Verasco: a Formally Verified C Static Analyzer

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Joint work with:
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Xavier Leroy, David Pichardie, . . .

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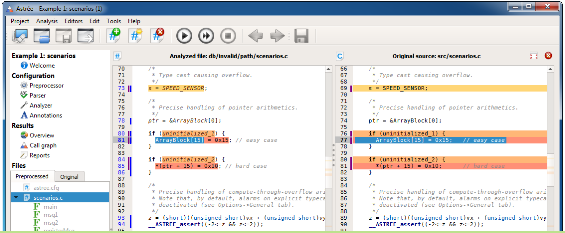
GdR GPL thesis prize

Static analyzers

They **automatically** prove the absence of certain kinds of bugs

- Examples : “No invalid memory access”, “No division by 0”, “Small rounding errors”, ...
- Undecidable problem:
  - ☐ Success ⇒ no bug of some class
  - ☐ In case of doubt, emit an alarm

Exemples : Astrée, Frama-C EVA, Fluctuat, Sparrow, ...



Analyzed file: db/invalid/path/scenarios.c

```
    /*
     * Type cast causing overflow.
     */
    s = SPEED_SENSOR;

    /*
     * Precise handling of pointer arithmetics.
     */
    ptr = &ArrayBlock[0];

    if (uninitialized_1) {
      ArrayBlock[15] = 0x15; // easy case
    }

    if (uninitialized_2) {
      *(ptr + 15) = 0x10; // hard case
    }

    /*
     * Precise handling of compute-through-overflow ari
     * Note that, by default, alarms on explicit typeca
     * deactivated (see Options->General tab).
     */
    z = (short)((unsigned short)vx + (unsigned short)vy
    __ASTREE_assert((-2<=z && z<=2));
```

Original source: src/scenarios.c

```
    /*
     * Type cast causing overflow.
     */
    s = SPEED_SENSOR;

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     * Precise handling of pointer arithmetics.
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    ptr = &ArrayBlock[0];

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    z = (short)((unsigned short)vx + (unsigned short)vy
    __ASTREE_assert((-2<=z && z<=2));
```

Abstract interpretation

Abstract interpretation: theory for building static analyzer

- Run the program using an **abstract semantics**
- Always **terminating** computation
- **Soundly** approximating the concrete semantics

Abstract domains used to approximate program states

- Ex: variation intervals for integer variables. . .

Abstract interpretation: example

```
x=0

loop {

  if x > 11

    break

  x+=2

}
```

Abstract interpretation: example

```
$\{\top\}$
x=0
$\{x = 0\}$
loop {
$\{x \in [0, 13] \land x \bmod 2 = 0\}$
  if x > 11
$\{x = 12\}$
    break
$\{x \in [0, 11] \land x \bmod 2 = 0\}$
  x+=2
$\{x \in [2, 13] \land x \bmod 2 = 0\}$
}
$\{x = 12\}$
```

Uses of static analyzers

Two main use cases:

- Bug finders
  - Very precise, no direct need for correctness
- Program verification
  - Used to prove properties on **critical code**
  - **Need for trust**

Static analyzers are **complex**

- Advanced algorithms (linear optimization, symbolic manipulations, . . .)
- Technical problems (floating-point, C semantics, . . .)

⇒ **probably buggy**

Our analyzer: Verasco

A static analyzer **is a program**, we can **prove it**!

Verasco:

- Programmed and **formally verified** using the Coq proof assistant
- Based on **abstract interpretation**
- Handles **most of C99**
  - ☐ industrial, widely used language
  - ☐ no dynamic memory allocation, no recursion
- Proves the absence of undefined behaviors
  - ☐ dynamic type errors
  - ☐ memory errors
  - ☐ arithmetic exceptions

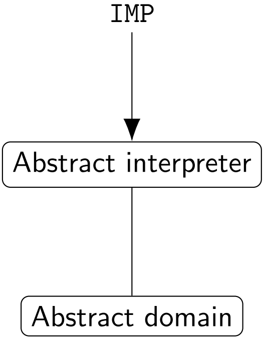
Introduction

Overview of Verasco

Technical zoom: numerical abstract domains

Conclusions

Textbook formalized static analyzers



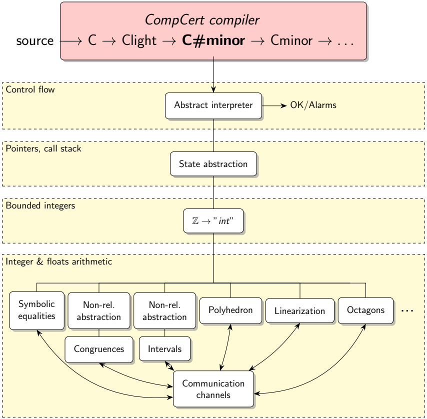
`IMP`

Abstract interpreter

Abstract domain

- `IMP` toy language
- No handling of pointers
- Unbounded integers abstract domain

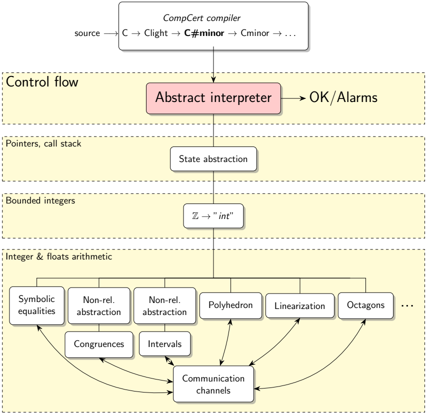
Modular architecture



Reuses the **CompCert** front-end

- Until C#minor
- Language simpler than C99
- Uses the same formal semantics as CompCert
  - **Guarantees** provided by the analyzer provably **extend to the assembly code**.
- A priori unsound if used with another C99 semantics

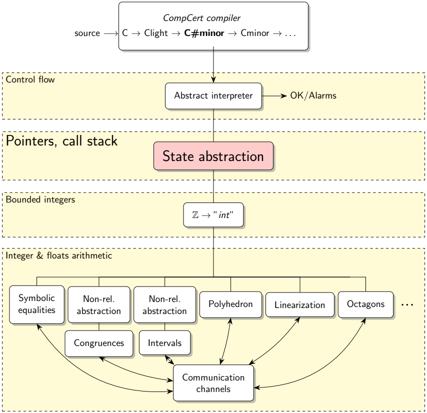
Modular architecture



Abstract interpreter

- Fixpoints using widening for loops and gotos
- Proved correct using a Hoare logic for C#minor
- Parameterized by a state abstract domain

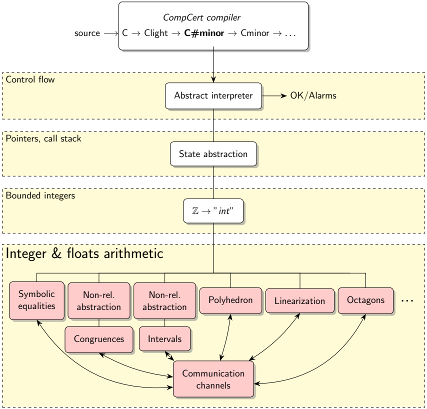
Modular architecture



State abstract domain

- Solves pointer references
  - ☐ Points-to domain
- Checks type and memory safety
  - ☐ Types domain
  - ☐ Permissions domain
- Design, implemented and proved correct by V. Laporte
- Parameterized by a numerical abstract domain
  - ☐ concretizes to *numerical* environments

Modular architecture


CompCert compiler

source ⟶ C → Clight → **C#minor** → Cminor → . . .

Control flow

Abstract interpreter ⟶ OK/Alarms

Pointers, call stack

State abstraction

Bounded integers

$\mathbb{Z} \to$ "*int*"

Integer & floats arithmetic

Symbolic equalities

Non-rel. abstraction

Non-rel. abstraction

Polyhedron

Linearization

Octagons

. . .

Congruences

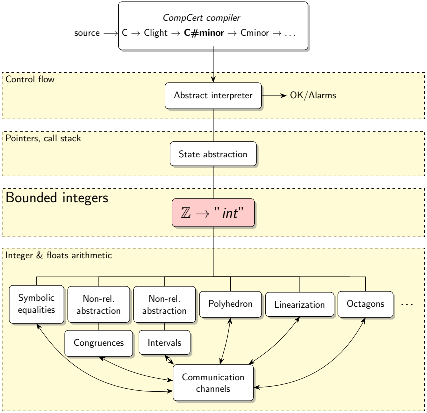
Intervals

Communication channels

Several numerical domains

- Intervals over $\mathbb{Z}$ and floats
- Arithmetical congruences
- Symbolic equalities
- Octagons
- Convex polyhedra
  - Contributed by Fouilhe, Boulmé and Périn (Verimag)
- Modular communication system using channels

Modular architecture



Bounded **machine integers** analysis

- Wraparound when overflow
- Checks numerical errors
  - ☐ Division by 0
  - ☐ Undefined overflows
- Parameterized by an abstract domain for $\mathbb{Z}$

Example 1

```
const double sqrt_tab[128] = { ... };

int main() {
  double x = verasco_any_double();
  verasco_assume(0.3 < x && x < 0.7);
  double y =  sqrt_tab[ (int)(x*128.) ] ;
   verasco_assert(0.54 < y && y < 0.84);
  return 0;
}
```

Example 1

```
const double sqrt_tab[128] = { ... };

int main() {
  double x = verasco_any_double();
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Integer & float intervals

Example 1

State & numerical domains cooperation

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const double sqrt_tab[128] = { ... };

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}
```
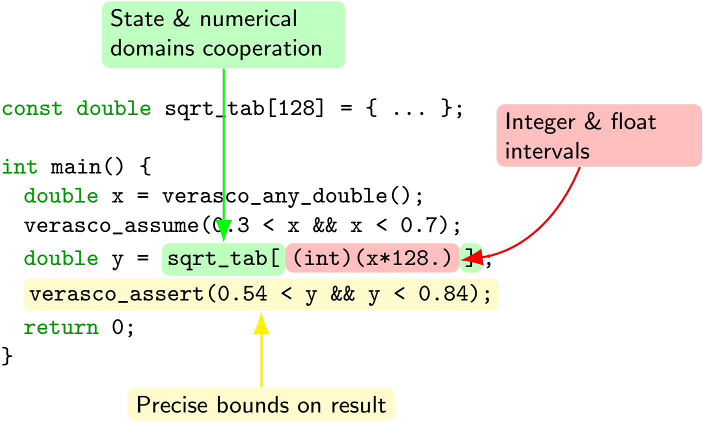

Integer & float intervals

Example 1



State & numerical domains cooperation

Integer & float intervals

```
const double sqrt_tab[128] = { ... };

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  double y = sqrt_tab[ (int)(x*128.) ];
  verasco_assert(0.54 < y && y < 0.84);
  return 0;
}
```

Precise bounds on result

Example 2

```
int main() {
  int v0 = 0, v1 = 1;
  int* tab[6] = {&v0, &v1, &v0, &v1, &v0, &v1};

  for(int i = -5; i < 6; i++) {
    int in_range = (0 <= i && i <= 2);
    int some_other_computation = i*i+32;
    if( in_range )
      verasco_assert( *(tab[ 2*i+1 ])  == 1);
  }
  return 0;
}
```

Example 2

```
int main() {
  int v0 = 0, v1 = 1;
  int* tab[6] = {&v0, &v1, &v0, &v1, &v0, &v1};

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  }
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```

Symbolic propagation of conditions

Example 2

```c
int main() {
  int v0 = 0, v1 = 1;
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  for(int i = -5; i < 6; i++) {
    int in_range = (0 <= i && i <= 2);
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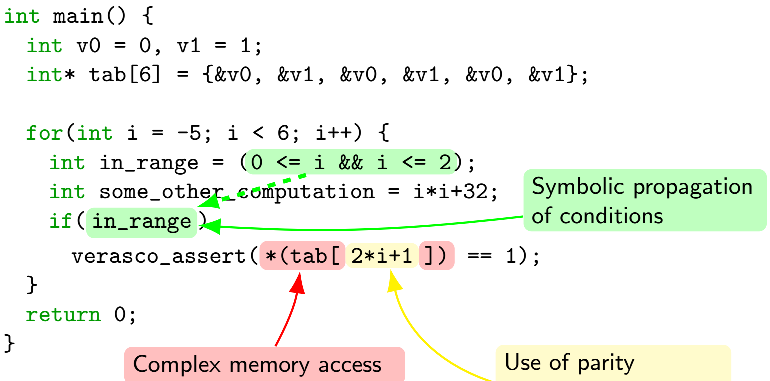
    if( in_range )
      verasco_assert( *(tab[ 2*i+1 ]) == 1);
  }
  return 0;
}
```

Symbolic propagation of conditions

Use of parity (congruence domain)

Example 2



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  int v0 = 0, v1 = 1;
  int* tab[6] = {&v0, &v1, &v0, &v1, &v0, &v1};

  for(int i = -5; i < 6; i++) {
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    int some_other_computation = i*i+32;
    if( in_range )
      verasco_assert( *(tab[ 2*i+1 ]) == 1);
  }
  return 0;
}
```

Symbolic propagation of conditions

Complex memory access

Use of parity (congruence domain)

Example 3

```
int src[10] = { ... };
int dst[10];

int main() {
  int i_src = 0, i_dst = 9;
  while(i_dst >= 0) {
    dst[i_dst] = src[i_src];
     i_dst--; i_src++;
  }
  verasco_assert(i_src == 10);
  return 0;
}
```

Example 3

```
int src[10] = { ... };
int dst[10];

int main() {
  int i_src = 0, i_dst = 9;
  while(i_dst >= 0) {
    dst[i_dst] = src[i_src];
    i_dst--; i_src++;
  }
  verasco_assert(i_src == 10);
  return 0;
}
```

Octagons prove the **relational** invariant $\mathrm{i\_src} + \mathrm{i\_dst} = 9$ …

Example 3

```
int src[10] = { ... };
int dst[10];

int main() {
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    dst[i_dst] = src[i_src];
    i_dst--; i_src++;
  }
  verasco_assert(i_src == 10);
  return 0;
}
```

Octagons prove the **relational** invariant `i_src` + `i_dst` = 9 …

… and deduce precise bounds for `i_src`

Modular interfaces between components

Operations:

- $\top \quad \sqcup \quad \sqsubseteq \quad \triangledown$
- Transfer functions

With Coq specifications

- Concretization function

  $\gamma : \texttt{Abs} \rightarrow \texttt{Concr} \rightarrow \texttt{Prop}$

- Soundness theorems
- Abstraction function α is not needed
  - No optimality result

Example of interface

State abstract domain

- Concrete states:

$$\underbrace{\texttt{list(}\ \underbrace{\texttt{ident}}_{\text{function}}\ *\ \underbrace{\texttt{env}}_{\text{local variables}}\ \texttt{)}}_{\text{call stack}}\ *\ \texttt{mem}$$

Operations

- Standard abstract interpretation operators:
  - $\sqsubseteq : \texttt{abstate} \to \texttt{abstate} \to \texttt{bool}$
  - $\sqcup, \nabla : \texttt{abstate} \to \texttt{abstate} \to \texttt{abstate}$
- Abstract transfer functions:
  - `assign`, `store`, `assume`, `push_frame`, `pop_frame`...

Example of specification

State abstract domain

$$\gamma : \texttt{abstate} \rightarrow \texttt{concrete\_state} \rightarrow \texttt{Prop}$$

- Specifications:
  - ☐ $\forall\ a\ b,\ \gamma(a) \cup \gamma(b) \subseteq \gamma(a \sqcup b)$
  - ☐ $\forall\ x\ e\ a,\ \{\rho[x := v] \mid \rho \in \gamma(a)\ \wedge\ \rho \vdash e \Downarrow v\} \subseteq \gamma(\texttt{assign}\ x\ e\ a)$
- Other domains have similar specifications

Methodology

- Programmed and proved correct in Coq.
- Extracted into OCaml, then compiled into an executable.
- No use of a posteriori validation.
    - Except for the third-party polyhedra domain (Farkas certificates).
- About 45000 lines of Coq.
    - Half proofs, half code & specs

Introduction

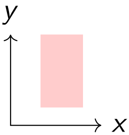
Overview of Verasco

Technical zoom: numerical abstract domains

Conclusions

Numerical abstract domains in Verasco

Intervals



$x \in [l, h]$

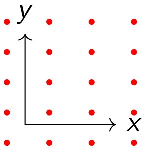
Symbolic equalities

$$z \doteq y * y$$

$$c \doteq (x < 1 \ \&\& \ 2 \leq y)$$

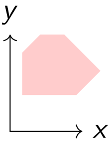
$$(y \leq 2.5) \doteq \texttt{true}$$

Congruences



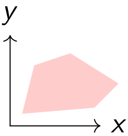
$x \bmod M = R$

Octagons



$\pm x \pm y \leq \mathrm{Cst}$

Polyhedron



$\sum_{i=0}^{n} \alpha_i x_i \leq \mathrm{Cst}$

Modularity of numerical abstract domains

Modular **communication** system between domain

- **Weakly reduced** product
  - **Precise** (vs. direct products) and **practical** (vs. reduced products)
  - All abstract domains share a **common interface**
  - A domain **pulls** information using **query channels**
  - A domain **pushes** information using **message channels**
  - Inspired from Astrée

- Easy to soundly add or deactivate an abstract domain
  - Flexible precision-performance tradeoff
  - Some abstract domains are essential (e.g., intervals) for precision

Octagons

Overview

- Very popular **weakly relational domain**
  - Originally by Miné from Astrée
- Inequalities of the form: $\pm x \pm y \leq \mathrm{Cst}$
- Interval constraints expressible:

$$x + x \leq 2h \qquad -x - x \leq -2l$$

- Data structure: **difference bound matrix** A_{xy} for x, y **signed variables**:

$$\forall x\ y,\ x + y \leq A_{xy}$$

Octagons

Sparse algorithms

Usual algorithms for Octagons:

- Maintain a saturated set of constraints $\pm x \pm y \leq \mathrm{Cst}$
- Problem:

$$\begin{cases} x + x \leq A_{x\bar{x}} \\ y + y \leq A_{y\bar{y}} \end{cases} \implies \quad x + y \leq A_{x\bar{y}} \leq \frac{A_{x\bar{x}} + A_{y\bar{y}}}{2}$$

$\implies$ **Dense constraints** even for interval bounds

Our algorithms for Octagons:

- **Weak** form of saturation
- **Maintain the sparsity** of the constraints

Octagons

Example

$$\begin{array}{c|cccccc} & -x & +x & -y & +y & -z & +z \\ \hline +x & 0 & & & & & \\ -x & & 0 & & & & \\ +y & & & 0 & & & \\ -y & & & & 0 & & \\ +z & & & & & 0 & \\ -z & & & & & & 0 \end{array}$$

Octagons

Example

$$\begin{array}{c|cccccc} & -x & +x & -y & +y & -z & +z \\ \hline +x & 0 & 2 & & & & \\ -x & 0 & 0 & & & & \\ +y & & & 0 & 6 & & \\ -y & & & -2 & 0 & & \\ +z & & & & & 0 & 4 \\ -z & & & & & 0 & 0 \end{array}$$

Interval constraints:

$$x \in [0, 1]$$
$$y \in [1, 3]$$
$$z \in [0, 2]$$

Octagons

Example

$$\begin{array}{cc} & \begin{array}{cccccc} -x & +x & -y & +y & -z & +z \end{array} \\ \begin{array}{c} +x \\ -x \\ +y \\ -y \\ +z \\ -z \end{array} & \begin{pmatrix} 0 & 2 & 0 & 4 & 1 & 3 \\ 0 & 0 & -1 & 3 & 0 & 2 \\ 3 & 4 & 0 & 6 & 3 & 5 \\ -1 & 0 & -2 & 0 & -1 & 1 \\ 2 & 3 & 1 & 5 & 0 & 4 \\ 0 & 1 & -1 & 3 & 0 & 0 \end{pmatrix} \end{array}$$

Strong saturation

$\Longrightarrow$ Dense matrix

Octagons

Example

$$\begin{array}{c|cccccc}
 & -x & +x & -y & +y & -z & +z \\
\hline
+x & 0 & 2 & & & & \\
-x & 0 & 0 & & & & \\
+y & & & 0 & 6 & & \\
-y & & & -2 & 0 & & \\
+z & & & & & 0 & 4 \\
-z & & & & & 0 & 0
\end{array}$$

Weak saturation
(nothing to do here)

Octagons

Example

$$\begin{array}{c|cccccc} & -x & +x & -y & +y & -z & +z \\ +x & 0 & 2 & & 2 & & \\ -x & 0 & 0 & & & & \\ +y & & 2 & 0 & 6 & & \\ -y & & & -2 & 0 & & \\ +z & & & & & 0 & 4 \\ -z & & & & & 0 & 0 \end{array}$$

Adding the constraint:

$$x + y \leq 2$$

Octagons

Example

$$\begin{array}{c|cccccc} & -x & +x & -y & +y & -z & +z \\ \hline +x & 0 & 2 & 0 & 2 & & \\ -x & 0 & 0 & -1 & 2 & & \\ +y & 2 & 2 & 0 & 4 & & \\ -y & -1 & 0 & -2 & 0 & & \\ +z & & & & & 0 & 4 \\ -z & & & & & 0 & 0 \end{array}$$

Weak saturation:

$$y + y \leq 4$$
$$y - x \leq 2$$
$$-y - x \leq -1$$
$$x - y \leq 0$$

Octagons

Example

$$\begin{array}{c|cccccc} & -x & +x & -y & +y & -z & +z \\ \hline +x & 0 & 2 & 0 & 2 & & \\ -x & 0 & 0 & -1 & 2 & & \\ +y & 2 & 2 & 0 & 4 & & \\ -y & -1 & 0 & -2 & 0 & & \\ +z & & & & & 0 & 4 \\ -z & & & & & 0 & 0 \end{array}$$

Weak saturation:

$$y + y \leq 4$$
$$y - x \leq 2$$
$$-y - x \leq -1$$
$$x - y \leq 0$$

Still sparse

Abstract domain of symbolic equalities

Motivating example

CompCert front-end transformation:

```
if(0 <= a && a < 10) {
  ...
}
```

⟹

```
if(0 <= a)
  tmp = a < 10;
else
  tmp = 0;
if(tmp) {
  ...
}
```

Need to reason on the **relation** between `a` and `tmp`.

Abstract domain of symbolic equalities

- Two kinds of equalities:
  - $\texttt{var} \doteq \texttt{expr}$
  - $\texttt{expr} \doteq \texttt{bool}$

- Example:

```
if(0 <= a)          (0 <= a) ≐ true
  tmp = a < 10;     (0 <= a) ≐ true     tmp ≐ a < 10
else                (0 <= a) ≐ false
  tmp = 0;          (0 <= a) ≐ false    tmp ≐ 0
                                        tmp ≐ (0 <= a) ? a < 10 : 0
if(tmp) {           Unfolding tmp
  ...               a ∈ [0, 9]
}
```

Introduction

Overview of Verasco

Technical zoom:
numerical abstract domains

Conclusions

Final theorem

```
Definition vanalysis prog = ... iter ...

Theorem vanalysis_correct:
 ∀ prog res tr,
   vanalysis prog = (res, nil) →
   program_behaves (semantics prog) (Goes_wrong tr) →
   False.
```

Empty alarm list

No wrong behavior

Conclusion

Proving correct a **realistic static analyzer** based on abstract interpretation is **feasible**

- Realistic, feature-rich language (C99)
- Advanced combination of abstract domains

By expliciting the proofs, we **clarified**:

- The specification of abstract domains
- The architecture of a static analyzer
- Their implementation

Future work

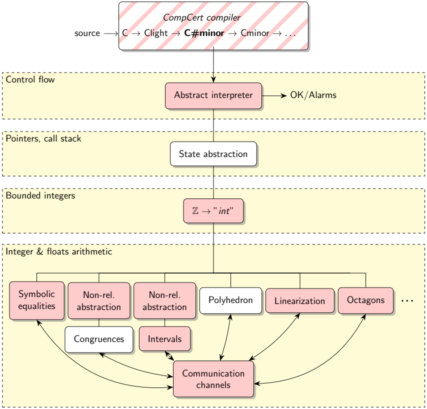
- New analysis techniques:
  - Better handling of control flow (trace partitioning, recursion, ...)
  - Other numerical abstract domains (linear filters, arithmetic-geometric progression, pentagons, ...)
  - Support for dynamic memory allocation
- Better performance
  - Faster abstract domains (arrays summarization, variable packing, ...)
  - Better tools for formally verified software
- Using the results of the analysis (Optimizations, other analyzers)
- Experimenting with industrial code

`http://compcert.inria.fr/verasco/`

Questions ?

Appendices

My contributions in Verasco



- In CompCert:
  - ☐ Parser (verified in Coq)
  - ☐ Floats (verified in Coq)
- Abstract interpreter
  - ☐ Dedicated program logic
- Most of the numerical domains
  - ☐ Handling of machine arithmetic
  - ☐ Symbolic equalities
  - ☐ Intervals
  - ☐ Linearization
  - ☐ Octagons
  - ☐ Communication channels

In my thesis...

- Design and proof of abstract iterator
    - Handles all C#minor control constructs
    - Proved using a dedicated program logic

- Sharing, hash-consing and memoization in Coq
    - Examplified on a BDD library
    - Applications in Verasco

- Contributions to CompCert
    - Parsing, support for floating-point numbers

Experiments

Program	Size	Time
`integr.c`	42 lines	< 0.1s
`smult.c`	330 lines	19.3s
`nbody.c`	179 lines	10.7s
`almabench.c`	352 lines	5.7s

- No alarms on those examples.
  - Pointers, arrays, floats
- Much room for improvement in performance.

Non-relational numerical abstract domains

Congruences & Intervals

Intervals

- On $\mathbb{Z}$ and floating-point numbers.
- Handles all arithmetic and bit-level operations of C99

Arithmetical congruences

- Needed to check alignment of memory accesses

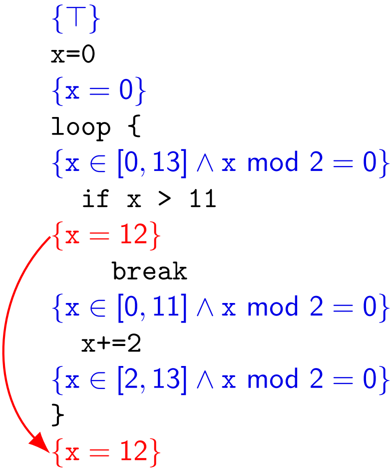
Specific interface for non-relationnal domains

- Common relational adaptation layer

Complex control flow

```
x=0
loop {
  if x > 11
    break
  x+=2
}
```

Complex control flow



```
{$\top$}
x=0
{$x = 0$}
loop {
{$x \in [0, 13] \wedge x \bmod 2 = 0$}
  if x > 11
{$x = 12$}
    break
{$x \in [0, 11] \wedge x \bmod 2 = 0$}
  x+=2
{$x \in [2, 13] \wedge x \bmod 2 = 0$}
}
{$x = 12$}
```

- Based on **control points**
- We want definitions **following the AST structure**

Complex control flow

```
x=0

loop {

  if x > 11
    {x = 12}
    break
    {⊥, x = 12}
  x+=2

}
```

Dedicated program logic:

$$\{P\}\ s\ \{Q,\ Q_b\}$$

- Several postconditions
- Defined structurally

Complex control flow

```
x=0

loop {
  {x ∈ [0, 13] ∧ x mod 2 = 0}
  if x > 11

    break

  x+=2
  {x ∈ [2, 13] ∧ x mod 2 = 0, x = 12}
}
```

Dedicated program logic:

$$\{P\}\ s\ \{Q,\ Q_b\}$$

- Several postconditions
- Defined structurally

Complex control flow

```
x=0
{x = 0}
loop {

  if x > 11

    break

  x+=2

}
{x = 12, ⊥}
```

Dedicated program logic:

$$\{P\}\ s\ \{Q,\ Q_b\}$$

- Several postconditions
- Defined structurally

Abstract interpreter

Simplified implementation & proof

```
Fixpoint iter (ab:abstate) (s:stmt) {struct s}
             : abstate * abstate := ...
```

- Proof step 1: interpreter soundness

```
Lemma iter_ok: ∀ ab_pre stmt ab_post ab_break,
  iter ab_pre stmt = (ab_post, ab_break) →
  { γ(ab_pre) } stmt { γ(ab_post), γ(ab_break) }.
```

- Proof step 2: program logic soundness

$$\{\cdot\}\ \cdot\ \{\cdot,\ \cdot\} \Longrightarrow \text{No undefined behavior}$$

Abstract interpreter

Big picture

- Handles all C#minor control constructs
    - Infinite `loop`, `break`, `if`/`else`, `switch`, `goto`, `call`, `return`
    - 2 pre-conditions, 4 post-conditions
- Parameterized by a state abstract domain
- Works in a monad for alarms
- Structural recursion on syntax tree
    - Unfolding functions at call sites
- Fixpoint iteration using widening and narrowing
    - One fixpoint iteration per loop
    - Gotos: one fixpoint iteration per function