« The ASTRÉE Static Analysis Tool »

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1. Informal Introduction to Abstract Interpretation

Abstract Interpretation

There are two fundamental concepts in computer science (and in sciences in general) :

- **Abstraction** : to reason on complex systems
- **Approximation** : to make effective undecidable computations

These concepts are formalized by abstract interpretation

References

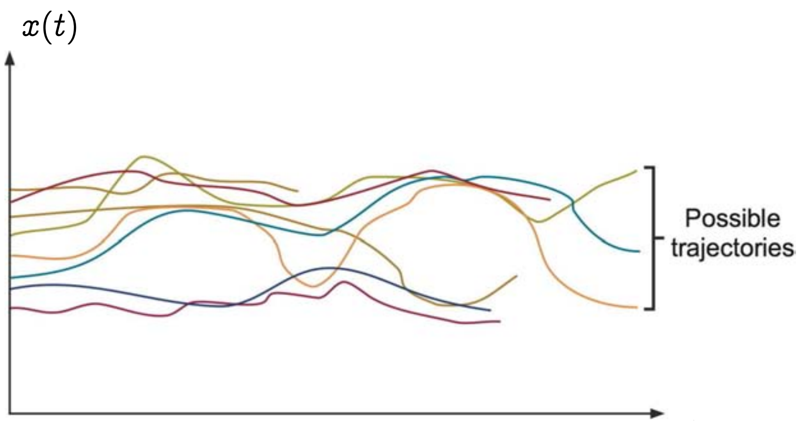
[POPL '77] P. Cousot and R. Cousot. Abstract interpretation: a unified lattice model for static analysis of programs by construction or approximation of fixpoints. In 4^{th} *ACM POPL*.

[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.

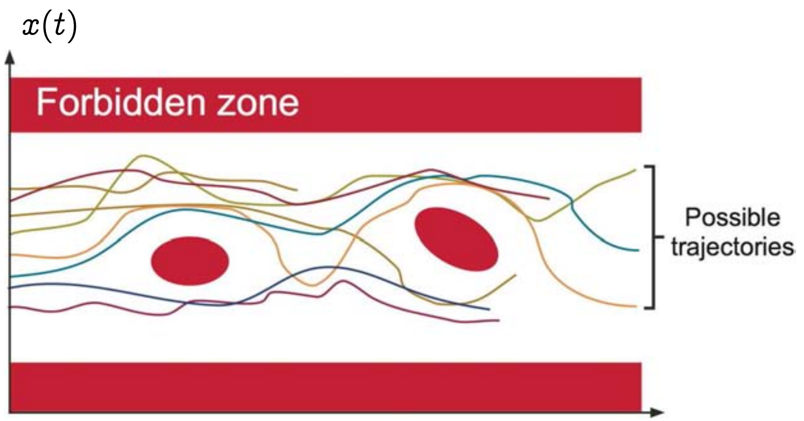
[POPL '79] P. Cousot & R. Cousot. Systematic design of program analysis frameworks. In 6^{th} *ACM POPL*.

Principle of Abstraction

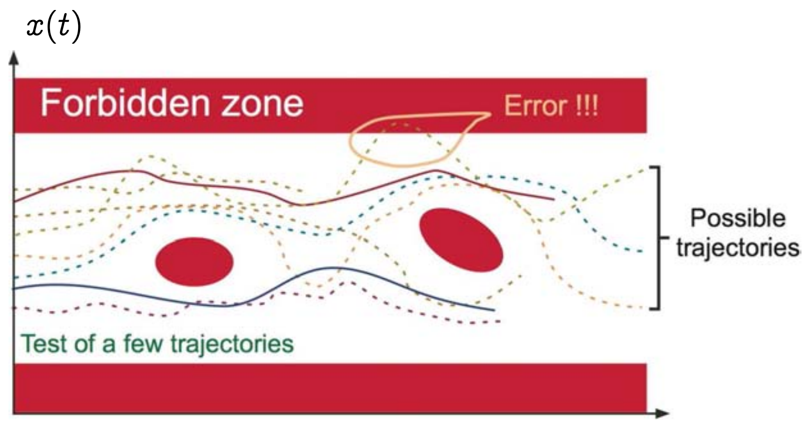
Operational semantics



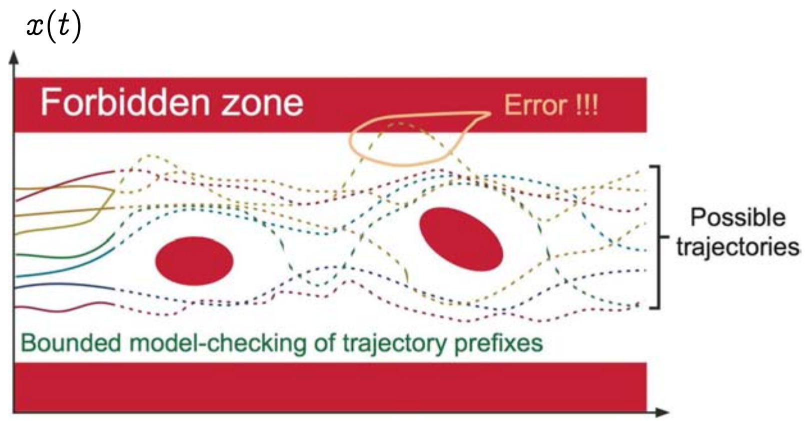
Safety property



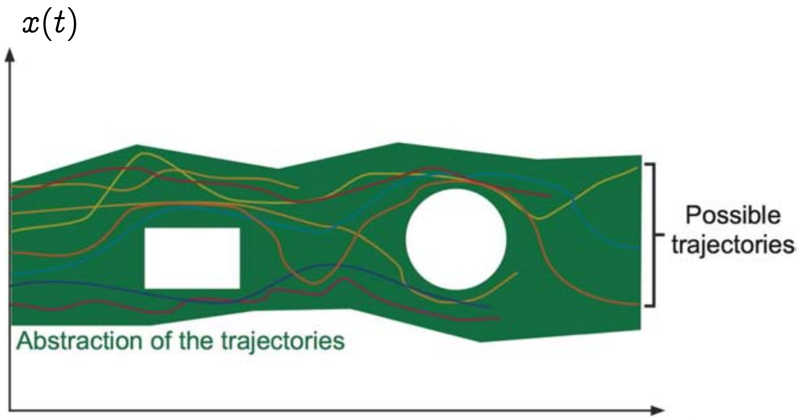
Test/Debugging is Unsafe



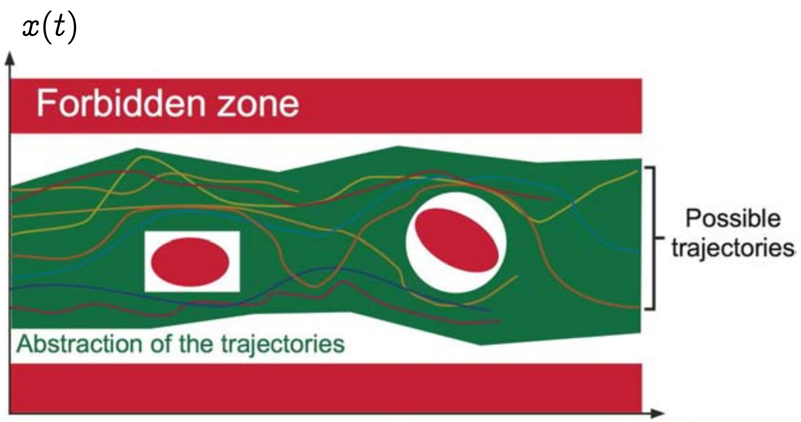
Bounded Model Checking is Unsafe



Over-Approximation

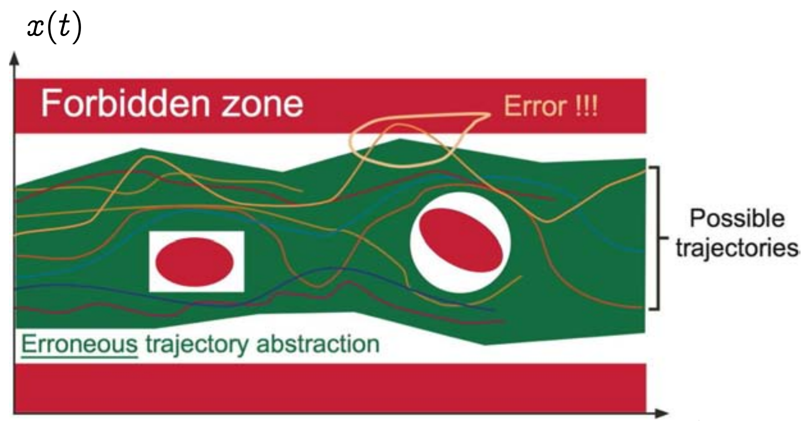


Abstract Interpretation is Sound



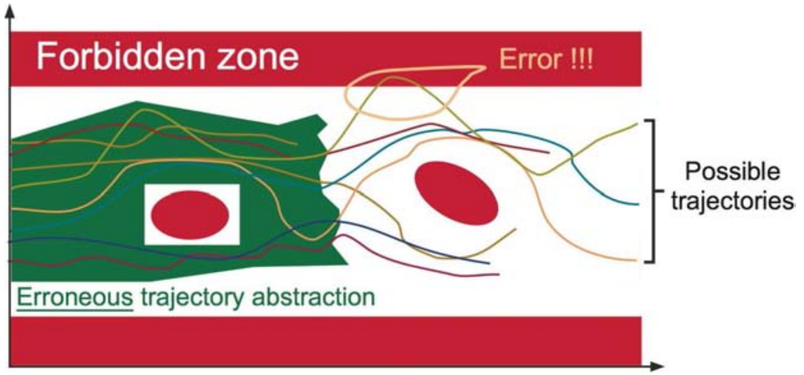
Soundness and Incompleteness

Soundness Requirement: Erroneous Abstraction[1]



[1] This situation is always excluded in static analysis by abstract interpretation.

Soundness Requirement: Erroneous Abstraction [2]

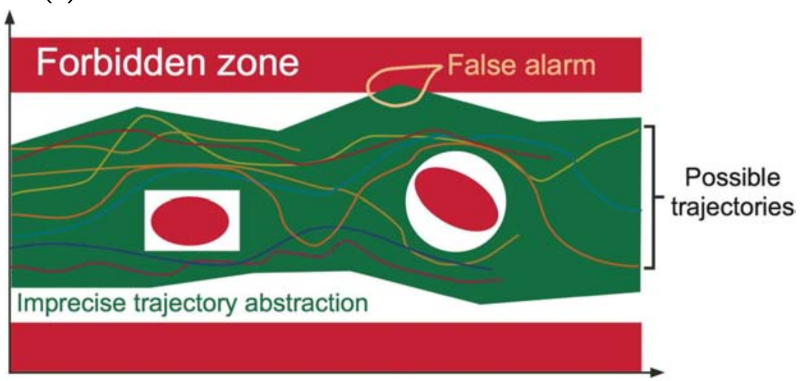


[2] This situation is always excluded in static analysis by abstract interpretation.

2. The ASTRÉE static analyzer

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

Imprecision ⇒ False Alarms



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Xavier RIVAL

[3] Nov. 2001 — Nov. 2003.
[4] Nov. 2001 — Aug. 2007.

Programs Analyzed by ASTRÉE and their Semantics

Programs analysed by ASTRÉE

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

– C programs:

- with
  - basic numeric datatypes, structures and arrays
  - pointers (including on functions),
  - floating point computations
  - tests, loops and function calls
  - limited branching (forward `goto`, `break`, `continue`)

– with (cont'd)

- `union` NEW [Min06a]
- pointer arithmetics & casts NEW [Min06a]

– without

- dynamic memory allocation
- recursive function calls
- unstructured/backward branching
- conflicting side effects
- C libraries, system calls (parallelism)

Such limitations are quite common for embedded safety-critical software.

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 output variables;
  __ASTREE_wait_for_clock ();
end loop
```

Task scheduling is static:

– Requirements: the only interrupts are clock ticks;

– Execution time of loop body less than a clock tick, as verified by the aiT WCET Analyzers [FHL+01].

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, execution stops on first runtime error [5])

[5] semantics of C unclear after an error, equivalent if no alarm

Different Classes of Run-time Errors

1. Errors terminating the execution [6]. ASTRÉE warns and continues by taking into account only the executions that did not trigger the error.
2. Errors not terminating the execution with predictable outcome [7]. ASTRÉE warns and continues with worst-case assumptions.
3. Errors not terminating the execution with unpredictable outcome [8]. ASTRÉE warns and continues by taking into account only the executions that did not trigger the error.

⇒ ASTRÉE is sound with respect to C standard, unsound with respect to C implementation, unless no false alarm.

[6] floating-point exceptions e.g. (invalid operations, overflows, etc.) when traps are activated
[7] e.g. overflows over signed integers resulting in some signed integer.
[8] e.g. memory corruptionss.

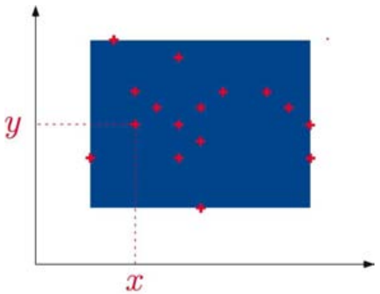
Specification Proved by ASTRÉE

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).

Examples of General Purpose Abstractions Used by ASTRÉE

Intervals [9]

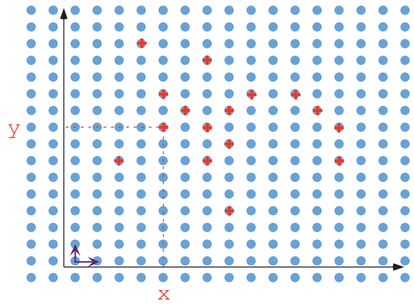


$$\begin{cases} x \in [19, 77] \\ y \in [20, 07] \end{cases}$$

Non-relational

[9] P. Cousot & R. Cousot. *Static determination of dynamic properties of programs.* Proc. 2nd Int. Symp. on Programming, Dunod, 1976.

Simple congruences



$$\begin{cases} x = 19 \bmod 77 \\ y = 20 \bmod 99 \end{cases}$$

Non-relational

[10] Ph. Granger. *Static Analysis of Arithmetical Congruences.* Int. J. Comput. Math. 30, 1989, pp. 165–190.

Intervals & Simple Congruences

```
% cat -n congruence.c
     1  /* congruence.c */
     2  int main()
     3  { int X;
     4    X = 0;
     5    while (X <= 128)
     6      { X = X + 4; };
     7    __ASTREE_log_vars((X));
     8  }
% astree congruence.c -no-relational -exec-fn main |& egrep "(WARN)|(X in)"
direct = <integers (intv+cong+bitfield+set): X in {132} /\ Top >
%
```

Symbolic abstract domain [Min04a, Min04b]

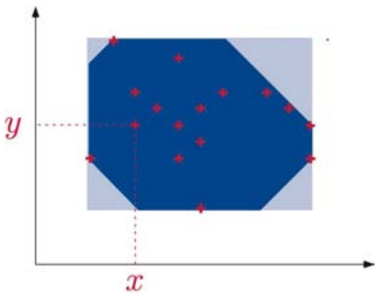
– Interval analysis: if $x \in [a, b]$ and $y \in [c, d]$ then $x - y \in [a - d, b - c]$ so if $x \in [0, 100]$ then $x - x \in [-100, 100]$!!!
– The symbolic abstract domain propagates the symbolic values of variables and performs simplifications;
– Must maintain the maximal possible rounding error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

```
% cat -n x-x.c
     1  void main () { int X, Y;
     2          __ASTREE_known_fact(((0 <= X) && (X <= 100)));
     3          Y = (X - X);
     4          __ASTREE_log_vars((Y));
     5  }
```

```
astree -exec-fn main -no-relational x-x.c
Call main@x-x.c:1:5-x-x.c:1:9:
<interval: Y in [-100, 100]>
```

```
astree -exec-fn main x-x.c
Call main@x-x.c:1:5-x-x.c:1:9:
<interval: Y in {0}> <symbolic: Y = (X -i X)>
```


Octagons



$$\begin{cases} 1 \leq x \leq 9 \\ x + y \leq 77 \\ 1 \leq y \leq 9 \\ x - y \leq 99 \end{cases}$$

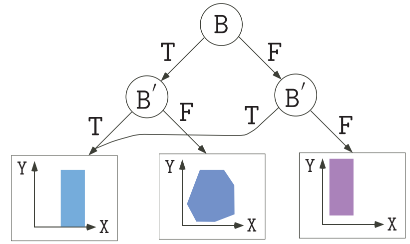
Weakly relational

[11] A. Miné. *A New Numerical Abstract Domain Based on Difference-Bound Matrices.* PADO'2001. LNCS 2053, pp. 155–172. Springer 2001. See the *The Octagon Abstract Domain Library* on http://www.di.ens.fr/~mine/oct/

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

(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).

Modular Arithmetic

Modular arithmetics is not very intuitive

In C:

```
% cat -n modulo-c.c
     1 #include <stdio.h>
     2 int main () {
     3 int x,y;
     4 x = -2147483647 / -1;
     5 y = ((-x) -1) / -1;
     6 printf("x = %i, y = %i\n",x,y);
     7 }
     8

% gcc modulo-c.c
% ./a.out
x = 2147483647, y = -2147483648
```


Static Analysis with Astrée

```
% cat -n modulo.c
     1 int main () {
     2 int x,y;
     3 x = -2147483647 / -1;
     4 y = ((-x) -1) / -1;
     5 __ASTREE_log_vars((x,y));
     6 }
     7
% astree -exec-fn main -unroll 0 modulo.c\
 |& egrep -A 1 "(<integers)|(WARN)"
modulo.c:4.4-18::[call#main@1:]: WARN: signed int arithmetic range
  {2147483648} not included in [-2147483648, 2147483647]
  <integers (intv+cong+bitfield+set): y in [-2147483648, 2147483647] /\ Top
   x in {2147483647} /\ {2147483647} >
```

Astrée signals the overflow and goes on with an unkown value.

Float Overflow

Float Arithmetics does Overflow

In C:

```
% cat -n overflow.c
 1  void main () {
 2  double x,y;
 3  x = 1.0e+256 * 1.0e+256;
 4  y = 1.0e+256 * -1.0e+256;
 5  __ASTREE_log_vars((x,y));
 6  }
% gcc overflow.c
% ./a.out
x = inf, y = -inf
```

```
% astree -exec-fn main
overflow.c |& grep "WARN"
overflow.c:3.4-23::[call#main1:]:
WARN: double arithmetic range
[1.79769e+308, inf] not
included in [-1.79769e+308,
1.79769e+308]
overflow.c:4.4-24::[call#main1:]:
WARN: double arithmetic range
[-inf, -1.79769e+308] not
included in [-1.79769e+308,
1.79769e+308]
```


The Ariane 5.01 maiden flight failure

– June 4th, 1996 was the maiden flight of Ariane 5

– The launcher was detroyed after 40 seconds of flight because of a software overflow[10]

[10] A 16 bit piece of code of Ariane 4 had been reused within the new 32 bit code for Ariane 5. This caused an uncaught overflow, making the launcher uncontrolable.

The Ariane 5.01 maiden flight

– June 4th, 1996 was the maiden flight of Ariane 5

Rounding

Example of accumulation of small rounding errors

```
% cat -n rounding-c.c
  1  #include <stdio.h>
  2  int main () {
  3   int i; double x; x = 0.0;
  4   for (i=1; i<=1000000000; i++) {
  5    x = x + 1.0/10.0;
  6   }
  7  printf("x = %f\n", x);
  8  }
% gcc rounding-c.c
% ./a.out
x = 99999998.745418
%
```

since $(0.1)_{10} = (0.0001100110011001100\ldots)_2$

Static analysis with Astrée

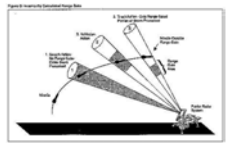
```
% cat -n rounding.c
     1  int main () {
     2   double x; x = 0.0;
     3   while (1) {
     4    x = x + 1.0/10.0;
     5    __ASTREE_log_vars((x));
     6    __ASTREE_wait_for_clock(());
     7   }
     8  }
% cat rounding.config
 __ASTREE_max_clock((1000000000));
% astree -exec-fn main -config-sem rounding.config -unroll 0 rounding.c\
 |& egrep "(x in)|(\|x\|)|(WARN)" | tail -2
direct = <float-interval: x in [0.1, 200000040.938] >
  |x| <= 1.*((0. + 0.1/(1.-1))*(1.)^clock - 0.1/(1.-1)) + 0.1
      <= 200000040.938
```


The Patriot missile failure

– "On February 25th, 1991, a Patriot missile ... failed to track and intercept an incoming Scud (*)."
– The software failure was due to accumulated rounding error (†)

(*) This Scud subsequently hit an Army barracks, killing 28 Americans.

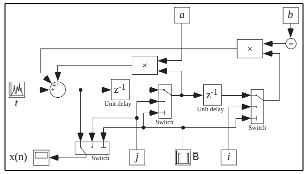
(†)– "Time is kept continuously by the system's internal clock in tenths of seconds"
– "The system had been in operation for over 100 consecutive hours"
– "Because the system had been on so long, the resulting inaccuracy in the time calculation caused the range gate to shift so much that the system could not track the incoming Scud"



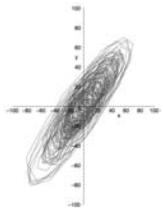
Filtering

Ellipsoid Abstract Domain for Filters

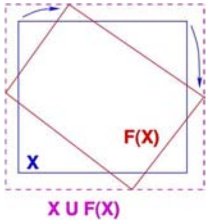
2^d Order Digital Filter:



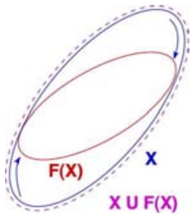
- Computes $X_n = \begin{cases} \alpha X_{n-1} + \beta X_{n-2} + Y_n \\ I_n \end{cases}$
- The concrete computation is bounded, which must be proved in the abstract.
- There is no stable interval or octagon.
- The simplest stable surface is an ellipsoid.



execution trace



unstable interval



stable ellipsoid

Filter Example [Fer04]

```
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; }
}
```


Time Dependence

Arithmetic-Geometric Progressions (Example 1)

```
% cat count.c
typedef enum {FALSE = 0, TRUE = 1} BOOLEAN;
volatile BOOLEAN I; int R; BOOLEAN T;
void main() {
  R = 0;
  while (TRUE) {
    __ASTREE_log_vars((R));
    if (I) { R = R + 1; }        ← potential overflow!
    else { R = 0; }
    T = (R >= 100);
    __ASTREE_wait_for_clock(());
  }}
% cat count.config
__ASTREE_volatile_input((I [0,1]));
__ASTREE_max_clock((3600000));
% astree -exec-fn main -config-sem count.config count.c|grep '|R|'
|R| <= 0. + clock *1. <= 3600001.
```

Arithmetic-Geometric Progressions: Example 2

```
% 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
```


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, now × 2
- A380: × 3/7

3. The industrial use of ASTRÉE

References

[1] D. Delmas and J. Souyris. ASTRÉE: *from Research to Industry*. Proc. 14th Int. Symp. SAS '07, G. Filé and H. Riis-Nielson (eds), 22–24 Aug. 2007, Kongens Lyngby, DK, LNCS 4634, pp. 437–451, Springer.

Benchmarks (Airbus A340 Primary Flight Control Software)

- V1 [13], 132,000 lines, 75,000 LOCs after preprocessing
- Comparative results (commercial software):
  4,200 (false?) alarms, 3.5 days;
- Our results:
  0 alarms,
  40mn on 2.8 GHz PC, 300 Megabytes
  ⟶ A world première in Nov. 2003!

[13] "Flight Control and Guidance Unit" (FCGU) running on the "Flight Control Primary Computers" (FCPC). The three primary computers (FCPC) and two secondary computers (FCSC) which form the A340 and A330 electrical flight control system are placed between the pilot's controls (sidesticks, rudder pedals) and the control surfaces of the aircraft, whose movement they control and monitor.

(Airbus A380 Primary Flight Control Software)

- 0 alarms (Nov. 2004), after some additional parametrization and simple abstract domains developments
- Now at 1,000,000 lines!

  34h,

  8 Gigabyte

  $\longrightarrow$ A world grand première!

4. Conclusion

Characteristics of the ASTRÉE Analyzer

Sound: – ASTRÉE is a bug eradicator: finds all bugs in a well-defined class (runtime errors)

- ASTRÉE is not a bug hunter: finding some bugs in a well-defined class (e.g. by *bug pattern detection* like FindBugs™, PREfast or PMD)
- ASTRÉE is exhaustive: covers the whole state space ($\neq$ MAGIC, CBMC)
- ASTRÉE is comprehensive: never omits potential errors ($\neq$ UNO, CMC from coverity.com) or sort most probable ones to avoid overwhelming messages ($\neq$ Splint)

Characteristics of the ASTRÉE Analyzer (Cont'd)

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), or PREfast (annotate functions with intended use)

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 ($\neq$ model checking based analyzers such as Bandera, Bogor, Java PathFinder, Spin, VeriSoft)

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

Characteristics of the ASTRÉE Analyzer (Cont'd)

Extensible/Specializable: can easily incorporate new abstractions (and reduction with already existing abstract domains) ($\neq$ 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

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!

The Future of the ASTRÉE Analyzer

- ASTRÉE has shown usable and useful in one industrial context (electric flight control);
- More applications are forthcoming (ES_PASSS project);
- Industrialization is simultaneously under consideration.

THE END, THANK YOU

5. Bibliography

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