Horn Clause-based Program Analysis and Verification with CiaoPP

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DPA Workshop @ ECOOP/ISSTA — Jul 18, 2018, Amsterdam

Outline:

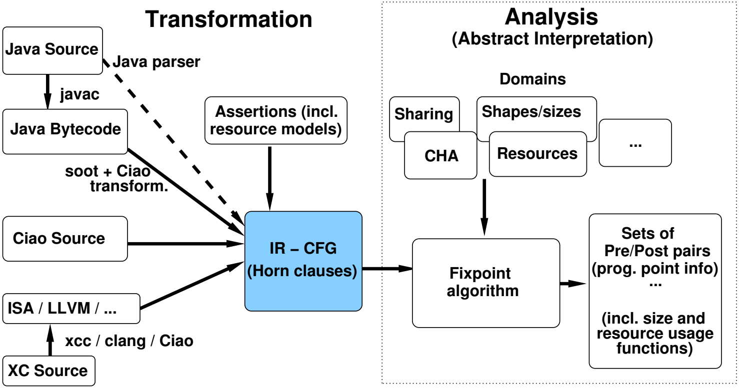
- The CiaoPP Horn clause analyzer.

Some recent results:

- Combining the incremental and the modular fixpoints.
- Energy analysis.
- Static guarantees on run-time checks.

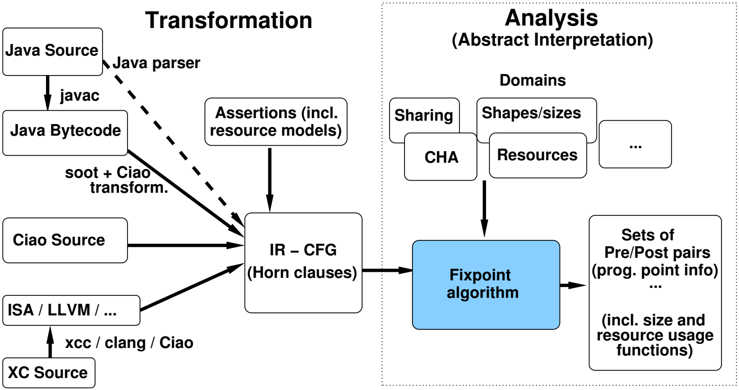
Intermediate Repr.: (Constraint) Horn Clauses (CiaoPP)

[LOPSTR'07]



- 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.

Analysis: CiaoPP Parametric AI Framework



- Analysis *parametric* w.r.t. abstractions, resources, ... (and languages).
- Efficient fixpoint algorithm for (C)HC IR.

[JLP'92, POPL'94, TOPLAS'99, SAS'96, TOPLAS'00, FTfJP'07, ICLP'18]

[NACLP'89, ICLP'91, ICLP'97, SAS'02, FLOPS'04, LOPSTR'04, PADL'06, PASTE'07]

[VMCAI'08, LCPC'08, PASTE'08, CC'08, ISMM'09, NGC'10, LCPC'08]

Efficient, Parametric Fixpoint Algorithm

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

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- 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}.

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  - **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).
    - $Dep(B : \lambda_{inB})$ = the set of entries depending on $B : \lambda_{inB}$.

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- Characteristics:
  - **Precision:** context-sensitivity / multivariance, prog. point info, ...
  - **Efficiency:** memoization, dependency tracking, SCCs, base cases, ...
  - **Genericity:** abstract domains are plugins, configurable, widening, ...
  - Handles mutually recursive methods.
  - Handles library calls, externals, ...
  - Modular and *incremental*

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  - **Genericity:** abstract domains are plugins, configurable, widening, ...
  - Handles mutually recursive methods.
  - Handles library calls, externals, ...
  - Modular and *incremental* $\rightarrow \rightarrow$ recently combined! $\rightarrow \rightarrow$

Combining the incremental and the modular fixpoints

Analysis running continuously in the background

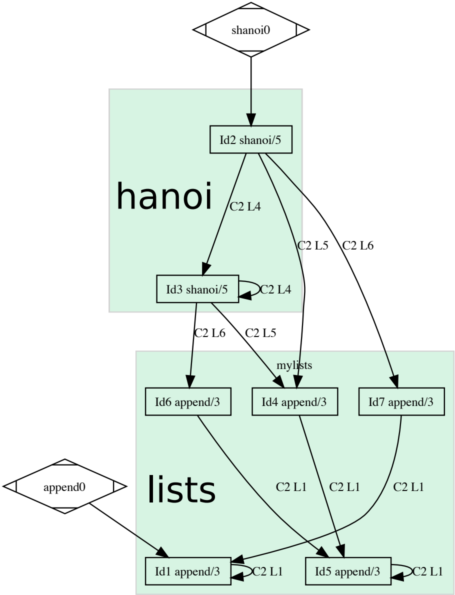
1. We take *"snapshots"* of the program sources (e.g., at each editor save/pause/... while developing).
2. We *detect the changes* w.r.t. the previous snapshot and *reanalyze*:
   - Annotate and remove potentially *outdated information*.
   - (Re-)Analyze *incrementally* (i.e., only parts needed) module by module until an intermodular fixpoint is reached again.

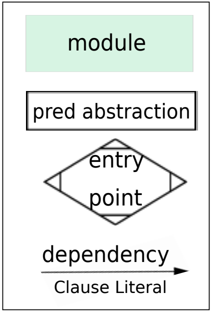
Our previous work:

- *Fine-grain* (block-level) incremental analysis for *non-modular* programs [SAS'96, TOPLAS'00].
- *Coarse-grain* (module level) incremental analysis for *modular* programs [ENTCS'00, LOPSTR'01].

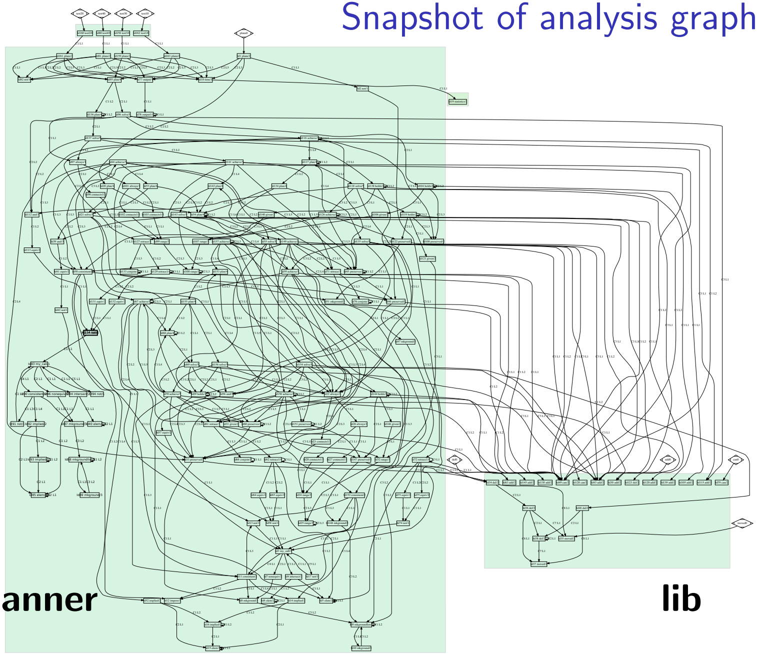
Recent work [ICLP'18]: combine (non-trivial).

Analysis result example





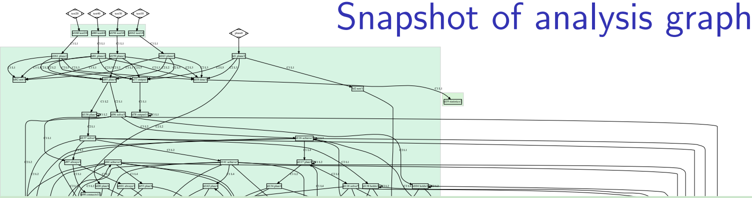
Snapshot of analysis graphs



planner

lib

Snapshot of analysis graphs



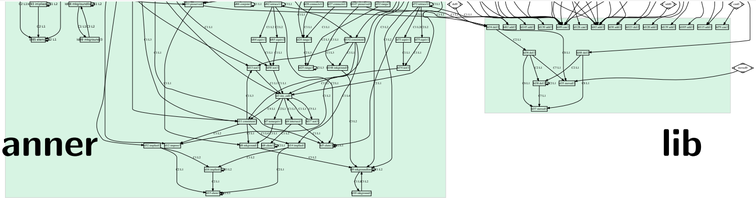
Changes detected!

planner.pl

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

lib.pl

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



planner **lib**

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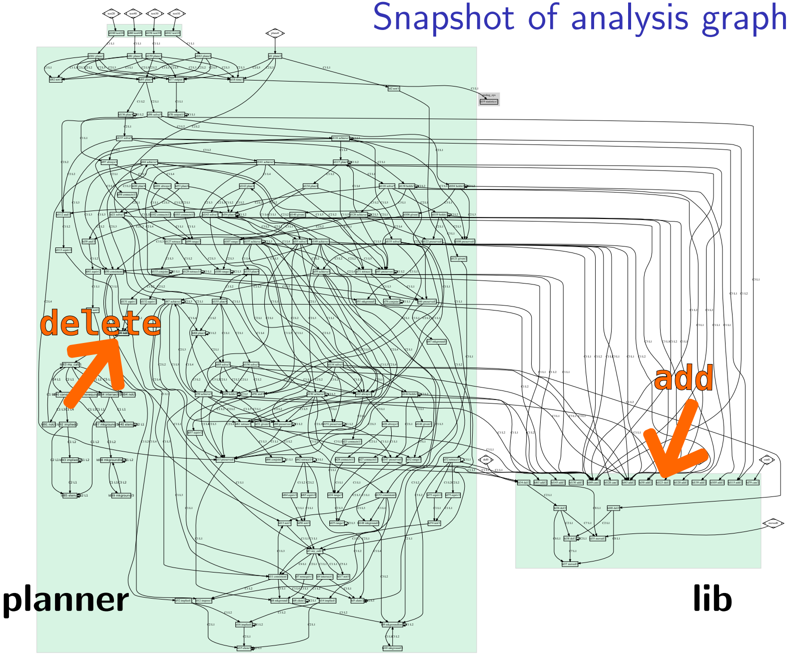

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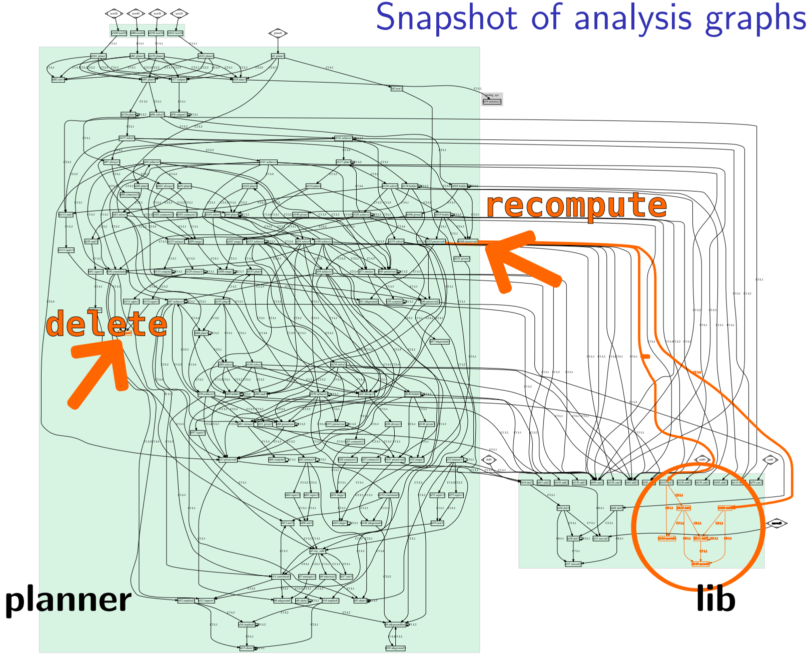

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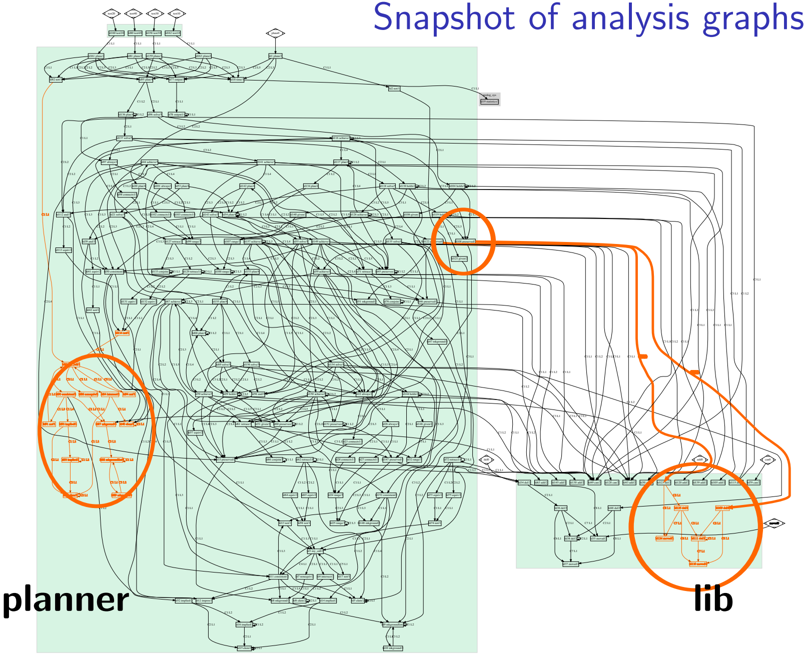

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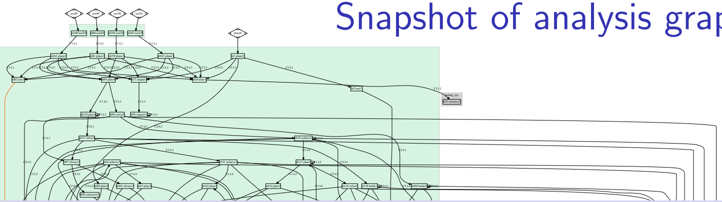
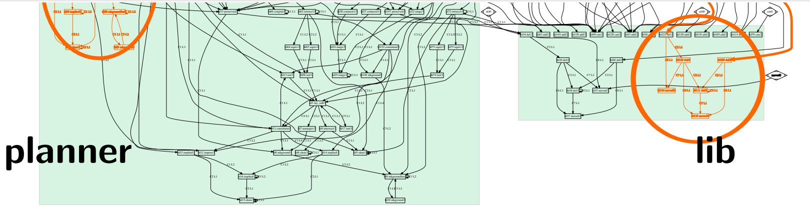


The algorithm:

- 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.



Fundamental results

Theorem 1 (Base PLAI analysis from scratch) *For a program P and initial λ^cs Es, the PLAI algorithm returns an AT and a DT which represents the* least *program analysis graph of P and Es.*

Proposition 1 (Analyzing a module from scratch) *If module M is analyzed for entries Es within the incremental modular analysis algorithm from scratch (i.e., with no previous information available):*

$$\mathscr{L}^M = \textsc{LocIncAnalyze}(M, Es, \mathcal{G}, (\emptyset,\emptyset), (\emptyset,\emptyset))$$

$\mathscr{L}^M$ will represent the least *module analysis graph of M and Es, assuming $\mathcal{G}$.*

Proposition 2 (Adding clauses to a module) *Given M and M' s.t., $M' = M \cup C_i$,*
$\mathscr{L}^M = \textsc{LocIncAnalyze}(M, Es, \mathcal{G}, (\emptyset,\emptyset), (\emptyset,\emptyset))$, *then*
$\textsc{LocIncAnalyze}(M', Es, \mathcal{G}, (\emptyset,\emptyset), (\emptyset,\emptyset)) =$
$\textsc{LocIncAnalyze}(M, Es, \mathcal{G}, \mathscr{L}^M, (C_i,\emptyset))$

Proposition 3 (Removing clauses from a module) *Given M and M' s.t. $M' = M \setminus C_i$,*
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Proposition 4 (Updating the $\mathscr{L}$) *Given $\mathscr{L}^M = \textsc{LocIncAnalyze}(M, Es, \mathcal{G}, (\emptyset,\emptyset), (\emptyset,\emptyset))$ if $\mathcal{G}$ changes to $\mathcal{G}'$:*
$\textsc{LocIncAnalyze}(M, Es, \mathcal{G}', (\emptyset,\emptyset), (\emptyset,\emptyset)) =$
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Proposition 5 (Analyzing modular programs from scratch) *If program P is analyzed for entries Es by the incremental modular analysis algorithm from scratch (with no previous information available):*

$$\mathcal{G} = \textsc{ModIncAnalyze}(P, Es, (\emptyset,\emptyset), (\emptyset,\emptyset))$$

$\mathcal{G}$ will represent the least *modular program analysis graph of* exports(M)*, s.t. $M \in P$.*

Theorem 2 (Modular incremental analysis) *Given modular programs P, P' s.t. $\Delta P = (C_i, C_j)$, $P' = (P \cup C_i) \setminus C_j$, entries Es, and $\mathcal{G} = \textsc{ModIncAnalyze}(P, Es, (\emptyset,\emptyset), (\emptyset,\emptyset))$:*
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Fundamental results

Theorem 1 (Base PLAI analysis from scratch)
For a program P and initial λ^cs Es, the PLAI algorithm returns an AT and a DT which represents the least *program analysis graph of P and Es.*

Proposition 1 (Analyzing a module from scratch)

What it means

The results from our incremental, modular analysis are:

- *Correct over-approximations*.
- The most *accurate* (lfp).

M *and* M' *s.t.,* $M' = M \cup C_i$,
$\mathscr{L}^M = \text{LocIncAnalyze}(M, Es, \mathcal{G}, (\emptyset,\emptyset), (\emptyset,\emptyset))$, *then*
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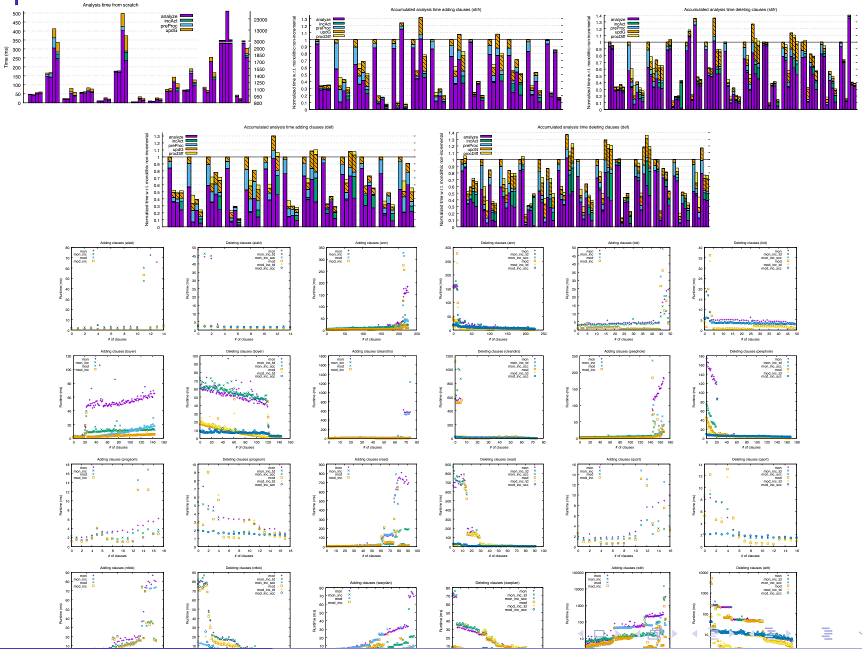
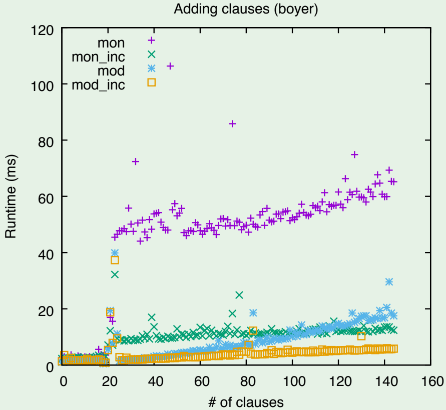
Experimental results



Experimental results

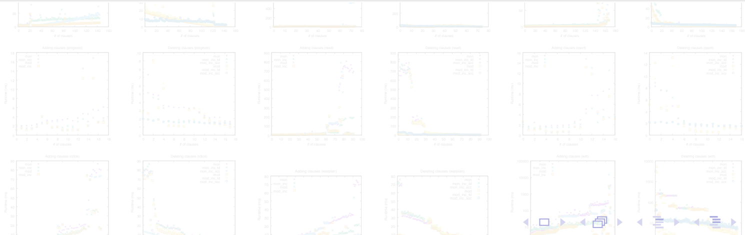
Addition experiment



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.



Energy analysis

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: [LOPSTR'13, FOPARA'15, HIP3ES'16]

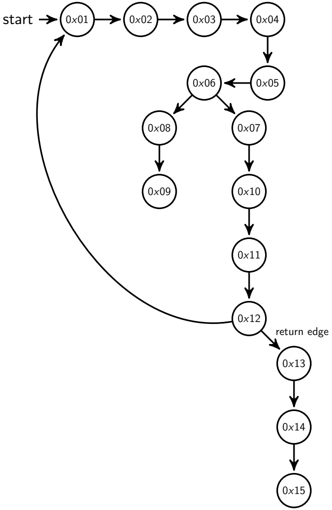
- Analysis of (embedded) programs written in XC, on XMOS processors.
- Using more sophisticated *ISA- and LLVM-level energy models* for XMOS XS1 (Bristol & XMOS).
- Comparing to measured energy consumption.

ENTRA Whole-Systems Energy Transparency · XMOS · Universitas Roskildensis · University of Bristol · imdea software

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
```



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
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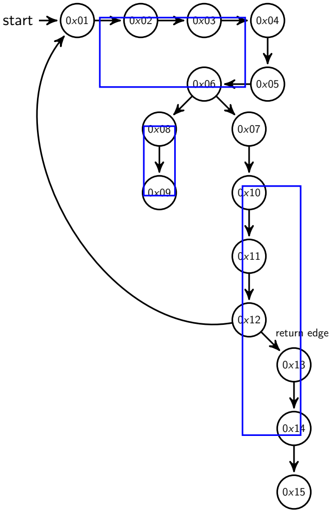


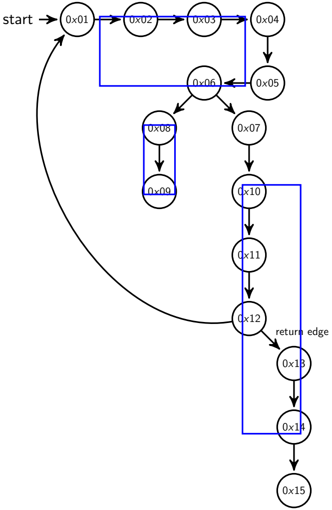
Transformation example - binaries

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).

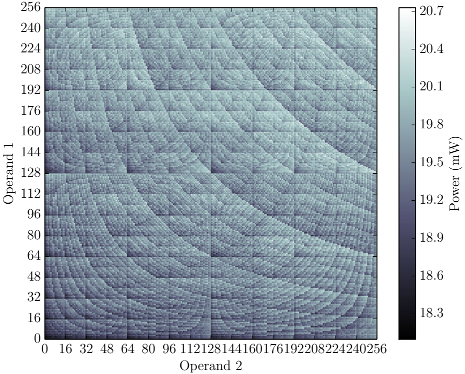
bf01(1,Sp0x1,R0_4,R1):-
      bu(_),
      ldw(R0_1,Sp0x1),
      sub(R0_2,R0_1,0x1),
      bl(_),
      fact(R0_2,R0_3),
      ldw(R1,Sp0x1),
      mul(R0_4,R1,R0_3),
      retsp(_).

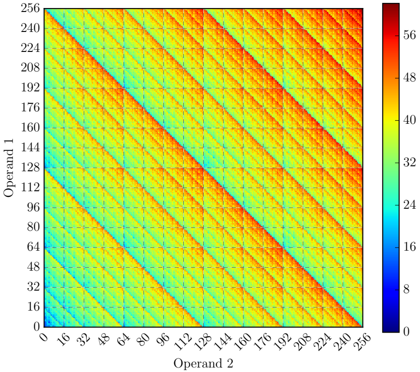
bf01(0,Sp0x1,R0,R1):-
      mkmsk(R0,0x1),
      retsp(_).
```



Low-level ISA characterization – operand size

Obtaining the cost model: energy consumption/instruction; operand size.

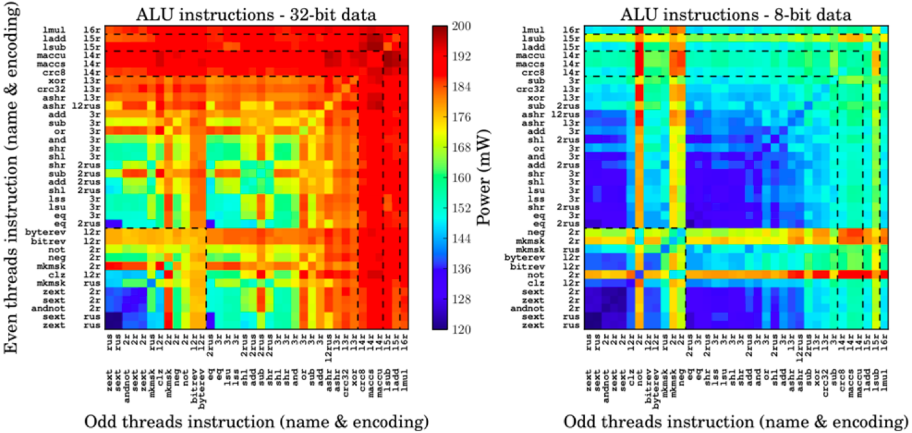




Eder, Kerrison – Bristol U / XMOS.

Low-level ISA characterization – interference

Obtaining the cost model: energy consumption/instruction; interference.



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Energy model, expressed in the Ciao assertion language

```
:- 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) ).

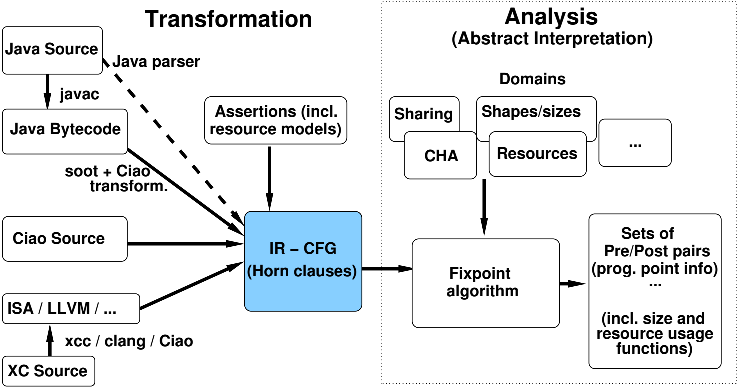
--:---  energy.pl      Top L1     (Ciao)----------------------------------------
```

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.

Intermediate Repr.: (Constraint) Horn Clauses (CiaoPP)

[LOPSTR'07]



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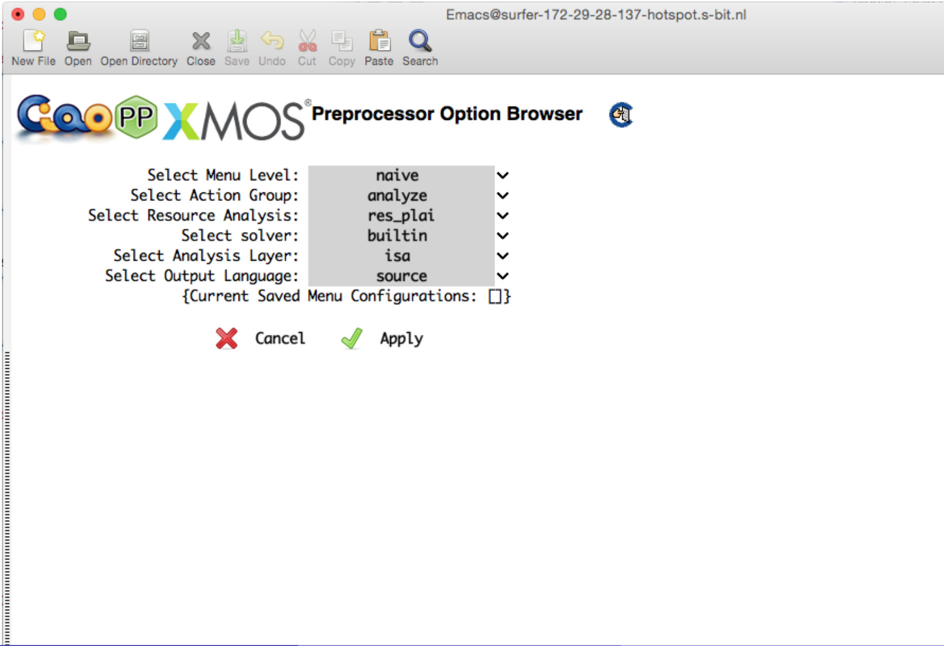
  - Target: A (C) Horn Clause program capturing $[\![P]\!]$ (or, possibly, $[\![P]\!]^\alpha$)
- Block-based CFG. Each block represented as a *Horn clause*.
- Used for all analyses: aliasing, CHA/shape/types, data sizes, resources, etc.
- Allows supporting multiple languages.

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

Emacs@surfer-172-29-28-137-hotspot.s-bit.nl

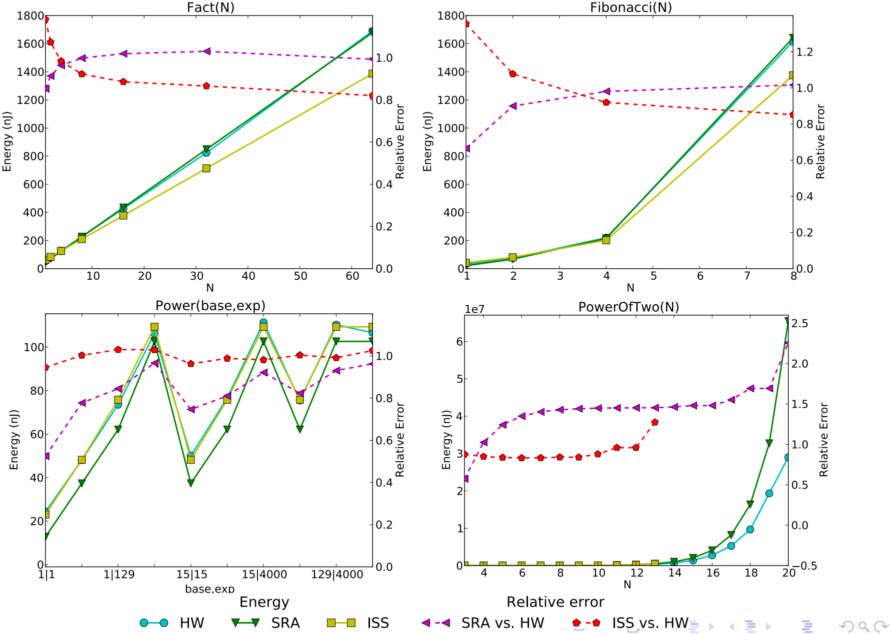
Visit New File Open Directory Close Save Save As Undo Cut Copy Paste String Forward Print Buffer

```
#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)

```
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;
}
```

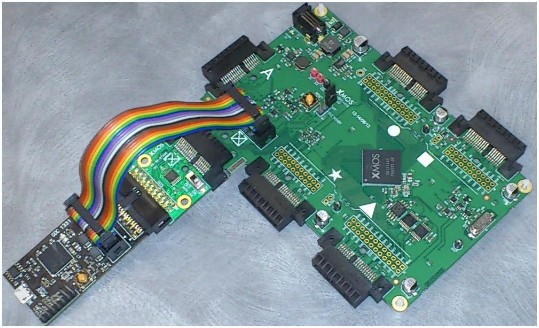
XC Analysis Results (FIR Filter, LLVM IR level)

```
#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;
}
```

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 LLVMIR)

[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 LLVMIR)

[FOPARA'15]

- 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]

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

```
#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) {
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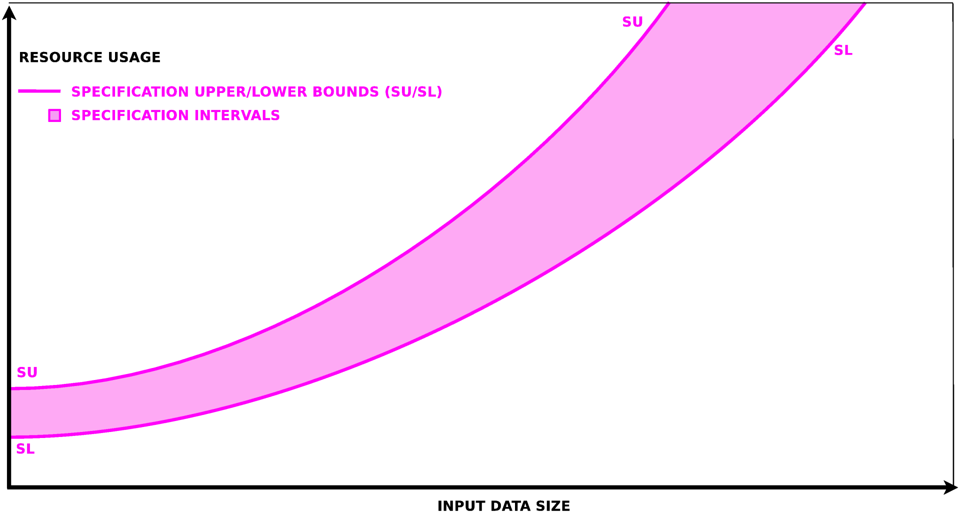
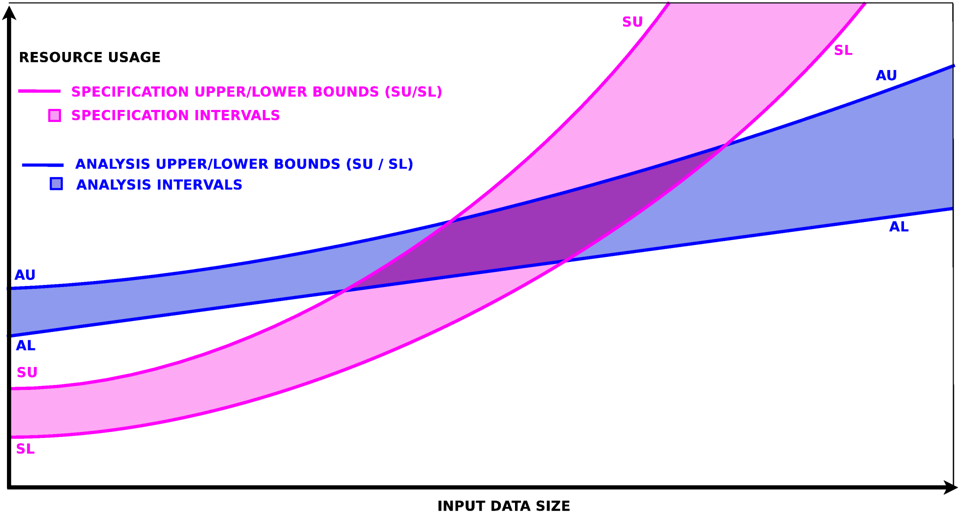
  else if (ynh < 0) { ynh = 0x80000000; }
  else { ynh = 0x7fffffff; }
  return ynh;
}
```

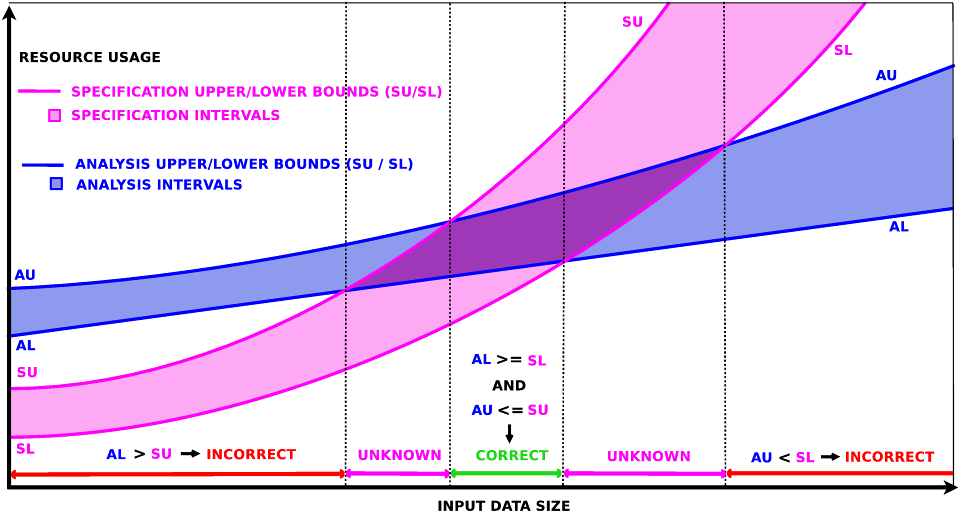
Resource Usage Verification – Function Comparisons
[ICLP'10, FOPARA'12]



Resource Usage Verification – Function Comparisons [ICLP'10, FOPARA'12]



Resource Usage Verification – Function Comparisons
[ICLP'10, FOPARA'12]



Static performance guarantees for programs with run-time checks

Our Static Cost Analysis (SCA) [PLDI'90, SAS'94, ILPS'97, ICLP'07, TPLP'14, TPLP'16]

Example

Consider the following predicate (`rev/2`) for reversing a list of terms.

```
:- pred rev/2:list*var.
rev([], []).
rev([X|Xs], Y):-
    rev(Xs, Ys),
    app1(Ys,X,Y).
```

```
app1([],X,[X]).
app1([E|Y],X,[E|T]):-
    app1(Y,X,T).
```

Our Static Cost Analysis (SCA) [PLDI'90, SAS'94, ILPS'97, ICLP'07, TPLP'14, TPLP'16]

Example

Consider the following predicate (`rev/2`) for reversing a list of terms.

```
:- pred rev/2:list*var.
rev([], []).
rev([X|Xs], Y):-
    rev(Xs, Ys),
    app1(Ys,X,Y).
```

```
app1([],X,[X]).
app1([E|Y],X,[E|T]):-
    app1(Y,X,T).
```

Result of SCA:

```
:- true pred rev(X,Y)
   : (list(X),var(Y),length(X,L))
  => (list(Y), length(Y,L))
   + cost(exact(1/2 L^2 + 3/2 L + 1)).
```

$$\texttt{cost(exact(}\tfrac{1}{2}L^2 + \tfrac{3}{2}L + 1\texttt{))}$$

```
:- true pred app1(X,Y,Z)
   : (list(X),var(Z),length(X,L))
  => (list(Z), length(Z,L+1))
   + cost(exact(L)).
```

Our Static Cost Analysis (SCA) [PLDI'90, SAS'94, ILPS'97, ICLP'07, TPLP'14, TPLP'16]

Example

$$\texttt{cost(exact(}\frac{1}{2}L^2 + \frac{3}{2}L + 1\texttt{))}$$

$$\texttt{cost(exact(}L\texttt{))}$$

```
rev([X|Xs], Y) :-
    rev(Xs, Ys),
    app1(Ys,X,Y).
```

Result of SCA:

```
:- true pred rev(X,Y)
   : (list(X),var(Y),length(X,L))
  => (list(Y), length(Y,L))
   + cost(exact(1/2 L^2 + 3/2 L + 1)).
```

$\texttt{cost(exact(}\frac{1}{2}L^2 + \frac{3}{2}L + 1\texttt{))}$

```
:- true pred app1(X,Y,Z)
   : (list(X),var(Z),length(X,L))
  => (list(Z), length(Z,L+1))
   + cost(exact(L)).
```

$\texttt{cost(exact(}L\texttt{))}$

Our Static Cost Analysis (SCA) [PLDI'90, SAS'94, ILPS'97, ICLP'07, TPLP'14, TPLP'16]

Example

Co length(X,L)) v/2) for reversing a list of terms.

```
rev([], []).                          app1([],X,[X]).
rev([X|Xs], Y):-      length(X,L))    [E|T]):-
    rev(Xs, Ys),                      T).
    app1(Ys,X,Y).
```

Result of SCA:

```
:- true pred rev(X,Y)                     :- true pred app1(X,Y,Z)
   : (list(X),var(Y),length(X,L))            : (list(X),var(Z),length(X,L))
  => (list(Y), length(Y,L))                 => (list(Z), length(Z,L+1))
   + cost(exact(1/2 L^2 + 3/2 L + 1)).       + cost(exact(L)).
```

$$\text{cost}(\text{exact}(\tfrac{1}{2}L^2 + \tfrac{3}{2}L + 1)) \qquad \text{cost}(\text{exact}(L))$$

Run-time Checks - Assertions and Admissible Overhead

check assertions specify pre- and post-conditions for calls to a given predicate.

Example (contd.)

```
:- check pred rev/2
   : list*var => list*list.
:- check pred app1/3
   : list*term*var => list*term*list.
rev([], []).
rev([X|Xs], Y):-
   rev(Xs, Ys), app1(Ys,X,Y).
app1([],X,[X]).
app1([E|Y],X,[E|T]):- app1(Y,X,T).
```

Run-time Checks - Assertions and Admissible Overhead

check assertions specify pre- and post-conditions for calls to a given predicate.

Example (contd.)

```
:- check pred rev/2
   : list*var => list*list.
:- check pred app1/3
   : list*term*var => list*term*list.
rev([], []).
rev([X|Xs], Y):-
    rev(Xs, Ys), app1(Ys,X,Y).
app1([],X,[X]).
app1([E|Y],X,[E|T]):- app1(Y,X,T).
```

Program code

Run-time Checks - Assertions and Admissible Overhead

check assertions specify pre- and post-conditions for calls to a given predicate.

Example (contd.)

Assertions

```
:- check pred rev/2
    : list*var => list*list.
:- check pred app1/3
    : list*term*var => list*term*list.
```

Program code

```
rev([], []).
rev([X|Xs], Y):-
    rev(Xs, Ys), app1(Ys,X,Y).
app1([],X,[X]).
app1([E|Y],X,[E|T]):- app1(Y,X,T).
```

Run-time Checks - Instrumentation

Program instrumented with run-time checking code (assuming no analysis, i.e., full RT checks).

```
rev(A,B) :-
    revC(A,B,C),
    rev_(A,B),
    revS(A,B,C).

revC(A,B,E) :-
    reify_check(list(A),C),
    reify_check(var(B), D),
    E is C/\D,
    warn_if_false(E,calls).

revS(A,B,E) :-
     reify_check(list(A),C),
     reify_check(list(B),D),
     F is C/\D,G is (E#1)\/F,
     warn_if_false(G,success).

 rev_([],[]).
 rev_([X|Xs],Y) :-
     rev(Xs,Ys),
     app1(Ys,X,Y).
```

```
app1(A,B,C) :-
    app1C(A,B,C,D),
    app1_(A,B,C),
    app1S(A,B,C,D).

app1C(A,B,C,G) :-
    reify_check(list(A),D),
    reify_check(term(B),E),
    reify_check(var(C),F),
    G is D/\(E/\F),
    warn_if_false(G,calls).

app1S(A,B,C,G) :-
    reify_check(list(A),D),
    reify_check(term(B),E),
    reify_check(list(C),F),
    H is D/\E/\F,K is (G#1)\/H,
    warn_if_false(K,success).

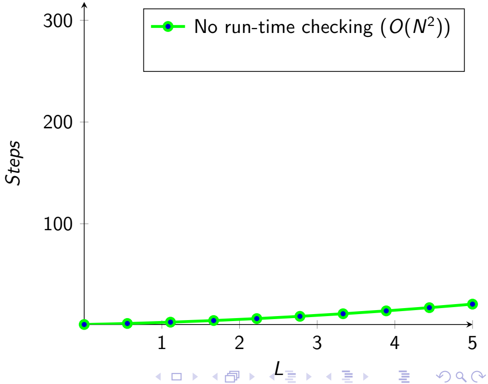
app1_([],X,[X]).
app1_([E|Y],X,[E|T]) :-
    app1(Y,X,T).
```

Run-time Checks - Analysis Results (1)

Our Static Cost Analysis analyzes both the original and the instrumented version .

[PLDI'90, SAS'94, ILPS'97, ICLP'07, TPLP'14, TPLP'16]

```
:- true pred rev(X,Y)
 : (list(X),var(Y),length(X,L))
 =>(list(Y), length(Y,L))
 + cost(exact(1/2 L^2 + 3/2 L + 1)).
```



Run-time Checks - Analysis Results (1)

Our Static Cost Analysis analyzes both the original and the instrumented version.

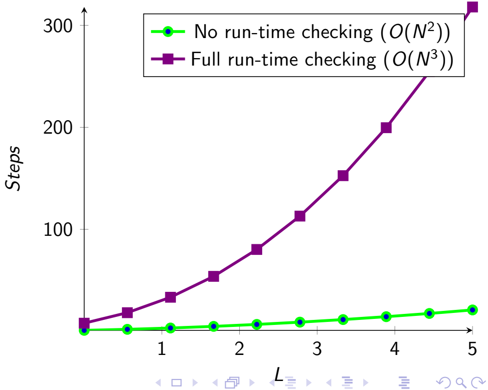
[PLDI'90, SAS'94, ILPS'97, ICLP'07, TPLP'14, TPLP'16] [PPDP'18]

```
:- true pred rev(X,Y)
 : (list(X),var(Y),length(X,L))
 =>(list(Y), length(Y,L))
 + cost(exact(1/2 L^2 + 3/2 L + 1)).
```

$\frac{1}{2}L^2 + \frac{3}{2}L + 1$

```
:- true pred rev(X,Y)
 : (list(X),var(Y),length(X,L))
 =>(list(Y), length(Y,L))
 + cost(exact(1/2 L^3 + 7L^2 + 29/2 L + 8)).
```

$\frac{1}{2}L^3 + 7L^2 + \frac{29}{2}L + 8$



Run-time Checks - Instrumentation

Program instrumented with run-time checking code (assuming no analysis, i.e., full RT checks).

```
rev(A,B) :-
    revC(A,B,C),
    rev_(A,B),
    revS(A,B,C).

revC(A,B,E) :-
    reify_check(list(A),C),
    reify_check(var(B), D),
    E is C/\D,
    warn_if_false(E,calls).

revS(A,B,E) :-
     reify_check(list(A),C),
     reify_check(list(B),D),
     F is C/\D,G is (E#1)\/F,
     warn_if_false(G,success).

 rev_([],[]).
 rev_([X|Xs],Y) :-
     rev(Xs,Ys),
     app1(Ys,X,Y).
```

```
app1(A,B,C) :-
    app1C(A,B,C,D),
    app1_(A,B,C),
    app1S(A,B,C,D).

app1C(A,B,C,G) :-
    reify_check(list(A),D),
    reify_check(term(B),E),
    reify_check(var(C),F),
    G is D/\(E/\F),
    warn_if_false(G,calls).

app1S(A,B,C,G) :-
    reify_check(list(A),D),
    reify_check(term(B),E),
    reify_check(list(C),F),
    H is D/\E/\F,K is (G#1)\/H,
    warn_if_false(K,success).

app1_([],X,[X]).
app1_([E|Y],X,[E|T]) :-
    app1(Y,X,T).
```

Run-time Checks - Instrumentation

Program instrumented with run-time checking code (assuming no analysis, i.e., full RT checks).

```
rev(A,B) :-
    revC(A,B,C),
    rev_(A,B),
    revS(A,B,C).

revC(A,B,E) :-
    reify_check(list(A),C),
    reify_check(var(B), D),
    E is C/\D,
    warn_if_false(E,calls).

revS(A,B,E) :-
     reify_check(list(A),C),
     reify_check(list(B),D),
     F is C/\D,G is (E#1)\/F,
     warn_if_false(G,success).

 rev_([],[]).
 rev_([X|Xs],Y) :-
      rev(Xs,Ys),
      app1(Ys,X,Y).
```

```
app1(A,B,C) :-
    app1C(A,B,C,D),
                 ,
                D).

                 -
                list(A),D),
                term(B),E),
                var(C),F),
                F),
                e(G,calls).

                 -
                list(A),D),
                term(B),E),
                (list(C),F),
    H is D/\E/\F,K is (G#1)\/H,
    warn_if_false(K,success).

app1_([],X,[X]).
app1_([E|Y],X,[E|T]) :-
     app1(Y,X,T).
```

list/1

```
:- true pred list(X)
   : length(X,L)
   + cost(exact(L+1)).

:- regtype list/1.
list([]).
list([_|T]):-
   list(T).
```

Run-time Checks - Instrumentation

Program instrumented with run-time checking code (assuming no analysis, i.e., full RT checks).

```
rev(A,B) :-
    revC(A,B,C),
    rev_(A,B),
    revS(A,B,C).

revC(A,B,E) :-
    reify_check(list(A),C),
    reify_check(var(B), D),
    E is C/\D,
    warn_if_false(E,calls).

revS(A,B,E) :-
     reify_check(list(A),C),
     reify_check(list(B),D),
     F is C/\D,G is (E#1)\/F,
     warn_if_false(G,success).

 rev_([],[]).
 rev_([X|Xs],Y) :-
      rev(Xs,Ys),
      app1(Ys,X,Y).
```

```
app1(A,B,C) :-
    app1C(A,B,C,D),
    app1_(A,B,C),
    app1S(A,B,C,D).

app1C(A,B,C,G) :-
    reify_check(list(A),D),
    reify_check(term(B),E),
    reify_check(var(C),F),
    G is D/\(E/\F),
    warn_if_false(G,calls).

app1S(A,B,C,G) :-
    reify_check(list(A),D),
    reify_check(term(B),E),
    reify_check(list(C),F),
    H is D/\E/\F,K is (G#1)\/H,
    warn_if_false(K,success).

app1_([],X,[X]).
app1_([E|Y],X,[E|T]) :-
     app1(Y,X,T).
```

Run-time Checks - Assertions and Admissible Overhead

We can also specify the admissible run-time overhead for a set of predicates.

Example (contd.)

```
:- check pred *   % Applies to all preds
   + cost(so_ub(constant),[steps,rtc_ratio]).
```

Assertions

```
:- check pred rev/2
   : list*var => list*list.
:- check pred app1/3
   : list*term*var => list*term*list.
```

Program code

```
rev([], []).
rev([X|Xs], Y):-
    rev(Xs, Ys), app1(Ys,X,Y).
app1([],X,[X]).
app1([E|Y],X,[E|T]):- app1(Y,X,T).
```

Run-time Checks - Assertions and Admissible Overhead

We can also specify the admissible run-time overhead for a set of predicates.

Example (contd.)

Admissible RT Overhead

```
:- check pred *  % Applies to all preds
   + cost(so_ub(constant),[steps,rtc_ratio]).
```

Assertions

```
:- check pred rev/2
   : list*var => list*list.
:- check pred app1/3
   : list*term*var => list*term*list.
```

Program code

```
rev([], []).
rev([X|Xs], Y):-
    rev(Xs, Ys), app1(Ys,X,Y).
app1([],X,[X]).
app1([E|Y],X,[E|T]):- app1(Y,X,T).
```

Run-time Checks - Analysis Results (1 contd.)

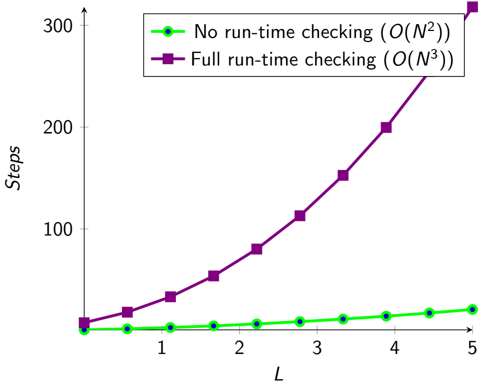
Given an admissible run-time checking overhead specification, our system automatically verifies whether it is met or not.

```
:- true pred rev(X,Y)
 : (list(X),var(Y),length(X,L))
 =>(list(Y), length(Y,L))
 + cost(exact(½L² + 3/2 L + 1)).
```

$\frac{1}{2}L^2 + \frac{3}{2}L + 1$

```
:- true pred rev(X,Y)
 : (list(X),var(Y),length(X,L))
 =>(list(Y), length(Y,L))
 + cost(exact(½L³ + 7L² + 29/2 L + 8)).
```

$\frac{1}{2}L^3 + 7L^2 + \frac{29}{2}L + 8$



Run-time Checks - Analysis Results (1 contd.)

Given an admissible run-time checking overhead specification, our system automatically verifies whether it is met or not.

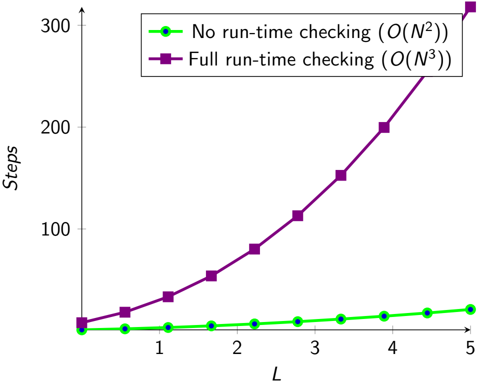
```
:- true pred rev(X,Y)
 : (list(X),var(Y),length(X,L))
 =>(list(Y), length(Y,L))
 + cost(exact(½L² + 3/2 L + 1)).
```

$$\text{cost(exact(}\frac{1}{2}L^2 + \frac{3}{2}L + 1\text{))}$$

```
:- true pred rev(
 : (list(
 =>
 +                        + 29/2 L + 8)).
```

NOT ADMISSIBLE

$$\frac{L^3}{L^2} = L > 1$$



Run-time Checks - Optimizing using Static Analysis

Static analysis can be applied to prove some run-time assertions, reducing the generated run-time code. [AADEBUG'97, LOPSTR'99, LPAR'06, SAS'03, PPDP'16]

```
 rev(A,B) :-
    revC(A,B,C),
    rev_(A,B).

revC(A,B,E) :-
    reify_check(list(A),C),
    reify_check(var(B), D),
    E is C/\D,
    warn_if_false(E,calls).

rev_(A,B) :- rev_i(A,B).

rev_i([],[]).
rev_i([X|Xs],Y) :-
    rev_i(Xs,Ys),app1(Ys,X,Y).

app1([],X,[X]).
app1([E|Y],X,[E|T]):-
    app1(Y,X,T).
```

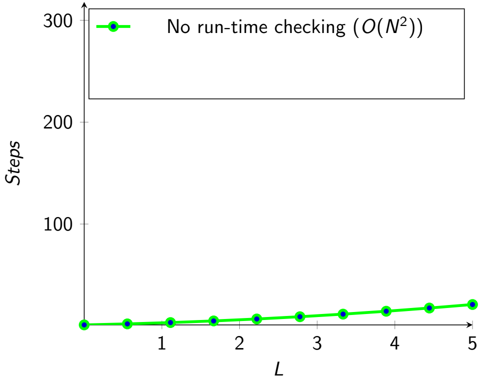
Static Analysis reduces the necessity for instrumentation (overhead), after proving the correctness of some assertions statically.
Here: **postcondition** *check eliminated by SA.*

However, some run-time checking may still remain.
Here: **precondition** *check left.*

Run-time Checks - Analysis Results (2)

```
:- true pred rev(X,Y)
 : (list(X),var(Y),length(X,L))
 =>(list(Y), length(Y,L))
 + cost(exact(½L² + 3/2 L + 1)).
```

$$\text{cost}(\text{exact}(\tfrac{1}{2}L^2 + \tfrac{3}{2}L + 1))$$



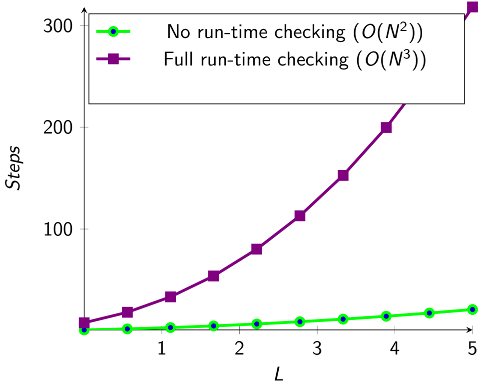
Run-time Checks - Analysis Results (2)

```
:- true pred rev(X,Y)
 : (list(X),var(Y),length(X,L))
 =>(list(Y), length(Y,L))
 + cost(exact(½L² + 3/2 L + 1)).
```

$$\texttt{+ cost(exact(}\tfrac{1}{2}L^2 + \tfrac{3}{2}L + 1\texttt{))}.$$

```
:- true pred rev(X,Y)
 : (list(X),var(Y),length(X,L))
 =>(list(Y), length(Y,L))
 + cost(exact(½L³ + 7L² + 29/2 L + 8)).
```

$$\texttt{+ cost(exact(}\tfrac{1}{2}L^3 + 7L^2 + \tfrac{29}{2}L + 8\texttt{))}.$$



Run-time Checks - Analysis Results (2)

```
:- true pred rev(X,Y)
 : (list(X),var(Y),length(X,L))
 =>(list(Y), length(Y,L))
 + cost(exact(1/2 L^2 + 3/2 L + 1)).
```

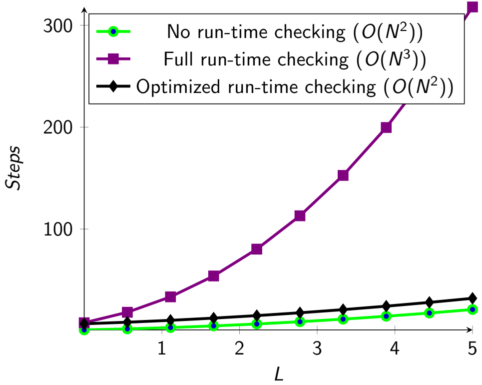
$$\frac{1}{2}L^2 + \frac{3}{2}L + 1$$

```
:- true pred rev(X,Y)
 : (list(X),var(Y),length(X,L))
 =>(list(Y), length(Y,L))
 + cost(exact(1/2 L^3 + 7L^2 + 29/2 L + 8)).
```

$$\frac{1}{2}L^3 + 7L^2 + \frac{29}{2}L + 8$$

```
:- true pred rev(X,Y)
 : (list(X),var(Y),length(X,L))
 =>(list(Y), length(Y,L))
 + cost(exact(1/2 L^2 + 5/2 L + 7)).
```

$$\frac{1}{2}L^2 + \frac{5}{2}L + 7$$



Run-time Checks - Analysis Results (2)

```
:- true pred rev(X,Y)
 : (list(X),var(Y),length(X,L))
 =>(list(Y), length(Y,L))
 + cost(exact(½L² + 3/2 L + 1)).
```

```
:- true pred r
 : (li
   ... L² + 29/2 L + 8)).
```

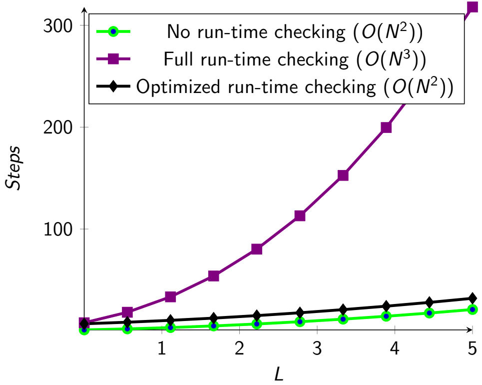
NOT ADMISSIBLE

$\frac{L^3}{L^2} = L > 1$

```
:- true pred r
 : (li
 =
 +          2 L + 7)).
```

OK

$\frac{L^2}{L^2} = 1$



Experimental Results - Verifying Admissible Overhead

The experimental evaluation suggests that our method is feasible and promising.

Bench	RTC	Bound Inferred	%D	T_A(ms)	Ovhd	Verif.
`app1(A,B,_)`	off	$l_A + 1$	0.0	98.13		
	full	$l_A{}^2 + 6 \cdot l_A \cdot l_B + 17 \cdot l_A + 6 \cdot l_B + 8$	0.0	521.18	$l_A + l_B$	false
	opt	$3 \cdot l_A + 2 \cdot l_B + 8$	0.0	311.98	$\frac{l_B}{l_A} + 1$	false
`nrev(L,_)`	off	$\frac{1}{2} \cdot l_L{}^2 + \frac{3}{2} \cdot l_L + 1$	0.0	218.15		
	full	$\frac{1}{2} \cdot l_L{}^3 + 7 \cdot l_L{}^2 + \frac{29}{2} \cdot l_L + 8$	0.0	885.08	l_L	false
	opt	$\frac{1}{2} \cdot l_L{}^2 + \frac{5}{2} \cdot l_L + 7$	0.0	756.82	1	checked
`sift(A,_)`	off	$\frac{1}{2} \cdot l_A{}^2 + \frac{3}{2} \cdot l_A + 1$	0.0	255.55		
	full	$\frac{2}{3} \cdot l_A{}^3 + \frac{15}{2} \cdot l_A{}^2 + \frac{95}{6} \cdot l_A + 7$	0.0	980.63	l_A	false
	opt	$\frac{1}{2} \cdot l_A{}^2 + \frac{7}{2} \cdot l_A + 7$	0.0	521.65	1	checked
`pfxsum(A,_)`	off	$l_A + 2$	0.0	146.98		
	full	$2 \cdot l_A{}^2 + 12 \cdot l_A + 14$	0.0	749.94	l_A	false
	opt	$3 \cdot l_A + 10$	0.0	469.71	1	checked

Experimental Results - Verifying Admissible Overhead

The experimental evaluation suggests that our method is feasible and promising.

Bench	RTC	Bound Inferred	%D	T_A(ms)	Ovhd	Verif.
`oins(E,L,_)`	off	$l_L + 2$	0.09	142.55		
	full	$\frac{1}{3} \cdot {l_L}^3 + \frac{9}{2} \cdot {l_L}^2 - \frac{5}{2} \cdot l_L + \frac{11}{3}$	99.93	917.39	${l_L}^2$	false
	opt*	$\frac{3}{2} \cdot l_L + 6$	50.14	340.15	1	checked
`mmtx(A,B,_)`	off	$r_A \cdot c_A \cdot c_B + 3 \cdot r_A \cdot c_B + 2 \cdot r_A - 2 \cdot c_B$	7.58	460.21		
	full	$4 \cdot {r_A}^2 c_A \cdot c_B + 4 \cdot {r_A}^2 \cdot c_A + 4 \cdot {r_A}^2 \cdot c_B + 4 \cdot {r_A}^2 + r_A \cdot {c_A}^2 \cdot c_B + 4 \cdot r_A \cdot {c_A}^2 + 2 \cdot r_A \cdot c_A \cdot {c_B}^2 + 11 \cdot r_A \cdot c_A \cdot c_B + 20 \cdot r_A \cdot c_A + 15 \cdot r_A + 7$	0.0	1682.54	$N^\dagger$	false
	opt	$r_A \cdot c_A \cdot c_B + 2 \cdot c_A \cdot c_B + 2 \cdot r_A \cdot c_A + 4 \cdot r_A \cdot c_A + 6 \cdot r_A + 2 \cdot c_A + 11$	0.0	1120.23	1	checked
`ldiff(A,B,_)`	off	$l_A \cdot l_B + 2 \cdot l_A + 1$	2.06	786.22		
	full	${l_A}^2 + 3 \cdot l_A \cdot l_B + 10 \cdot l_A + 2 \cdot l_B + 7$	0.27	1769.22	$\frac{l_A}{l_B} + 1$	false
	opt	$l_A \cdot l_B + 5 \cdot l_A + 2 \cdot l_B + 8$	0.0	1226.15	1	checked
`bsts(N,T)`	off	$d_T + 3$	0.1	714.83		
	full	$3 \cdot 2^{(d_T+2)} + 3 \cdot 2^{(d_T+1)} + 3 \cdot 2^{(d_T-1)} + 3 \cdot 2^{d_T} + \frac{3}{2} \cdot (d_T - 1)^2 + \frac{47}{2} \cdot (d_T + 2) - \frac{27}{2}$	1.19	438.72	$\frac{2^{d_T}}{d_T}$	false
	opt*	$3 \cdot 2^{(d_T+1)} + 4 \cdot d_T + 14$	4.01	245.09	$\frac{2^{d_T}}{d_T}$	false

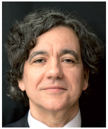
$\dagger N = max(r_A, c_A, c_B)$

Demo!

Please see examples in the CiaoPP playground.

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

The Team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Playground at: `http://play.ciao-lang.org`

Thank you!

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