Automatic Verification of Avionic Synchronous Safety Critical Embedded Software

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Talk Outline

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Motivation



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All Computer Scientists Have Experienced Bugs







Ariane 5.01 failure Patriot failure Mars orbiter loss (overflow) (float rounding) (unit error)

It is preferable to verify that mission/safety-critical programs do not go wrong before running them.



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Static Analysis by Abstract Interpretation

Static analysis: analyse the program at compile-time to verify a program runtime property (e.g. the absence of some categories of bugs)

Undecidability \longrightarrow

Abstract interpretation: effectively compute an abstraction/ sound approximation of the program semantics,

- -which is precise enough to imply the desired property, and
- -coarse enough to be efficiently computable.





Abstract Interpretation, Reminder

<u>Reference</u>

- [POPL'77] P. Cousot and R. Cousot. Abstract interpretation: a unified lattice model for static analysis of programs by construction or approximation of fixpoints. In 4th ACM POPL.
- [Thesis '78] P. Cousot. Méthodes itératives de construction et d'approximation de points fixes d'opérateurs monotones sur un treillis, analyse sémantique de programmes. Thèse ès sci. math. Grenoble, march 1978.
- [POPL'79] P. Cousot & R. Cousot. Systematic design of program analysis frameworks. In 6th ACM POPL.







Syntax of programs







Postcondition semantics





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States

Values of given type:

$$\mathcal{V}\llbracket T
rbracteft \ : ext{ values of type } T \in \mathbb{T}$$

 $\mathcal{V}\llbracket ext{int}
rbracett = \{z \in \mathbb{Z} \mid ext{min_int} \leq z \leq ext{max_int} \}$

Program states $\Sigma \llbracket P \rrbracket^{1}$:

洲

$$\begin{split} & \Sigma \llbracket D \ C \rrbracket \stackrel{\text{def}}{=} \Sigma \llbracket D \rrbracket \\ & \Sigma \llbracket T \ X \, ; \rrbracket \stackrel{\text{def}}{=} \{X\} \mapsto \mathcal{V} \llbracket T \rrbracket \\ & \Sigma \llbracket T \ X \, ; \ D \rrbracket \stackrel{\text{def}}{=} \{X\} \mapsto \mathcal{V} \llbracket T \rrbracket \end{split}$$



 $^{^1}$ States $ho\in \varSigma[\![P]\!]$ of a program P map program variables X to their values ho(X)

Concrete Semantic Domain of Programs

Concrete semantic domain for reachability properties:

$\mathcal{D}[\![P]\!] \stackrel{\text{def}}{=} \wp(\Sigma[\![P]\!])$ sets of states

i.e. program properties where \subset is implication, \emptyset is false, \cup is disjunction.





Concrete Reachability Semantics of Programs $\mathcal{S}[X = E;]R \stackrel{\text{def}}{=} \{ \rho[X \leftarrow \mathcal{E}[E]] \rho] \mid \rho \in R \cap \operatorname{dom}(E) \}$ $\rho[X \leftarrow v](X) \stackrel{\text{def}}{=} v, \qquad \rho[X \leftarrow v](Y) \stackrel{\text{def}}{=} \rho(Y)$ \mathcal{S} [if B C'] $R \stackrel{\text{def}}{=} \mathcal{S}$ [C'] $(\mathcal{B}$ [B]R) $\cup \mathcal{B}$ [$\neg B$]R $\mathcal{B}[\![B]\!]R \stackrel{\text{def}}{=} \{ \rho \in R \cap \operatorname{dom}(B) \mid B \text{ holds in } \rho \}$ \mathcal{S} [if $B \ C'$ else C''] $R \stackrel{\text{def}}{=} \mathcal{S}$ [C'] $(\mathcal{B}$ [B]R) $\cup \mathcal{S}$ [C''] $(\mathcal{B}$ [$\neg B$]R) $\mathcal{S}[[while \ B \ C']] R \stackrel{\text{def}}{=} \operatorname{let} \mathcal{W} = \operatorname{lfp}_{a}^{\subseteq} \lambda \mathcal{X} \cdot R \cup \mathcal{S}[[C']](\mathcal{B}[\![B]]\mathcal{X}))$ in $(\mathcal{B}[\neg B]\mathcal{W})$ $S[{}]R \stackrel{\text{def}}{=} R$ $\mathcal{S}[{C_1 \dots C_n}] \mathbb{R} \stackrel{\text{def}}{=} \mathcal{S}[C_n] \circ \dots \circ \mathcal{S}[C_1] \quad n > 0$ $\mathcal{S}\llbracket D \ C \rrbracket R \stackrel{\text{def}}{=} \mathcal{S}\llbracket C \rrbracket (\Sigma \llbracket D \rrbracket) \quad (\text{uninitialized variables})$ Not computable (undecidability). Programming Languages Seminar, Northeastern U. June 1st, 2005 — 11 — (C) P. Cousot

Abstract Semantic Domain of Programs

$$\langle \mathcal{D}^{\sharp}\llbracket P
rbracket, \sqcup, \sqcup
angle$$

such that:

$$\langle \mathcal{D}, \subseteq \rangle \xleftarrow{\gamma}{\alpha} \langle \mathcal{D}^{\sharp}\llbracket P \rrbracket, \sqsubseteq \rangle$$

hence $\langle \mathcal{D}^{\sharp}[P], \sqsubseteq, \bot, \sqcup \rangle$ is a complete lattice such that $\perp = \alpha(\emptyset) \text{ and } \sqcup X = \alpha(\cup \gamma(X))$





Reduced Product of Abstract Domains

To combine abstractions

 $\langle \mathcal{D}, \subseteq \rangle \stackrel{\gamma_1}{\longleftrightarrow} \langle \mathcal{D}_1^{\sharp}, \sqsubseteq_1 \rangle \text{ and } \langle \mathcal{D}, \subseteq \rangle \stackrel{\gamma_2}{\longleftrightarrow} \langle \mathcal{D}_2^{\sharp}, \sqsubseteq_2 \rangle$ the reduced product is $\boldsymbol{\alpha}(X) \stackrel{\text{def}}{=} \sqcap \{ \langle x, y \rangle \mid X \subseteq \boldsymbol{\gamma}_1(X) \land X \subseteq \boldsymbol{\gamma}_2(X) \}$ such that $\Box \stackrel{\text{def}}{=} \Box_1 \times \Box_2$ and $\langle \mathcal{D}, \subseteq \rangle \xleftarrow{\gamma_1 \times \gamma_2} \langle \alpha(\mathcal{D}), \sqsubseteq \rangle$

Example: $x \in [1, 9] \land x \mod 2 = 0$ reduces to $x \in [2, 8] \land$ $x \mod 2 = 0$





Approximate Fixpoint Abstraction





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Abstract Reachability Semantics of Programs $\mathcal{S}^{\sharp} \llbracket X = E;
Vert R \stackrel{\mathrm{def}}{=} \pmb{\alpha}(\{
ho \llbracket X \leftarrow \mathcal{E} \llbracket E
Vert
ho
Vert \mid
ho \in \pmb{\gamma}(R) \cap \mathrm{dom}(E)\})$ \mathcal{S}^{\sharp} [if $B C'] R \stackrel{\text{def}}{=} \mathcal{S}^{\sharp} [C'] (\mathcal{B}^{\sharp} [B] R) \sqcup \mathcal{B}^{\sharp} [\neg B] R$ $\mathcal{B}^{\sharp}[B]R \stackrel{\text{def}}{=} \alpha(\{\rho \in \gamma(R) \cap \operatorname{dom}(B) \mid B \text{ holds in } \rho\})$ \mathcal{S}^{\sharp} [if $B \ C'$ else C''] $R \stackrel{\text{def}}{=} \mathcal{S}^{\sharp}$ [C'] $(\mathcal{B}^{\sharp}$ [B] $R) \sqcup \mathcal{S}^{\sharp}$ [C''] $(\mathcal{B}^{\sharp}$ [$\neg B$]R) \mathcal{S}^{\sharp} [while $B \ C'$] $R \stackrel{\text{def}}{=} \operatorname{let} \mathcal{W} = \operatorname{lfp}_{\downarrow}^{\sqsubseteq} \lambda \mathcal{X} \cdot R \sqcup \mathcal{S}^{\sharp}$ [C'] $(\mathcal{B}^{\sharp}$ [B] \mathcal{X}) in $(\mathcal{B}^{\sharp} \llbracket \neg B \rrbracket \mathcal{W})$ S^{\sharp} \mathbb{S}^{\sharp} \mathbb{S}^{\dagger} \mathbb{S}^{\dagger} \mathbb{S}^{\dagger} \mathbb{S}^{\dagger} \mathbb{S}^{\dagger} \mathbb{S}^{\dagger} \mathbb{S}^{\dagger} \mathbb{S}^{\dagger} $\mathcal{S}^{\sharp} \llbracket \{C_1 \dots C_n\} \rrbracket R \stackrel{\text{def}}{=} \mathcal{S}^{\sharp} \llbracket C_n \rrbracket \circ \dots \circ \mathcal{S}^{\sharp} \llbracket C_1 \rrbracket \quad n > 0$ $\mathcal{S}^{\sharp} \llbracket D \ C \rrbracket R \stackrel{\text{def}}{=} \mathcal{S}^{\sharp} \llbracket C \rrbracket (\top) \quad (\text{uninitialized variables})$



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Convergence Acceleration with Widening





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Abstract Semantics with Convergence Acceleration² $\mathcal{S}^{\sharp}[X = E;]R \stackrel{\text{def}}{=} \alpha(\{\rho[X \leftarrow \mathcal{E}[E]] \rho] \mid \rho \in \gamma(R) \cap \operatorname{dom}(E)\})$ \mathcal{S}^{\sharp} [if $B C' || R \stackrel{\text{def}}{=} \mathcal{S}^{\sharp} || C' || (\mathcal{B}^{\sharp} || B || R) \sqcup \mathcal{B}^{\sharp} || \neg B || R$ $\mathcal{B}^{\sharp}[B]R \stackrel{\text{def}}{=} \alpha(\{\rho \in \gamma(R) \cap \operatorname{dom}(B) \mid B \text{ holds in } \rho\})$ \mathcal{S}^{\sharp} [if $B \ C'$ else C''] $R \stackrel{\text{def}}{=} \mathcal{S}^{\sharp}$ [C'] $(\mathcal{B}^{\sharp}$ [B] $R) \sqcup \mathcal{S}^{\sharp}$ [C''] $(\mathcal{B}^{\sharp}$ [$\neg B$]R) \mathcal{S}^{\sharp} [while $B C' || R \stackrel{\text{def}}{=} \operatorname{let} \mathcal{F}^{\sharp} = \lambda \mathcal{X} \cdot \operatorname{let} \mathcal{Y} = R \sqcup \mathcal{S}^{\sharp} [\![C']\!] (\mathcal{B}^{\sharp} [\![B]\!] \mathcal{X})$ in if $\mathcal{Y} \sqsubset \mathcal{X}$ then \mathcal{X} else $\mathcal{X} \nabla \mathcal{Y}$ and $\mathcal{W} = \mathsf{lfp}^{\perp} \mathcal{F}^{\sharp}$ in $(\mathcal{B}^{\sharp} \llbracket \neg B \rrbracket \mathcal{W})$ S^{\sharp} \mathbb{S}^{\sharp} \mathbb{S}^{\dagger} \mathbb{S}^{\dagger} \mathbb{S}^{\dagger} \mathbb{S}^{\dagger} \mathbb{S}^{\dagger} \mathbb{S}^{\dagger} \mathbb{S}^{\dagger} \mathbb{S}^{\dagger} $\mathcal{S}^{\sharp}[\{C_1 \dots C_n\}] R \stackrel{\text{def}}{=} \mathcal{S}^{\sharp}[[C_n]] \circ \dots \circ \mathcal{S}^{\sharp}[[C_1]] \quad n > 0$ $\mathcal{S}^{\sharp} \llbracket D \ C \rrbracket R \stackrel{\text{def}}{=} \mathcal{S}^{\sharp} \llbracket C \rrbracket (\top) \quad (\text{uninitialized variables})$

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² Note: \mathcal{F}^{\sharp} <u>not</u> monotonic!

Applications of Abstract Interpretation





Applications of Abstract Interpretation

- Static Program Analysis [POPL '77], [POPL '78], [POPL '79] including Dataflow Analysis [POPL '79], [POPL '00], Setbased Analysis [FPCA '95], Predicate Abstraction [Manna's festschrift '03], ...
- -Syntax Analysis [TCS 290(1) 2002]
- Hierarchies of Semantics (including Proofs) [POPL '92], TCS 277(1-2) 2002
- Typing & Type Inference [POPL '97]





Applications of Abstract Interpretation (Cont'd)

- -(Abstract) Model Checking [POPL '00]
- **Program Transformation** [POPL '02]
- -Software Watermarking [POPL '04]
- **Bisimulations** [RT-ESOP '04]

All these techniques involve sound approximations that can be formalized by abstract interpretation





A Practical Application of Abstract Interpretation to the Verification of Safety Critical Embedded **Control-Command Software**

Reference

http://www.astree.ens.fr/





ASTRÉE: A Sound, Automatic, Specializable, Domain-Aware, Parametric, Modular, Efficient and Precise Static Program Analyzer

www.astree.ens.fr

- -C programs:
 - -<u>with</u>
 - pointers (including on functions), structures and arrays
 - floating point computations
 - tests, loops and function calls
 - limited branching (forward goto, break, continue)





-without

- union
- dynamic memory allocation
- recursive function calls
- backward branching
- conflict side effects
- C libraries

- Application Domain: safety critical embedded real-time synchronous software for non-linear control of very complex control/command systems.





Concrete Operational Semantics

- -International norm of C (ISO/IEC 9899:1999)
- restricted by implementation-specific behaviors depending upon the machine and compiler (e.g. representation and size of integers, IEEE 754-1985 norm for floats and doubles)
- *restricted by* user-defined programming guidelines (such as no modular arithmetic for signed integers, even though this might be the hardware choice)
- -*restricted by* program specific user requirements (e.g. assert)



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Abstract Semantics

- -Reachable states for the concrete trace operational semantics
- -Volatile environment is specified by a *trusted* configuration file.
 - Requirements:
 - -Soundness: absolutely essential
 - -Precision: few or no false alarm (full certification)
 - -Efficiency: rapid analyses and fixes during development





Implicit Specification: Absence of Runtime Errors

- -No violation of the norm of C (e.g. array index out of bounds, division by zero)
- -No implementation-specific undefined behaviors (e.g. maximum short integer is 32767, NaN)
- -No violation of the programming guidelines (e.g. static variables cannot be assumed to be initialized to 0)
- -No violation of the programmer assertions (must all be statically verified).



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Example application

-Primary flight control software of the Airbus A340 family/A380 fly-by-wire system



- -C program, automatically generated from a proprietary high-level specification (à la Simulink/SCADE)
- A340 family: 132,000 lines, 75,000 LOCs after preprocessing, 10,000 global variables, over 21,000 after expansion of small arrays
- $-A380: \times 3$



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The Class of Considered Periodic Synchronous Programs

declare volatile input, state and output variables; initialize state and output variables; loop forever

- read volatile input variables,
- compute output and state variables,
- write to volatile output variables;

wait for clock ();

end loop

- -<u>Requirements</u>: the only interrupts are clock ticks;
- -Execution time of loop body less than a clock tick EMSOFT '01.





Challenging aspects

- -Size: > 100 kLOC, > 1000 variables
- -Floating point computations including filtering, non linear control with feedback, interpolations...
- -Interdependencies among variables:
 - Stability of computations should be established
 - Complex relations should be inferred among numerical and boolean data
 - Very long data paths from input to outputs





Characteristics of the ASTRÉE Analyzer

Static: compile time analysis (\neq run time analysis **Rational** Purify, Parasoft Insure++)

Program Analyzer: analyzes programs not micromodels of programs (\neq PROMELA in SPIN or Alloy in the Alloy Analyzer)

Automatic: no end-user intervention needed (\neq ESC Java, ESC Java 2)

Sound: covers the whole state space (\neq MAGIC, CBMC) so never omit potential errors (\neq UNO, CMC from coverity.com) or sort most probable ones (\neq Splint)





Characteristics of the ASTRÉE Analyzer (Cont'd)

Multiabstraction: uses many numerical/symbolic abstract domains (\neq symbolic constraints in Bane or the canonical abstraction of TVLA)

Infinitary: all abstractions use infinite abstract domains
with widening/narrowing (≠ model checking based
analyzers such as VeriSoft, Bandera, Java PathFinder)

Efficient: always terminate (\neq counterexample-driven automatic abstraction refinement BLAST, SLAM)



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Characteristics of the ASTRÉE Analyzer (Cont'd)

Specializable: can easily incorporate new abstractions (and reduction with already existing abstract domains) (≠ general-purpose analyzers PolySpace Verifier)
 Domain-Aware: knows about control/command (e.g. digital filters) (as opposed to specialization to a mere programming style in C Global Surveyor)

Parametric: the precision/cost can be tailored to user needs by options and directives in the code



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Characteristics of the ASTRÉE Analyzer (Cont'd)

Automatic Parametrization: the generation of parametric directives in the code can be programmed (to be specialized for a specific application domain)

- Modular: an analyzer instance is built by selection of O-CAML modules from a collection each implementing an abstract domain
- Precise: very few or no false alarm when adapted to an application domain \longrightarrow it is a VERIFIER!



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Example of Analysis Session







Benchmarks (Airbus A340 Primary Flight Control Software)

- -132,000 lines, 75,000 LOCs after preprocessing
- -Comparative results (commercial software): 4,200 (false?) alarms,
 - 3.5 days;
- -Our results:
 - $\underbrace{0}_{40mn on 2.8 GHz PC,}
 300 Megabytes
 <math>\rightarrow$ A world première!



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(Airbus A380 Primary Flight Control Software)

- -450,000 lines
- $-\mathbf{0}$ alarms (Nov. 2004),
 - 7h³ on 2.8 GHz a PC,
 - 1 Gigabyte
 - \longrightarrow A world grand première!

 $^{^{3}}$ It would be possible to favour computation costs rather than precision, and this should go down. For example, the A340 analysis went up to 5 h, before being reduced by requiring less precision while still getting no false alarm.





Examples of Abstractions





General-Purpose Abstract Domains: Intervals and Octagons



Difficulties: many global variables, arrays (smashed or not), IEEE 754 floating-point arithmetic (in program <u>and</u> analyzer) [10, 11]

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Floating-Point Computations

```
/* float-error.c */
int main () {
  float x, y, z, r;
  x = 1.00000019e+38;
  y = x + 1.0e21;
  z = x - 1.0e21;
  r = y - z;
 printf("%f\n", r);
}
% gcc float-error.c
% ./a.out
0.00000
```

```
/* double-error.c */
int main () {
double x; float y, z, r;
/* x = ldexp(1.,50)+ldexp(1.,26); */
x = 1125899973951488.0;
y = x + 1;
z = x - 1;
r = y - z;
printf("%f\n", r);
% gcc double-error.c
% ./a.out
134217728.000000
```

 $(\mathbf{x} + \mathbf{a}) - (\mathbf{x} - \mathbf{a}) \neq 2\mathbf{a}$



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Floating-Point Computations

```
/* float-error.c */
int main () {
  float x, y, z, r;
  x = 1.00000019e+38;
  y = x + 1.0e21;
  z = x - 1.0e21;
  r = y - z;
 printf("%f\n", r);
}
% gcc float-error.c
% ./a.out
0.00000
```

```
/* double-error.c */
int main () {
double x; float y, z, r;
/* x = ldexp(1.,50)+ldexp(1.,26); */
x = 1125899973951487.0;
y = x + 1;
z = x - 1;
r = y - z;
printf("%f\n", r);
% gcc double-error.c
% ./a.out
0.00000
```

 $(\mathbf{x} + \mathbf{a}) - (\mathbf{x} - \mathbf{a}) \neq 2\mathbf{a}$



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Explanation of the huge rounding error



Symbolic abstract domain

- -Interval analysis: if $x \in [a, b]$ and $y \in [c, d]$ then $x y \in [a d, b c]$ so if $x \in [0, 100]$ then $x x \in [-100, 100]!!!$
- -The symbolic abstract domain propagates the symbolic values of variables and performs simplifications;
- -Must maintain the maximal possible rounding error for float computations (overestimated with intervals);



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Clock Abstract Domain for Counters

– Code Sample:

```
R = 0;
while (1) {
    if (I)
        { R = R+1; }
    else
        { R = 0; }
    T = (R>=n);
    wait_for_clock ();
}
```

- Output T is true iff the volatile input I has been true for the last n clock ticks.
- The clock ticks every s seconds for at most h hours, thus R is bounded.
- To prove that R cannot overflow, we must prove that R cannot exceed the elapsed clock ticks (impossible using only intervals).

- Solution:

- We add a phantom variable clock in the concrete user semantics to track elapsed clock ticks.
- For each variable X, we abstract three intervals: X, X+clock, and X-clock.
- If X+clock or X-clock is bounded, so is X.



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Boolean Relations for Boolean Control

- Code Sample:

```
/* boolean.c */
typedef enum {F=0,T=1} BOOL;
BOOL B;
void main () {
  unsigned int X, Y;
  while (1) {
    . . .
    B = (X == 0);
    . . .
    if (!B) {
      Y = 1 / X;
    }
     . . .
```



The boolean relation abstract domain is parameterized by the height of the decision tree (an analyzer option) and the abstract domain at the leafs



Control Partitionning for Case Analysis

-Code Sample:

```
/* trace_partitionning.c */
void main() {
  float t[5] = {-10.0, -10.0, 0.0, 10.0, 10.0};
  float c[4] = {0.0, 2.0, 2.0, 0.0};
  float d[4] = {-20.0, -20.0, 0.0, 20.0};
  float x, r;
  int i = 0;
    ... found invariant -100 ≤ x ≤ 100 ...
  while ((i < 3) && (x >= t[i+1])) {
      i = i + 1;
    }
    r = (x - t[i]) * c[i] + d[i];
}
```



Fork Join

Delaying abstract unions in tests and loops is more precise for non-distributive abstract domains (and much less expensive than disjunctive completion).



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2^d Order Digital Filter:



Ellipsoid Abstract Domain for Filters

- Computes
$$X_n = \left\{ egin{array}{c} lpha X_{n-1} + eta X_{n-2} + Y_n \ I_n \end{array}
ight.$$

- The concrete computation is bounded, which must be proved in the abstract.
- There is no stable interval or octagon.
- The simplest stable surface is an ellipsoid.



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```
Filter Example [7]
typedef enum {FALSE = 0, TRUE = 1} BOOLEAN;
BOOLEAN INIT; float P, X;
void filter () {
  static float E[2], S[2];
  if (INIT) { S[0] = X; P = X; E[0] = X; }
  else { P = (((((0.5 * X) - (E[0] * 0.7)) + (E[1] * 0.4))
             + (S[0] * 1.5)) - (S[1] * 0.7)); \}
  E[1] = E[0]; E[0] = X; S[1] = S[0]; S[0] = P;
  /* S[0], S[1] in [-1327.02698354, 1327.02698354] */
}
void main () { X = 0.2 * X + 5; INIT = TRUE;
  while (1) {
    X = 0.9 * X + 35; /* simulated filter input */
    filter (); INIT = FALSE; }
}
```



Arithmetic-geometric progressions

```
% cat retro.c
typedef enum {FALSE=0, TRUE=1} BOOL;
BOOL FIRST;
volatile BOOL SWITCH;
volatile float E;
float P, X, A, B;
void dev( )
{ X=E;
  if (FIRST) { P = X; }
  else
    \{ P = (P - (((2.0 * P) - A) - B)) \}
            * 4.491048e-03)); };
  B = A;
  if (SWITCH) \{A = P;\}
  else {A = X;}
}
```

```
void main()
{ FIRST = TRUE;
 while (TRUE) {
    dev( );
   FIRST = FALSE;
    __ASTREE_wait_for_clock(());
 }}
% cat retro.config
__ASTREE_volatile_input((E [-15.0, 15.0]));
__ASTREE_volatile_input((SWITCH [0,1]));
__ASTREE_max_clock((3600000));
|P| <= (15. + 5.87747175411e-39
/ 1.19209290217e-07) * (1 +
1.19209290217e-07)^clock -
5.87747175411e-39 / 1.19209290217e-07
<= 23.0393526881
```





(Automatic) Parameterization

- -All abstract domains of ASTRÉE are parameterized, e.g.
 - variable packing for octagones and decision trees,
 - partition/merge program points,
 - loop unrollings,
 - thresholds in widenings, ...;
- -End-users can either parameterize by hand (analyzer options, directives in the code), or
- -choose the automatic parameterization (default options, directives for pattern-matched predefined program schemata).





The main loop invariant for the A340

A textual file over 4.5 Mb with

- -6,900 boolean interval assertions ($x \in [0; 1]$)
- -9,600 interval assertions $(x \in [a; b])$
- -25,400 clock assertions $(x + clk \in [a; b] \land x clk \in [a; b])$
- -19,100 additive octagonal assertions $(a \le x + y \le b)$
- -19,200 subtractive octagonal assertions $(a \le x y \le b)$
- -100 decision trees
- -60 ellipse invariants, etc ...

involving over 16,000 floating point constants (only 550 appearing in the program text) \times 75,000 LOCs.



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Possible origins of imprecision and how to fix it

In case of false alarm, the imprecision can come from:

- -Abstract transformers (not best possible) \rightarrow improve algorithm;
- -Automatized parametrization (e.g. variable packing) \longrightarrow improve pattern-matched program schemata;
- -Iteration strategy for fixpoints \longrightarrow fix widening ⁴;
- -Inexpressivity i.e. indispensable local inductive invariant are inexpressible in the abstract \longrightarrow add a new abstract domain to the reduced product (e.g. filters).

⁴ This can be very hard since at the limit only a precise infinite iteration might be able to compute the proper abstract invariant. In that case, it might be better to design a more refined abstract domain.



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Conclusion

- Most applications of abstract interpretation tolerate a small rate (typically 5 to 15%) of false alarms:
 - Program transformation \rightarrow do not optimize,
 - Typing \rightarrow reject some correct programs, etc,
 - WCET analysis \rightarrow overestimate;
- Some applications require no false alarm at all:
 - Program verification.

- Theoretically possible [SARA '00], practically feasible [PLDI '03]

- [SARA '00] P. Cousot. Partial Completeness of Abstract Fixpoint Checking, invited paper. In 4th Int. Symp. SARA '2000, LNAI 1864, Springer, pp. 1-25, 2000.
- [PLDI'03] B. Blanchet, P. Cousot, R. Cousot, J. Feret, L. Mauborgne, A. Miné, D. Monniaux, and X. Rival. A static analyzer for large safety-critical software. PLDI'03, San Diego, June 7–14, ACM Press, 2003.







The Future & Grand Challenges

- Forthcoming (1 year):
- -More general memory model (union)
- Future (5 years):
- -Asynchronous concurrency (for less critical software)
- -Functional properties (reactivity)
- Industrialization
- Grand challenge:
- -Verification from specifications to machine code (verifying compiler)
- -Verification of systems (quasi-synchrony, distribution)







THE END, THANK YOU

More references at URL www.di.ens.fr/~cousot www.astree.ens.fr.



Programming Languages Seminar, Northeastern U. June 1st, 2005 — 54 —



References

- [2] www.astree.ens.fr [4, 5, 6, 7, 8, 9, 10, 11]
- [3] P. Cousot. Méthodes itératives de construction et d'approximation de points fixes d'opérateurs monotones sur un treillis, analyse sémantique de programmes. Thèse d'État ès sciences mathématiques, Université scientifique et médicale de Grenoble, Grenoble, France, 21 March 1978.
- [4] B. Blanchet, P. Cousot, R. Cousot, J. Feret, L. Mauborgne, A. Miné, D. Monniaux, and X. Rival. Design and implementation of a special-purpose static program analyzer for safety-critical real-time embedded software. The Essence of Computation: Complexity, Analysis, Transformation. Essays Dedicated to Neil D. Jones, LNCS 2566, pp. 85-108. Springer, 2002.
- [5] B. Blanchet, P. Cousot, R. Cousot, J. Feret, L. Mauborgne, A. Miné, D. Monniaux, and X. Rival. A static analyzer for large safety-critical software. PLDI'03, San Diego, pp. 196–207, ACM Press, 2003.
- [POPL'77] P. Cousot and R. Cousot. Abstract interpretation: a unified lattice model for static analysis of programs by construction or approximation of fixpoints. In Conference Record of the Fourth Annual ACM SIGPLAN-SIGACT Symposium on Principles of Programming Languages, pages 238–252, Los Angeles, California, 1977. ACM Press, New York, NY, USA.
- [PACJM '79] P. Cousot and R. Cousot. Constructive versions of Tarski's fixed point theorems. Pacific Journal of Mathematics 82(1):43-57 (1979).
- [POPL'78] P. Cousot and N. Halbwachs. Automatic discovery of linear restraints among variables of a program. In Conference Record of the Fifth Annual ACM SIGPLAN-SIGACT Symposium on Principles of Programming Languages, pages 84–97, Tucson, Arizona, 1978. ACM Press, New York, NY, U.S.A.





- [POPL '79] P. Cousot and R. Cousot. Systematic design of program analysis frameworks. In Conference Record of the Sixth Annual ACM SIGPLAN-SIGACT Symposium on Principles of Programming Languages, pages 269–282, San Antonio, Texas, 1979. ACM Press, New York, NY, U.S.A.
- [POPL'92] P. Cousot and R. Cousot. Inductive Definitions, Semantics and Abstract Interpretation. In Conference Record of the 19th ACM SIGACT-SIGMOD-SIGART Symposium on Principles of Programming Languages, pages 83-94, Albuquerque, New Mexico, 1992. ACM Press, New York, U.S.A.
- [FPCA'95] P. Cousot and R. Cousot. Formal Language, Grammar and Set-Constraint-Based Program Analysis by Abstract Interpretation. In SIGPLAN/SIGARCH/WG2.8 7th Conference on Functional Programming and Computer Architecture, FPCA'95. La Jolla, California, U.S.A., pages 170–181. ACM Press, New York, U.S.A., 25-28 June 1995.
- [POPL'97] P. Cousot. Types as Abstract Interpretations. In Conference Record of the 24th ACM SIGACT-SIGMOD-SIGART Symposium on Principles of Programming Languages, pages 316-331, Paris, France, 1997. ACM Press, New York, U.S.A.
- [POPL'00] P. Cousot and R. Cousot. Temporal abstract interpretation. In Conference Record of the Twentyseventh Annual ACM SIGPLAN-SIGACT Symposium on Principles of Programming Languages, pages 12-25, Boston, Mass., January 2000. ACM Press, New York, NY.
- [POPL'02] P. Cousot and R. Cousot. Systematic Design of Program Transformation Frameworks by Abstract Interpretation. In Conference Record of the Twentyninth Annual ACM SIGPLAN-SIGACT Symposium on Principles of Programming Languages, pages 178–190, Portland, Oregon, January 2002. ACM Press, New York, NY.
- [TCS 277(1-2) 2002] P. Cousot. Constructive Design of a Hierarchy of Semantics of a Transition System by Abstract Interpretation. Theoretical Computer Science 277(1-2):47-103, 2002.



— 56 —



- [TCS 290(1) 2002] P. Cousot and R. Cousot. Parsing as abstract interpretation of grammar semantics. Theoret. Comput. Sci., 290:531-544, 2003.
- [Manna's festschrift '03] P. Cousot. Verification by Abstract Interpretation. Proc. Int. Symp. on Verification Theory & Practice – Honoring Zohar Manna's 64th Birthday, N. Dershowitz (Ed.), Taormina, Italy, June 29 – July 4, 2003. Lecture Notes in Computer Science, vol. 2772, pp. 243–268. © Springer-Verlag, Berlin, Germany, 2003.
- [6] P. Cousot, R. Cousot, J. Feret, L. Mauborgne, A. Miné, D. Monniaux, and X. Rival. The ASTRÉE analyser. ESOP 2005, Edinburgh, LNCS 3444, pp. 21–30, Springer, 2005.
- [7] J. Feret. Static analysis of digital filters. ESOP'04, Barcelona, LNCS 2986, pp. 33-48, Springer, 2004.
- [8] J. Feret. The arithmetic-geometric progression abstract domain. In VMCAI'05, Paris, LNCS 3385, pp. 42– 58, Springer, 2005.
- [9] Laurent Mauborgne & Xavier Rival. Trace Partitioning in Abstract Interpretation Based Static Analyzers. ESOP'05, Edinburgh, LNCS 3444, pp. 5–20, Springer, 2005.
- [10] A. Miné. A New Numerical Abstract Domain Based on Difference-Bound Matrices. PADO'2001, LNCS 2053, Springer, 2001, pp. 155–172.
- [11] A. Miné. Relational abstract domains for the detection of floating-point run-time errors. ESOP'04, Barcelona, LNCS 2986, pp. 3—17, Springer, 2004.
- [POPL '04] P. Cousot and R. Cousot. An Abstract Interpretation-Based Framework for Software Watermarking. In Conference Record of the Thirtyfirst Annual ACM SIGPLAN-SIGACT Symposium on Principles of Programming Languages, pages 173–185, Venice, Italy, January 14-16, 2004. ACM Press, New York, NY.



— 57 —



- [DPG-ICALP'05] M. Dalla Preda and R. Giacobazzi. Semantic-based Code Obfuscation by Abstract Interpretation. In Proc. 32nd Int. Colloquium on Automata, Languages and Programming (ICALP'05 - Track B). LNCS, 2005 Springer-Verlag. July 11-15, 2005, Lisboa, Portugal. To appear.
- [EMSOFT '01] C. Ferdinand, R. Heckmann, M. Langenbach, F. Martin, M. Schmidt, H. Theiling, S. Thesing, and R. Wilhelm. Reliable and precise WCET determination for a real-life processor. ESOP (2001), LNCS 2211, 469-485.
- [RT-ESOP '04] F. Ranzato and F. Tapparo. Strong Preservation as Completeness in Abstract Interpretation. ESOP 2004, Barcelona, Spain, March 29 - April 2, 2004, D.A. Schmidt (Ed), LNCS 2986, Springer, 2004, pp. 18-32.



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