A scalable static analysis framework for reliable program development exploiting incrementality and modularity

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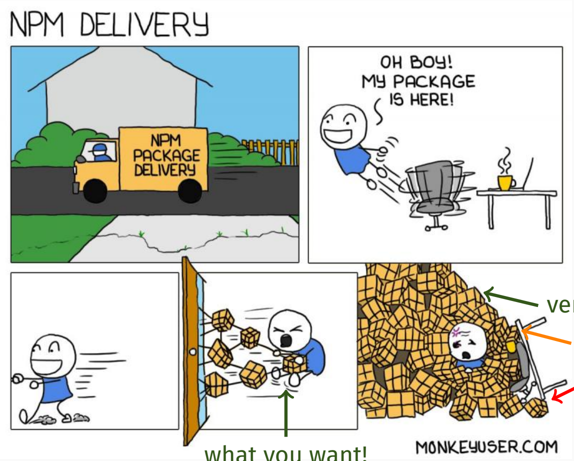
Why analyze/verify software?

A motivation for us programmers



verified library

random github project

ML-generated code

what you want!

Introduction

Context: analyzing/verifying software projects during development to:

- detect and report bugs as early as possible (e.g., on-the-fly, at commit, ...),
- optimize code and libraries globally for the program being developed.

Problem: context-sensitive analysis can be quite precise but also expensive, specially for interactive uses.

Challenges addressed in this thesis:

- performance: incremental and modular analysis to take advantage of localized changes,
    - application: *on-the-fly* assertion checking,
- precision: allowing the programmer to guide the analysis,
- incomplete code: manual specification + reanalysis, and
- precision: incomplete abstract intepretations.

Motivation – (incremental) static *on-the-fly* verification

```
      P = B
    ; rewrite(clause(H,B),clause(H,P),I,G,Info)
    ).

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)).

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,G),
    (       var(Code),!,
            Phrase = PCode
    ;       Vars = [],!,
            Phrase = Code
    ;       Phrase = (PCode,Code)
    ).
```

```
Verified assertion:
:- check calls add_annotations(Info,Phrase,Ind,Gnd)
   : ( var(Phrase), indep(Info,Phrase) ).
Verified assertion:
:- check success add_annotations(Info,Phrase,Ind,Gnd
)
   : ( var(Phrase), indep(Info,Phrase) )
```

*actual in-Emacs footage

Basics

Constraint Logic Programs/Horn Clauses

$$Head_k \leftarrow B_{k,1}, \ldots, B_{k,n_k}$$

We use **Prolog** syntax (“`:-`” instead of “$\leftarrow$”):

```
list([]).           % fact
list([X|Xs]) :-     % rule head
    list(Xs).       % rule body
```

Abstract Interpretation [Cousot & Cousot POPL’77]

Simulates the execution of the program using an **abstract domain** D_α, simpler than the contrete one. Guarantees:

- analysis termination, provided that D_α meets some conditions,
- results are **safe approximations** of the concrete semantics.

Concrete semantics – AND trees

```
par([], P, P).
par([C|Cs], P0, P) :-
    xor(C, P0, P1),
    par(Cs, P1, P).
```

```
xor(0,0,0).
xor(0,1,1).
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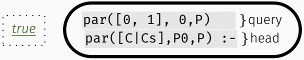
Top-down AND tree of `:- par([0, 1], 0,P).` [Bruynooghe JLP'91]



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true

`par([0, 1], 0,P)` }query
`par([C|Cs],P0,P) :-` }head

C = 0,
Cs = [1],
P0 = 0

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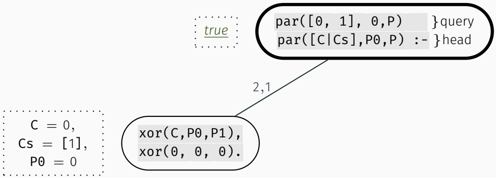

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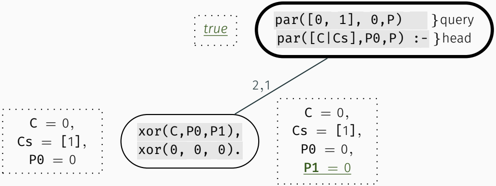

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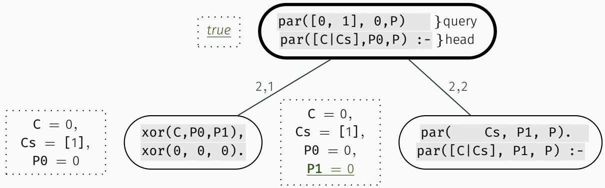

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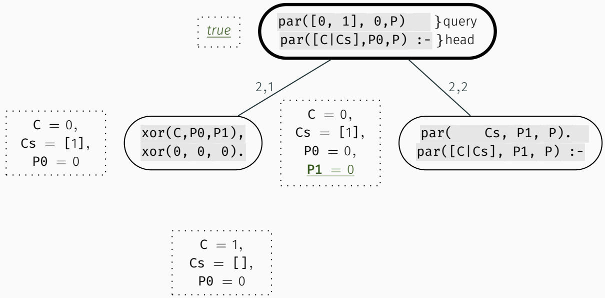

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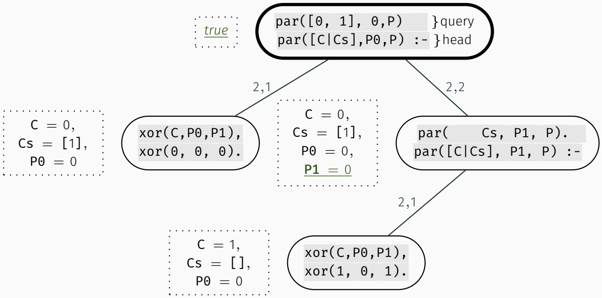

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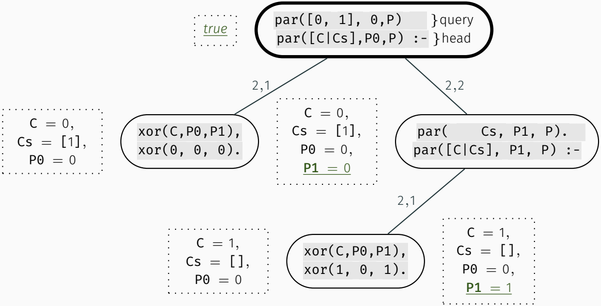

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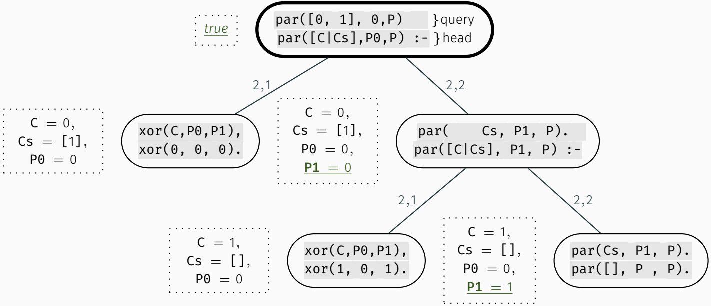

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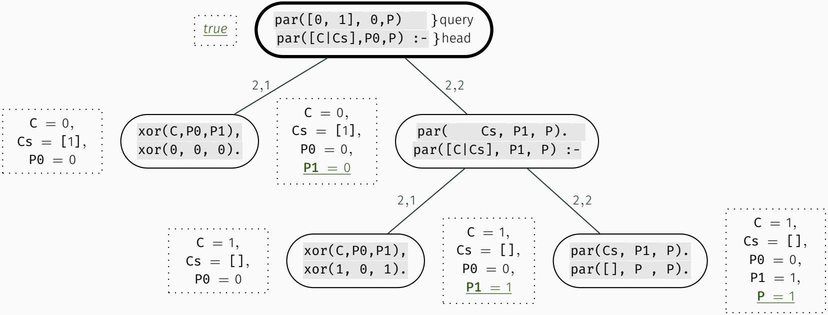

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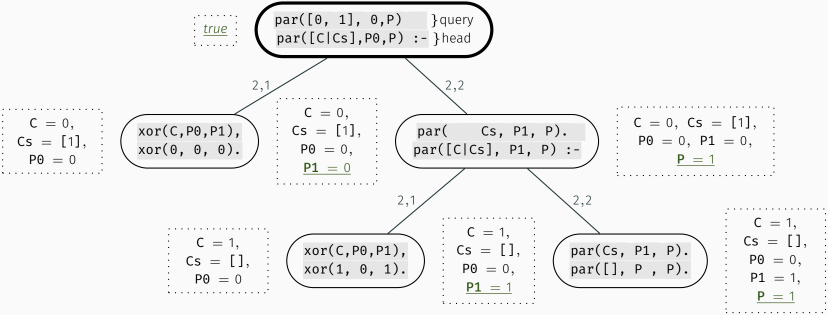

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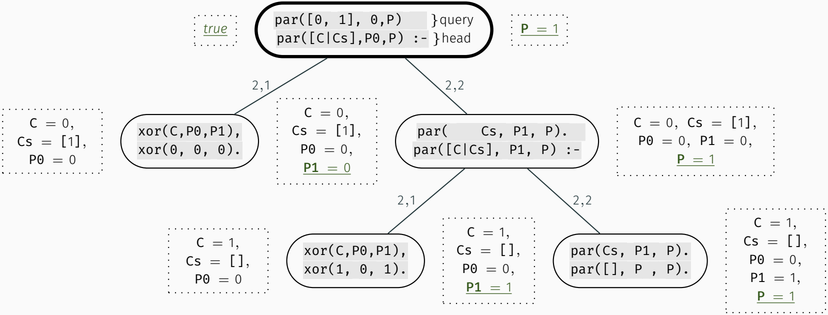

Abstract semantics

A PLAI **analysis graph** ($\mathscr{A}$) has a set of **nodes** $\langle A, \lambda^c \rangle \mapsto \lambda^s$ for every potentially reachable predicate, where: [NACLP'89, TOPLAS'00]

- A is an atom, the predicate identifier,
- λ^c is an abstract call to A, and
- λ^s is the abstract answer for A and λ^c if any call succeeds.

λ^c and λ^s are values of some abstract domain D_α.

Example

```
par([], P, P).
par([C|Cs], P0, P) :-
    xor(C, P0, P1),
    par(Cs, P1, P).

xor(0,0,0).
xor(0,1,1).
xor(1,0,1).
xor(1,1,0).
```

Example nodes:

$\langle \texttt{par(L,P0,P)}, \top \rangle \mapsto (P0/_{bit}, P/_{bit})$

For any call to `par` *that succeeds, P0 and P are either 1 or 0.*

$\langle \texttt{par(L,P0,P)}, (P0/-) \rangle \mapsto \bot$

If `par` *is called with P0 a negative number, it always fails.*

Building an analysis graph

```prolog
par([], P, P).
par([C|Cs], P0, P) :-
    xor(C, P0, P1),
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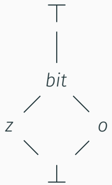
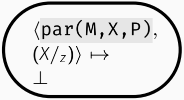


Initial query $\langle par(M, X, P), (X/z)\rangle$



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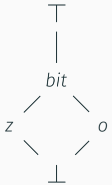

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$\langle$`par(M,X,P)`, $(X/_z)\rangle \mapsto (X/_z, P/_z)$

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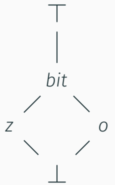

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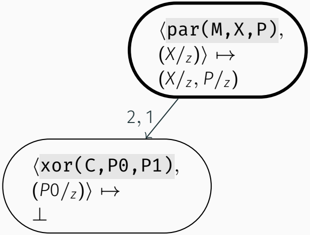

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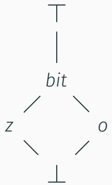

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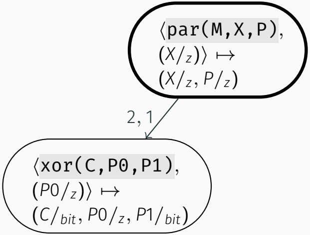

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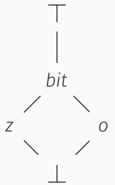

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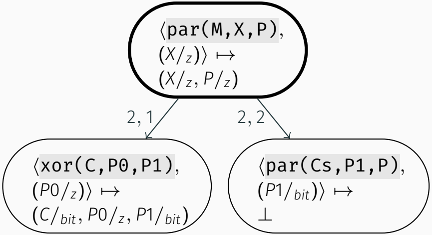

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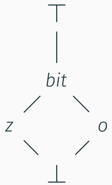

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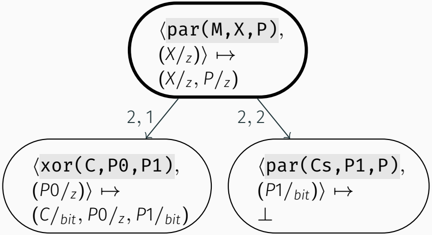

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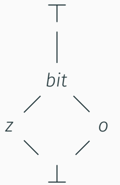

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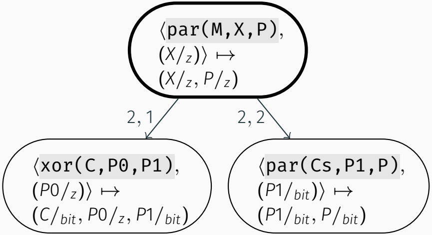

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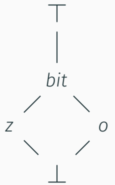

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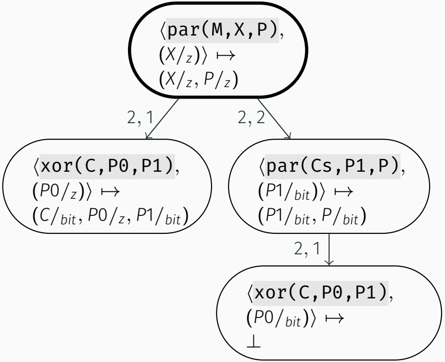

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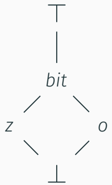

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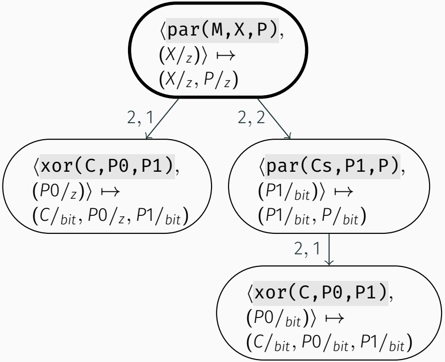

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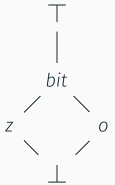

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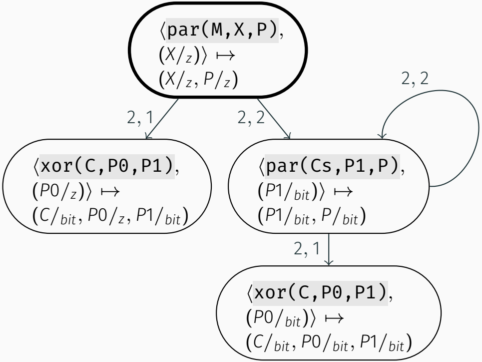

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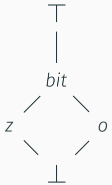

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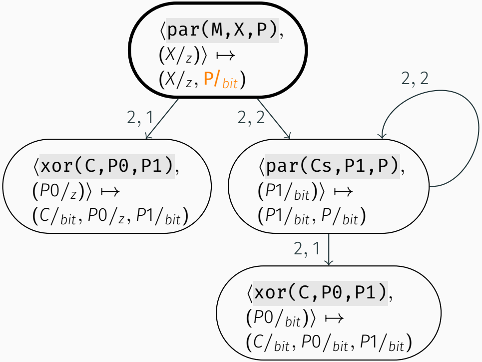
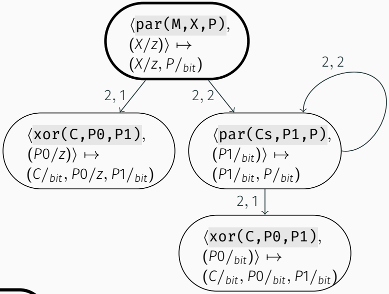
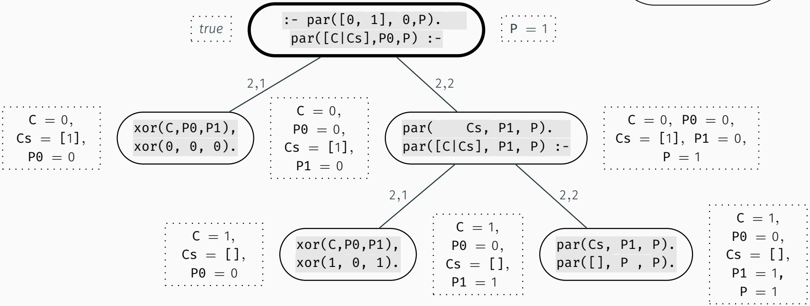


Analysis correctness

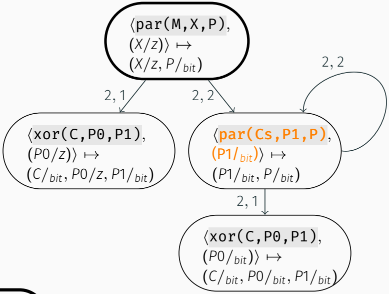
An analysis graph $\mathscr{A}$ is **correct** for a program P and a set of queries Q if it approximates all the calls, answers, and dependencies in the concrete semantics $[\![P]\!]_{\mathscr{Q}}$ (a set of AND trees).

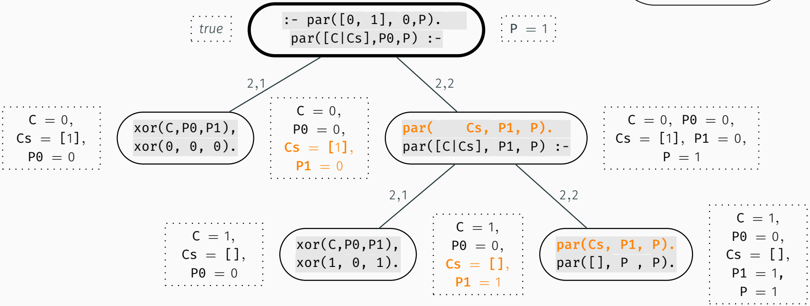




Analysis correctness

An analysis graph $\mathscr{A}$ is **correct** for a program P and a set of queries Q if it approximates all the **calls**, answers, and dependencies in the concrete semantics $[\![P]\!]_{\mathcal{Q}}$ (a set of AND trees).





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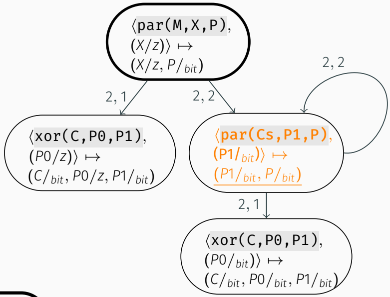

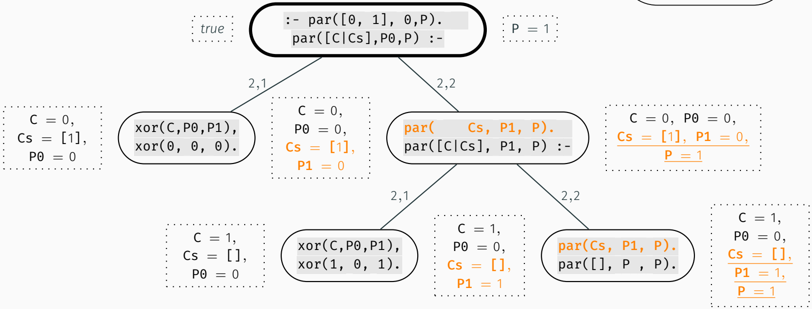

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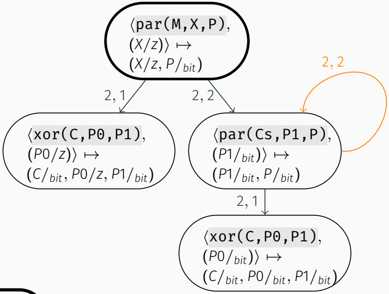
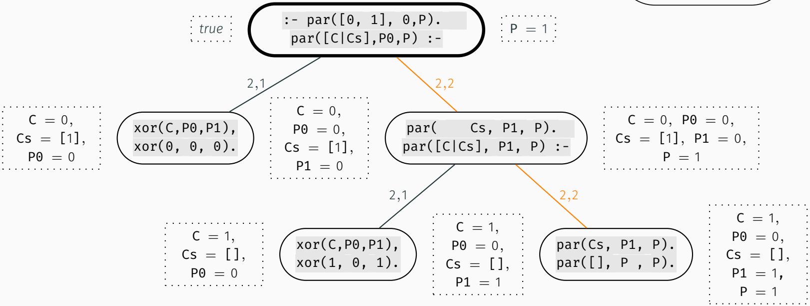




Analysis graphs

Two levels of abstraction of program execution:

- control: unbounded number of AND trees as a graph,
- data: parametric abstraction by providing domain operations.

Properties:

- interprocedural: each node contains a summary of the behavior of a predicate,
- multivariance: distinguish different abstract call patterns for
  - precision – differentiate contexts (for optimizations/verification),
  - efficiency – localize recomputation,
- path approximations: the edges in a path of the graph abstract the call stack and ordered literals form a regular approximation of all previously called predicates,

Note that analysis graphs may be used to analyze imperative programs, either via translation to Horn clauses [LOPSTR07] or directly [FTfJP07].

Incremental analysis algorithm

[TOPLAS'00]

Input	$\mathcal{Q}_\alpha$: initial abstract queries. P': target program (changed). Δ: clauses that changed from P to P'. $\mathcal{A}$: analysis results of P.
Output	a correct analysis graph for P' and $\mathcal{Q}_\alpha$.

The algorithm is based on:

- events to trigger (re)analysis at the level of literals,
- when abstractly executing a predicate call, a subgraph is reused if possible,
- for abstract domains requiring widening:
  - successive increasing calls turned into a cycle in the graph,
  - successive increasing successes are generalized (widened),
  - the order in event processing affects the abstract values in analysis result.

Adding clauses

Expand the graph for the new possible calls (and update answers).

Deleting clauses

For precision: remove subgraphs and recompute.

General conditions when restarting an analysis

The following conditions justify all incremental algorithms in the thesis, as well as the adding and deleting clauses.

Starting from a correct partial analysis

If an analysis graph correctly abstracts all the behaviors represented in calls of its node, it can be reused to obtain a correct and precise analysis.

Starting from any partial analysis

An analysis graph can be reused to obtain a correct and precise analysis if for any node:

- it correctly abstracts all the behaviors represented by its call, or
- it is scheduled to be reanalyzed.

Key: when reusing an analysis result, for efficiency, subgraphs are never (re)checked, only the success of its root node is reused when abstractly executing a literal.

Incremental and modular analysis

1. Take “snapshots” of the program sources
   (e.g., at each editor save/pause while developing, each commit, ...).
2. Detect the changes w.r.t. the previous snapshot.
3. Reanalyze:
   - annotate and remove potentially outdated information,
   - (re-)analyze incrementally module by module until an intermodular fixpoint is reached again.

So far, in abstract interpretation:

- fine-grain (clause-level) incremental analysis for non-modular programs.
  [ICLP’95, SAS’96, Kelly et. al ACSC’97, TOPLAS’00, Albert et. al PEPM’12]
- coarse-grain (module-level) analysis aimed at reducing memory consumption.
  [Codish et. al POPL’93, ENTCS’00, LOPSTR’01, Cousot & Cousot CC’02]

Modular logic programs

Strict module system

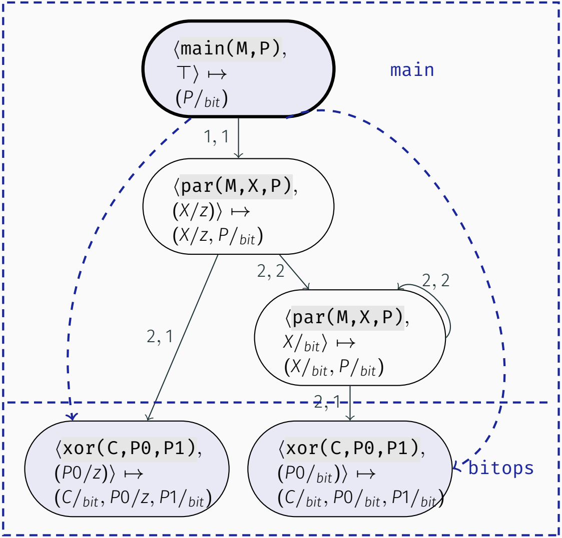
- Modules define an interface of exported and imported predicates.
- Non-exported predicates cannot be seen or used in other modules.

Modular program

```prolog
:- module(main, [main/2]).

:- use_module(bitops, [xor/3]).

main(L,P) :-
    par(L,0,P).

par([], P, P).
par([C|Cs], P0, P) :-
    xor(C, P0, P1),
    par(Cs, P1, P).
```

```prolog
:- module(bitops, [xor/3]).

xor(0,0,0).
xor(0,1,1).
xor(1,0,1).
xor(1,1,0).
```

Analysis graphs for incremental and modular analysis



We have:

- a **global analysis graph** $\mathcal{G}$: call dependencies among imported/exported predicates.
- a **local analysis graph** $\mathscr{L}_M$ per module M: limited to the predicates used in M.

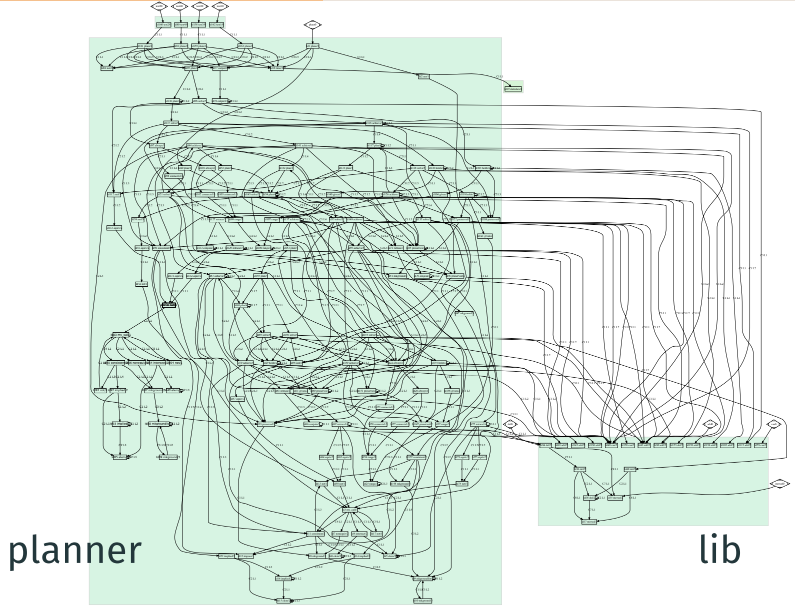
Incremental and modular analysis algorithm

Input	$\mathcal{Q}_\alpha$: initial abstract queries.
	P' ($\{M_i\}$): target program (changed).
	Δ: clauses that changed from **P** to **P'** (split by module).
	$\mathscr{A}$ ($\mathcal{G}$, $\{\mathscr{L}_i\}$): analysis results of **P**.
Output	a correct analysis graph for **P'** and $\mathcal{Q}_\alpha$.

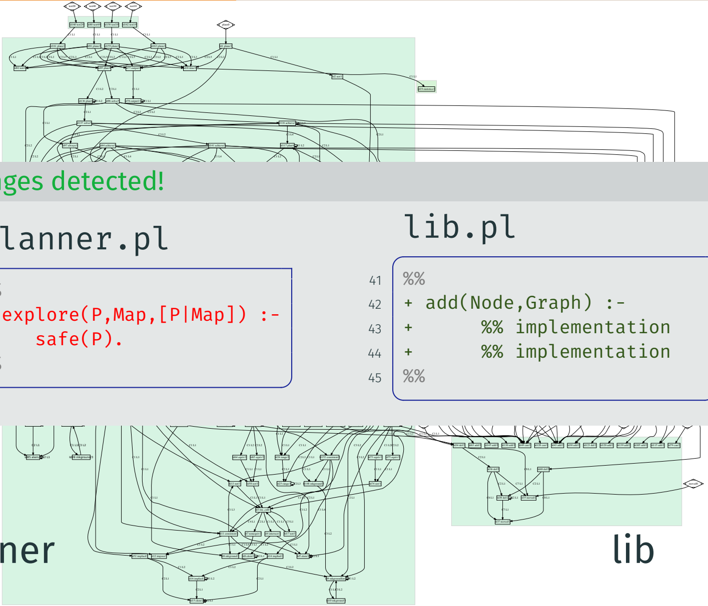
The algorithm:

- assumes as answer $\perp$ when a module has not been analyzed yet,
- (re)starts the analysis of modules using the dependencies in $\mathcal{G}$,
- updates the answers of the imported modules by scheduling new events,
- iterates until an intermodular fixpoint is reached, i.e., the global analysis graph does not change.

Snapshot of analysis graphs



Snapshot of analysis graphs



Changes detected!

planner.pl

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

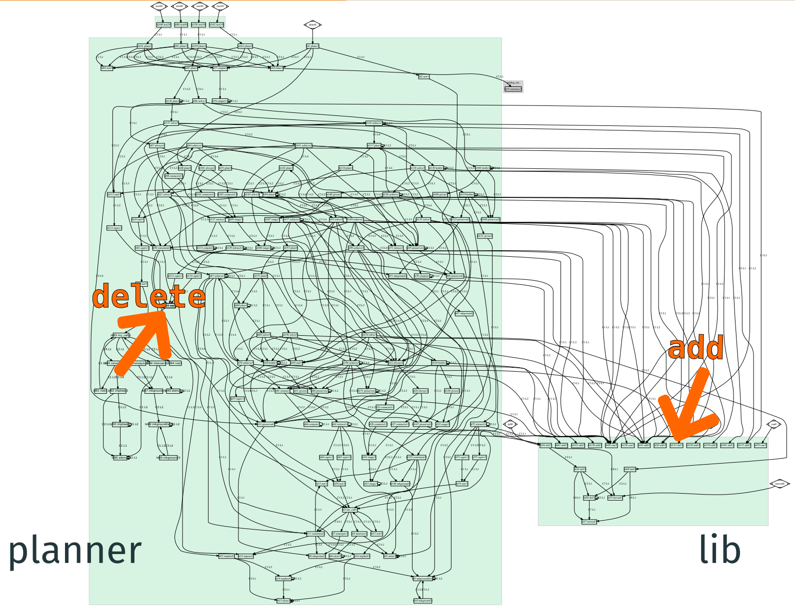
lib.pl

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

planner

lib

Snapshot of analysis graphs



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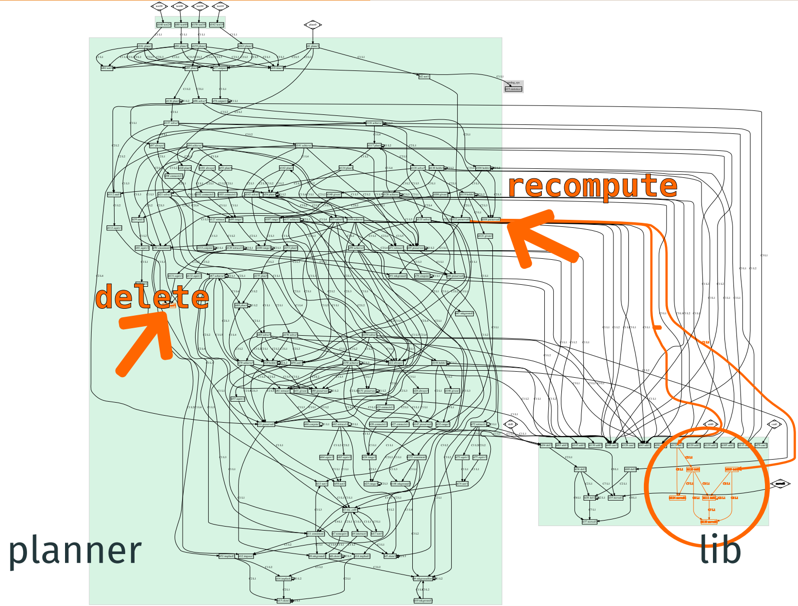
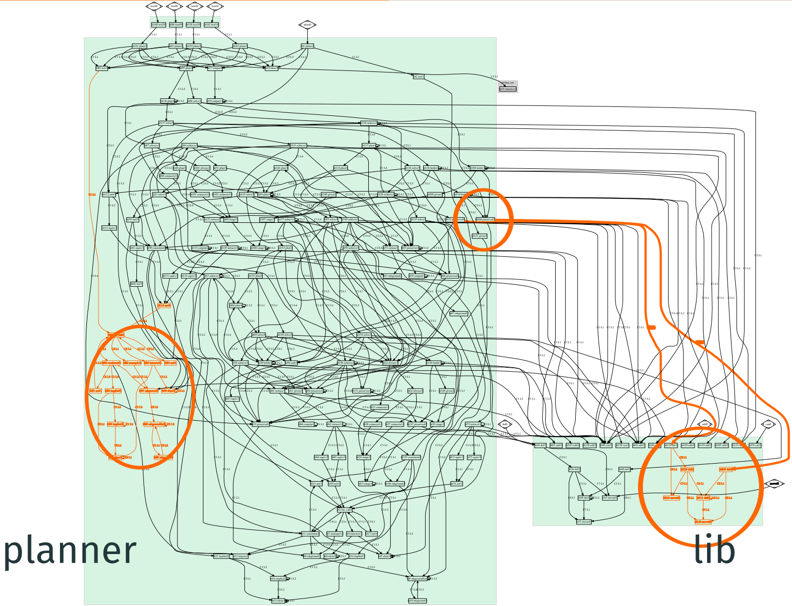
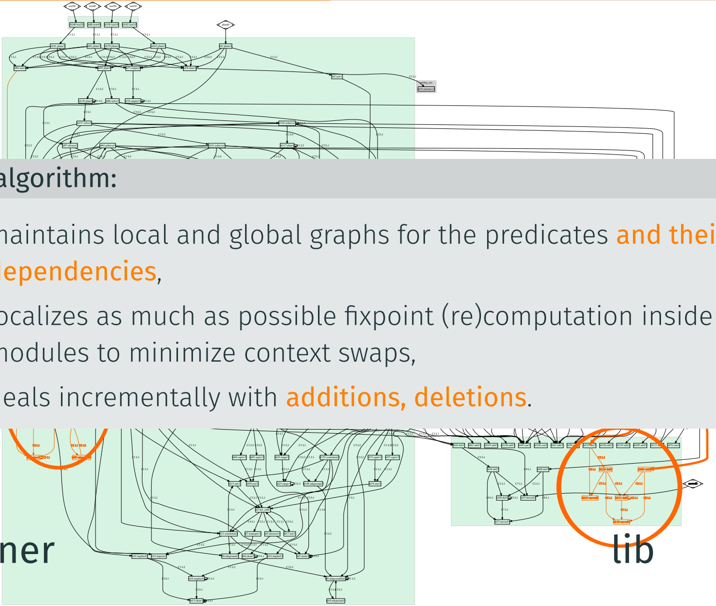


Snapshot of analysis graphs



Snapshot of analysis graphs



The algorithm:

- maintains local and global graphs for the predicates and their dependencies,
- localizes as much as possible fixpoint (re)computation inside modules to minimize context swaps,
- deals incrementally with additions, deletions.

planner

lib

Fundamental results

Lemma 4.10 (Correctness of IncAnalyze starting from a correct partial analysis)**.** *Let P be a program, Q_α be a set of abstract queries, and fix $q \in Q_\alpha$. Suppose that $\mathscr{A}_0$ is the analysis result $\mathscr{A}_0 = \text{IncAnalyze}(P, Q_\alpha \setminus \{q\}, \emptyset, \emptyset)$. Then the analysis result $\mathscr{A} = \text{IncAnalyze}(P, Q_\alpha, \emptyset, \mathscr{A}_0)$ is correct for P and $\gamma(Q_\alpha)$.*

Theorem 4.11 (Correctness of IncAnalyze starting from a partial analysis)**.** *Let P be a program, Q_α a set of abstract queries, and $\mathscr{A}_0$ a well-formed analysis graph for P. Suppose for all concrete queries $q \in \gamma(Q_\alpha)$, for all nodes n from which there is a path in the concrete execution $q \rightsquigarrow n$ in $[\![P]\!]_Q$, and for all $n_\alpha \in \mathscr{A}_0$ such that $n \in \gamma(n_\alpha)$ either:*

a) $n_\alpha \in Q_\alpha$, or

b) the subgraph with root n_α is correct for P and $\{\gamma(n_\alpha)\}$.

Then $\mathscr{A} = \text{IncAnalyze}(P, Q_\alpha, \emptyset, \mathscr{A}_0)$ is correct for P and $\gamma(Q_\alpha)$.

Theorem 4.12 (Correctness and precision of IncAnalyze95 starting from a partial analysis)**.** *Under the same conditions as Theorem 4.11, if $\mathscr{A}_0 \sqsubseteq \mathscr{A}$, then:*

$$\text{IncAnalyze95}(P, Q_\alpha, \emptyset, \emptyset) = \text{IncAnalyze95}(P, Q_\alpha, \emptyset, \mathscr{A}_0).$$

Lemma 4.13 (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 4.13 (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 $\forall \langle A, \lambda^c \rangle \in \mathscr{L}_0.\mathsf{mod}(A) \in \mathsf{imports}(M)$ correctly and precisely approximates the behavior of the imported predicates. The analysis result*

$$\mathscr{L} = \text{IncAnalyze95}(M, E, \emptyset, \mathscr{L}_0)$$

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

Lemma 5.1 (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 5.3 (Correctness of ModIncAnalyze)**.** *Let P, P' be modular programs that differ by Δ, Q_α a set of abstract queries, and $\mathscr{A} = \text{ModIncAnalyze}(P, Q_\alpha, \emptyset, (\emptyset, \emptyset))$, then if:*

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

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

Lemma 5.4 (Correctness and 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 $\mathscr{L}_M = \text{LocIncAnalyzeI95}(M, E, \mathcal{G}, \emptyset, \emptyset)$. If $\mathcal{G}$ changes to $\mathcal{G}'$ the analysis result:*

$$\text{LocIncAnalyzeI95}(M, E, \mathcal{G}', \mathscr{L}_M, \emptyset) = \text{LocIncAnalyzeI95}(M, E, \mathcal{G}', \emptyset, \emptyset)$$

is the same as analyzing from scratch, i.e., the least correct analysis graph of M, E.

Theorem 5.6 (Correctness and precision of ModIncAnalyze)**.** *Let P and P' be modular programs that differ by Δ, Q_α a set of abstract queries, and $\mathscr{A} = \text{ModIncAnalyzeI95}(P, Q_\alpha, \emptyset, (\emptyset, \emptyset))$, then*

$$\text{ModIncAnalyzeI95}(P', Q_\alpha, \emptyset, (\emptyset, \emptyset)) = \text{ModIncAnalyzeI95}(P', Q_\alpha, \mathscr{A}, \Delta).$$

Fundamental results

Lemma 4.10 (Correctness of IncAnalyze starting from a correct partial analysis). *Let P be a program, Q_α be a set of abstract queries, and fix $q \in Q_\alpha$. Suppose that $\mathscr{A}_0$ is the analysis result $\mathscr{A}_0 = \textsc{IncAnalyze}(P, Q_\alpha \setminus \{q\}, \emptyset, \emptyset)$. Then the analysis result*

$\mathscr{L}_0.\mathsf{mod}(A) \in \mathsf{imports}(M)$ *correctly and precisely approximates the behavior of the imported predicates. The analysis result*

$$\mathscr{L} = \textsc{IncAnalyze95}(M, E, \emptyset, \mathscr{L}_0)$$

Contributions

The results from our incremental, modular analysis are:

- **correct over-approximations** of the AND tree semantics, and
- the **least correct analysis graph** if no widening is performed.

Additionally:

- extended traditional algorithm with **widening** (not formalized before),
- **split correctness and precision** of incremental analysis,
- new results **reanalyzing** starting from a **partial analysis**,
- **formalized** results of an **existing modular** algorithm (non incremental).

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

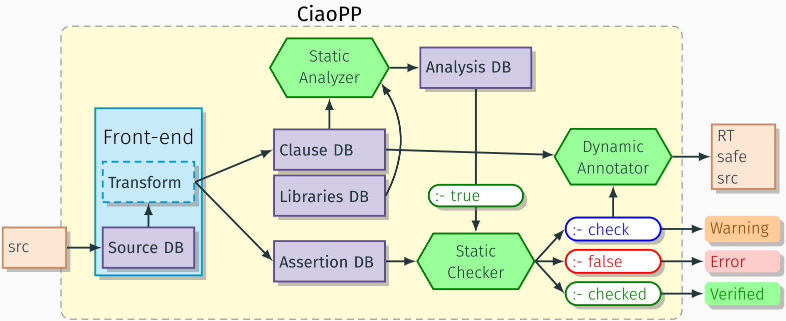
is correct for M and $\gamma(E)$ assuming $\mathscr{L}_0$.

Lemma 4.13 (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 $\forall \langle A, \lambda^c \rangle \in$*

Theorem 5.6 (Correctness and precision of ModIncAnalyze). *Let P and P' be modular programs that differ by Δ, Q_α a set of abstract queries, and $\mathscr{A} = \textsc{ModIncAnalyzeI95}(P, Q_\alpha, \emptyset, (\emptyset, \emptyset))$, then*

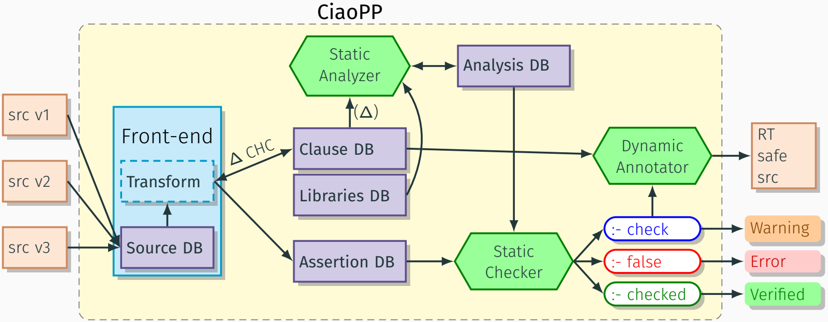
$$\textsc{ModIncAnalyzeI95}(P', Q_\alpha, \emptyset, (\emptyset, \emptyset)) = \textsc{ModIncAnalyzeI95}(P', Q_\alpha, \mathscr{A}, \Delta).$$

Implementation: the `Ciao` model and `CiaoPP` architecture

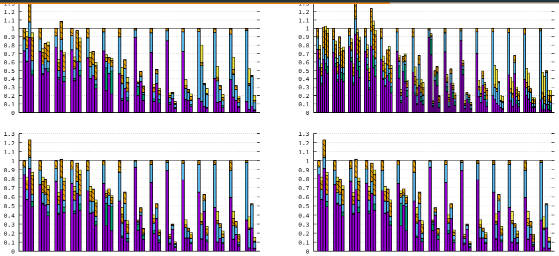


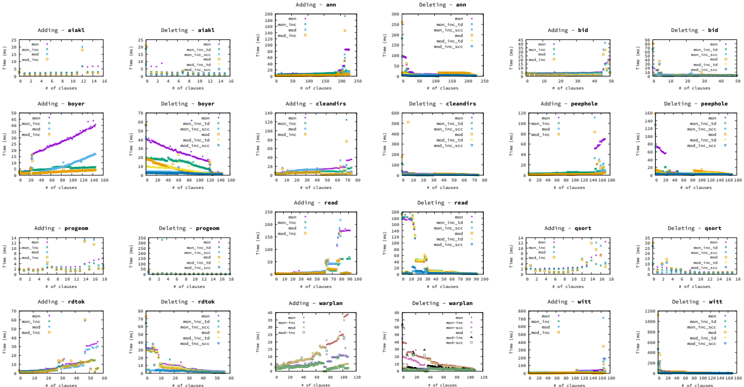
The `Ciao` model is an antecedent to the popular gradual- and hybrid-typing approaches.

Implementation: CiaoPP architecture with incrementality

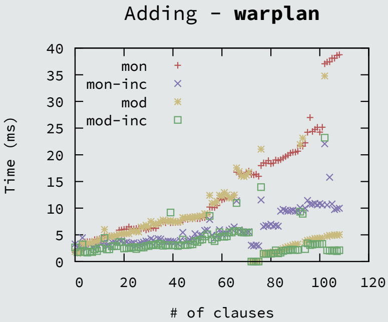


Experimental evaluation



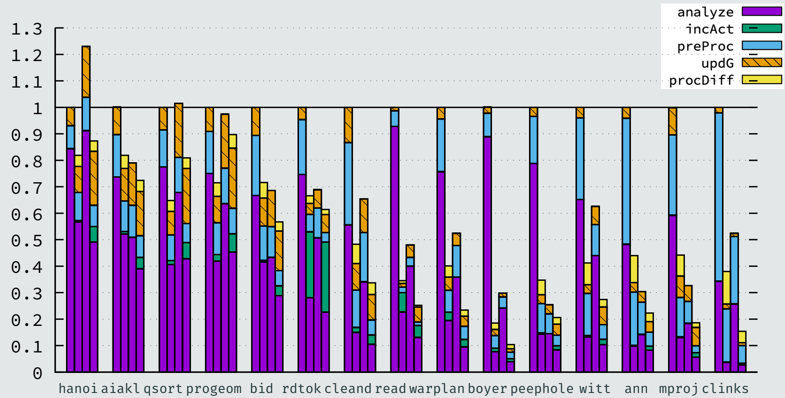


Addition experiment (time in ms) – `def` domain



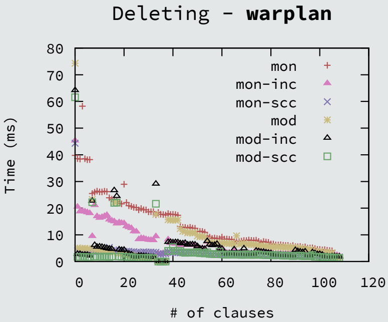
Experimental evaluation

Accumulated normalized time (def) – clause addition



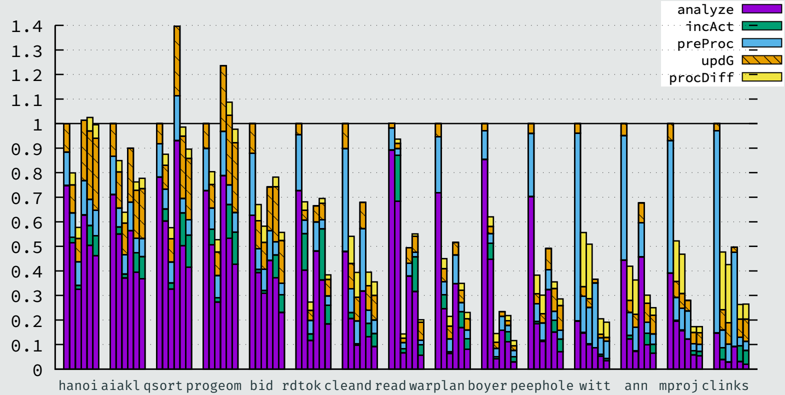
The order inside each set of bars is: |mon|mon_inc|mod|mod_inc|.

Deletion experiment (time in ms) - **def** domain



Experimental evaluation

Accumulated normalized time (def) – clause deletion



The order inside each set of bars is: |mon|mon_td|mon_scc|mod|mod_td|mod_scc|

Experimental evaluation

Summary

- almost **immediate** response when the changes do not affect the result,
- up to 13× overall speedup w.r.t. the original non-incremental algorithm,
- modular analysis from scratch is improved up to 9×,
- maximum **size** of analysis graphs **reduced**,
- keeping structures for incrementality produces **small overhead**.

Static *on-the-fly* verification in CiaoPP

```prolog
        P = B
    ;   rewrite(clause(H,B),clause(H,P),I,G,Info)
    ).

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)).

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,G),
    (       var(Code),!,
            Phrase = PCode
    ;       Vars = [],!,
            Phrase = Code
    ;       Phrase = (PCode,Code)
    ).
```

```
Verified assertion:
:- check calls add_annotations(Info,Phrase,Ind,Gnd)
   : ( var(Phrase), indep(Info,Phrase) ).
Verified assertion:
:- check success add_annotations(Info,Phrase,Ind,Gnd
)
   : ( var(Phrase), indep(Info,Phrase) )
```

↖ Part of the parallelizer code.

Static *on-the-fly* verification in CiaoPP

```
      P = B
    ;  rewrite(clause(H,B),clause(H,P),I,G,Info)
    ).

rewrite( clause(H,B), clause(H,P),I,G,Info) :-
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```
Verified assertion:
:- check calls add_annotations(Info,Phrase,Ind,Gnd)
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Verified assertion:
:- check success add_annotations(Info,Phrase,Ind,Gnd
```

Average assertion checking time (s)

Benchmark: `chat-80` port – 5.2*k* LOC across 27 files (`Ciao` Prolog).

	E1			E2			E3		
domain	*noinc*	*inc*	*speedup*	*noinc*	*inc*	*speedup*	*noinc*	*inc*	*speedup*
`pairSh`	2.8	1.6	×1.8	2.9	1.5	×1.9	2.8	1.6	×1.8
`def`	3.0	1.6	×1.9	2.7	1.5	×1.8	2.9	1.7	×1.7
`ShGrC`	18.1	5.1	×3.5	18.3	5.1	×3.6	18.1	4.5	×4.0

Static *on-the-fly* verification in CiaoPP

```
        P = B
    ;   rewrite(clause(H,B),clause(H,P),I,G,Info)
    ).

rewrite( clause(H,B), clause(H,P),I,G,Info) :-
    numbervars_2(H,0,Lhv),
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:- pred add_annotations(Info,Phrase,Ind,Gnd)
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   => (ground(Ind), ground(Gnd)).

add_annotations([],[],_,_).
add_annotations([I|Is],[P|Ps],Indep,Gnd)
```

```
Verified assertion:
:- check calls add_annotations(Info,Phrase,Ind,Gnd)
   : ( var(Phrase), indep(Info,Phrase) ).
Verified assertion:
:- check success add_annotations(Info,Phrase,Ind,Gnd
```

Average assertion checking time (s) – only changing assertions

Benchmark: `chat-80` port – 5.2*k* LOC across 27 files (`Ciao` Prolog).

	E1			E2			E3		
domain	*noinc*	*inc*	*speedup*	*noinc*	*inc*	*speedup*	*noinc*	*inc*	*speedup*
`pairSh`	2.8	1.7	×1.6	2.7	1.6	×1.7	2.9	1.7	×1.7
`def`	3.1	1.5	×2.0	2.9	1.4	×2.0	3.0	1.6	×1.9
`ShGrC`	18.2	2.0	×9.1	18.1	1.9	×9.6	18.2	1.9	×9.6

Guiding the analyzer

Two problems that motivate allowing the user to guide the analyzer:

1. Automatic **approximations** may lead to **imprecise results**:
    - desired **optimizations** cannot be applied,
    - **assertions** cannot be **verified** ("false alarms").
2. Analysis may require excessive **resources** (time or space):

Techniques to optionally annotate program parts to **guide invariants inference**:

Astrée [Cousot et. al ESOP'05] uses at program point:

- *asserts* with properties that have to be verified,
- *known facts* used to refine abstract state.

CiaoPP [ESOP'96] uses assertions that can be qualified with a status:

- *check*: meaning that it needs to be verified,
- *trust*: representing knowledge that the user guarantees to be true (beliefs).

The `Ciao` assertion language

Assertions express abstractions of the behavior of programs.

[ILPSW'97, LP25Y'99]

`pred` assertions

`:- [Status] pred` *Head* `[:` *Pre*`] [=>` *Post*`].`

- *Head*: predicate that the assertion applies to,
- *Pre*: properties about how the predicate is used (hold when called),
- *Post*: properties that hold if Pre holds and the predicate succeeds,
- `Status` qualifies the meaning of assertions.

```
:- trust pred fact(N, R)         => (int(N), R > 0).
:- trust pred fact(N, R) : N > 1 => even(R).
```

Using trust assertions

Trust assertions may be used to:

- **regain precision** during analysis.

Using trust assertions

Trust assertions may be used to:

- **regain precision** during analysis.

```
% (y > 0) % Analyzing with an intervals domain (non relational)
x = y + 2;
% (x > 2, y > 0)
z = x - y;
% (int(z), x > 2, y > 0)
```

Using trust assertions

Trust assertions may be used to:

- **regain precision** during analysis.

```
% (y > 0) % Analyzing with an intervals domain (non relational)
x = y + 2;
% (x > 2, y > 0)
z = x - y;
% (int(z), x > 2, y > 0)
```

But we know `x = y + 2`.

Using trust assertions

Trust assertions may be used to:

- **regain precision** during analysis.

```
1 % (y > 0) % Analyzing with an intervals domain (non relational)
2 x = y + 2;
3 % (x > 2, y > 0)
4 z = x - y;
5 % (int(z), x > 2, y > 0)
```

But we know `x = y + 2`.

```
1 % (y > 0)
2 x = y + 2;
3 % (x > 2, y > 0)
4 z = x - y;
5 % (int(z), x > 2, y > 0)
6 trust(z == 2); % Because of line 2
7 % (z = 2, x > 2, y > 0)
```

Using trust assertions

Trust assertions may be used to:

- **regain precision** during analysis.
- **speed up computation** of analysis.

```
:- trust pred html_escape(S0, S) => (string(S0), string(S)).
html_escape( "``"||S0 , "&ldquo;"||S ) :- !, html_escape(S0, S).
html_escape( "''"||S0 , "&rdquo;"||S ) :- !, html_escape(S0, S).
html_escape( "'" ||S0 , "&quot;" ||S ) :- !, html_escape(S0, S).
html_escape( """"||S0 , "&apos;" ||S ) :- !, html_escape(S0, S).
html_escape(    [X|S0],        [X | S]) :- !,
    character_code(X),
    html_escape(S0, S).
html_escape("","").
```

Using trust assertions

Trust assertions may be used to:

- **regain precision** during analysis.
- **speed up computation** of analysis.
- define **abstract usage or specifications** of libraries or dynamic predicates.

```
:- module(sockets, []).

:- export(receive/2).
:- pred receive(S, M) : (socket(S), var(M)) => list(M, utf8).
:- impl_defined(receive/2).
% receive is written in C
```

Using trust assertions

Trust assertions may be used to:

- **regain precision** during analysis.
- **speed up computation** of analysis.
- define **abstract usage or specifications** of libraries or dynamic predicates.
- (re)define the **language semantics** for abstract domains.

```
:- trust pred '*'(A, B, C) : (int(A), int(B)) => int(C).
:- trust pred '*'(A, B, C) : (flt(A), int(B)) => flt(C).
:- trust pred '*'(A, B, C) : (int(A), flt(B)) => flt(C).
:- trust pred '*'(A, B, C) : (flt(A), flt(B)) => flt(C).
```

Guided analysis

- Precision: assertions are precisely applied during analysis:
    - the abstract success states inferred are covered by the success assertion conditions (if they exist).
    - the abstract call states inferred are covered by the call assertion conditions.
- Correctness modulo assertions: the computed analysis is correct for $P, \mathcal{Q}$ if all conditions are correct.

Reacting incrementally to assertion edits

Why? In generic code assertions play a very important role as a place holder for the code that is not available yet, e.g.:

- yet to be implemented,
- compiled in a different language, or
- linked dynamically.

The contributions are:

- an incremental fixpoint algorithm that reacts to changes in both the program and the assertions, and
- an application of this approach to the scalable analysis of generic programming (based on open predicates).

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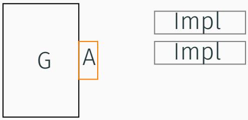

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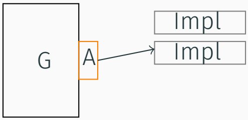

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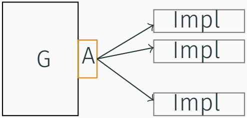

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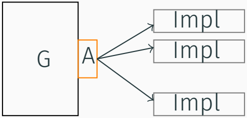

(And we also proposed an encoding of generic programming in (Ciao) Prolog.)

Abstract extensionality

How does **the way programs are written** (or transformed) **affect** analysis **precision**?

- **semantically equivalent** programs may exhibit **different properties**.
- **semantically different** programs may **appear identical** when analyzed.
- two classes of programs for a given program P and a given abstraction A – **completeness/incompleteness cliques** ($\mathbb{C}(P, \mathrm{A})/\overline{\mathbb{C}}(P, \mathrm{A})$):
  - $\mathbb{C}(P, \mathrm{A})$ is the class of all variants of P for which the analysis with A is precise (no false alarms)
  - $\overline{\mathbb{C}}(P, \mathrm{A})$ is the class of all variants of P for which analysis with A is imprecise.

  - automatic removal of false alarms is impossible: there is no many-to-one reducibility of $\overline{\mathbb{C}}(P, \mathrm{A})$ to $\mathbb{C}(P, \mathrm{A})$
  - we provide systematic reduction of $\mathbb{C}(P, \mathrm{A})$ into $\overline{\mathbb{C}}(P, \mathrm{A})$ (obfuscation).

Conclusions

Incremental and modular analysis [ICLP TC'18, TAPAS'19, TPLP'21]

- theoretical results of correctness,
- generalized conditions to reuse an analysis graph correctly,
- almost immediate response when the changes do not affect the result,
- up to 13× speedup w.r.t. the original non-incremental algorithm,
- being aware of modular structures is useful: up to 2× speedup when compared with the original incremental algorithm,
- modular analysis from scratch is improved up to 9×,
- keeping structures for incrementality produces small overhead,
- analyzing interactively, on-the-fly is practical! [F-IDE'21, ICLP'21]

Conclusions

Guided analysis [LOPSTR'18]

- we extended the algorithm to use trusted assertions,
- we showed how safely assuming assertions affects the analysis result,
- we provided means to detect incompatible assertions.

Incremental analysis with assertions [LOPSTR'19]

- we extended the context-sensitive analysis algorithm to react incrementally to fine grain changes in (multivariant) assertions,
- we showed an application for generic code, to efficiently specialize the analysis result as implementations become available,
- we provided a syntax to build generic programs in Prolog using traits.

Conclusions

Abstract extensionality [POPL'20]

- non-trivial abstract interpretation always unveils implicitly also properties concerning the way programs are written,
- automatic **semantic** code **obfuscation**,
- systematic **removal of false alarms** is **impossible**,
- the class of all programs that are incomplete for a given non-trivial abstraction is **Turing complete**.

Future work

- Applications of incremental and modular analysis:
  - improving performance when combining analysis with other techniques (e.g., transformations),
  - semantic code search,
  - parallel fixpoint computation,
- Heuristics for automatic configuration of incrementality settings.
- Amenability of abstract domains to incrementality.
- Incrementality-aware transformations (from other source languages).

A scalable static analysis framework for reliable program development exploiting incrementality and modularity

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PhD Thesis Defense
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