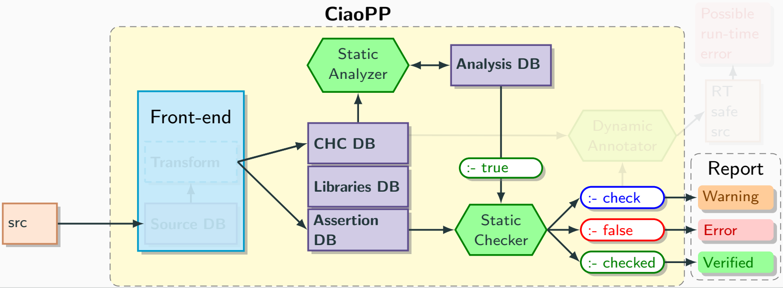

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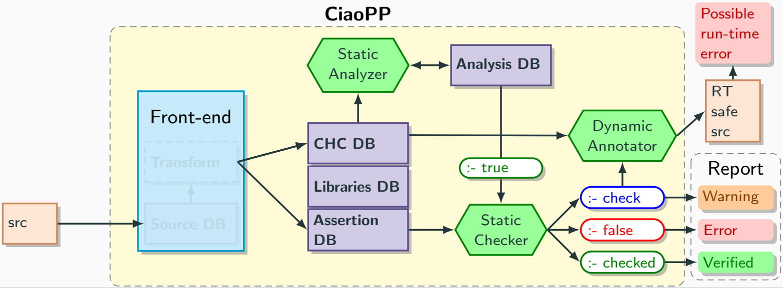

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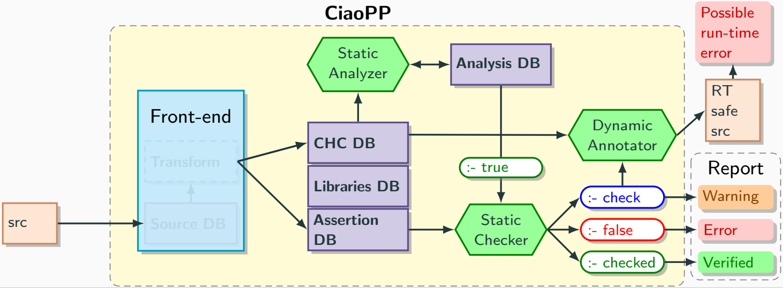

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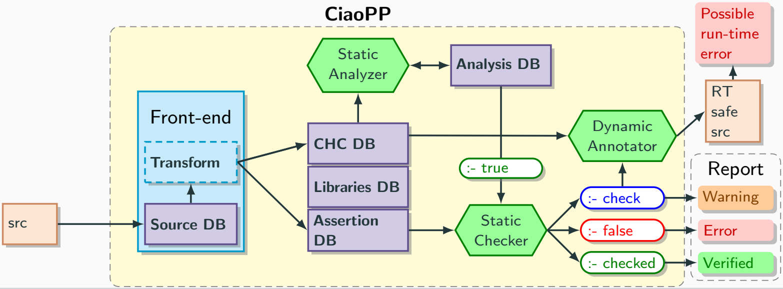

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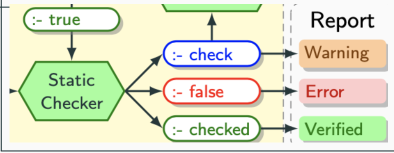
Front end

Different source languages supported, by translation to Horn clauses.

Energy Usage Verification

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




```
#pragma check fir(xn, coeffs, state, ELEMENTS) :
          (1 <= ELEMENTS && energy <= 416.0)
#pragma true fir(xn, coeffs, state, ELEMENTS) :
          ( energy >= 3.35*ELEMENTS + 13.96 &&
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#pragma checked fir(xn, coeffs, state, ELEMENTS) :
          (1 <= ELEMENTS && ELEMENTS <= 120 && energy <= 416.1)
#pragma false fir(xn, coeffs, state, ELEMENTS) :
          (121 <= ELEMENTS && energy <= 416.1)

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;
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  if (sext(ynh,24) == ynh) {
      ynh = (ynh << 8) | (((unsigned) ynl) >> 24);}
  else if (ynh < 0) { ynh = 0x80000000; }
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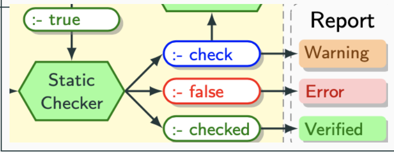


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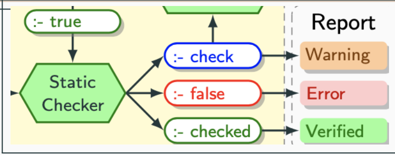


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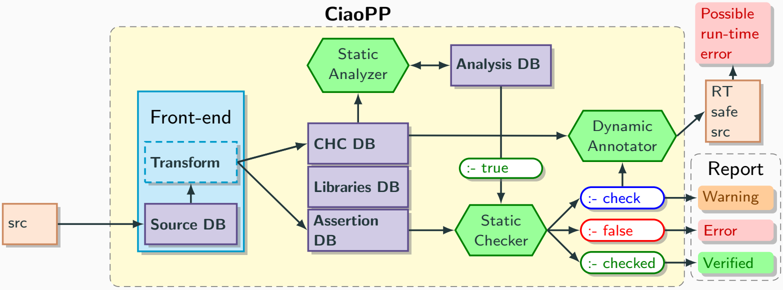
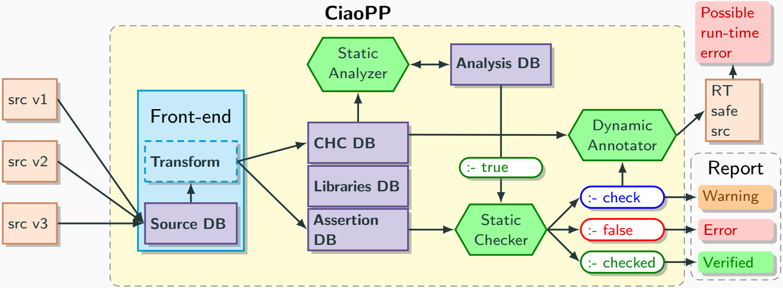


Incremental Analysis/Verification: Basic Idea



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3. Reanalyze:
   - Annotate and remove potentially
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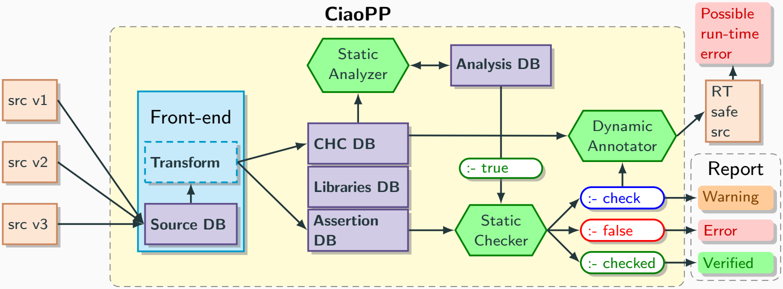

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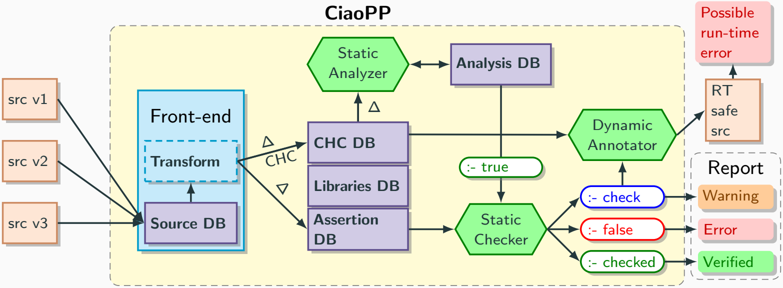

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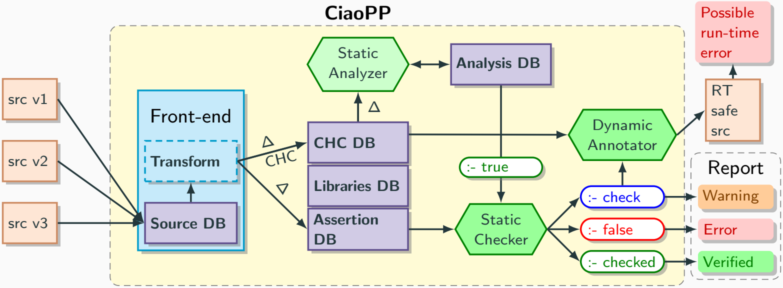

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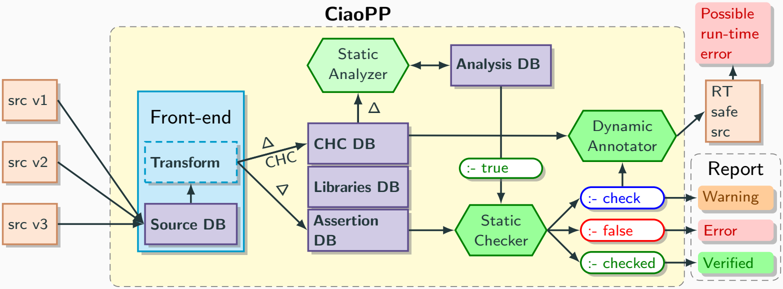

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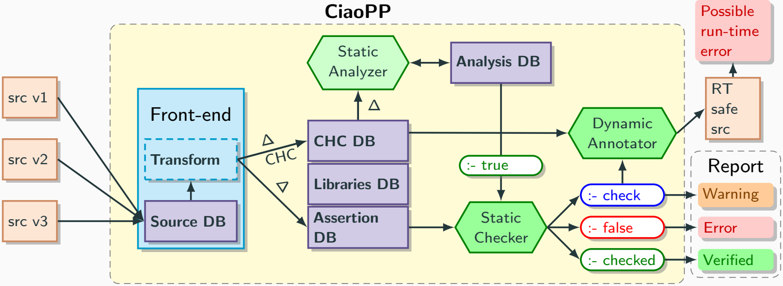

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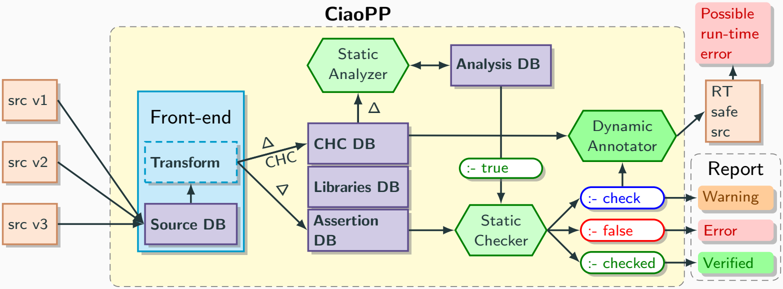

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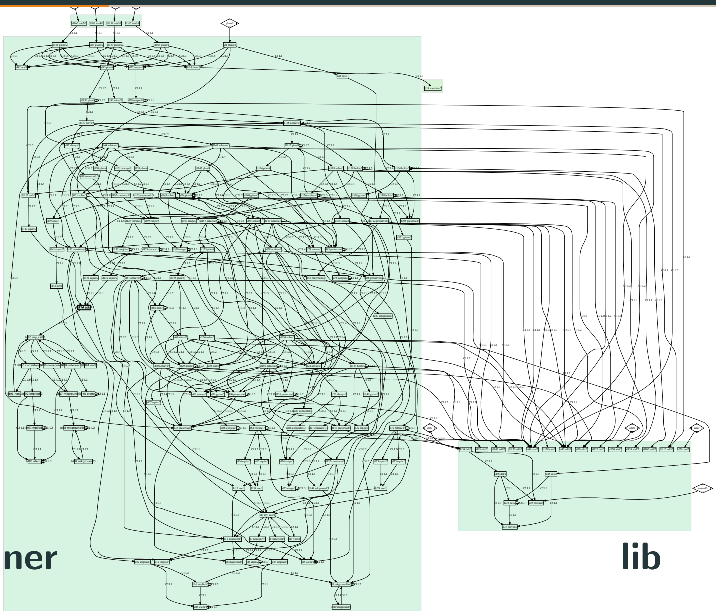
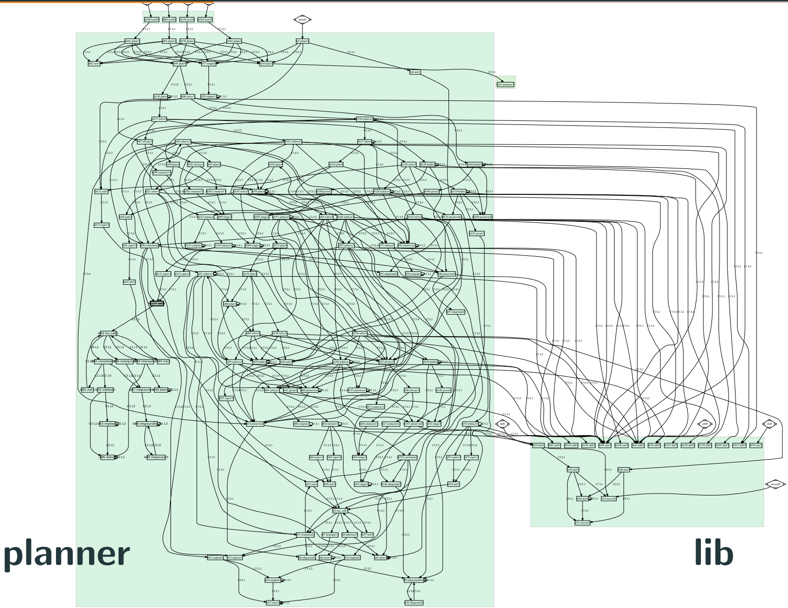
Modular and Incremental Analysis: Initial Analysis



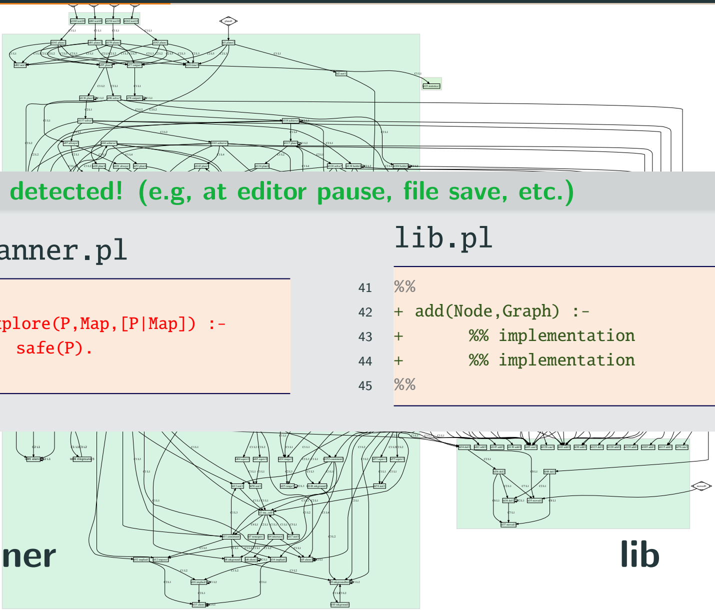
planner

lib

Modular and Incremental Analysis: Initial Analysis



Modular and Incremental: Changes Detected



Changes detected! (e.g, at editor pause, file save, etc.)

planner.pl

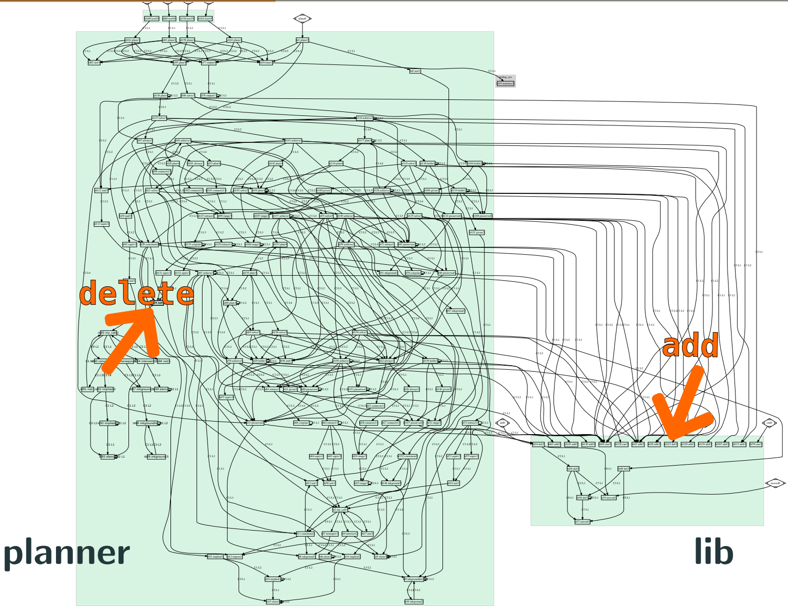
```
%%
- explore(P,Map,[P|Map]) :-
-     safe(P).
%%
```

lib.pl

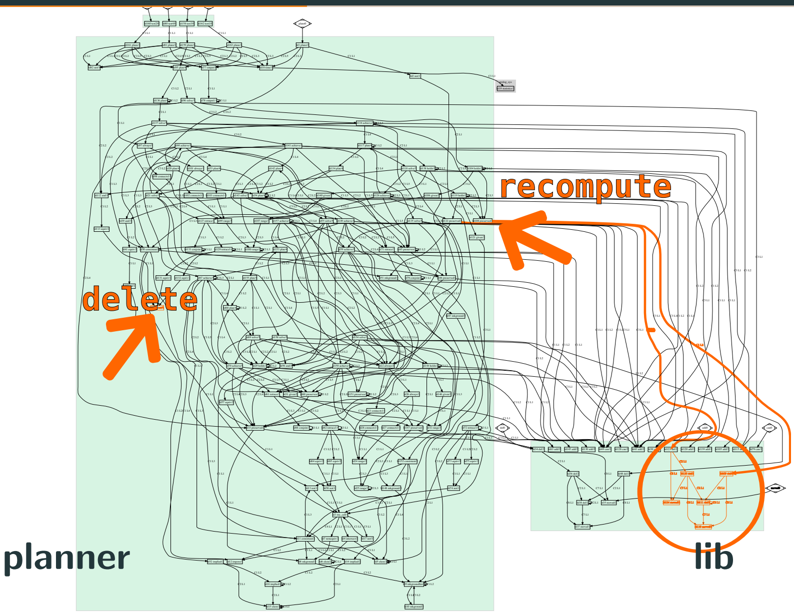
```
%%
+ add(Node,Graph) :-
+       %% implementation
+       %% implementation
%%
```

planner **lib**

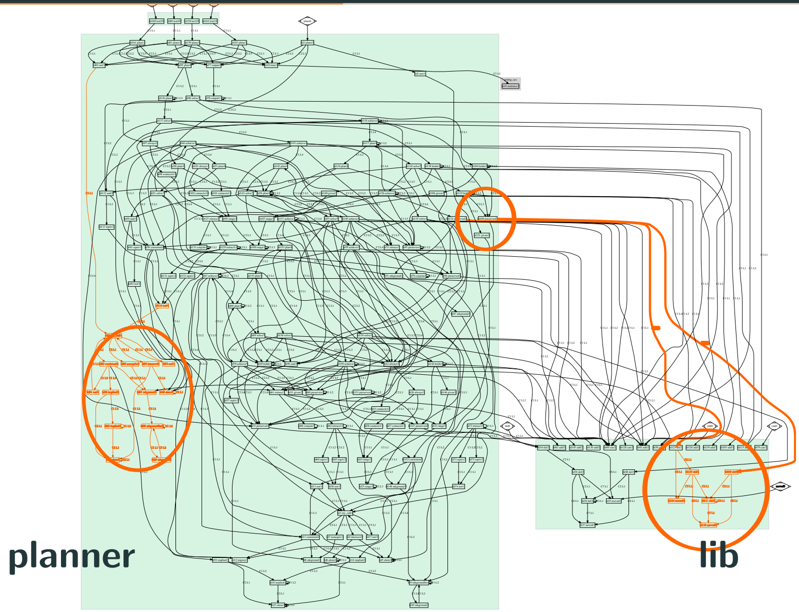
Modular and Incremental: Changes Detected



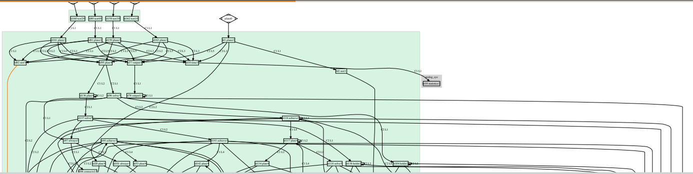
Modular and Incremental: Annotate/Remove Outdated Parts



Re-Analyze Only Parts Needed (Following Dependencies)

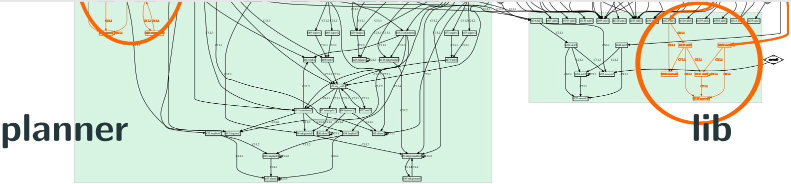


Modular and Incremental: Characteristics



The algorithm:

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



Fundamental results

Theorem 4 (Correctness of IncAnalyze starting from a partial analysis)**.** *Let P be a program, Q_α a set of abstract queries, and $\mathscr{A}_0$* any *analysis graph. Let* $\mathscr{A} = \text{IncAnalyze}(P, Q_\alpha, \emptyset, \mathscr{A}_0)$*. $\mathscr{A}$ is* correct *for P and $\gamma(Q_\alpha)$ if for all concrete queries $q \in \gamma(Q_\alpha)$ all nodes n from which there is a path in the concrete execution $q \rightsquigarrow n$ in $[\![P]\!]_Q$, that are abstracted in the analysis $\mathscr{A}_0$ are included in Q_α, i.e.:*

$$\forall Q, n. Q \in \gamma(Q_\alpha) \wedge q \rightsquigarrow n \in [\![P]\!]_Q,$$
$$\forall n_\alpha \in \mathscr{A}_0 . n \in \gamma(n_\alpha) \Rightarrow n_\alpha \in Q_\alpha.$$

Theorem 6 (Precision of IncAnalyze)**.** *Let P, P' be programs, such that P differs from P' by Δ, let Q_α a set of abstract queries, and $\mathscr{A}_0 = \text{IncAnalyze}(P', Q_\alpha, \emptyset, \emptyset)$ an analysis graph. The following hold:*

- *If $\mathscr{A} = \text{IncAnalyze}(P, Q_\alpha, \emptyset, \emptyset)$, then $\mathscr{A}$ is the* least program analysis graph *for P and $\gamma(Q_\alpha)$, and*
- $\text{IncAnalyze}(P, Q_\alpha, \Delta, \mathscr{A}_0) = \text{IncAnalyze}(P, Q_\alpha, \emptyset, \emptyset)$.

Lemma 1 (Correctness of IncAnalyze modulo imported predicates)**.** *Let M be a module of program P, E a set of abstract queries. Let $\mathscr{L}_0$ be an analysis graph such that $\forall \langle A, \lambda^c \rangle \in \mathscr{L}_0 . \mathsf{mod}(A) \in \mathsf{imports}(M)$. The analysis result*

$$\mathscr{L} = \text{IncAnalyze}(M, E, \emptyset, \mathscr{L}_0)$$

is correct *for M and $\gamma(E)$ assuming $\mathscr{L}_0$.*

Lemma 2 (Precision of IncAnalyze modulo imported predicates)**.** *Let M be a module of program P, E a set of abstract queries. Let $\mathscr{L}_0$ be an analysis graph such that $\forall \langle A, \lambda^c \rangle \in \mathscr{L}_0 . \mathsf{mod}(A) \in \mathsf{imports}(M)$ if $\mathscr{L}_0$ contains* the least fixed point *as defined in Theorem 6. The analysis result*

$$\mathscr{L} = \text{IncAnalyze}(M, E, \emptyset, \mathscr{L}_0)$$

is the least program analysis graph *for M and $\gamma(E)$ assuming $\mathscr{L}_0$.*

Lemma 3 (Correctness updating $\mathscr{L}$ modulo $\mathcal{G}$)**.** *Let M be a module of program P and E a set of entries. Let $\mathcal{G}$ be a previous state of the global analysis graph, if $\mathscr{L}_M$ is correct for M and $\gamma(E)$ assuming $\mathcal{G}$. If $\mathcal{G}$ changes to $\mathcal{G}'$ the analysis result*

$$\mathscr{L}'_M = \text{LocIncAnalyze}(M, E, \mathcal{G}', \mathscr{L}_M, \emptyset)$$

is correct *for M and $\gamma(E)$ assuming $\mathcal{G}$.*

Theorem 10 (Correctness of ModIncAnalyze from scratch)**.** *Let P be a modular program, and Q_α a set of abstract queries. Then, if:*

$$\{\mathcal{G}, \{\mathscr{L}_{M_i}\}\} = \text{ModIncAnalyze}(P, Q_\alpha, \emptyset, \emptyset)$$

$\mathcal{G}$ is correct *for P and $\gamma(Q_\alpha)$.*

Lemma 4 (Precision updating $\mathscr{L}$ modulo $\mathcal{G}$)**.** *Let M be a module contained in program P, E a set of entries. Let $\mathcal{G}$ be a previous state of the global analysis graph, if $\mathscr{L}_M = \text{LocIncAnalyze}(M, E, \mathcal{G}, \emptyset, \emptyset)$. If $\mathcal{G}$ changes to $\mathcal{G}'$ the analysis result:*

$$\text{LocIncAnalyze}(M, E, \mathcal{G}', \mathscr{L}_M, \emptyset) = \text{LocIncAnalyze}(M, E, \mathcal{G}', \emptyset, \emptyset)$$

is the same as analyzing from scratch, i.e., the lfp *of M, E.*

Theorem 11 (Precision of ModIncAnalyze from scratch)**.** *Let P be a modular program and Q_α a set of abstract queries. The analysis result*

$$\mathscr{A} = \text{ModIncAnalyze}(P, Q_\alpha, \emptyset, \emptyset) = \text{ModAnalyze}(P, Q_\alpha)$$

such that $\mathscr{A} = \{\mathcal{G}, \{\mathscr{L}_{M_i}\}\}$, then $\mathcal{G} = \mathcal{G}'$.

Theorem 12 (Precision of ModIncAnalyze)**.** *Let P, P' be modular programs that differ by Δ, Q_α a set of queries, and $\mathscr{A} = \text{ModIncAnalyze}(P, Q_\alpha, \emptyset, (\emptyset, \emptyset))$, then*

$$\text{ModIncAnalyze}(P', Q_\alpha, \emptyset, (\emptyset, \emptyset)) = \text{ModIncAnalyze}(P', Q_\alpha, \mathscr{A}, \Delta).$$

Fundamental results (very summarized)

Theorem 4 (Correctness of IncAnalyze starting from a partial analysis). *Let P be a program, Q_α a set of abstract queries, and $\mathscr{A}_0$ any analysis graph. Let $\mathscr{A}$ =* IncAnalyze$(P, Q_\alpha, \emptyset, \mathscr{A}_0)$. *$\mathscr{A}$ is* correct *for P and $\gamma(Q_\alpha)$ if for all concrete queries $q \in \gamma(Q_\alpha)$ all nodes n from which there is a path in the concrete execution $q \rightsquigarrow n$ in $[\![P]\!]_Q$, that are abstracted in the analysis $\mathscr{A}_0$ are included in Q_α, i.e.:*

$$\forall Q, n. Q \in \gamma(Q_\alpha) \wedge q \rightsquigarrow n \in [\![P]\!]_Q,$$
$$\forall n_\alpha \in \mathscr{A}_0 . n \in \gamma(n_\alpha) \Rightarrow n_\alpha \in Q_\alpha.$$

Lemma 3 (Correctness updating $\mathscr{L}$ modulo $\mathcal{G}$). *Let M be a module of program P and E a set of entries. Let $\mathcal{G}$ be a previous state of the global analysis graph, if $\mathscr{L}_M$ is correct for M and $\gamma(E)$ assuming $\mathcal{G}$. If $\mathcal{G}$ changes to $\mathcal{G}'$ the analysis result*

$$\mathscr{L}'_M = \text{LocIncAnalyze}(M, E, \mathcal{G}', \mathscr{L}_M, \emptyset)$$

is correct *for M and $\gamma(E)$ assuming $\mathcal{G}$.*

Theorem 10 (Correctness of ModIncAnalyze from scratch). *Let P be a modular program, and Q_α a set of abstract queries.*

Guarantees

- Correct over-approximation of the semantics (also with widening).
- But for most accurate (lfp): no widening, or conditions on the widening.

- IncAnalyze$(P, Q_\alpha, \Delta, \mathscr{A}_0)$ = IncAnalyze$(P, Q_\alpha, \emptyset, \emptyset)$.

be a previous state of the global analysis graph, if $\mathscr{L}_M$ = LocIncAnalyze$(M, E, \mathcal{G}, \emptyset, \emptyset)$. *If $\mathcal{G}$ changes to $\mathcal{G}'$ the analy-*

Additionally

- New results for reanalyzing starting from a partial analysis.

$$\mathscr{L} = \text{IncAnalyze}(M, E, \emptyset, \mathscr{L}_0)$$

is correct *for M and $\gamma(E)$ assuming $\mathscr{L}_0$.*

Lemma 2 (Precision of IncAnalyze modulo imported predicates). *Let M be a module of program P, E a set of abstract queries. Let $\mathscr{L}_0$ be an analysis graph such that $\forall \langle A, \lambda^c \rangle \in \mathscr{L}_0$.*mod$(A) \in$ imports(M) *if $\mathscr{L}_0$ contains* the least fixed point *as defined in Theorem 6. The analysis result*

$$\mathscr{L} = \text{IncAnalyze}(M, E, \emptyset, \mathscr{L}_0)$$

is the least program analysis graph *for M and $\gamma(E)$ assuming $\mathscr{L}_0$.*

Theorem 11 (Precision of ModIncAnalyze from scratch). *Let P be a modular program and Q_α a set of abstract queries. The analysis result*

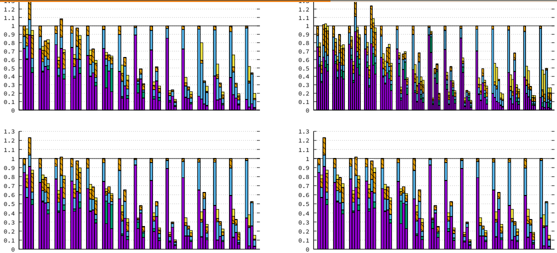
$$\mathscr{A} = \text{ModIncAnalyze}(P, Q_\alpha, \emptyset, \emptyset) = \text{ModAnalyze}(P, Q_\alpha)$$

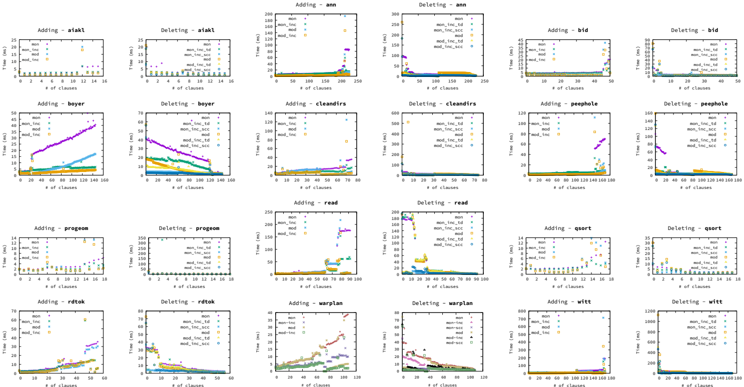
such that $\mathscr{A} = \{\mathcal{G}, \{\mathscr{L}_{M_i}\}\}$, then $\mathcal{G} = \mathcal{G}'$.

Theorem 12 (Precision of ModIncAnalyze). *Let P, P' be modular programs that differ by Δ, Q_α a set of queries, and $\mathscr{A}$ =* ModIncAnalyze$(P, Q_\alpha, \emptyset, (\emptyset, \emptyset))$*, then*

$$\text{ModIncAnalyze}(P', Q_\alpha, \emptyset, (\emptyset, \emptyset)) = \text{ModIncAnalyze}(P', Q_\alpha, \mathscr{A}, \Delta).$$

Modular and Incremental: Experimental Results





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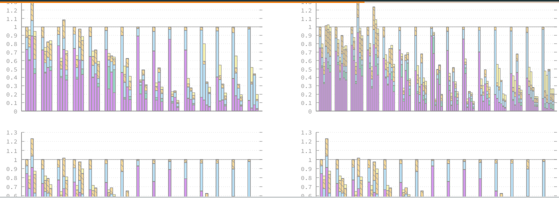
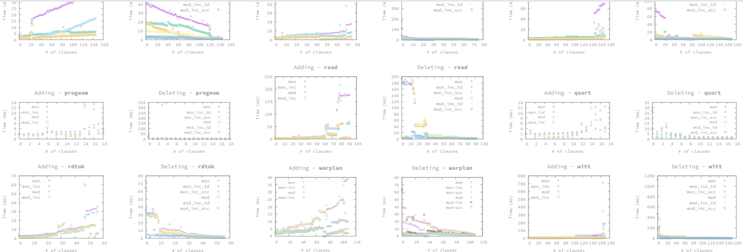
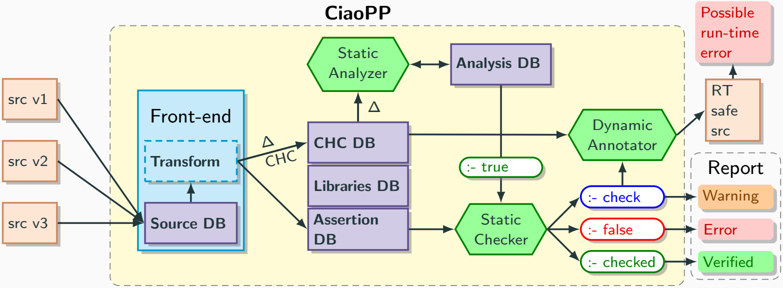


To take home:

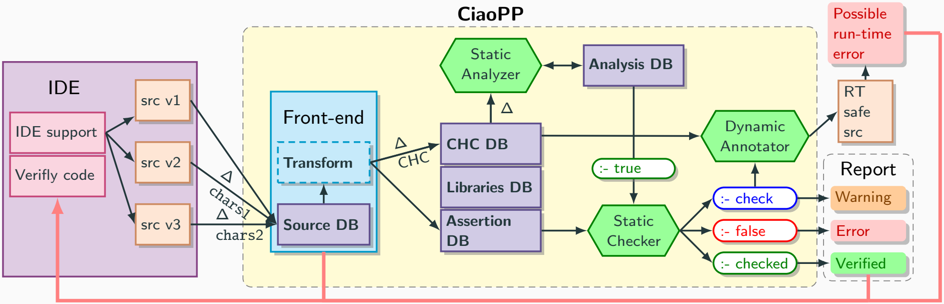
- Speedup due to incrementality in benchmarks often an order of magnitude w.r.t. non-incremental algorithm (really, unbounded).
- Modular-incremental typically $2\times$ speedup w.r.t. incremental (plus memory).
- Modular analysis from scratch also typically improved (up to $9\times$).



Incremental Verification



VeriFly: On-the-fly Verification/IDE Integration



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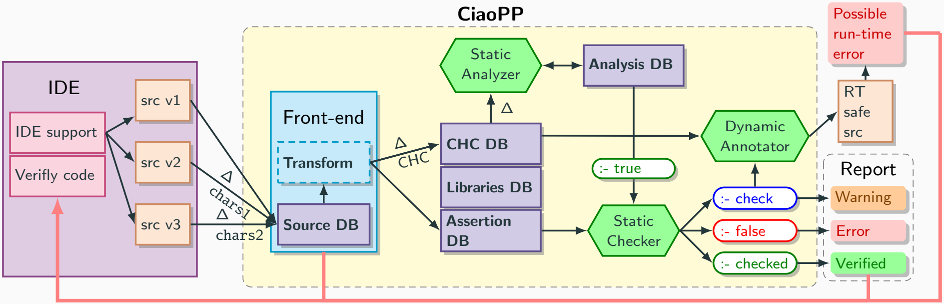

Tool interface components

The tool interface is implemented within the IDE, e.g.:

- In the case of Emacs, we extend `flycheck`.
- Browser version: everything runs in the browser:
  - CiaoPP runs via `ciao_wasm`
  - Verifly code and IDE are in JS (Monaco + extra code)

(Approach and results equally valid for other IDEs.)

The Assertion Language

Assertions: :- **pred** *Head* [: *Pre*] [=> *Post*] [+ *Comp*] .

```
:- 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 (normal predicates, but: termination, steadfastness, ...):

```
color(green).  color(blue).  color(red).          color := green | blue | red.
list([]).   list([H|T]) :- list(T).                     list := [] | [_|list].
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```

Modes (are essentially "assertion macros"):

```
:- pred qs(+,-).                ↦   :- pred qs(X,Y) : (nonvar(X), var(Y)).
:- pred qs(+list,-list).}       ↦   :- pred qs(X,Y) : (list(X), var(Y)) =>
     list(Y).
```

Defined as follows:

```
:- modedef +(A) : nonvar(A)          :- modedef +(A,X) : X(A).
:- modedef -(A) : var(A).            :- modedef -(A,X) : var(A) => X(A).
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Program-point Assertions: ..., check((int(X), X>0)), ...

Also tests, documentation, ...

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```

Program-point Assertions: `..., check(( int(X), X>0 )), ...`

Also tests, documentation, ...

Motivation - (Incremental) Static On-the-fly Verification

```
rewrite( clause(H,B), clause(H,P),I,G,Info) :-
    numbervars_2(H,0,Lhv),
    collect_info(B,Info,Lhv,_X,_Y),
    add_annotations(Info,P,I,G),!.

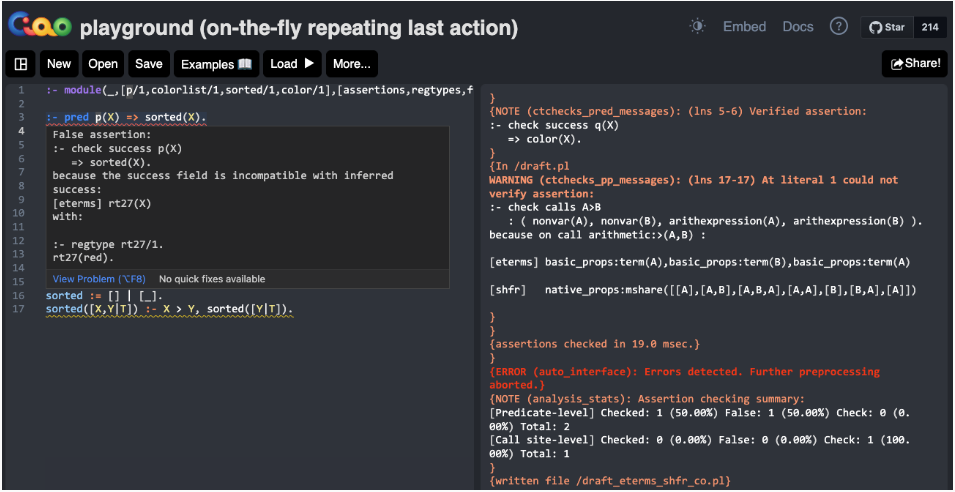
:- pred add_annotations(Info,Phrase,Ind,Gnd)
   :  (var(Phrase),indep(Info,Phrase))
   => (ground(Ind),ground(Gnd))
   +  not_fails.

add_annotations([],[],_,_).
add_annotations([I|Is],[P|Ps],Indep,Gnd) :-
    add_annotations(I,P,Indep,Gnd),
    add_annotations(Is,Ps,Indep,Gnd).
add_annotations(Info,Phrase,I,G) :- !,
    para_phrase(Info,Code,Type,Vars,I,G),
    make_CGE_phrase( Type,Code,Vars,PCode,I
    (       var(Code),!,
            Phrase = PCode
    ;       Vars = [],!,
            Phrase = Code
    ;       Phrase = (PCode,Code)
    ).


collect_info( (A;B),([],sequential,(A;B)),Cin,Cout,_X) :- !,
    collect_info(A,_Y,Cin,C,_Z),
    collect_info(B,_N,C,Cout,_M).
```

```
➤ Verified assertion:
:- check calls add_annotations(Info,Phrase,Ind,Gnd)
   : ( var(Phrase), indep(Info,Phrase) ).
➤ Verified assertion:
:- check comp add_annotations(Info,Phrase,Ind,Gnd)
   : ( var(Phrase), indep(Info,Phrase) )
   + not_fails.
➤ Verified assertion:
:- check success add_annotations(Info,Phrase,Ind,Gnd)
   : ( var(Phrase), indep(Info,Phrase) )
   => ( ground(Ind), ground(Gnd) ).
```

Interactive Verification in the Browser (Static Error Flagged)



Interactive Verification in the Browser (All Assertions Verified)

playground (on-the-fly repeating last action)

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```
1  :- module(_,[qsort/2],[assertions,nativeprops]).
2
3  %% Quick-sort with difference lists (constant time append)
4  %% Verifying various assertions
5
6  :- pred qsort(X,Y) : (ground(X),list(X),var(Y)) => ground(Y).
7  qsort(X,Y) :- qsort_(X,Y,T), T=[].
8
9  :- pred qsort_(X,Y,Z) : (list(X),var(Y),var(Z),indep(Y,Z)) => ground(X).
10 qsort_([], E, E).
11 qsort_([First|Rest],SmB,LgE) :-
12     partition(Rest,First,Sm,Lg),
13     qsort_(Sm,SmB,SmE),
14     SmE=[First|LgB],
15     qsort_(Lg,LgB,LgE).
16
17 :- pred partition(L,P,Lg,Sm)
18    => (list(Lg), list(Sm), ground(Lg), ground(Sm)).
19 partition([],_,[],[]).
20 partition([X|Y],F,[X|Y1],Y2) :-
21     X @=< F,
22     partition(Y,F,Y1,Y2).
23 partition([X|Y],F,Y1,[X|Y2]) :-
24     X @> F,
25     partition(Y,F,Y1,Y2).
26
```

```
{NOTE (ctchecks_pred_messages): (lns 9-9) Verified assertion:
:- check success qsort_(X,Y,Z)
   : ( list(X), var(Y), var(Z), indep(Y,Z) )
   => ground(X).
}
{NOTE (ctchecks_pred_messages): (lns 13-15) Verified assertion:
:- check success partition(L,P,Lg,Sm)
   => ( list(Lg), list(Sm), ground(Lg), ground(Sm) ).
}
{In /draft.pl
NOTE (ctchecks_pp_messages): (lns 17-19) At literal 1 successfully
checked assertion:
:- check calls B@=<A.

}
{In /draft.pl
NOTE (ctchecks_pp_messages): (lns 20-22) At literal 1 successfully
checked assertion:
:- check calls B@>A.

}
}
{assertions checked in 32.0 msec.}
}
{NOTE (analysis_stats): Assertion checking summary:
[Predicate-level] Checked: 4 (100.00%) False: 0 (0.00%) Check: 0 (0.
00%) Total: 4
[Call site-level] Checked: 0 (--) False: 0 (--) Check: 0 (--)
Total: 0
}

yes
?-
```

Embedding the Analyzer for Teaching Abstract Interpretation

Exercise 8 (Making predicates deterministic). *Modify the predicate to make it deterministic:*

```
:- pred sorted_insert(A,B,C) : (list_pair(A), num_pair(B), var(C)) => list_pair1(C).

sorted_insert([], X, [X]).
sorted_insert([(X1,F1)|L1], (X,F), [(X,F), (X1,F1)|L1]) :- X =< X1.
sorted_insert([P|L1], X, [P|L]) :- sorted_insert(L1, X, L).
```

the output includes the following assertions:

```
%% %% :- check pred sorted_insert(A,B,C)
%% %%    : ( list_pair(A), num_pair(B), var(C) )
%% %%    => list_pair1(C).

:- checked calls sorted_insert(A,B,C)
   : ( list_pair(A), num_pair(B), var(C) ).

:- checked success sorted_insert(A,B,C)
   : ( list_pair(A), num_pair(B), var(C) )
   => list_pair1(C).
```

Thus, we can see that the analyzer does verify the assertion that we had included. However, we can also see these other assertions:

```
:- true pred sorted_insert(A,B,C)
   : ( mshare([[C]]),
       var(C), ground([A,B]), list_pair(A), num_pair(B), term(C) )
   => ( ground([A,B,C]), list_pair(A), num_pair(B), list_pair1(C) )
   + ( multi, covered, possibly_not_mut_exclusive ).

:- true pred sorted_insert(A,B,C)
   : ( mshare([[C]]),
       var(C), ground([A,B]), list_pair(A), num_pair(B), term(C) )
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```

Summary

- **Objective:** Analyze/Verify software projects interactively, during development:
  - Detect bugs, verify assertions on-the-fly, in the editor (also at commit, etc.).
- **Problem:** Precision (e.g., context-sensitivity, complex domains, ...) can be expensive.

In our tool (CiaoPP) we address this challenge through:

- Efficient, context/path-sensitive fixpoint (the "top-down algorithm," PLAI) [NACLP'89, MCC'90]
- Fine-grain (clause-level) incremental analysis (originally not exploiting module structure). [SAS'96, TOPLAS'00]
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All while:

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Plus of course making Ciao Prolog even better!

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CiaoPP Team


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Remy Haemmerlé	David Trallero	Gopal Gupta	Michael Codish
Christian Holzbaur	Kim Marriott	Enrico Pontelli	Ángel Pineda

- Playground at: `http://ciao-lang.org/playground`

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'17-19	**Combined modular/incremental analysis (scalability)**, fixpoint guidance.
'19-'23	**Verify: Interactive Verification via Abstract Interpretation**.
'19-'23	**Smart contracts**: verification of resources (gas, storage, commands, ...).

Thanks!

Ciao/CiaoPP

Site:	`https://ciao-lang.org`
Playground:	`https://ciao-lang.org/playground`
Source:	`https://github.com/ciao-lang`

Energy Usage Verification

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

```
#pragma check fir(xn, coeffs, state, ELEMENTS) :
          (1 <= ELEMENTS && energy <= 416.0)
#pragma true fir(xn, coeffs, state, ELEMENTS) :
          ( energy >= 3.35*ELEMENTS + 13.96 &&
            energy <= 3.35*ELEMENTS + 14.4 )
#pragma checked fir(xn, coeffs, state, ELEMENTS) :
          (1 <= ELEMENTS && ELEMENTS <= 120 && energy <= 416.1)
#pragma false fir(xn, coeffs, state, ELEMENTS) :
          (121 <= ELEMENTS && energy <= 416.1)

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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  else { ynh = 0x7fffffff; }
  return ynh; }
```

Results for some sample contracts (I)

Contract	Metrics		Resource A.	Time
	Parameter (α)	Storage (β)	gas	(ms)
`reverse`	*length*	*length*	α	216
`addition`	*value*	*value*	$\log \alpha$	147
`michelson_arith`	*value*	*value*	$\log(\alpha^2 + 2 * \beta)$	208
`bytes`	*value*	*length*	β	229
`list_inc`	*value*	*length*	β	273
`lambda`	*value*	*value*	$\log \alpha$	99
`lambda_apply`	(*value*, *size*)	*size*	k	114
`inline`	*size*	*value*	$\log \beta$	870
`cross_product`	(*length*, *length*)	*value*	$\alpha_1 + \alpha_2$	424
`lineal`	*value*	*value*	α	244
`assertion_map`	(*value*, *size*)	*length*	$\log \beta * \log \alpha_1$	393

Results for some sample contracts (II)

Contract	Metrics		Resource A.	Time
	Parameter (α)	Storage (β)	gas	(ms)
`quadratic`	*length*	*length*	$\alpha * \beta$	520
`queue`	*size*	(*value*, *size*, *length*)	$\log \beta_1 * \log \beta_3$	831
`king_of_tez`	*size*	(*value*, *value*, *size*)	k	635
`set_management`	*length*	*length*	$\alpha * \log \beta$	357
`lock`	*size*	(*value*, *value*, *size*)	k	421
`max_list`	*length*	*size*	α	473
`zipper`	*length*	(*length*, *length*, *length*)	k	989
`auction`	*size*	(*value*, *value*, *size*)	k	573
`union`	(*length*, *length*)	*length*	$\alpha_1 * \log \alpha_2$	486
`append`	(*length*, *length*)	*length*	α_1	371
`subset`	(*length*, *length*)	*size*	$\alpha_1 * \log \alpha_2$	389

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