Static Analysis-based Debugging, Certification, Testing, and Optimization with CiaoPP

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Objective

- *Facilitate the development of safe, efficient programs*.
- Approach:
  - Next-generation, higher-level, *multiparadigm* prog. languages.
  - *Improved program development environments.*
    - A framework (CiaoPP) which *integrates*:
      - Debugging.
      - Verification and certification.
      - Testing.
      - Optimization (optimized compilation, parallelization, ...).

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Verification, Diagnosis, and Safe Approximations

- Need to compare actual semantics $[\![P]\!]$ with intended semantics $\mathcal{I}$:

P is *partially correct* w.r.t. $\mathcal{I}$ iff	$[\![P]\!] \leq \mathcal{I}$
P is *complete* w.r.t. $\mathcal{I}$ iff	$\mathcal{I} \leq [\![P]\!]$
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  Usually, partial descriptions of $\mathcal{I}$ available, typically as *assertions*.

- *Problem:* difficulty computing $[\![P]\!]$ w.r.t. interesting observables.
- *Approach:* use a *safe approximation* of $[\![P]\!] \rightarrow$ i.e., $[\![P]\!]_{\alpha^+}$ or $[\![P]\!]_{\alpha^-}$
- Specially attractive if compiler computes (most of) $[\![P]\!]_{\alpha^+}$ anyway.

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P is prt. correct w.r.t. $\mathcal{I}_\alpha$ if	$\alpha([\![P]\!]) \leq \mathcal{I}_\alpha$	$[\![P]\!]_{\alpha^+} \leq \mathcal{I}_\alpha$
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[BDD+97, HPB99, PBH00c, PBH00a, HPBLG03]

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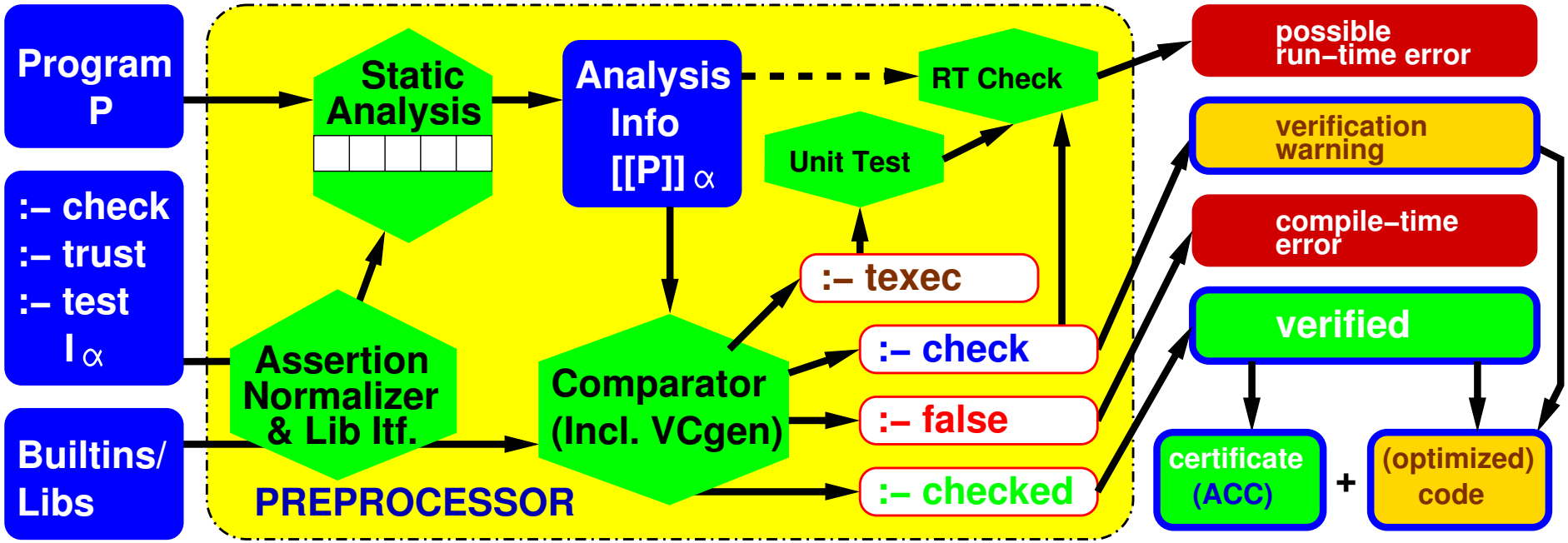
The CiaoPP Framework



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[BDD+97, HPB99, PBH00c, PBH00a, HPBLG03, APH05, MLGH09]

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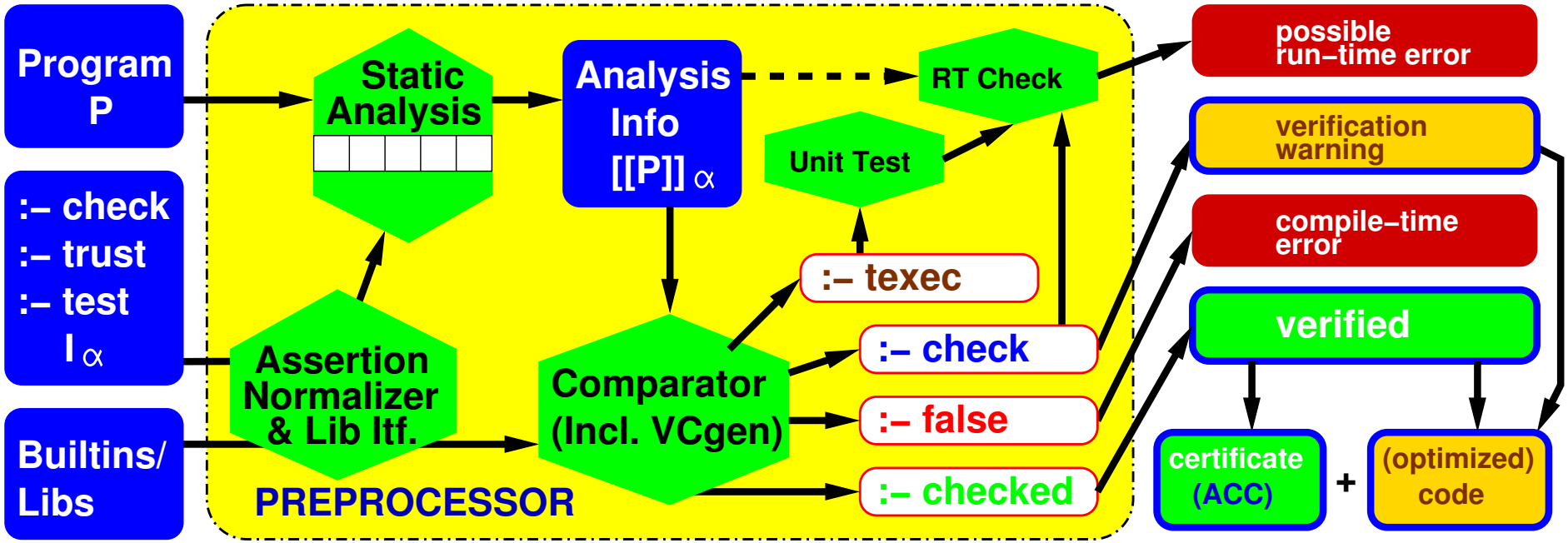
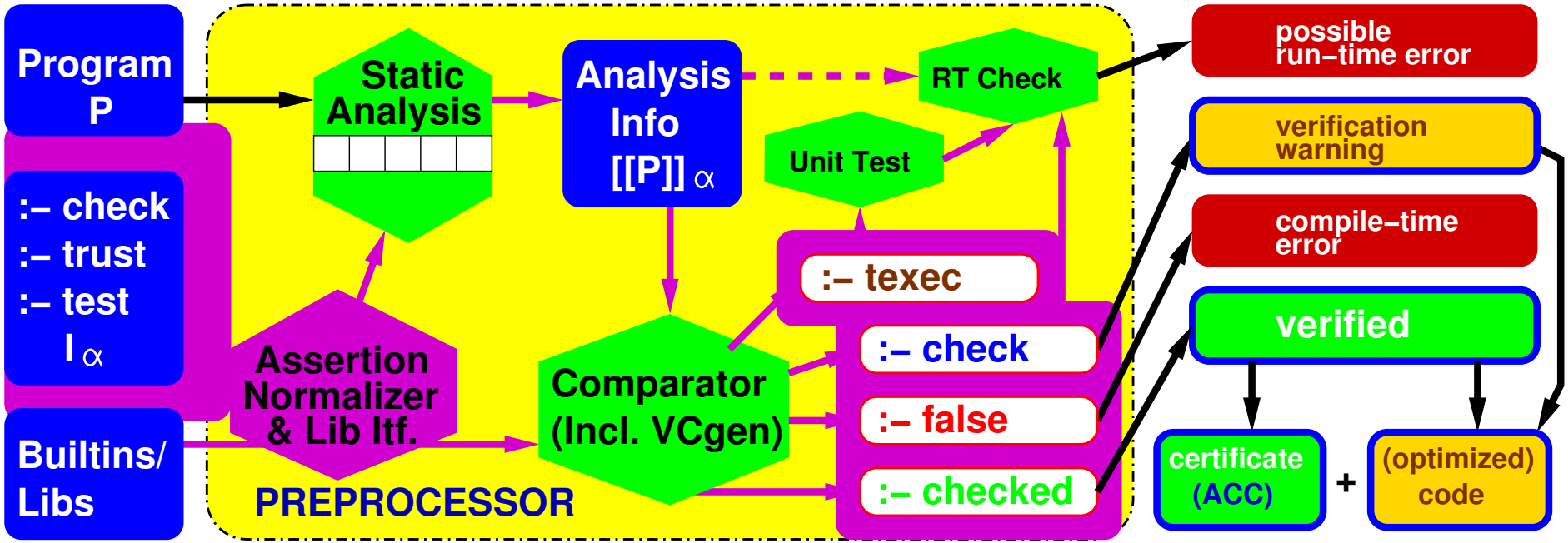


- Java source / bytecode.
- Ciao (multi-paradigm):
  - Functions (including higher-order, types, etc.).
  - Predicates (unification, search, including ISO-Prolog).
  - Constraints.
  - Objects and imperative constructs.

[BDD+97, HPB99, PBH00c, PBH00a, HPBLG03, APH05, MLGH09]

The Assertion Language



- Assertions optional, can be added at any time.
- *Sets* of pre/post/global triples (+ "status" field, documentation, ...).
- Use everywhere, for many purposes (including doc generation).
- Make it worthwhile to the programmer to include them.
- Part of the programming language and "runnable" (Ciao).

[BDD+97, PBH97, HPB99, PBH00b, MLGH09]

The Assertion Language (*simplified* grammar, Java)

$$
\begin{array}{lcl}
\langle primitive\_assrt \rangle & ::= & primitive\_name(var^*)\langle assrt \rangle^* \\
\langle assrt \rangle & ::= & \texttt{@requires (} \langle prop \rangle^* \texttt{)} \\
 & | & \texttt{@ensures (} \langle prop \rangle^* \texttt{)} \\
 & | & \texttt{@cost (} \langle resource\_usage \rangle^* \texttt{)} \\
 & | & \texttt{@if (} \langle prop \rangle^* \texttt{) \{ } \langle prop \rangle^* \texttt{ \} [cost (} \langle resource\_usage \rangle^* \texttt{)]} \\
\langle resource\_usage \rangle & ::= & \text{res\_usage}(res\_name, \langle expr \rangle) \\
 & & \\
\langle prop \rangle & ::= & type \\
 & | & \text{size}(var, \langle sz\_metric \rangle, \langle expr \rangle) \\
 & | & \text{size\_metric}(var, \langle sz\_metric \rangle) \\
 & & \\
\langle expr \rangle & ::= & \langle expr \rangle \langle bin\_op \rangle \langle expr \rangle \mid (\sum \mid \prod) \langle expr \rangle \\
 & | & \langle expr \rangle^{\langle expr \rangle} \mid \log_{num} \langle expr \rangle \mid -\langle expr \rangle \\
 & | & \langle expr \rangle ! \mid \infty \mid \text{num} \\
 & | & \text{size}([\langle sz\_metric \rangle,]\text{arg(r num)}) \\
\langle bin\_op \rangle & ::= & + \mid - \mid \times \mid / \mid \% \\
 & & \\
\langle sz\_metric \rangle & ::= & \text{int} \mid \text{ref} \mid \ldots
\end{array}
$$

The Assertion Language (Grammar, Ciao)

$$
\begin{array}{lcl}
\langle program\_assrt \rangle & ::= & \textbf{:-}\ \langle status\_flag \rangle\ \langle pred\_assrt \rangle . \\
 & | & \textbf{:-}\ \textbf{head\_cost}(\langle approx \rangle, \text{Res\_name}, \Delta^{H}). \\
 & | & \textbf{:-}\ \textbf{literal\_cost}(\langle approx \rangle, \text{Res\_name}, \Delta^{L}). \\
\langle status\_flag \rangle & ::= & \textbf{trust} \mid \textbf{check} \mid \textbf{true} \mid \epsilon \\
\langle pred\_assrt \rangle & ::= & \textbf{pred}\ \langle pred\_desc \rangle\ \langle pre\_cond \rangle\ \langle post\_cond \rangle\ \langle comp\_cond \rangle . \\
\langle pred\_desc \rangle & ::= & \text{Pred\_name} \mid \text{Pred\_name}(\langle args \rangle) \\
\langle args \rangle & ::= & \text{Var} \mid \text{Var}, \langle args \rangle \\
\langle pre\_cond \rangle & ::= & : \langle state\_props \rangle \mid \epsilon \\
\langle post\_cond \rangle & ::= & => \langle state\_props \rangle \mid \epsilon \\
\langle comp\_cond \rangle & ::= & + \langle comp\_props \rangle \mid \epsilon \\
\langle state\_prop \rangle & ::= & \textbf{size}(\text{Var}, \langle approx \rangle, \langle sz\_metric \rangle, \langle arith\_expr \rangle) \mid \text{State\_prop} \\
\langle state\_props \rangle & ::= & \langle state\_prop \rangle \mid \langle state\_prop \rangle, \langle state\_props \rangle \\
\langle comp\_prop \rangle & ::= & \textbf{size\_metric}(\text{Var}, \langle sz\_metric \rangle) \mid \langle cost \rangle \mid \text{Comp\_prop} \\
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\langle cost \rangle & ::= & \textbf{cost}(\langle approx \rangle, \text{Res\_name}, \langle arith\_expr \rangle) \\
\langle approx \rangle & ::= & \textbf{ub} \mid \textbf{lb} \mid \textbf{oub} \mid \textbf{olb} \\
\langle sz\_metric \rangle & ::= & \textbf{value} \mid \textbf{length} \mid \textbf{size} \mid \textbf{void} \\
\langle arith\_expr \rangle & ::= & - \langle arith\_expr \rangle \mid \langle arith\_expr \rangle\ ! \mid \langle quantifier \rangle\ \langle arith\_expr \rangle \\
 & | & \langle arith\_expr \rangle\ \langle bin\_op \rangle\ \langle arith\_expr \rangle \\
 & | & \langle arith\_expr \rangle^{\langle arith\_expr \rangle} \mid log_{Num}\ \langle arith\_expr \rangle \\
 & | & \text{Num} \mid \langle sz\_metric \rangle(\text{Var}) \\
\langle bin\_op \rangle & ::= & + \mid - \mid * \mid / \\
\langle quantifier \rangle & ::= & \sum \mid \prod
\end{array}
$$

The Ciao Assertion Language

```
:- pred Pred [:Precond] [=> Postcond] [+ Comp-formula ] .
```

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

```
:- pred qs(X,Y) : list(int) * var => sorted(Y) + (det,not_fails).
:- pred qs(X,Y) : var * list(int) => ground(X) + not_fails.
```

Properties (from libraries or user defined):

```
:- regtype color := green | blue | red.
:- regtype list(X) := [] | [X|list].
:- prop sorted := [] | [ _ ] | [X,Y|Z] :- X > Y, sorted([Y|Z]).
```

Program-point Assertions

- Property calls inlined with code: `..., check( X>0 ), ...`.

Assertion Status

- Each assertion has prefix **check**, **trust**, **true**, **false**, etc. –its "status."

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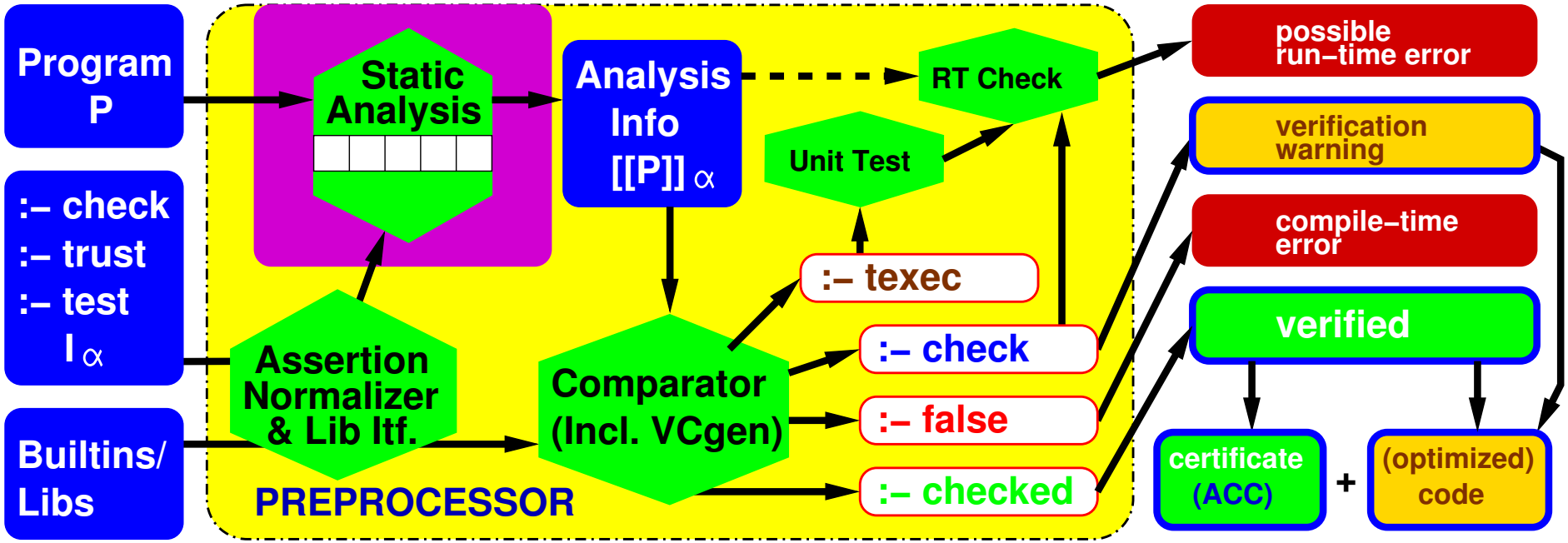
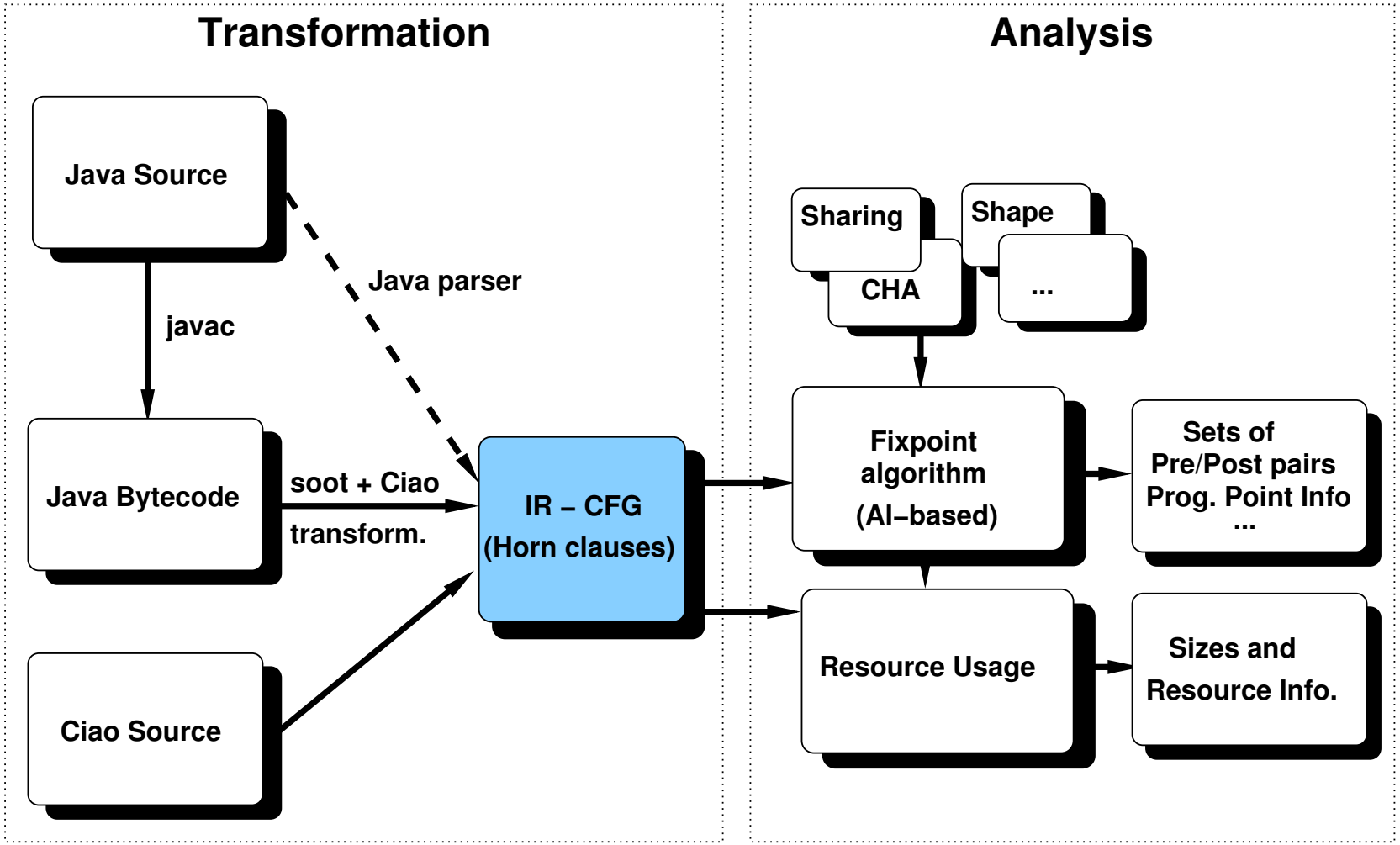
The Analyses



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

Starting Point: The Intermediate Representation



[MLNH07]

Intermediate Representation

- Used for all analyses: aliasing, CHA, resources, shape/types, data sizes, etc.
- Used to support several languages / paradigms.
- Based on "blocks" (each block represented as a *Horn clause*).
- E.g., for Java:
  - Elimination of stack variables.
  - Conversion to three-address statements.
  - SSA transformation (e.g., splitting of input/output param).
  - Explicit representation of this and ret as extra block parameters.
  - Conversion of loops into recursions among blocks.
  - Branching, cases, and dynamic dispatch $\rightarrow$ blocks w/same signature.
  - Generation of block-based CFG.
  - Conversion to horn clauses for easier manipulation.

Example: sending SMSs

```
public class CellPhone {

 void sendSms(SmsPacket smsPk,
              Encoder enc,
              Stream stm) {
 if (smsPk != null) {
  stm.send(
        enc.format(smsPk.sms));
  sendSms(smsPk.next,enc,stm);
 }}}

class SmsPacket{
   String sms;
   SmsPacket next;
}

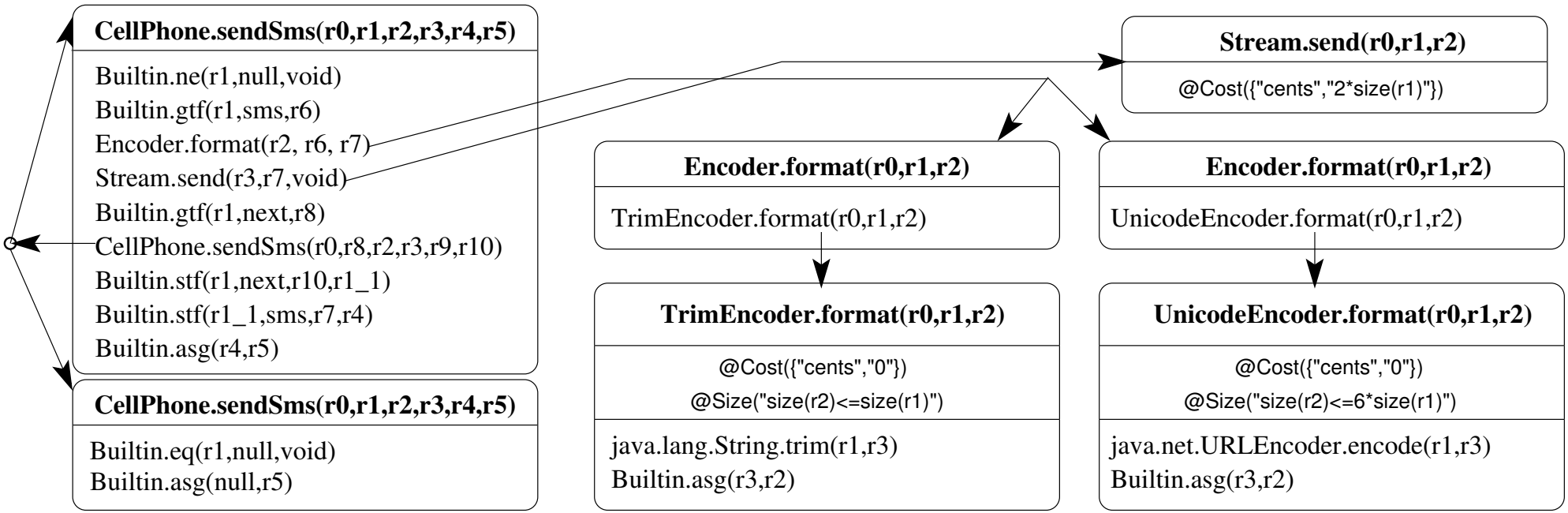
abstract class Stream{
   @Cost({"cents","2*size(data)"})
   native void send(String data);
}
```

```
interface Encoder{
   String format(String data);
   }

class TrimEncoder implements Encoder{
   @Cost({"cents","0"})
   @Size("size(ret)<=size(s)")
   public String format(String s){
     return s.trim();
   }}

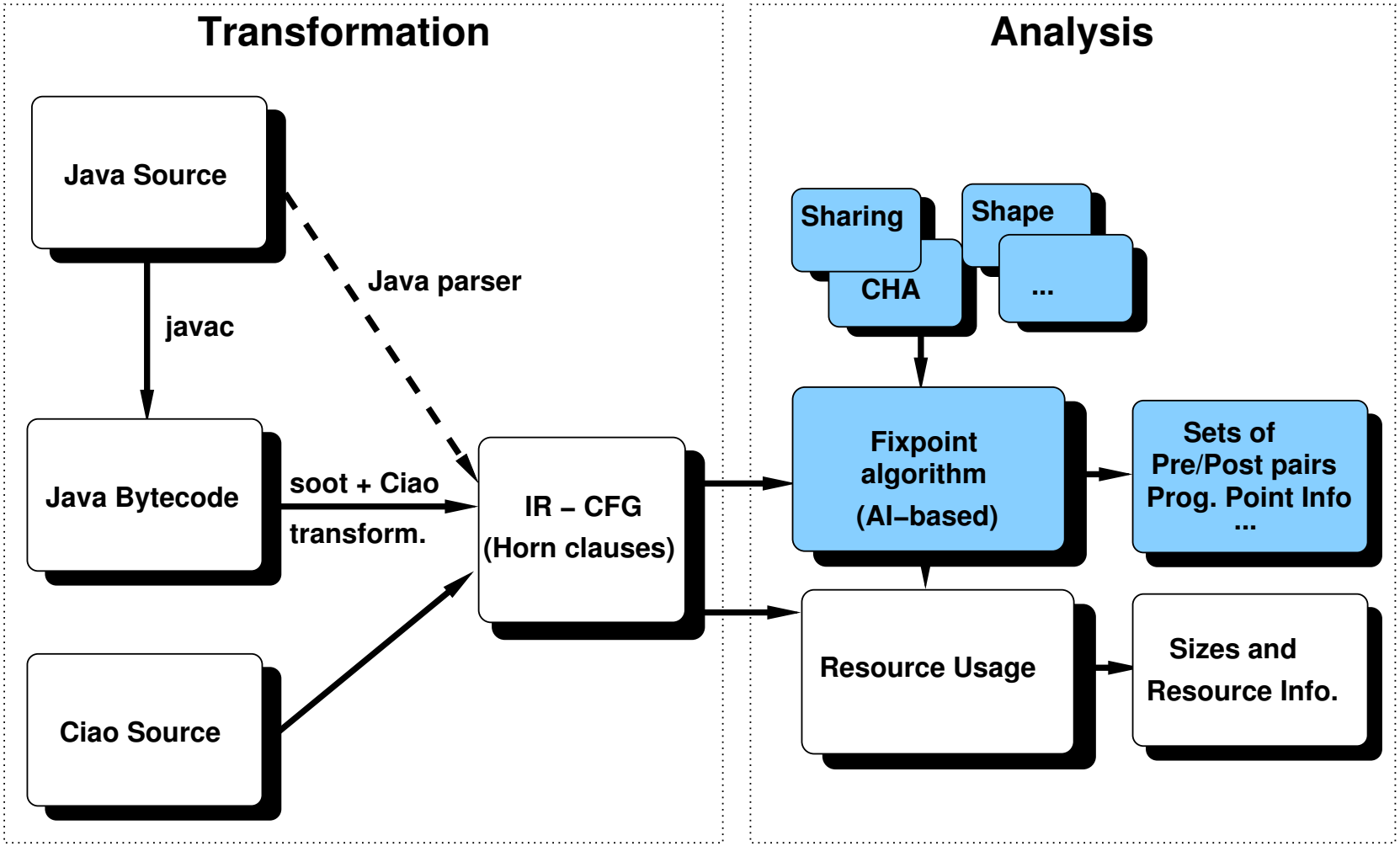
class UnicodeEncoder implements Encoder{
   @Cost({"cents","0"})
   @Size("size(ret)<=6*size(s)")
   public String format(String s){
     return java.net.URLEncoder.encode(s)
   }}
```

Example: sending SMSs – IR



- Internal representation: basic block → Horn clause.
- Annotations (since Java 1.5) are preserved in the bytecode so they can be carried over to our IR.

Fixpoint-based Analyzers



[MH92, BGH99, PH96, HPMS00, NMLH07]

[MGH94, BCHP96, PH00, BdlBH+01, PCPH06, PCPH08]

An Efficient, Parametric Fixpoint Algorithm

- Computes $\mathrm{lfp}(S_P^\alpha) = [\![P]\!]_\alpha$, s.t. $[\![P]\!]_\alpha$ safely approximates $[\![P]\!]$.
- It maintains and computes as a result (simplified):
  - **An answer table**: $\{block : \lambda_{in} \mapsto \lambda_{out}\}$.
    - 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).
    - $Dep(B : \lambda_{inB})$ = the set of entries depending on $B : \lambda_{inB}$.
- Characteristics:
  - **Precision:** context-sensitivity / multivariance, prog. point info, ...
  - **Efficiency:** memoization, dependency tracking, SCCs, base cases, ...
  - **Genericity:** abstract domains are plugins, configurable, ...
  - Handles mutually recursive methods.
  - Handles library calls (essential for Java), externals, ...
  - Modular, incremental.

Generic framework for implementing analyses / generating certificates.

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CFG traversal

- Blocks are nodes; edges are invocations.
- Top-down traversal of this CFG, starting from entry point.
- Within each block: sequence of builtins, handled in the domain.
- Inter-block calls/edges: *project*, *extend*, etc. (next slide).
- As graph is traversed, triples $(block, \lambda_{in}, \lambda_{out})$ are stored for each block in a *memo table*.
- Memo table entries have status $\in \{fixpoint, approx., complete\}$.
- Iterate until all *complete*.

Interprocedural analysis / reursion support

- **Project** the caller state over the actual parameters,
- find all the **compatible implementations** (blocks),
- **rename** to their formal parameters,

... abstractly execute each compatible block, ...

- calculate the **least upper bound** of the partial results of each block (if "monovariant on success" flag),
- **rename back** to the actual parameters and, finally
- **extend** (reconcile) return state into calling state.

Speeding up convergence

- Analyze non-recursive blocks first,
  use as starting λ_{out} in recursions.
- Blocks derived from conditionals treated specially
  (no *project* or *extend* operations required).
- The $(block, \lambda_{in}, \lambda_{out})$ tuples
  act as a cache that avoids recomputation.
- Use strongly-connected components (on the fly).

Domain examples

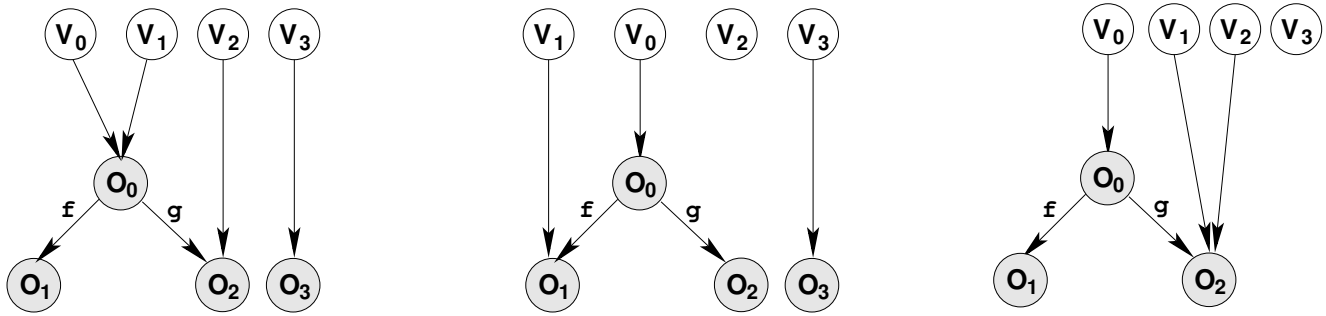
Quite a number of domains: shape, aliasing, nullity, CHA, polyhedra, data sizes, depth-k, determinacy, termination, non-failure, ...

Set-sharing (non-aliasing + nullity):

- Uses set of sets of variables to approximate all possible sharing that occur at a given program point (plus nullity):

$$SH_p = \{\{v_0, v_1\}, \{v_0, v_1, v_2\}, \{v_3\}\}$$

"v_0 may share with v_1 & v_2, or just v_1; v_3 may point to a non-null loc."



Analysis ensures that v_3 definitely does not share with v_0, or v_1, or v_2.

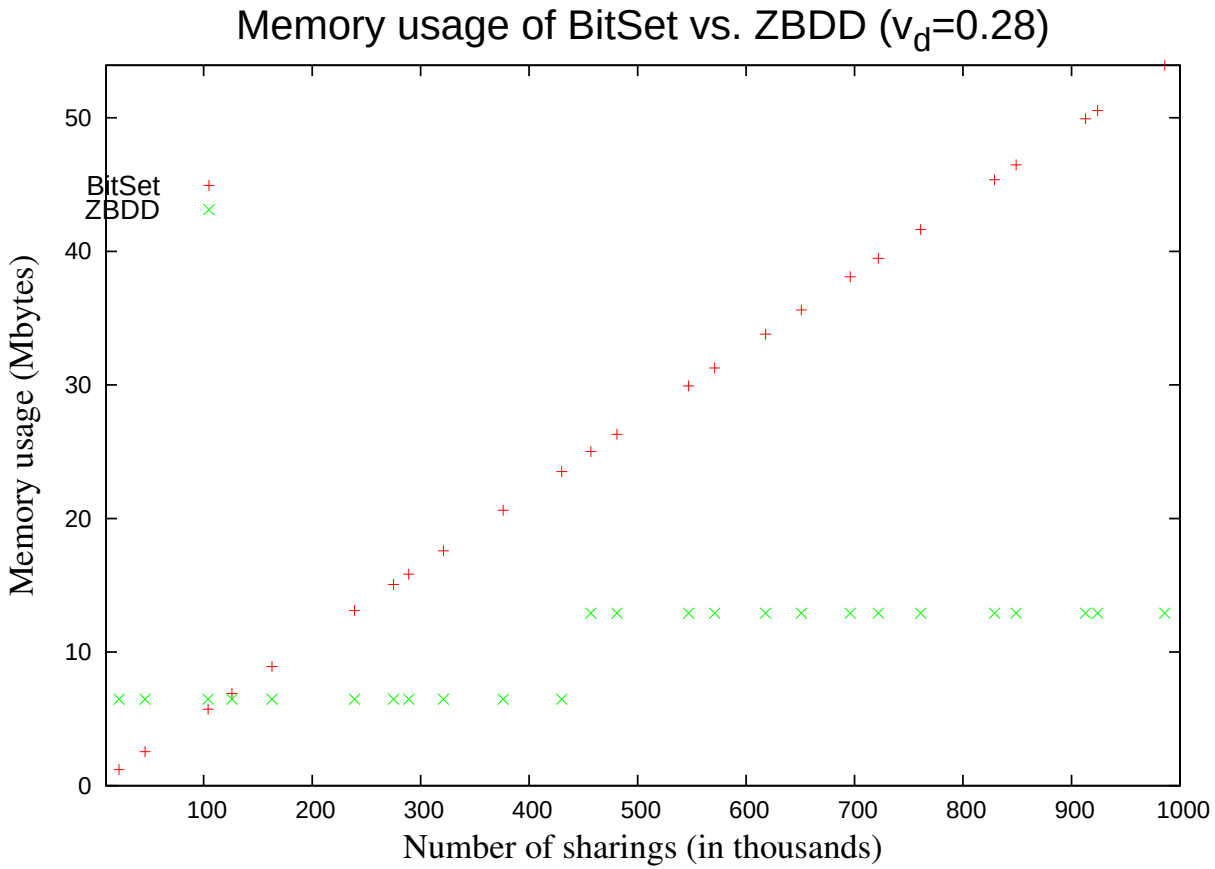
- Much work optimizing it: using ZBDDs, negative representations, etc.

[MH89, MH91, DLGH97, VB02, BLGH04, LGBH05, NBH06, MSHK07]

[MLH08, MKSH08, MMLH+08, MHKS08, MKH09, LGBH10]

Sharing, experimental results, memory usage

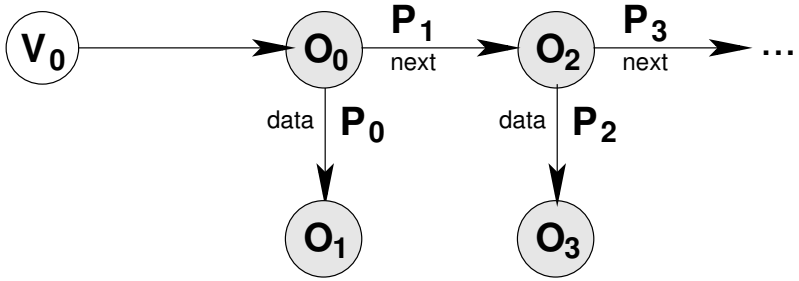
`BitSet` vs. `ZBDD`-based implementation.



[MLLH08]

Shape+set sharing

- Sharing can be combined with *structural* information. Set sharing can talk about *any* pointer (not just local vars). E.g., this linked list:



Can be abstracted as ("depth-k"):

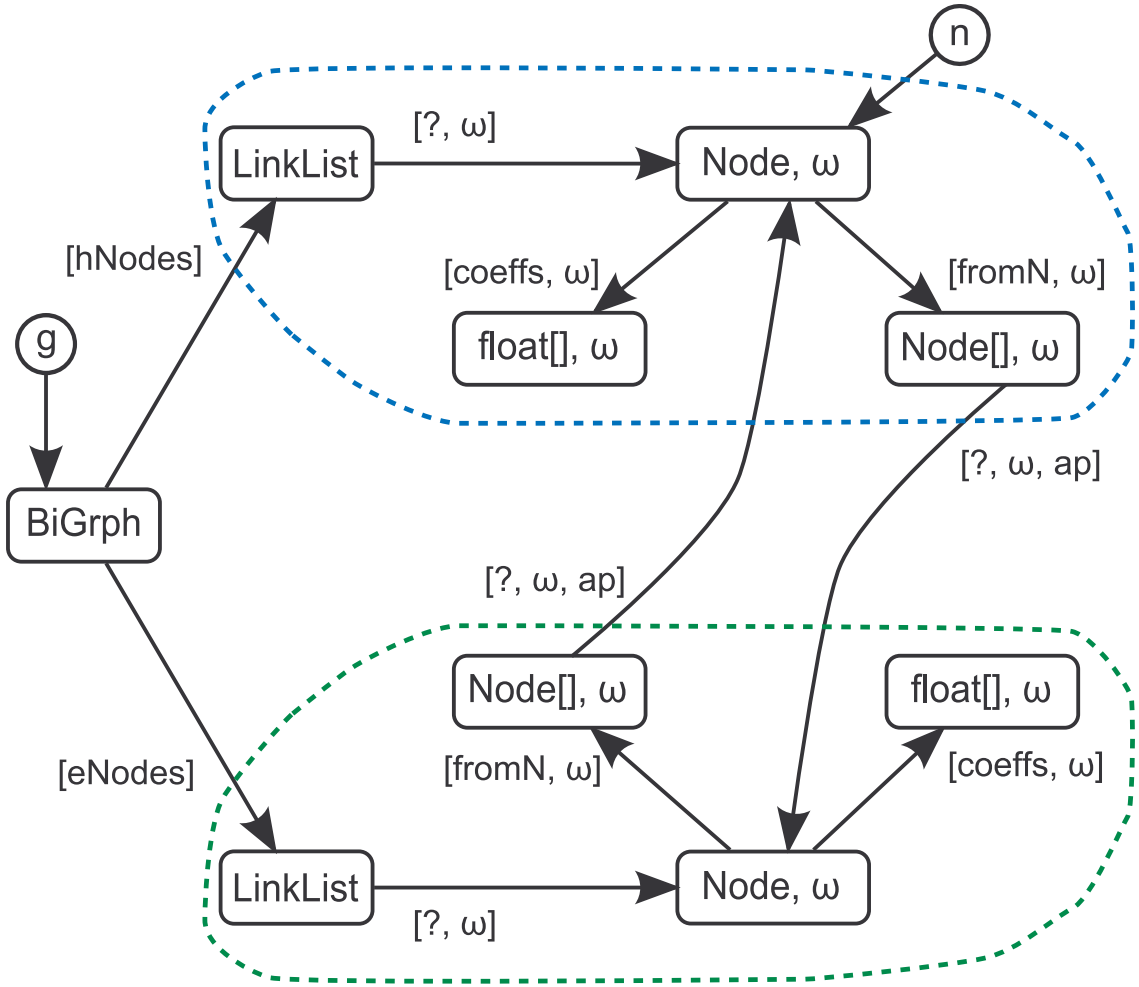
$$(\underbrace{\{v_0 = (\text{data}{:}p_0, \text{next}{:}p_1)\}}_{\text{shape}}, \underbrace{\{\{v_0, p_0\}, \{v_o, p_1\}\}}_{\text{set sharing}})$$

A statement like $v_1 = v_0\,.\,\texttt{data}$ will result in a final abstract state:

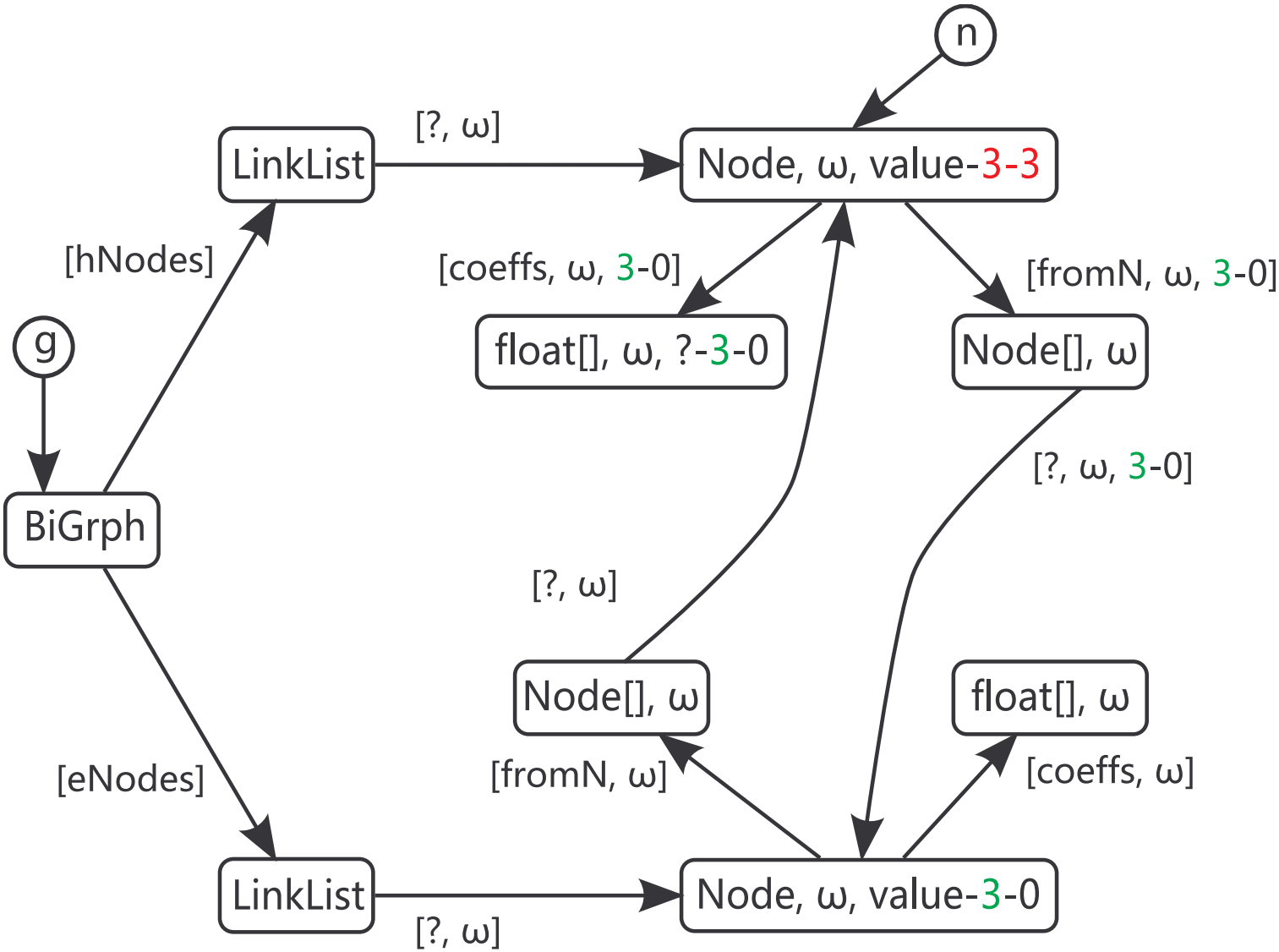
$$(\{v_0 = (\text{data}{:}p_0, \text{next}{:}p_1)\}, \{\{v_0, v_1, p_0\}, \{v_o, p_1\}\})$$

- General support in framework for domain combinations.

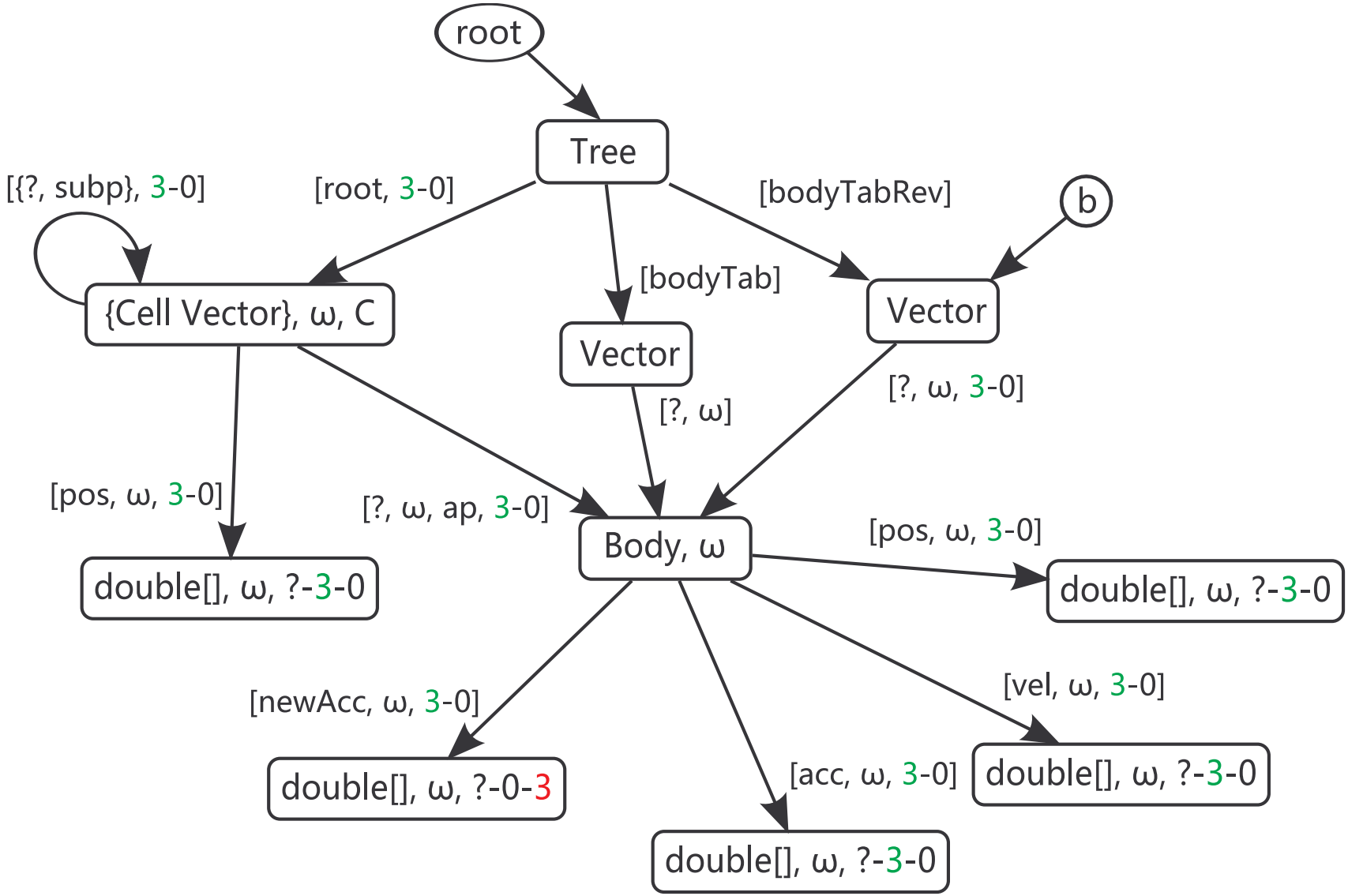
Example: Shape / Heap Dependency (em3d, regions)



Example: Shape / Heap Dependency (em3d, r-w deps)



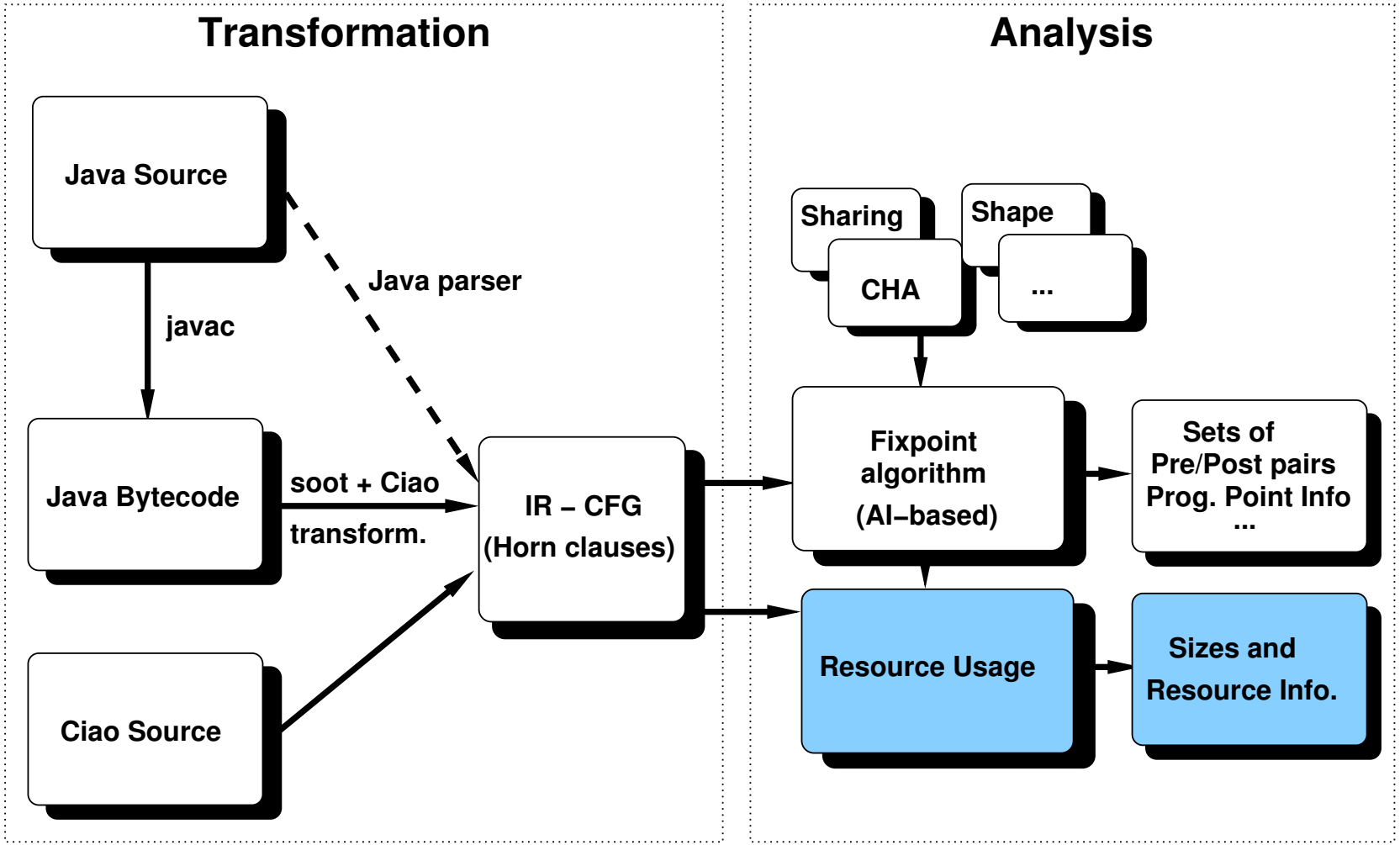
Example: Shape / Heap Dependency (bh, r-w deps)



Example: Shape / Heap Dependency (JOlden,SPECjvm98)

Benchmark	LOC	Classes	Methods	Time	Shape	RW Dep
bisort	560	36	348	0.26s	Y	Y
mst	668	52	485	0.12s	Y	Y
tsp	910	42	429	0.15s	Y	Y
em3d	1103	56	488	0.31s	Y	Y
perimeter	1114	44	381	0.91s	P	N
health	1269	59	534	1.25s	Y	Y
voronoi	1324	58	549	1.80s	Y	Y
power	1752	57	520	0.36s	Y	Y
bh	2304	61	576	1.84s	P	Y
db	1985	68	562	1.42s	Y	Y
logic	3960	72	620	48.26s	P	Y
raytrace	5809	63	506	37.09s	Y	Y

Resource Analyzers



[DLH90, LGHD94, LGHD96, DLGHL94, DLGHL97, NMLGH07, MLGCH08, NMLH08, NMLH09]

Inference of user-defined resource usage

Build analysis which automatically infers upper bounds on the usage that a program makes of a general notion of user-definable resources.

- Examples:
  - Memory, execution time, execution steps, data sizes.
  - Bits sent or received over a socket, SMSs sent or received, accesses to a database, calls to a procedure, files left open, money spent, ..
  - Energy consumed, ...
- Approach:
  1. Programmer defines via *assertions* resource-related properties for basic procedures (e.g., libraries).
  2. System infers the resource usage bounds for rest of program as **functions of input data sizes**.
- Property clearly undecidable → approximation required (**bounds** that are safe and also as accurate as possible).
- Applications: performance debugging and verification, proof carrying code, resource-oriented optimization, ...

[NMLGH07, NMLH09]

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[NMLGH07, NMLH09]

User-definable aspects of the analysis

- A *cost model* defines an *upper/lower bound cost* for primitive operations (e.g., methods, bytecode instructions).
  - Provided by the user, via *the assertion language*.

```
@Cost("cents","2*size(data)")
public native void Stream.send(java.lang.String data);
```

  - Some predefined in system libraries.

  For platform-dependent resources such as execution time or energy consumption model needs to consider low level factors.
- Assertions:
  - Also used to provide other inputs to the resource analysis such as argument sizes, size metrics, etc. if needed.
  - Also allow improving the accuracy and scalability of the system.
  - Output of resource analysis also expressed via assertions.
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Overview of the Analysis

1. Pre-analysis phase using the fixpoint analyzers:
   - Class hierarchy analysis simplifies CFG and improves overall precision.
   - Sharing analysis for correctness (conservative: only when there is no sharing among data structures –currently limited to acyclic).
   - *Determinacy* information inferred and used to obtain tighter bounds.
   - *Non-failure* (no exceptions) inferred for non-trivial lower bounds.
2. Set up recurrence equations representing the size of each output argument as a function of the input data sizes.
   - Data dependency graphs determine *relative* sizes of variable contents. (Size measures are derived from inferred shape information.)
3. Compute upper bounds to the solutions of these recurrence equations to obtain bounds on output argument **sizes**.
   - We have a simple recurrence solver, although the system can easily interface with tools like Parma, PUBS, Mathematica, Matlab, etc.
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Example: sending SMSs

```
public class CellPhone {

 void sendSms(SmsPacket smsPk,
              Encoder enc,
              Stream stm) {
 if (smsPk != null) {
  stm.send(
        enc.format(smsPk.sms));
  sendSms(smsPk.next,enc,stm);
 }}}

class SmsPacket{
   String sms;
   SmsPacket next;
}

abstract class Stream{
   @Cost({"cents","2*size(data)"})
   native void send(String data);
}
```

```
interface Encoder{
   String format(String data);
   }

class TrimEncoder implements Encoder{
   @Cost({"cents","0"})
   @Size("size(ret)<=size(s)")
   public String format(String s){
     return s.trim();
   }}

class UnicodeEncoder implements Encoder{
   @Cost({"cents","0"})
   @Size("size(ret)<=6*size(s)")
   public String format(String s){
     return java.net.URLEncoder.encode(s)
   }}
```

Example (I)

1. System takes by default size of input data: $size(\texttt{smsPk}) = n$.
   - Result will be parametric on this.
2. The number of characters *sent* depends on the formatting done by the different encoders:
   - The user indicates that the encoding in `TrimEncoder` results in a smaller or equal (output) string.

```
class TrimEncoder implements Encoder{
    @Size("size(ret)<=size(s)")
    public String format(String s){
```

   - And that the result of `UnicodeEncoder` can be up to 6 times larger (\uxxxx) than the one received.

```
class UnicodeEncoder implements Encoder{
    @Size("size(ret)<=6*size(s)")
    public String format(String s){
```

Example (II)

3. After setting up and solving the size equations the system obtains that the upper bound on the number of characters sent is:

$$max(6,1) * n = 6 * n = 6 * size(\texttt{smsPk})$$

4. The analysis establishes then (cost) recurrences for every method:

$$\begin{array}{lcl} Cost_{sendSms}(r0,0,r2,r3) & = & 0 \\ Cost_{sendSms}(r0,r1,r2,r3) & = & cost\ of\ sending\ a\ char \times Cost_{sendSms}(r0,r1-1,r2,r3) \end{array}$$

where $r0$,$r1$,$r2$, and $r3$ represent the size of This, SmsPk, enc, and stm, respectively.

5. Given that we are charged 2 cents per character sent:

```
@Cost({"cents","2*size(data)"})
native void send(String data);
```

$$\begin{array}{lcl} Cost_{sendSms}(r0,0,r2,r3) & = & 0 \\ Cost_{sendSms}(r0,r1,r2,r3) & = & 2\times \underbrace{6 \times (r1-1)}_{character\ size} \times Cost_{sendSms}(r0,r1-1,r2,r3) \end{array}$$

and the total cost of the `sendSMS` method is $6 \times r1^2 - 6 \times r1$ cents.

Some results (Java)

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

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

Some results (Ciao)

Program	Resource	Usage Function	Metrics	Time
client	"bits received"	$\lambda x.8 \cdot x$	length	186
color_map	"unifications"	39066	size	176
copy_files	"files left open"	$\lambda x.x$	length	180
eight_queen	"queens movements"	19173961	length	304
eval_polynom	"FPU usage"	$\lambda x.2.5x$	length	44
fib	"arith. operations"	$\lambda x.2.17 \cdot 1.61^x + 0.82 \cdot (-0.61)^x - 3$	value	116
grammar	"phrases"	24	length/size	227
hanoi	"disk movements"	$\lambda x.2^x - 1$	value	100
insert_stores	"accesses Stores" "insertions Stores"	$\lambda n, m.n + k$ $\lambda n, m.n$	length	292
perm	"WAM instructions"	$\lambda x.(\sum_{i=1}^{x} 18 \cdot x!) + (\sum_{i=1}^{x} 14 \cdot \frac{x!}{i}) + 4 \cdot x!$	length	98
power_set	"output elements"	$\lambda x.\frac{1}{2} \cdot 2^{x+1}$	length	119
qsort	"lists parallelized"	$\lambda x.4 \cdot 2^x - 2x - 4$	length	144
send_files	"bytes read"	$\lambda x, y.x \cdot y$	length/size	179
subst_exp	"replacements"	$\lambda x, y.2xy + 2y$	size/length	153
zebra	"resolution steps"	302328442957130 61	size	292

Interesting Resource: Execution Time

- Important: e.g., verification of real-time constraints.
- Very hard in current architectures, (e.g., worst-case cache behavior).
  - Certainly feasible in simple processors and with caches turned off.
  - Our approach is *complementary* to accurate WCET models, which consider cache behavior, pipeline state, etc. (inputs to us).
- Approach:
  - Obtain timing model of abstract machine instructions through a one-time profiling phase (results provided as assertions).
    - Includes fitting constants in a function if the execution time depends on the argument's properties.
  - Static cost analysis phase which infers a function which returns (bounds on) the execution time of program for given input data sizes.

[MLGCH08]

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[MLGCH08]

First Phase Output

Cost assertions automatically generated in first phase and stored to make the instruction execution costs available to the static analyzer.

Examples

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

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

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

Observed and Estimated Execution Time (Intel)

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

Energy Consumption

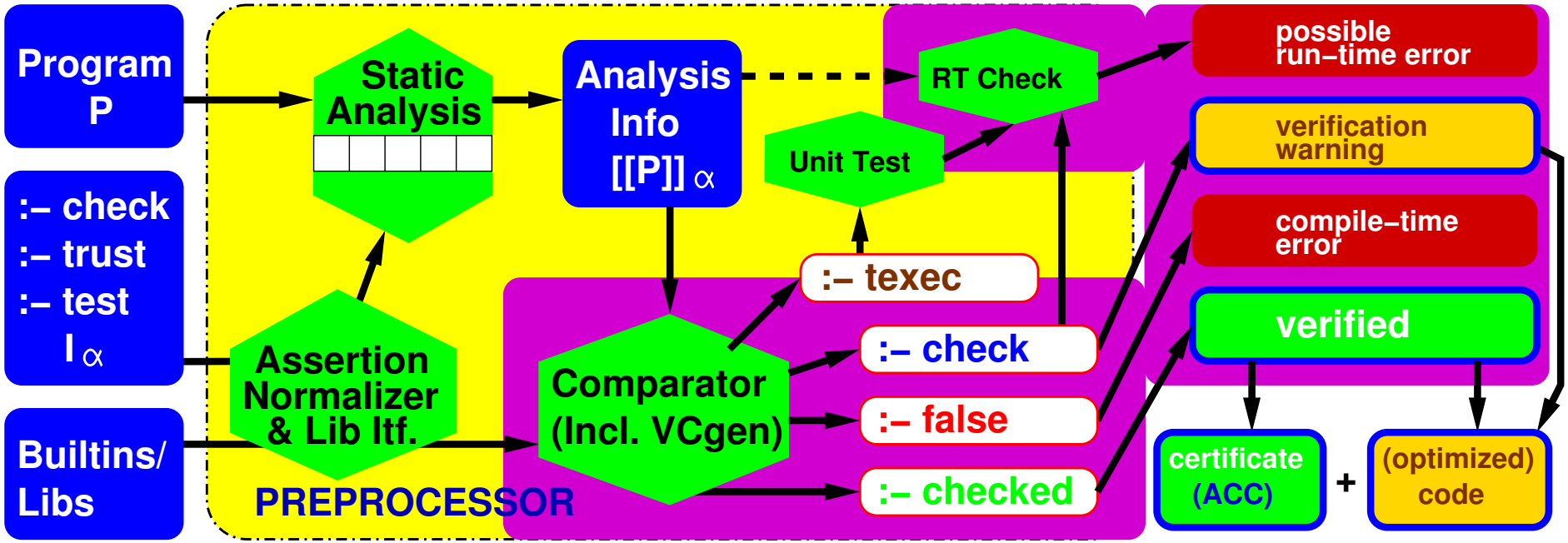
- Energy Consumption Analysis:
  - *Energy consumption model* (available for simple processors): describe upper bound consumption of each bytecode inst. in terms of joules:

Opcode	Inst. Cost in μJ	Mem. Cost in μJ	Total Cost in in μJ
`iadd`	.957860	2.273580	3.23144
`isub`	.957360	2.273580	3.230.94
...	...	...	...

  - Resource analysis generates at compile time equations and returns safe, upper- and lower-bound *energy consumption functions*.

[NMLH08]

Debugging and Verification



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

[BDD+97, HPB99, PBH00c, PBH00a, HPBLG03, HALGP05, PCPH06, PCPH08, MLGH09]

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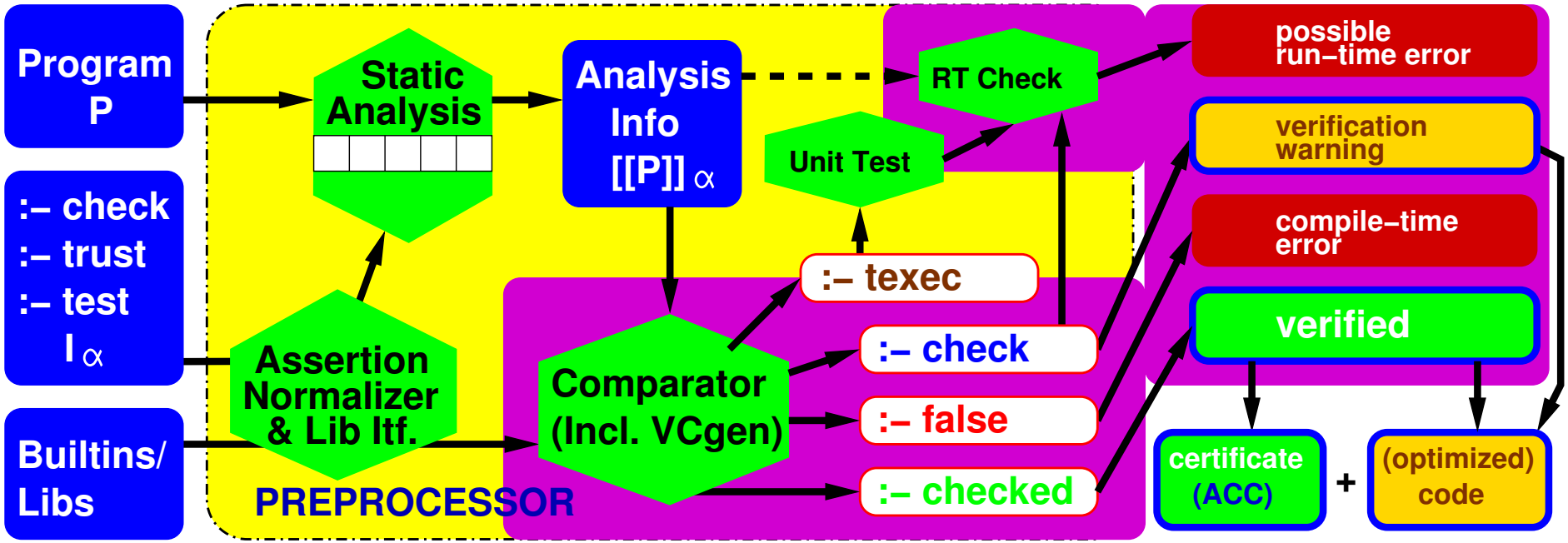


- *Parts* of assertions not verified statically generate run-time checks.
- Diagnosis (for both static and dynamic errors).
- Comparison not always trivial. E.g., resource debugging/certification:
  - Need to compare functions.
  - "Segmented" answers.

[BDD+97, HPB99, PBH00c, PBH00a, HPBLG03, HALGP05, PCPH06, PCPH08, MLGH09]

Non-trivial: e.g., Resource Debugging / Certification

- Approximated and intended semantics given as *resource usage functions*:

  Monotonic arithmetic functions expressing lower or upper bounds on the resource usage of a predicate depending on input data sizes.

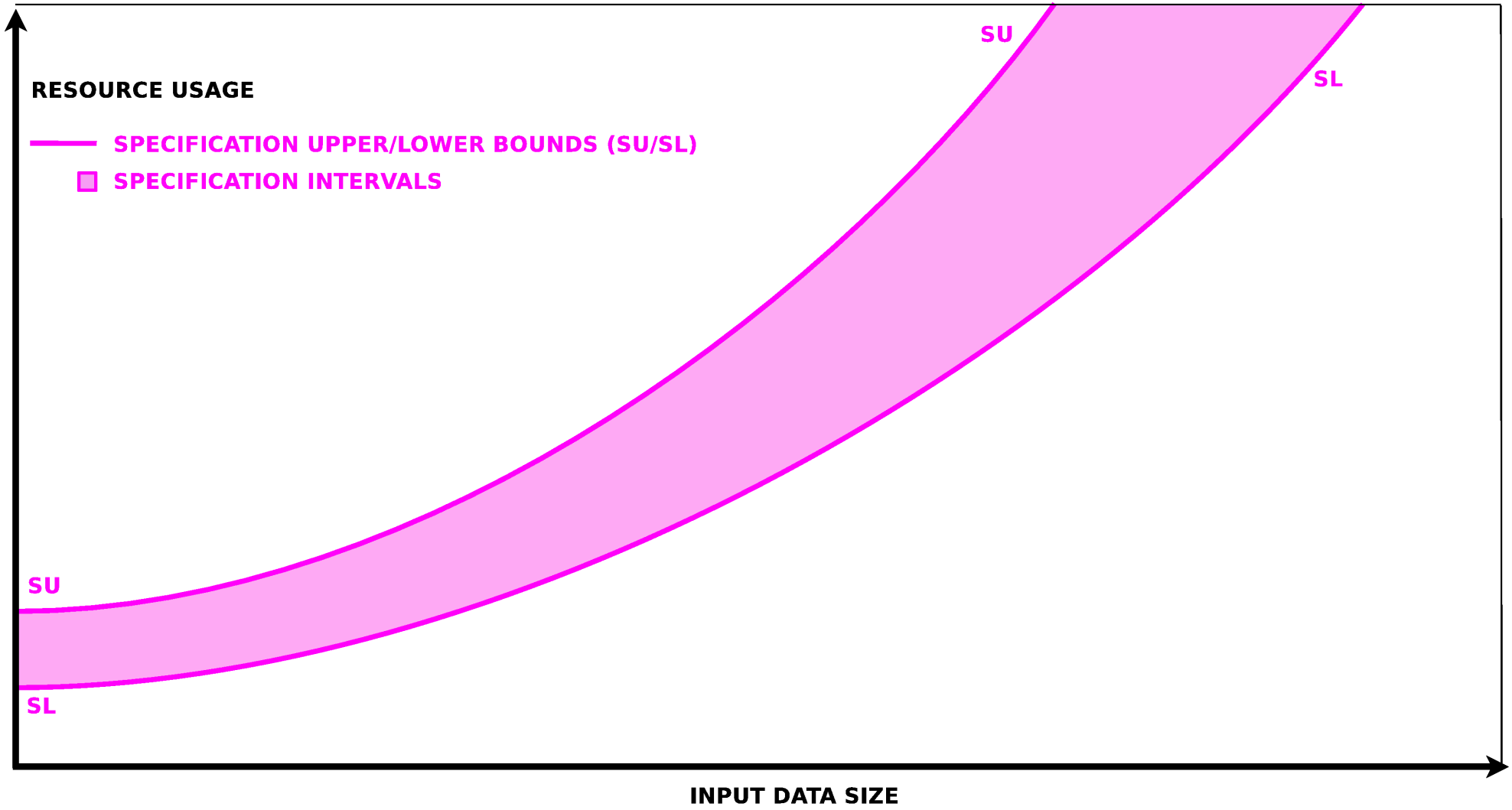
Example of intended semantics (partial specifications):

```
:- check comp nrev(A,B) :   (ground(A), list(A), var(B) )
                      +     (resource(lb, steps, length(A)),
                             resource(ub, steps, 1 + exp(length(A), 2)) .
```

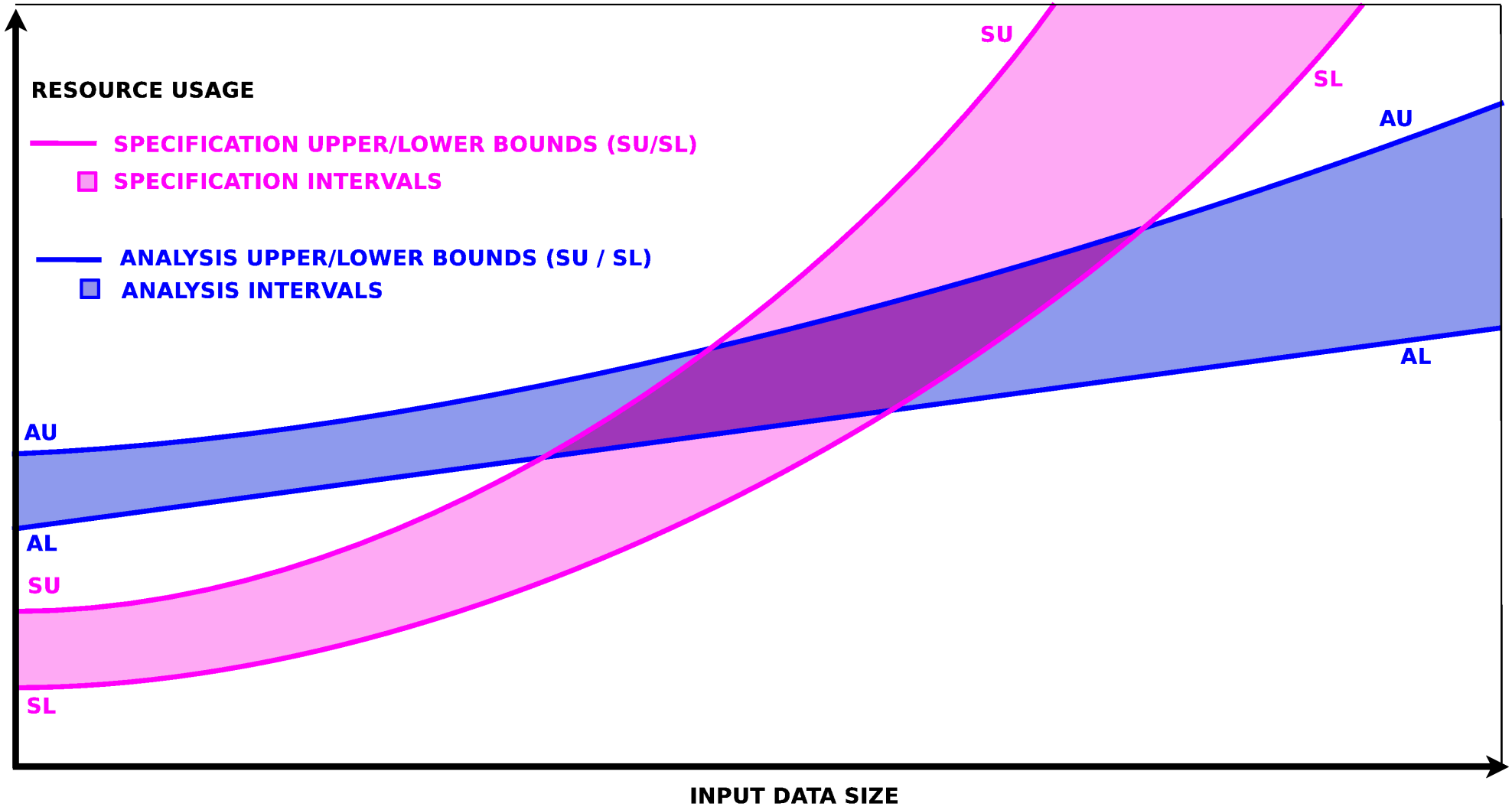
- Number of steps $\in [length(A), 1 + length(A)^2]$.

[HALGP05, LGDB10]

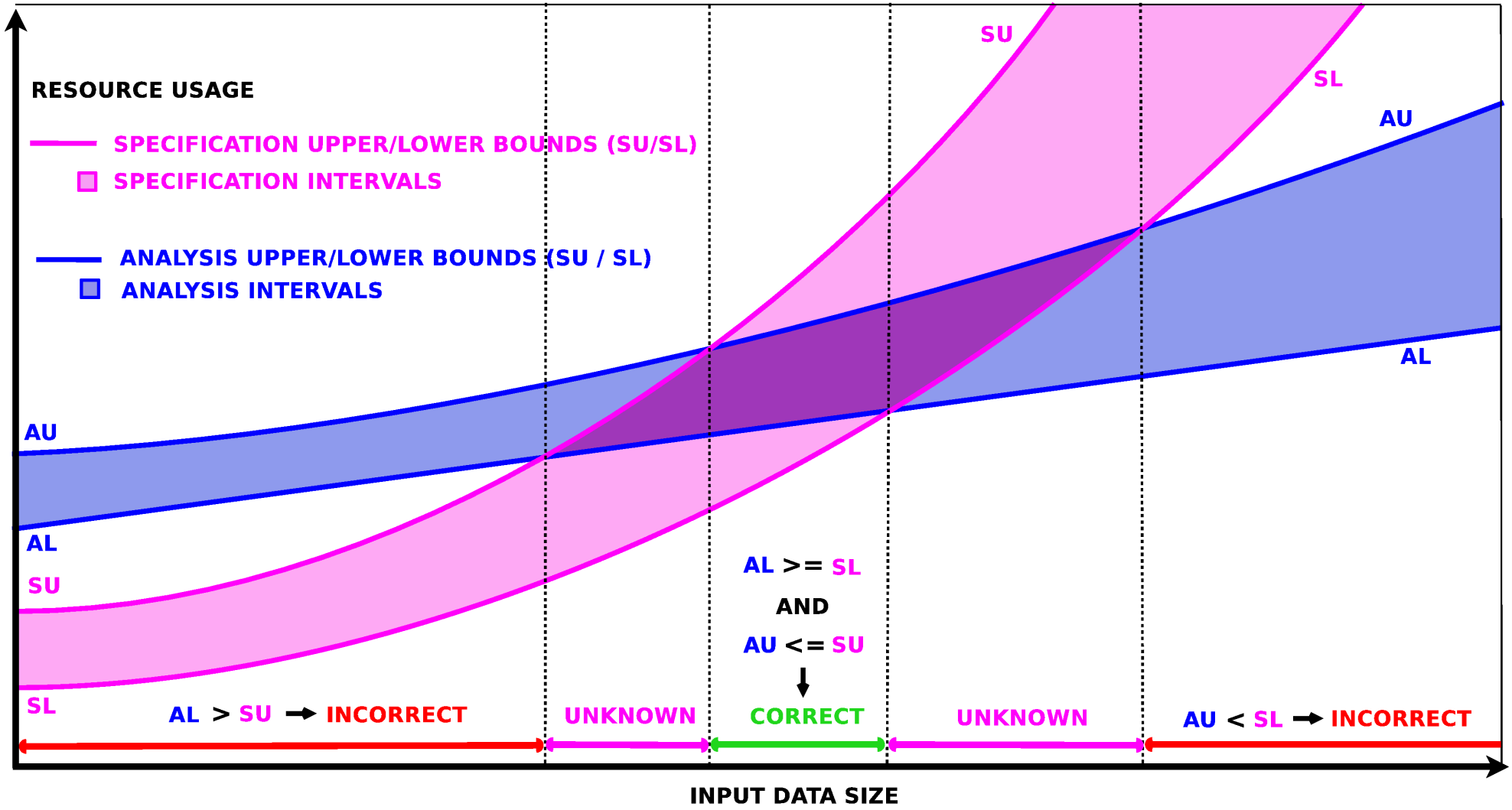
Resource Usage Verification



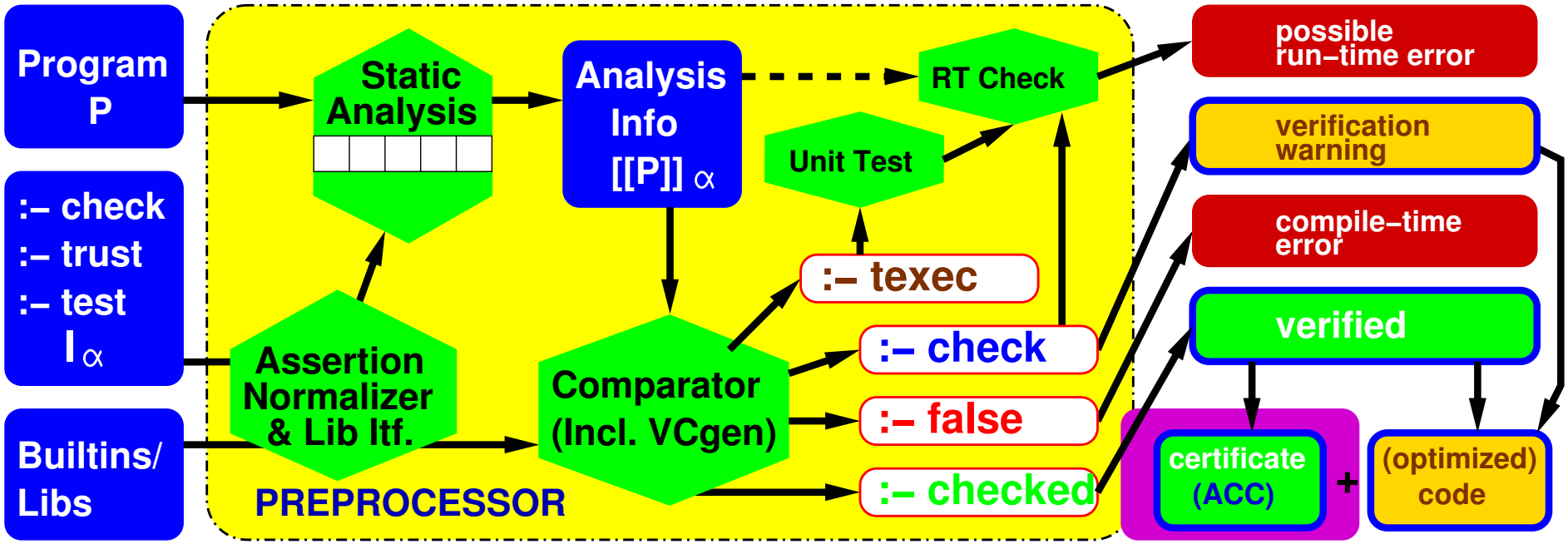
Resource Usage Verification



Resource Usage Verification

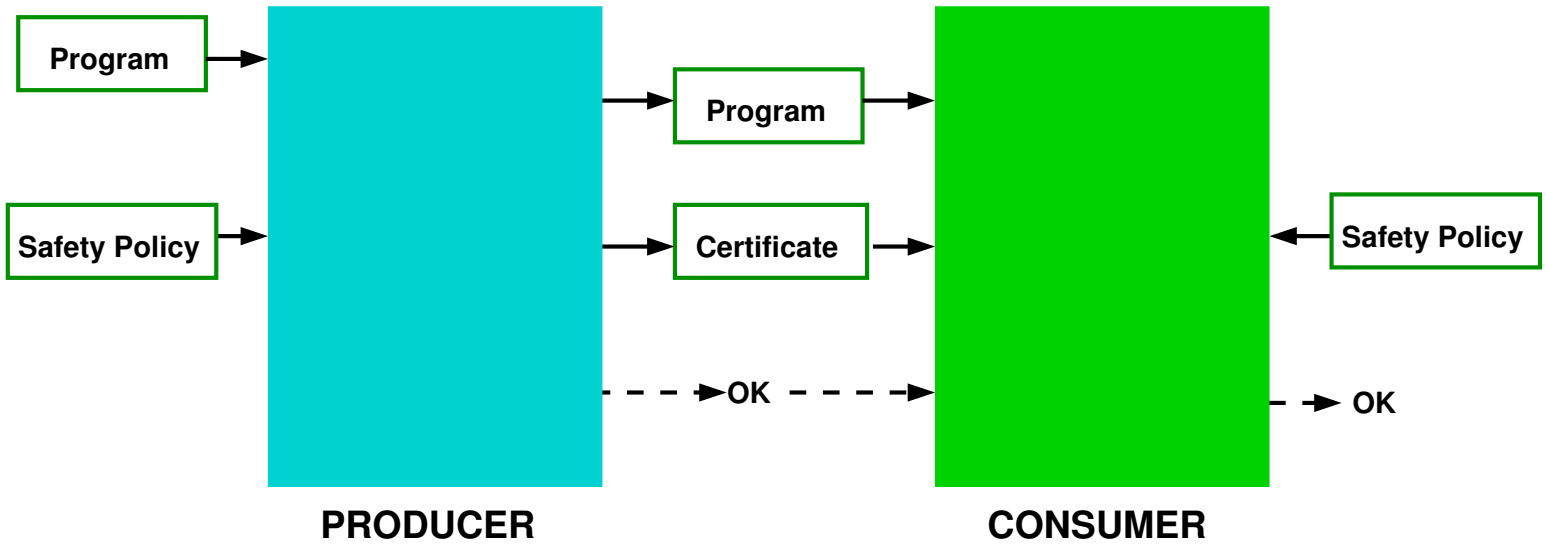


Certification / Abstraction Carrying Code



[APH05, HALGP05, AAPH06]

Code Certification and Proof-Carrying Code



Many challenges:

- Generating the certificates automatically.
- Generating minimal certificates.
- Designing *simple, reliable, and efficient checkers* for the certificates.

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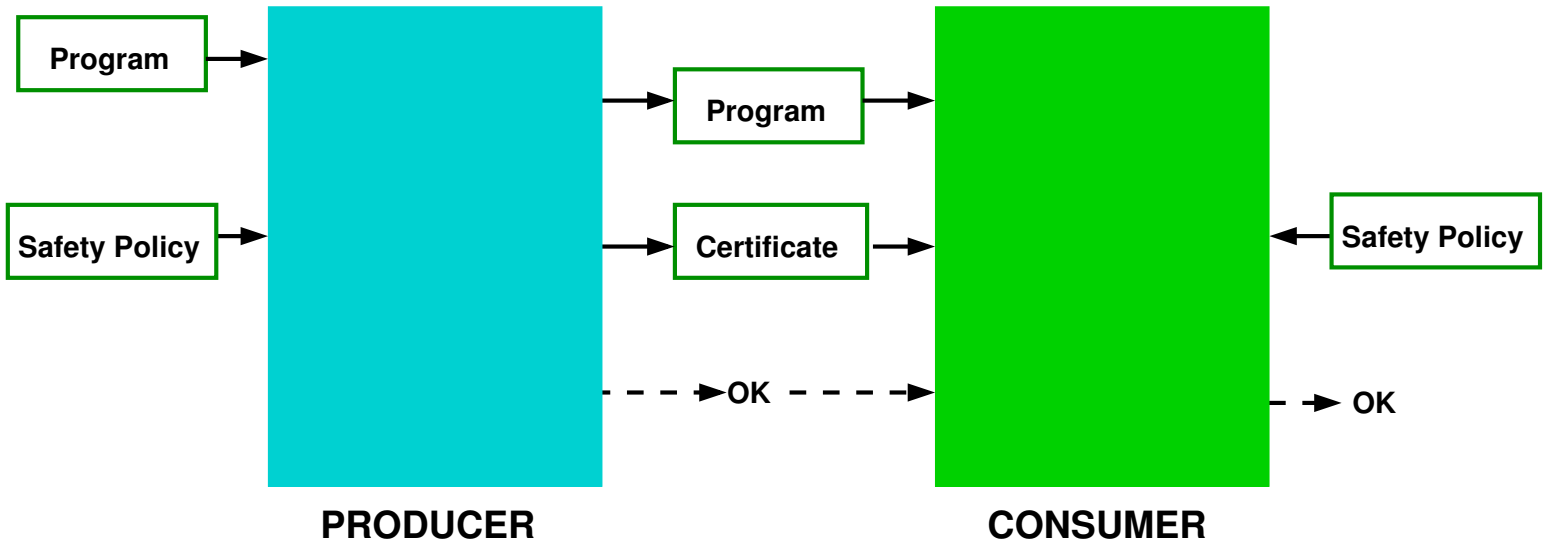

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Abstraction-based Certification, Abstraction-Carrying Code

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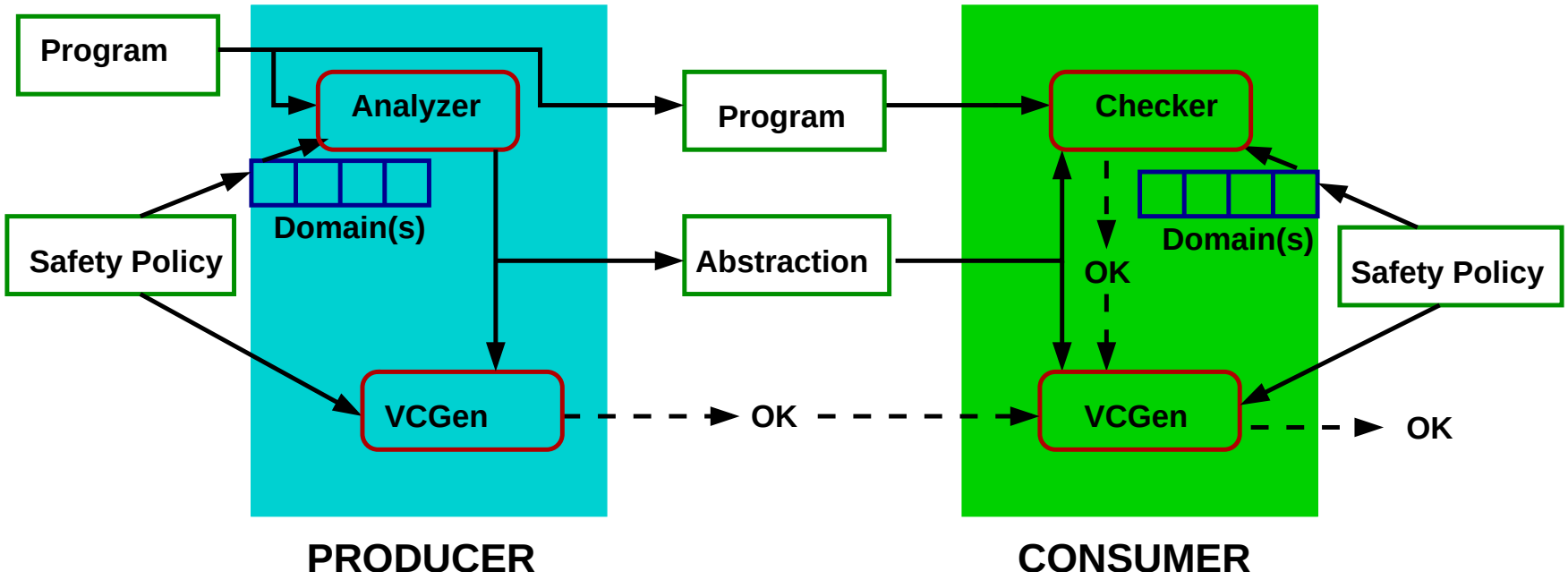

$[\![P]\!]_\alpha = \text{Analysis} = \mathbf{lfp}(\mathit{analysis\_step})$

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

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- Many interesting extensions: reduced certificates, incrementality, ...

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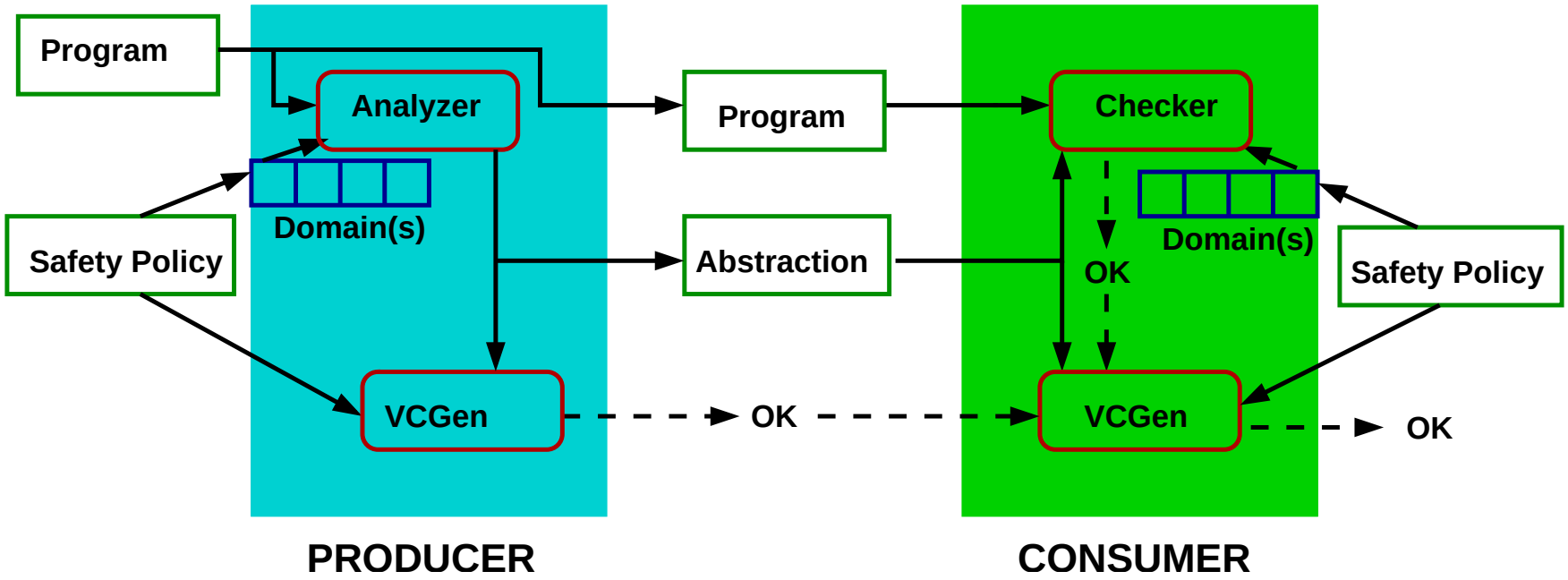

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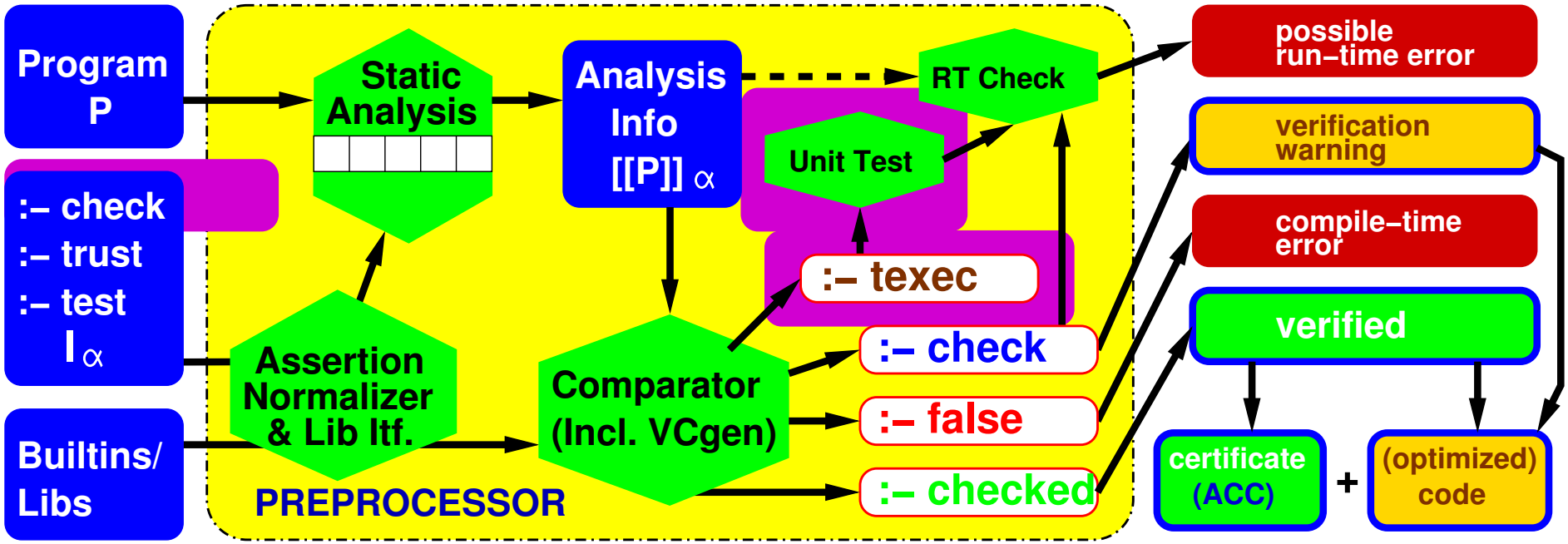
Integration of testing



[MLGH09]

Supporting unit testing

Assertion schema used:

```
:- test Pred[:Precond][=>Postcond][+CompExecProps].
```

Such test assertions translate into:

What needs to be checked (normal assertions):

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

What test case needs to be run (test driver):

```
:-       texec   Pred [:Precond] [+Exec-Formula].
```

Many interactions within the integrated framework:

- (Unit) tests are part of the assertion language.
- Parts of unit tests that can be verified at compile-time are deleted.
- Rest of unit testing uses the run-time assertion-checking machinery.
- Unit tests also provide test cases for run-time checks coming from assertions.
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Example assertion and testing output:

```
:- test qsort(A,_) : (A=[1,3,2]) => (ground(B),list(num,B),sorted(B)).
```

```
{In /tmp/qsort.pl
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Example application:

- Coded 976 unit tests for ISO compliance of Ciao `prolog` package.
- Detected large number of previously unknown limitations/errors.
- The tests currently run in under 15 seconds.

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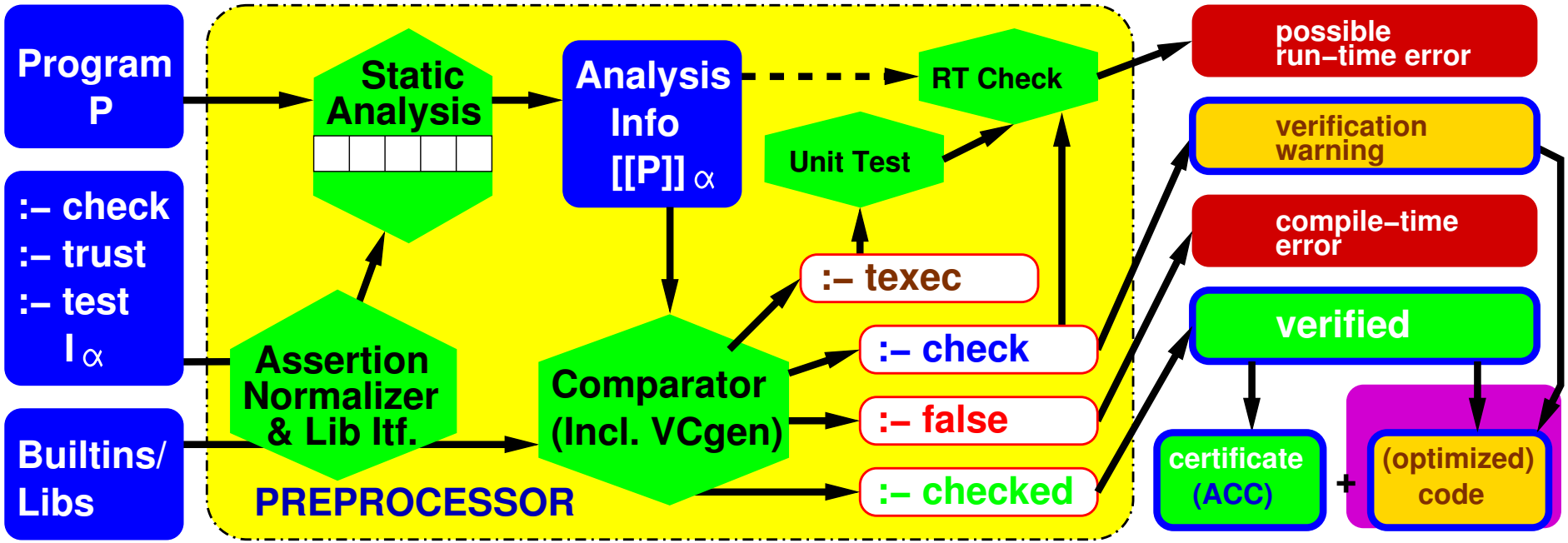
Optimizations and Parallelization



[GH91, PH97, PHG99, PAH06] [PH99, MBdlBH99, BGH99, CCH08, MKSH08] [MCH04, CMM+06]

Also, optimizations

- Preprocessor architecture useful not just for verification / debugging, but also for optimization:
  - Source-level optimizations:
    - Partial evaluation, (multiple) (abstract) specialization, ...
  - Low-level (WAM) optimizations:
    - Use of specialized instructions.
    - Optimized native code generation.

    $\rightarrow$ obtaining close-to-C performance for declarative languages (Ciao).

  - Parallelization.

- But this is a topic for other talks...

[GH91, PH97, PHG99, PAH06] [MCH04, CMM+06]

Parallelization: Motivation

- Power limits frequency... but available area takes us to tera-device: 1000 billion devices by 2020.
- Move from superscalar to multicore: large (100+) numbers of (possibly less complex) (possibly slower) (possibly heterogeneous) cores.
- Novel performance guarantees and architectural contracts (e.g., the memory model) that may not stabilize for several generations.
- Programmability is a huge challenge.

[PH99, MBdlBH99, BGH99, PH97, PH03, CCH08, MKSH08]

(Semi-)Automatic Parallelization and Verification

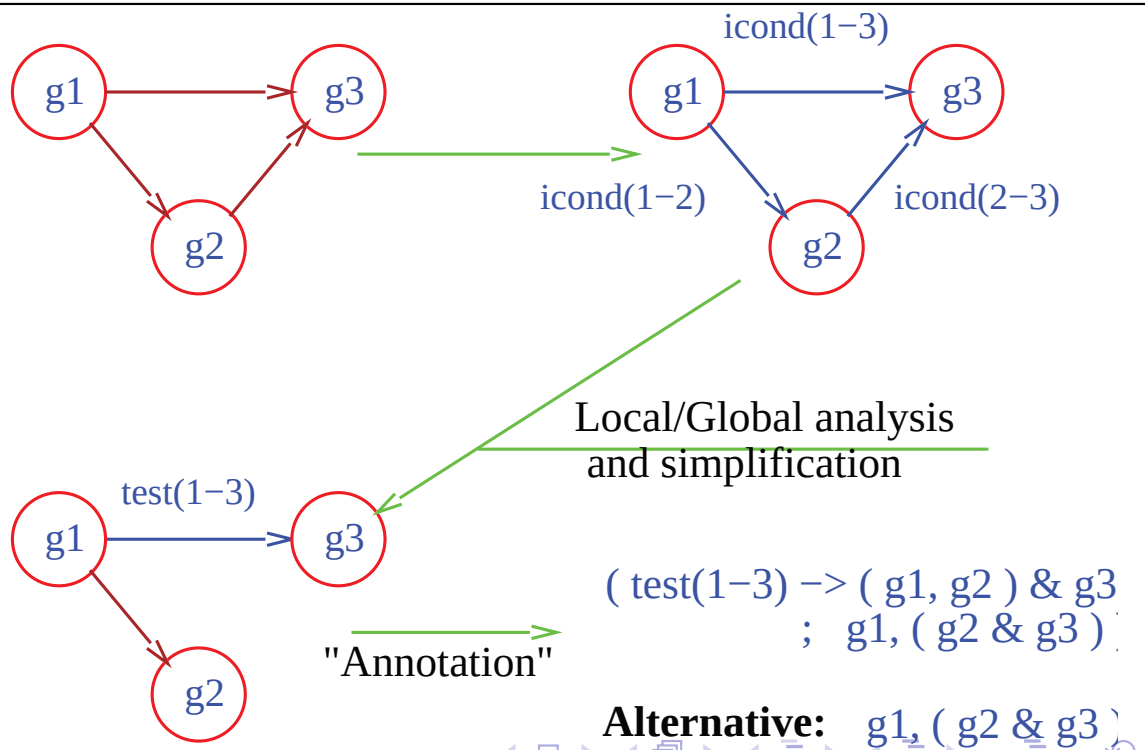
- Automatic parallelization of traditional languages.
  - Limited because of serial nature but still needs to be done:
    - Large number of existing programs.
    - A paradigm shift will take time.
  - Some success for loops. Now, some more progress in dealing with:
    - Irregular control.
    - Complex, dynamically managed data structures.

    Major advances in technology:
    - Aliasing analysis, heap shape analysis, heap dependence tracking, ...
    - Taking into account (new) memory models (coherence models, transactional, parallel garbage collection, ...).
- Compiler-*aided parallelization* and *verification* of parallel programs.
- *Automatic parallelization of less serial (more declarative) languages*.
  - Significant experience from declarative languages needs to be carried over to these new paradigms (see later).

Parallelization Process

- Conditional dependency graph (of some code segment, e.g., a clause):
  - Vertices: possible tasks (statements, calls,...),
  - Edges: possible dependencies (labels: conds. needed for independence).
- Local or global analysis used to reduce/remove checks in the edges.
- Annotation process converts graph into parallel expressions in source.

```
foo(...)   :-
      g1(...),
      g2(...),
      g3(...).
```



Automatic Program Parallelization (Contd.)

- *Example:*

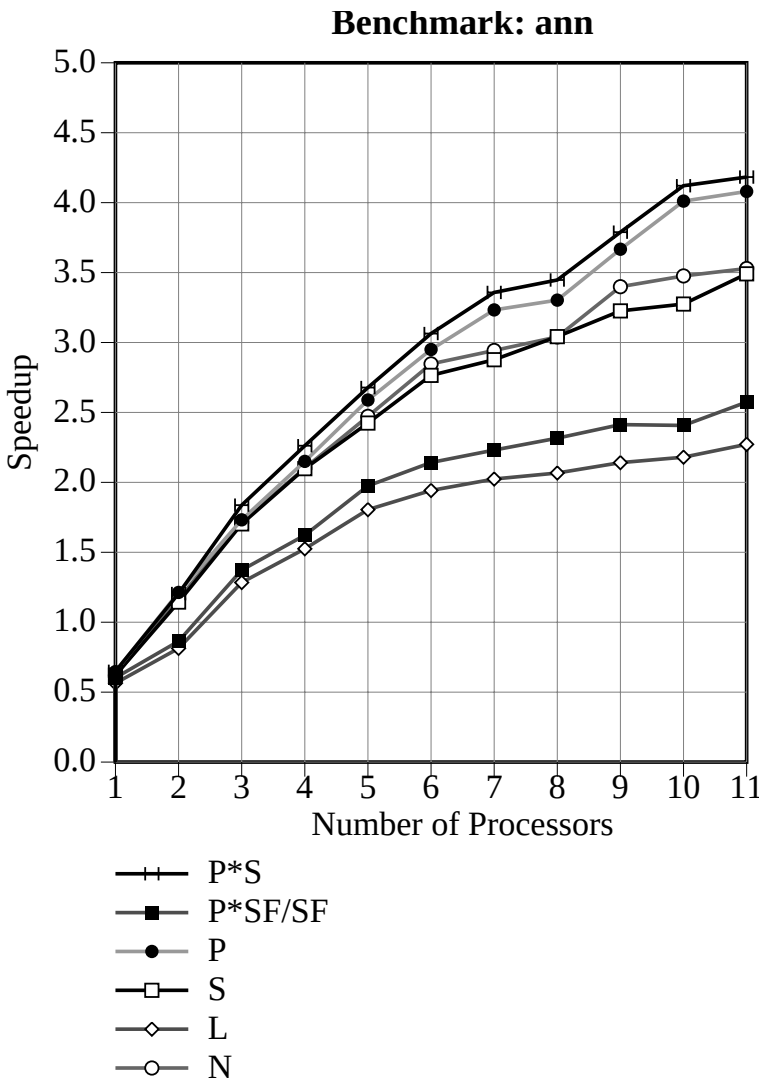
```
qs([X|L],R) :- part(L,X,L1,L2),
               qs(L2,R2), qs(L1,R1),
               app(R1,[X|R2],R).
```

Might be annotated in &-Prolog (or Ciao), using local analysis, as:

```
qs([X|L],R) :-
          part(L,X,L1,L2),
          ( indep(L1,L2) ->
               qs(L2,R2) & qs(L1,R1)
          ;    qs(L2,R2) , qs(L1,R1) ),
          app(R1,[X|R2],R).
```

Global analysis would eliminate the `indep(L1,L2)` check.

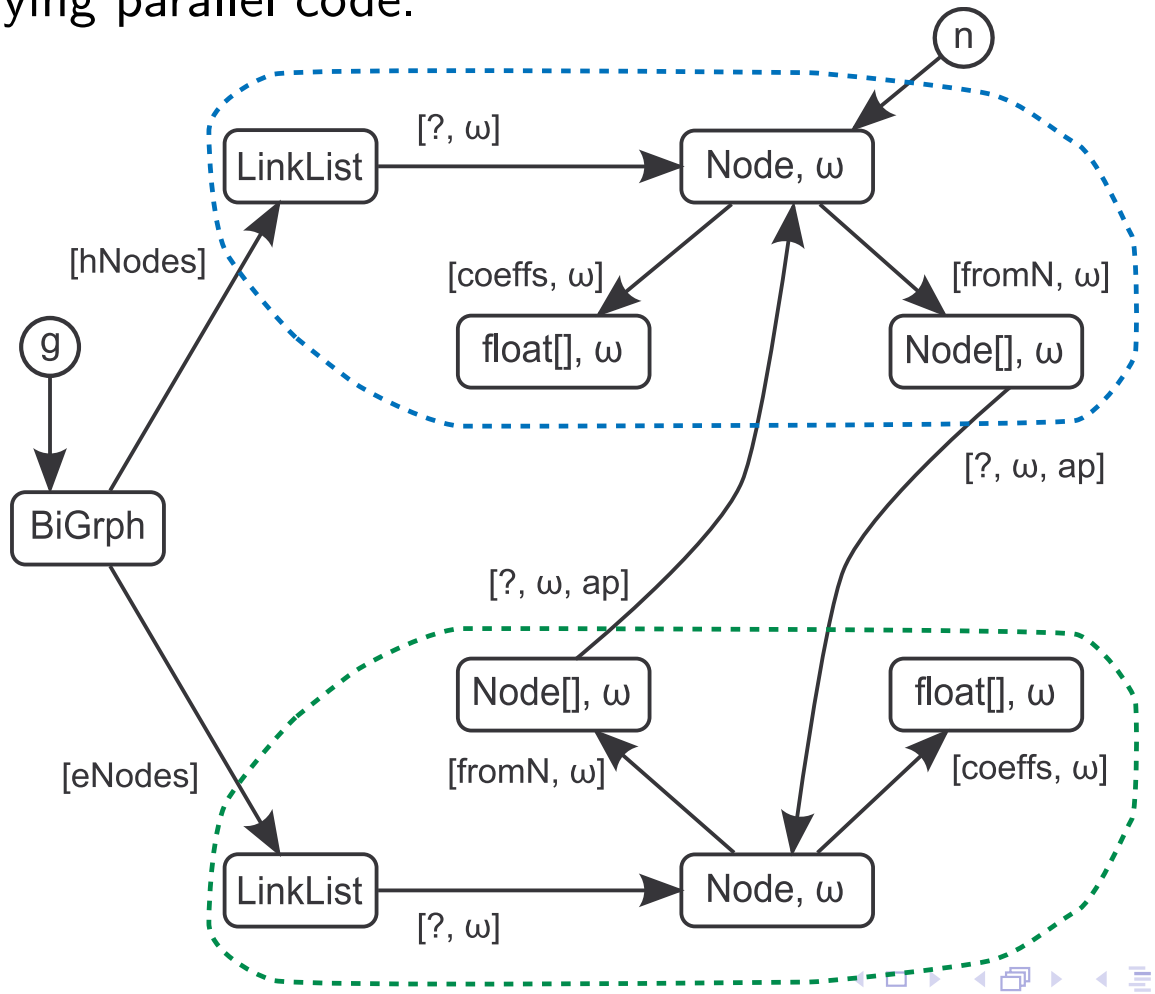
Some Speedups (for different analysis abstract domains)



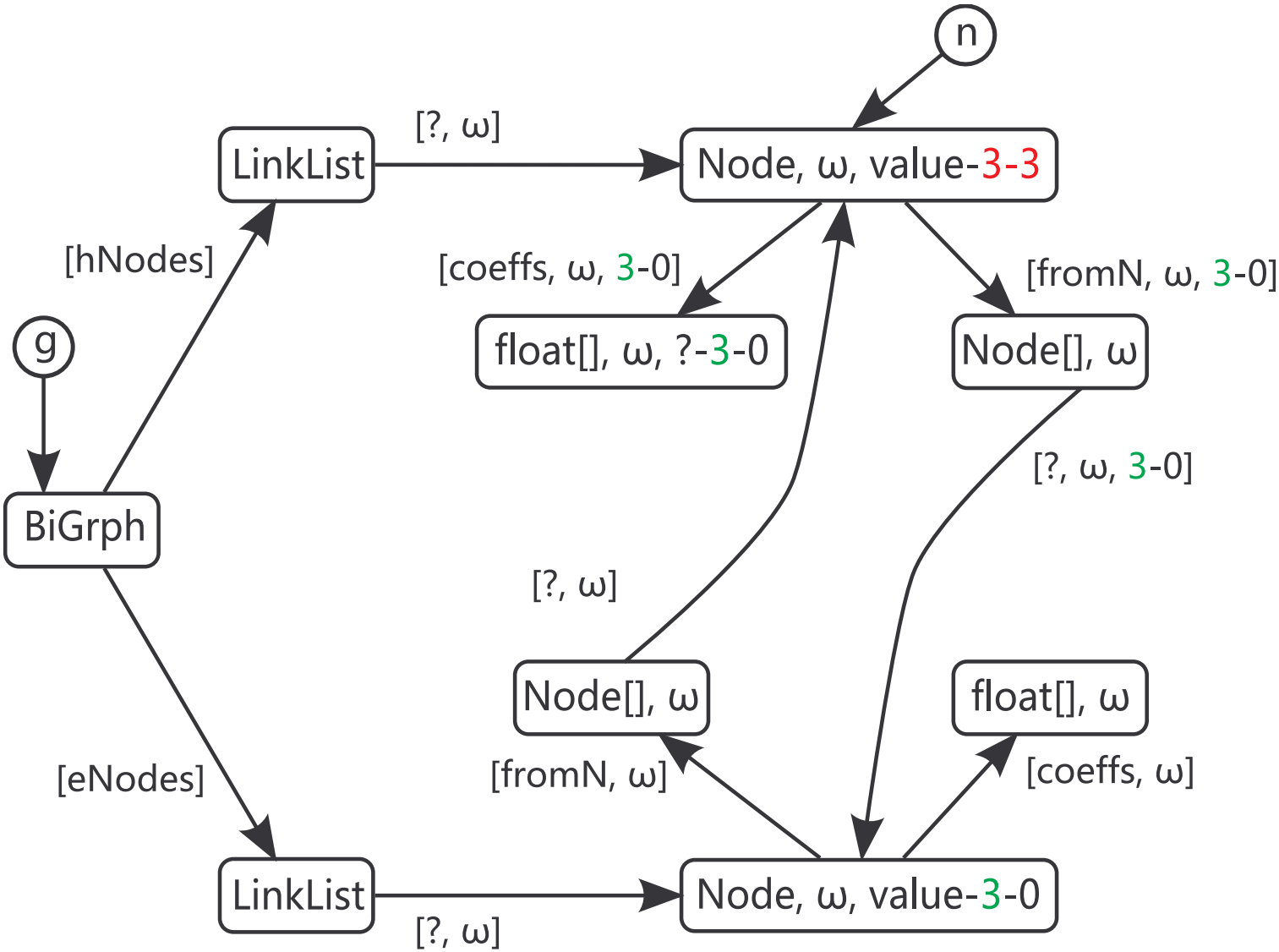
The parallelizer, self-parallelized.

Example: Heap Dependency Analysis (em3d, regions)

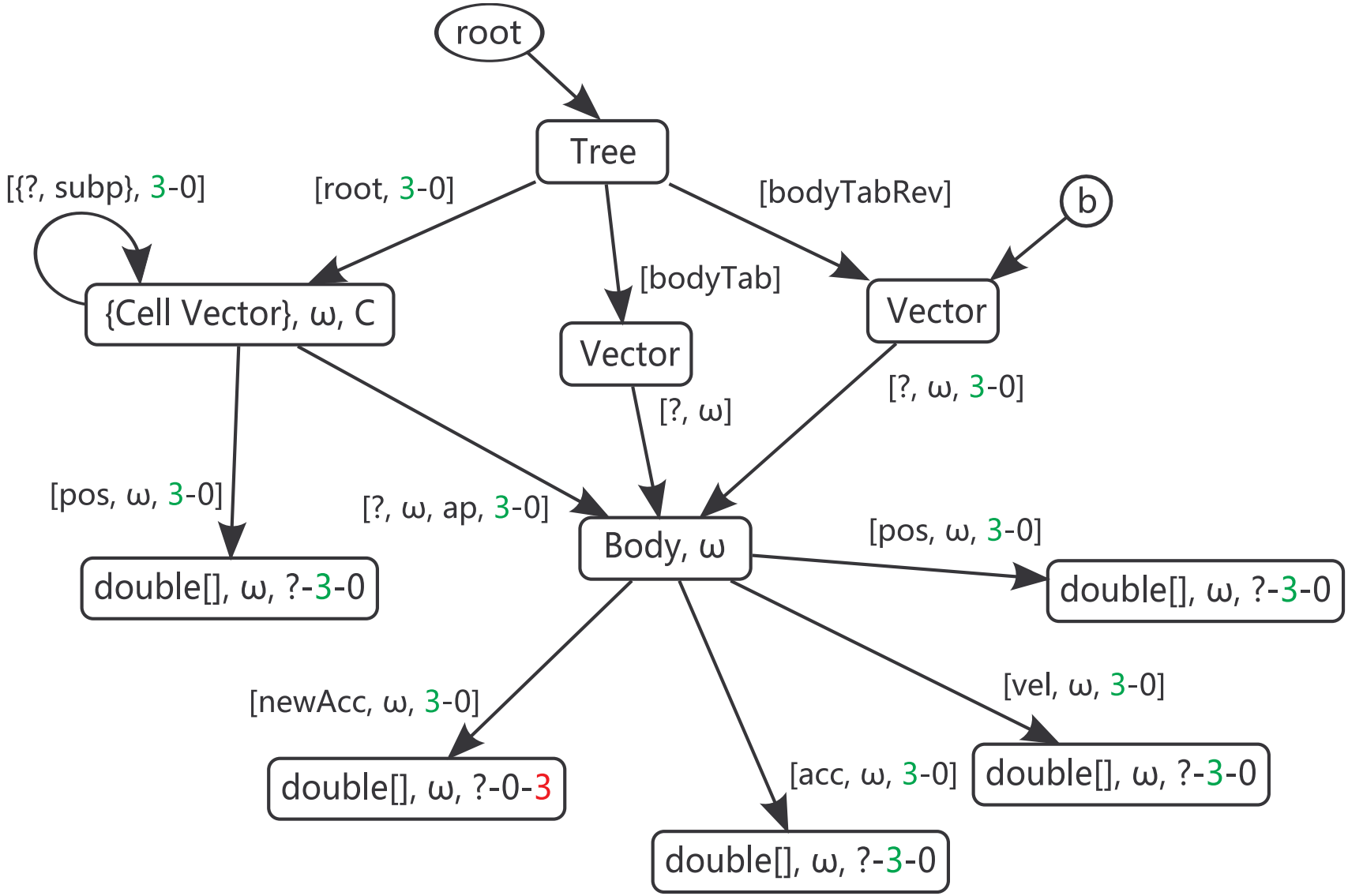
- Can be used for:
  - Parallelizing programs (independence detection).
  - Verifying/debugging user-provided parallel code.
  - Certifying parallel code.



Example: Heap Dependency Analysis (em3d, r-w deps)



Example: Heap Dependency Analysis (bh, r-w deps)

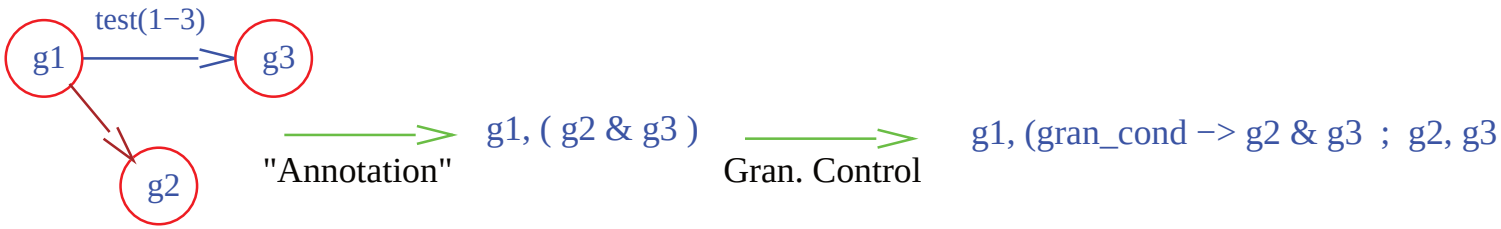


Granularity Control

- Replace parallel with seq. execution based on task size & overheads.
- Cannot be done completely at compile-time: cost often depends on input (hard to approximate precisely even w/abstract interpretation).

```
main :- read(X), read(Z), inc_all(X,Y) & r(Z,M), ...
```

- Our approach:
  - Derive at compile-time cost *functions* (to be evaluated at run-time) that efficiently bound task size (lower, upper *bounds*).
  - Transform programs to carry out run-time granularity control.



- For `inc_all`, (assuming "threshold" is 100 units):

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[DLH90, LGHD94, LGHD96, DLGHL94, DLGHL97, MLGCH08]

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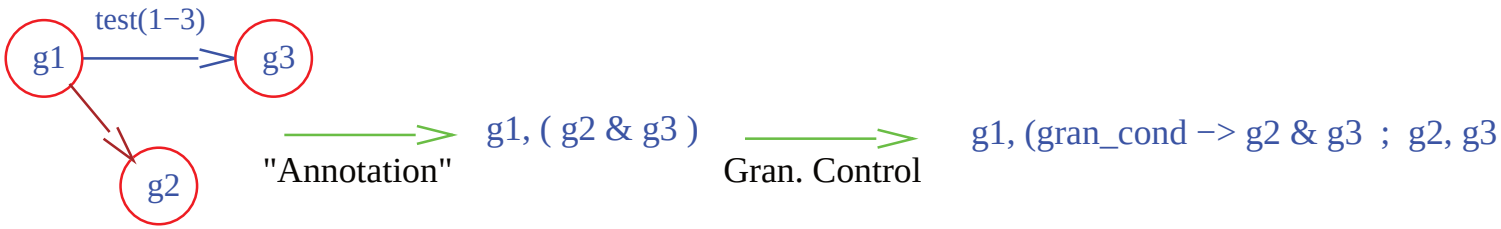

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Refinements: Granularity Control Optimizations

- Simplification of cost functions:

```
..., ( length(X) > 50 -> inc_all(X,Y) & r(Z,M)
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```

```
..., ( length_gt(LX,50) -> inc_all(X,Y) & r(Z,M)
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```

- Complex thresholds: use also communication cost functions, load, ...

  Example: Assume $CommCost(inc\_all(X)) = 0.1\ (length(X) + length(Y))$

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  Guaranteed speedup for any data size! $\Leftarrow$ $2 > 0.2$

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- Static task clustering (loop unrolling), static placement, etc.

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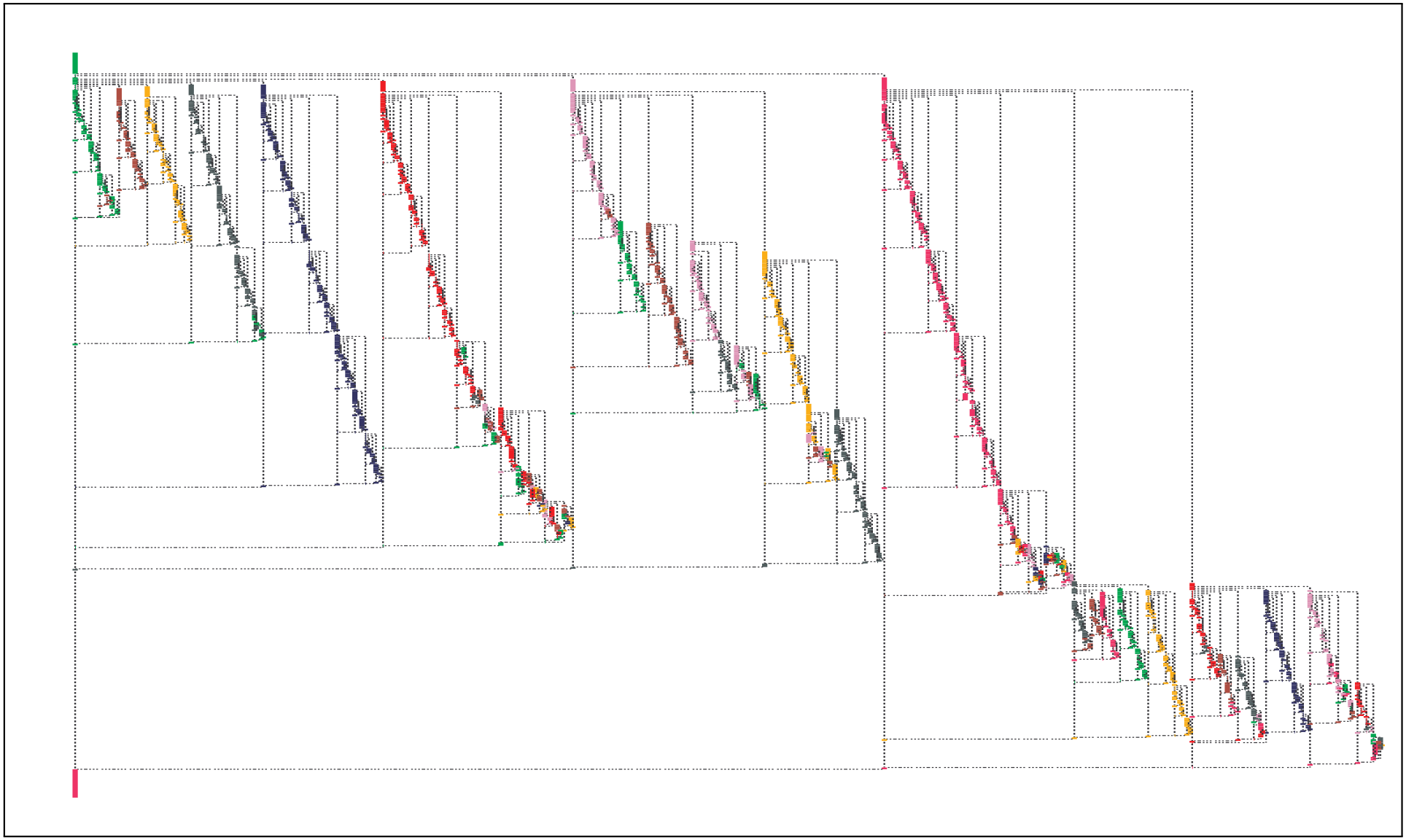
Granularity Control System Output Example

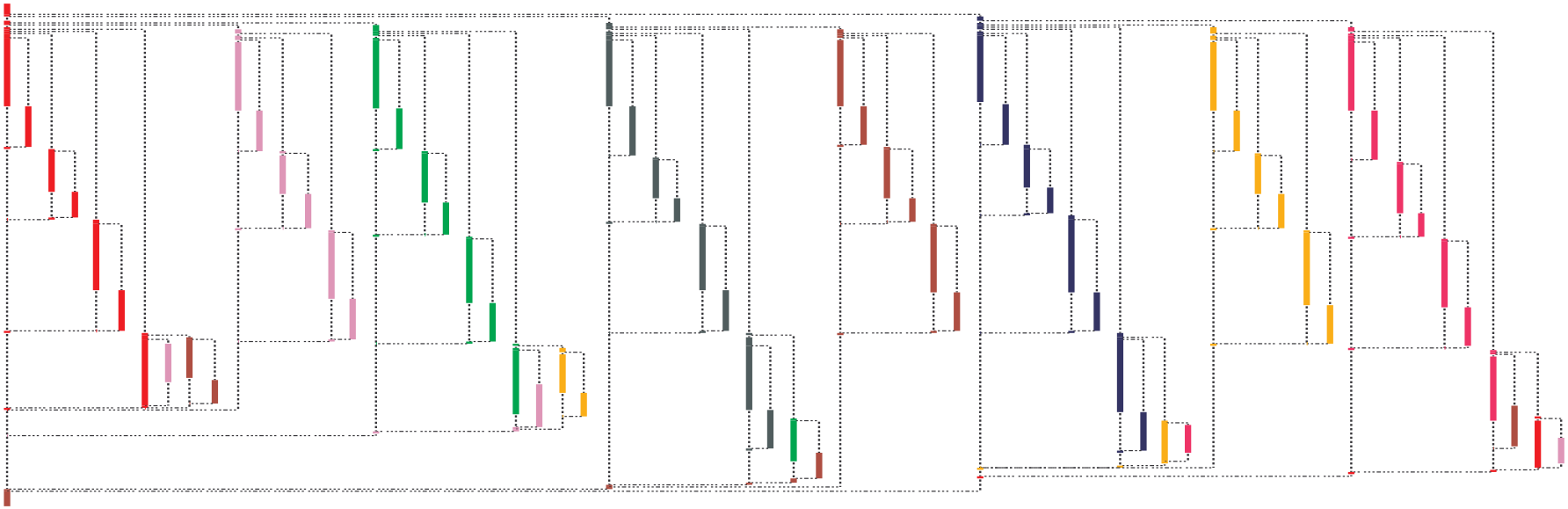
```
g_qsort([], []).
g_qsort([First|L1], L2) :-
  partition3o4o(First, L1, Ls, Lg, Size_Ls, Size_Lg),
  Size_Ls > 20 -> (Size_Lg > 20 -> g_qsort(Ls, Ls2) & g_qsort(Lg, Lg2)
                                ;  g_qsort(Ls, Ls2) , s_qsort(Lg, Lg2))
                ;  (Size_Lg > 20 -> s_qsort(Ls, Ls2) , g_qsort(Lg, Lg2)
                                ;  s_qsort(Ls, Ls2) , s_qsort(Lg, Lg2))),
  append(Ls2, [First|Lg2], L2).

partition3o4o(F, [], [], [], 0, 0).
partition3o4o(F, [X|Y], [X|Y1], Y2, SL, SG) :-
  X =< F, partition3o4o(F, Y, Y1, Y2, SL1, SG), SL is SL1 + 1.
partition3o4o(F, [X|Y], Y1, [X|Y2], SL, SG) :-
   X > F, partition3o4o(F, Y, Y1, Y2, SL, SG1), SG is SG1 + 1.
```

8 processors



8 processors, with granularity control (same scale)



Summarized System Timeline

- The original problem: auto-parallelization (1983).
- MA3 System - 1988 - Memo tables, practicality.
- 1989 - PLAI framework/fixpoint. Set sharing, side-effects.
- 1990 - First cost analysis (for task granularity), upper bounds.
- 1991 - Sharing+Freenes, def (dependencies).
- Early 90's - Practical auto-parallelization.
- 90's - Incrementality, modularity, extension to constraint programming, concurrency (dynamic scheduling), domain combinations.
- Mid 90's, 2006 - Combination with partial evaluation, lower bounds.
- Mid-Late 90's - CiaoPP: Integrated verification, debugging, optimization.
- Late 90's - Non-failure (no exceptions), determinacy,
- 2001-05 - Modularity, diagnosis.
- 2001-... Verification of cost, resources, ...
- 2002-... New shape/type domains, widenings.
- 2003-... Abstraction carrying code, reduced certificates, ...
- 2003-... User-defined resources. Time, energy, ...
- 2005-... *Multi-language support*, Java, C# (shapes, resources, ...).

Final Remarks

- Instead of full specifications a priori (waterfall):
  - Develop program and specifications gradually, not necessarily in sync.
  - Both can be incomplete (including types!).
    - Temporarily use spec (including tests) as implementation.
  - Go from types, to more complex assertions, to full specifications.
    - Can incrementally strengthen them to defs of full functional correctness.

  Safe approximations / abstractions everywhere –essential role!
- View debugging, verification, certification, testing, optimization *in an integrated way:* strong synergy.
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Final Remarks

- Instead of full specifications a priori (waterfall):
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    - Temporarily use spec (including tests) as implementation.
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Final Remarks

- Some Plans for CiaoPP/Ciao:
  - Continue multi-language analysis: programs in several languages.
  - Increase scalability by exploiting further modularity and incrementality of underlying technology.
  - Package parts as reusable components (perhaps part of a more general project?).
  - Applications in security (including, e.g., timing attacks).
  - Continue with language design (Ciao).
  - Continue exploring synergies. E.g., combine with theorem proving and/or model checking?

Some Members of The Ciao Forge

- CiaoPP/Ciao is really a widely distributed collaborative effort:
  - Directly within the CLIP Group (UPM and IMDEA Software):
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  - Plus lots of contributors worldwide:
    G. Gupta (UT Dallas), E. Pontelli (NM State University), P. Stuckey and M. García de la Banda (Melbourne U.), K. Marriott (Monash U.), M. Bruynooghe, A. Mulkers, G. Janssens, and V. Dumortier (K.U. Leuven), S. Debray (U. of Arizona), J. Maluzynski and W. Drabent, (Linkoping U.), P. Deransart (INRIA), J. Gallagher (Roskilde University), C. Holzbauer (Austrian Research Institute for AI), M. Codish (Beer-Sheva), SICS, ...

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