40 Years of Adventure in Abstract Interpretation of Logic Programs

Manuel Hermenegildo

with lots of help over the years from (among others):

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Or: *From Parallelism to Program Development and Back*

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The Paper

Non-Strict Independence-Based
Program Parallelization
Using Sharing and Freeness Information

Daniel Cabeza and Manuel Hermenegildo

- Abstract Interpretation, Logic Programming, Parallelism.
- Done within the ParForCE project, time of great Pisa-Madrid collaboration.
- An attempt to complete some missing parts on this (now old, but relevant) topic.

Provide context: what happened before and after.
~

The Original Challenge / Early Steps: Parallelization and Abs. Int.

- The original problem: LP parallelization (circa 1983 in US: UT Austin, MCC):
  - Parallel abstract machine, &-Prolog [ICLP'86, ICLP'87, ...] $\Rightarrow$ real speedups!
  - Detecting dependencies (pointer "sharing") among proc. calls, statements, etc.

  Traditional approach (ad-hoc dataflow analysis [Chang, Despain, Degroot '85]): correctness? — we wanted something *rigorous and more powerful*.

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- Our first "obsession:" correctness/practicality –speedups possible? AI practical? Built system [Warren, Debray, Herme. "MA3 system" ICSLP'88]
- Bruynooghe's framework [87-91]: multivariance + genericity of framework –parametric on the domains– (but no tabling or efficient fixpoint).
- The fixpoint algorithm and PLAI analyzer: efficient, context sensitive, multivariant, parametric analysis! [Muthukumar, Herme. NACLP'89]
  - Tabling, multiple call–success pairs Dependency tracking Interprocedural, dealing with mutual recursion, etc. (project/extend).
- Many useful extensions (1990 on, Spain, mostly at UPM; also UNM): Incremental framework; CLP; concurrent programs; Extension to Java/Java bytecode

Some Achievements in Parallelization

- Fully automatic parallelizers for logic programs
  – arguably the most powerful parallelizers for "irregular" applications.
  [Herme. and Warren, CAN'87, Bueno, G. de la Banda, and Herme. ICLP'94, TOPLAS'99]
  - Parallelization using non-strict independence [Cabeza and Herme. SAS'94]
  - Parallelization of constraint programs [G. de la Banda and Herme. PLILP'96]

  Perhaps the first fully implemented, practical application of AI?
- Prompted considerable *abstract domain development*:
  - Set sharing. [Jacobs-Langen NACLP 89, Muthukumar and Herme. NACLP'89 (abstr. unif.)]
  - Set sharing and freeness. [Muthukumar and Herme. ICLP'91]
  - Def (propositional horn clauses) [de la Banda/Herme. WSA'92, Sondergaard, Marriott]
  - Combinations with depth-k, shape analysis (regular types), etc.
  - *Set sharing for Java* [Méndez-Lojo, Herme. VMCAI'08]
- (C)LP/Prolog/Ciao very useful: allow studying challenging problems (pointers, irregular computations, irregular data, dynamic heap, dynamic dispatch, etc.) in much better context.

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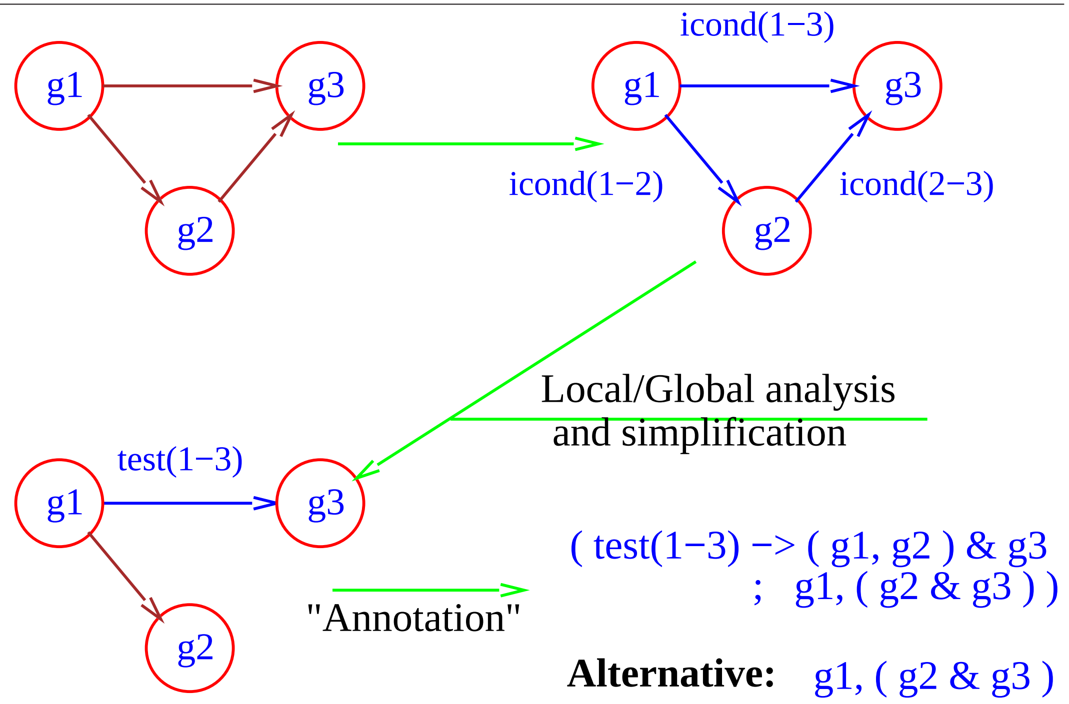
- **ParForCE and other projects –much collaboration with Giorgio / Pisa!**

Parallelization Process

- Conditional dependency graph (of some segment, e.g., a clause):
  - vertices are possible tasks (statements, calls,...),
  - edges=possible dependency (labels=conditions needed for independence).
- Local or global analysis used to reduce/remove checks in the edges.

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

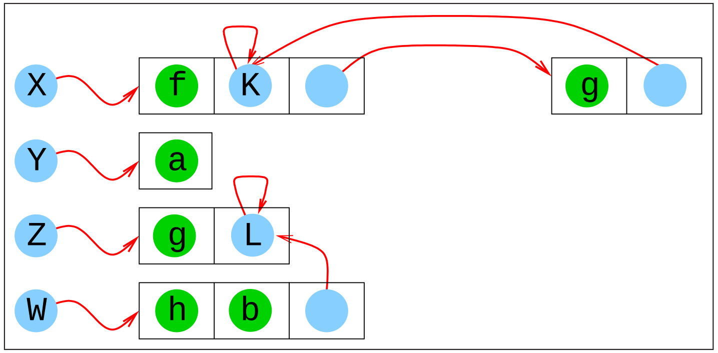


A Priori Independence: Strict Independence

- Correctness and efficiency (search space preservation) guaranteed for `p & q` if no shared variables.

- The “pointers” view:
  correctness and efficiency guaranteed if there are no “pointers” between `p` and `q`.

```
main :- X=f(K,g(K)), Y=a,
        Z=g(L), W=h(b,L),
        --------------------->
        p(X,Y),
        q(Y,Z),
        r(W).
```



`p` and `q` are strictly independent, but `q` and `r` are not.

Independence – Non-Strict Independence

- Pure goals: only one thread “touches” each shared variable. Example:

```
main :- t(X,Y), p(X), q(Y).
t(X,Y) :- Y = f(X).
```

- Impure goals: only rightmost “touches” each shared variable. Example:

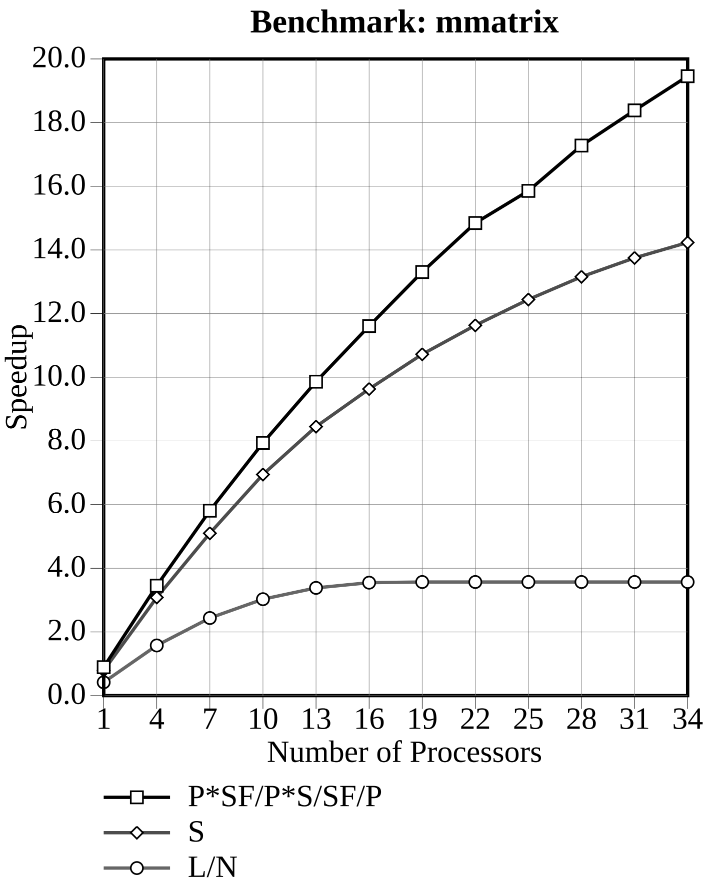
```
main :- t(X,Y), p(X), q(Y).
t(X,Y) :- Y = a.   p(X) :- var(X), ..., X=b, ...
```

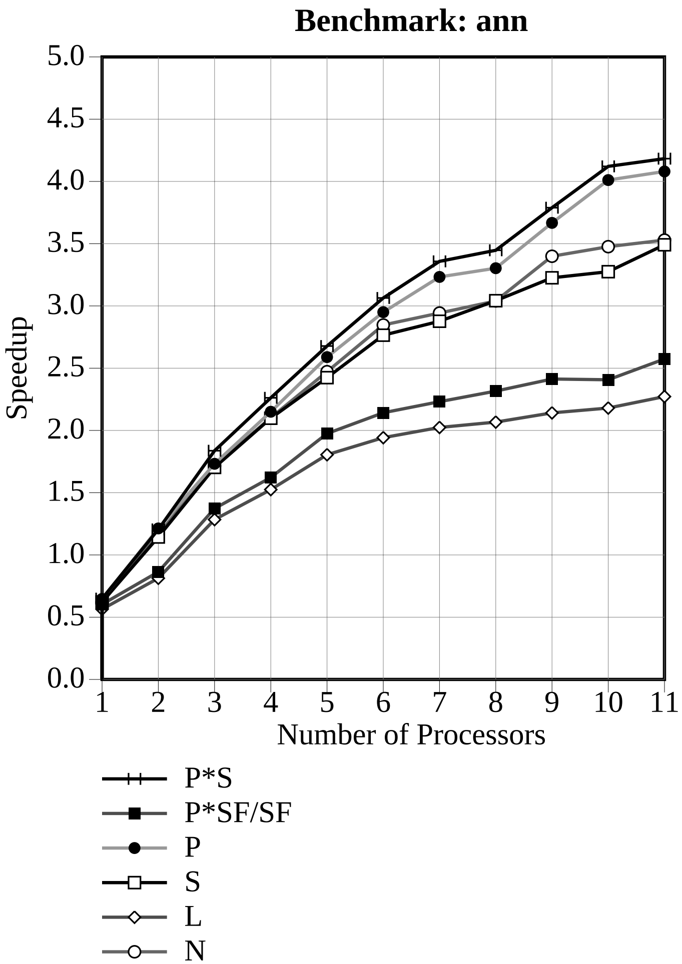
- Very important in programs using “incomplete structures.”

```
flatten(Xs,Ys) :- flatten(Xs,Ys,[]).
flatten([], Xs, Xs).
flatten([X|Xs],Ys,Zs)  :- flatten(X,Ys,Ys1), flatten(Xs,Ys1,Zs).
flatten(X, [X|Xs], Xs) :- atomic(X), X \== [].
```

- Another example: qsort with difference lists.
- **Paper:** NSI from sharing+freeness; new run-time tests (`allvars`, `sharedvars`).

Some Speedups (Using Different Abstract Domains)



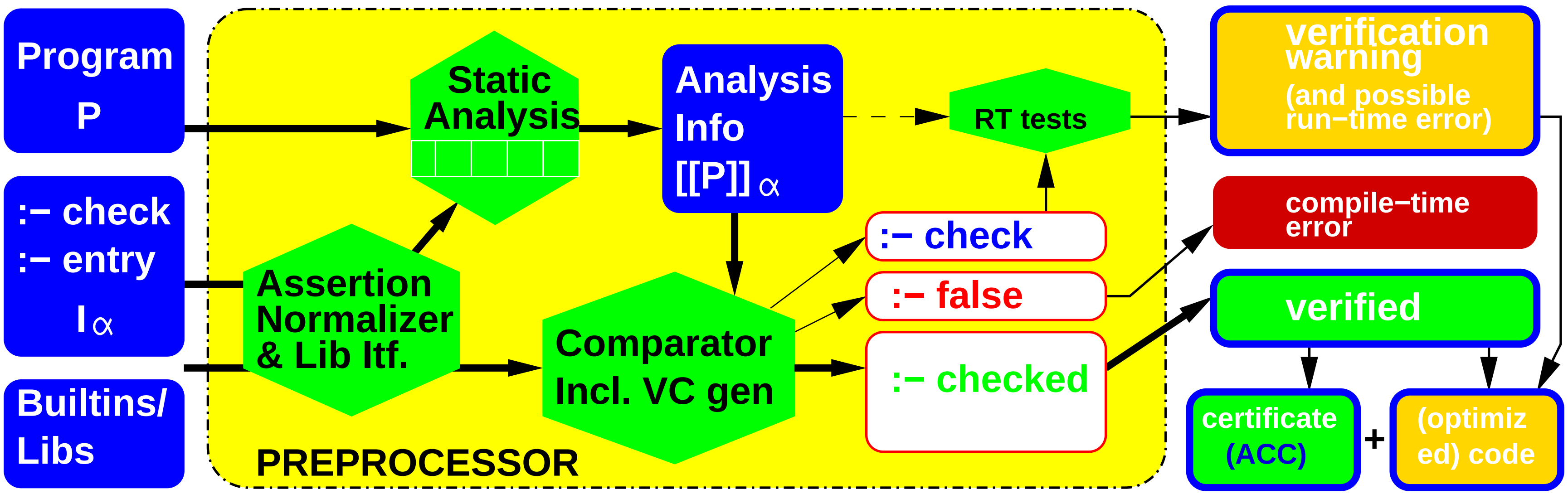


(ann is the parallelizer parallelizing itself;
1-10 proc.: actual speedups on Sequent Symmetry; 10+ simulator projections from execution traces)

The Second Phase: Program Development using AI / Next Gen. LP

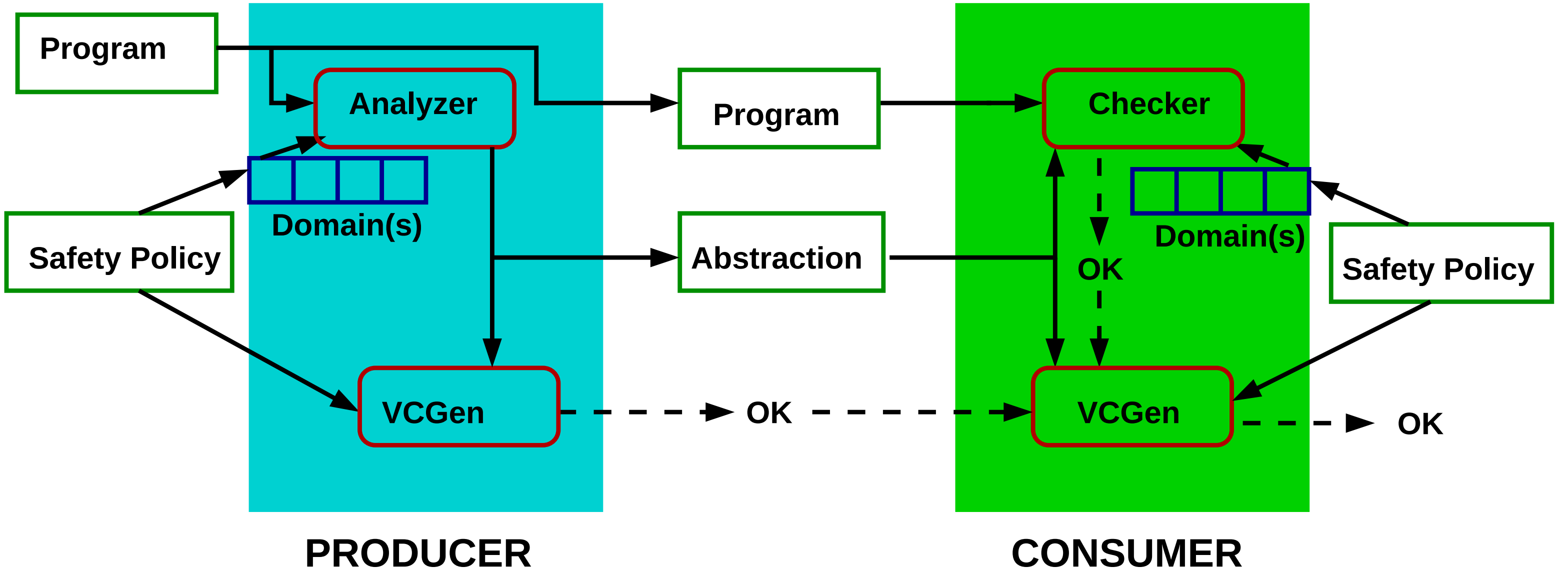
- The next stage:
  - not just optimization (parallelization, abstract partial evaluation, ...), but
  - **program development** fundamentally based on abstract interpretation.
- Great influence of AI and LP in **programming language design**:
  the “Ciao” language and environment design;
  AI-based compiler / env. (assertion based vs. strongly-typed, type systems as domains, multiparadigm –again, Giorgio–, etc.).
- Ideas lurking for a long time, crystallized in first prototypes in 1994-97 [PPCP’94, Ciao system design], and:
  - Overall design [ILPS’97, AADEBUG’97, ICLP’99, LOPSTR’99, SAS’03, SCP’05]
  - Assertion language [LNCS 1870]
  - Modular extensions [Pietrzak, Correas, Puebla, Herme. LPAR’06]
  - Abstract diagnosis [Alpuente, Comini, Escobar, Falaschi, Lucas, LOPSTR’02] [Gallardo, Merino, Pimemtel, SAS’02] [Pietrzak, Herme. ICLP’07]
  - Extensions to Java [Albert, Gómez-Zamalloa, Hubert, Puebla PADL’07]

The CiaoPP Verification/Diagnosis Framework [AADEBUG'97]



- I_α (partial specification) provided via a language of *optional* assertions.
  - State properties at relevant points.
  - Talk about properties which can be predefined or user-defined.
    Types, cost, data sizes, termination, pointer aliasing, no-except, ...
- Implemented for Ciao and (less mature) for Java and Java bytecode.

The Abstraction Carrying Code (ACC) Scheme

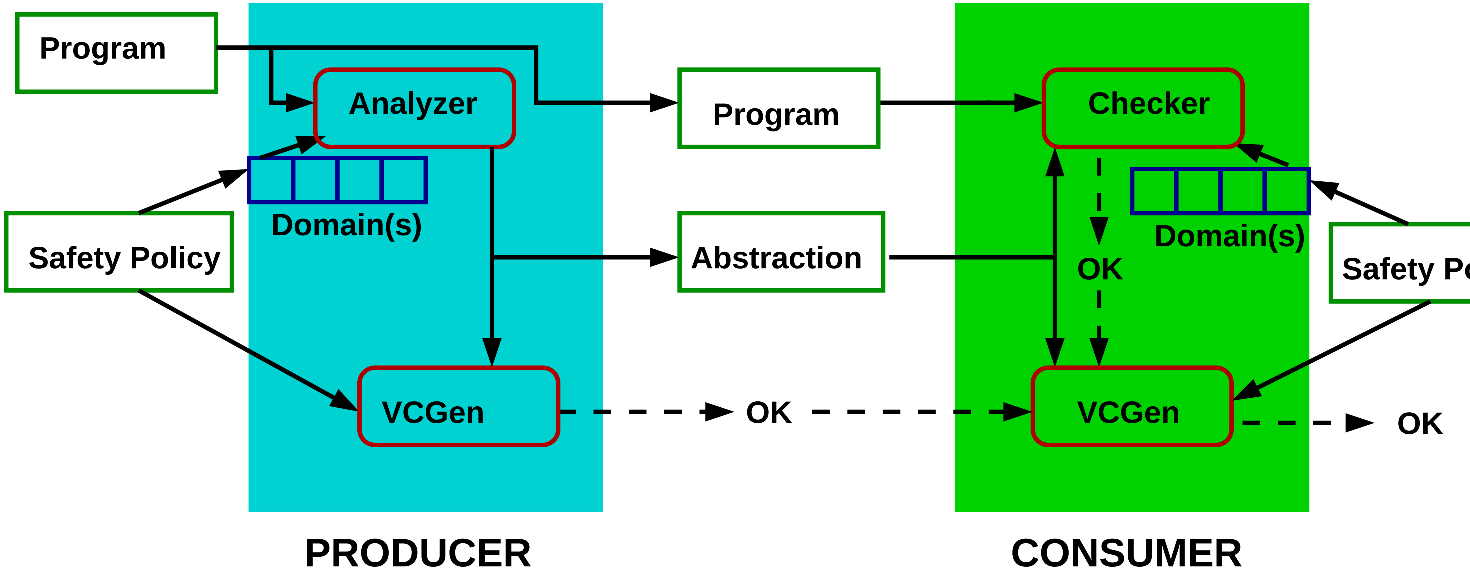


$[\![P]\!]_\alpha = \text{Analysis} = \text{lfp}(analysis\_step)$

$\text{Certificate} \subset [\![P]\!]_\alpha$

$\text{Checker} = analysis\_step$

The Abstraction Carrying Code (ACC) Scheme



$[\![P]\!]_\alpha$ = Analysis = lfp($analysis\_step$) | Certificate $\subset [\![P]\!]_\alpha$ | Checker = $analysis\_step$

- Basic proposal [Albert, Puebla, Herme. COCV'04, LPAR'04, ICLP'04, PPDP'05, NGC'08]
- Incremental version [Albert, Arenas, Puebla LPAR'06]
- Certificate reduction (fixpoint compression) [Albert, Arenas, Puebla, Herme. ICLP'06]
- MOBIUS project [TGC'06].
- Incorporated in `CiaoPP` for types, modes, shapes, sizes, cost, det, termination, non-failure, resources, etc.

Combination with Partial Evaluation; Optimization; Scalability

- Combination with Partial Evaluation:
  - Abstract executability. Multiple abstract specialization [Puebla, Herme. PEPM'95]; application in parallelization [LOPSTR'97, JLP'99]
  - Full integration of Partial Evaluation and AI [Puebla, Albert, Herme. SAS'06]

  → important contribution to the AI-based program development model.
- Application to program optimization (other than parallelization): abstract machines and native compilation [Morales, Carro, Herme. PADL'04, ICLP'05, LOPSTR'06]; embedded systems [Carro, Morales, Muller, Puebla, Herme. CASES'06].
- Modularity, Scalability, Practicality Issues:
  - Efficient, incremental intermodular analysis / fixpoint calculation [Bueno, G. de la Banda, Herme., Marriott, Puebla, Stuckey, Correas LOPSTR'01, LOPSTR'04, LOPSTR'05].
  - Widening of set-sharing [Navas, Bueno, Herme. PADL'06]
  - Dealing with the full ISO-Prolog standard [Bueno, Cabeza, Herme., Puebla ESOP'96]
- Domain combinations, goal-dependent vs. goal indep. analysis (flow sensitivity) [Codish, Mulkers, Bruy., G. de la Banda, Herme. PEPM'93, LPAR'94, TOPLAS'95, JLP'97]

Inference of Resource-related and other Complex Properties

- Cost, resources (motivated by granularity control –lots of AI!):
  - Upper bounds (execution steps); application to granularity control [Debray, Lin, Herme., PLDI'90].
  - Lower bounds (execution steps) [w/López-García, ILPS'97, SAS'94].
  - Extension to Java bytecode [Albert, Arenas, Genaim, Puebla, Zanardini ESOP'07].
  - Execution times [Mera, López-García, Puebla, Carro, Herme., PADL'07].
  - User-definable resources for LP [Navas, Mera, López-García, Herme., ICLP'07].
  - Heap space analysis (Java bytecode) [Albert, Genaim, Gómez-Zamalloa, ISMM '07].
- Non-failure / no exceptions [Bueno, Debray, López-García, Herme. ICLP'97]; multivariant version [FLOPS'04].
- Determinacy analysis [Bueno, López-García, Herme. LOPSTR'04].
- Heap / shape analysis (C++/Java) [Marron, Herme., Kapur, Stefanovic LCPC'06, PASTE'07, CC'08]; Type domains, type widenings [Vaucheret, Bueno SAS'02].
- Termination analysis (Java) [Albert, Arenas, Codish, Genaim, Puebla, Zanardini WST'07].

Final Thoughts / The Next 25 Years!

- Go mainstream, make everyday tools! (Ciao, COSTA, ...) –coll. w/Industry (e.g., ES_PASS).
  - Further work on scalability, modularity, domains, widenings, ...
  - Emphasis on resource-related properties; specially *user-defined*.
  - Improve diagnosis.
  - Develop ACC further, apply in practice to, e.g., small devices (MOBIUS).
  - Multi-language environments.
- *Back to parallelism! A big push to parallelization, granularity control, ...*
- *Develop new, even more dynamic, multiparadigm, high-level languages, getting correctness and real speed (without user burden), thanks to LP and AI.*

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But, mainly, thanks Giorgio –what an adventure!
Look forward to the next 25 years together!

Conditions for Non-Strict Independence Based on ShFr Info

- We consider the parallelization of pairs of goals.
- Let the situation be: $\{\widehat{\beta}\}\ p\ \{\widehat{\psi}\}\ \ldots\ q$.
  We define:

  $$\mathrm{S}(p) = \{L \in \widehat{\beta}_{\mathrm{SH}} \mid L \cap (\neq \emptyset\}$$
  $$\mathrm{SH} = \mathrm{S}(p) \cap \mathrm{S}(q) = \{L \in \widehat{\beta}_{\mathrm{SH}} \mid L \cap (\neq \emptyset$$
  $$\wedge L \cap (\neq \emptyset\}$$

- Conditions for non-strict independence for p and q:

  C1 $\forall L \in \mathrm{SH}\ L \cap \widehat{\psi}_{\mathrm{FR}} \neq \emptyset$

  C2 $\neg\,(\exists N_1 \ldots N_k \in \mathrm{S}(p)\ \exists L \in \widehat{\psi}_{\mathrm{SH}}$
  $L = \cup_{i=1}^{k} N_i \ \wedge\ N_1, N_2 \in \mathrm{SH}$
  $\wedge \forall i, j\ \ 1 \leq i < j \leq k\ \ N_i \cap N_j \cap \widehat{\beta}_{\mathrm{FR}} = \emptyset)$

- C1: preserves freeness of shared variables.
- C2: preserves independence of shared variables.
- More relaxed conditions if information re. partial answers and purity of goals.

Run-Time Checks for NSI Based on ShFr Info

- Run-time checks can be automatically included to ensure NSI when the previous conditions do not hold.
- The method uses analysis information.
- Possible checks are:
  - `ground(X)`: `X` is ground.
  - `allvars(X,`$\mathcal{F}$`)`: every free variable in `X` is in the list $\mathcal{F}$.
  - `indep(X,Y)`: `X` and `Y` do not share variables.
  - `sharedvars(X,Y,`$\mathcal{F}$`)`: every free variable shared by X and Y is in the list $\mathcal{F}$.
- The method generalizes the techniques previously proposed for detection of SI.
- Even when only SI is present, the tests generated may be better than the traditional tests.