Experiences in designing scalable static analyses

LOPSTR/ WFLP invited talk

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Sept 4th, 2018
Compilation and Analysis for Software and Hardware - Location

LIP: Laboratoire de l'Informatique du Parallélisme
Optimized (software/hardware) compilation for HPC software with data-intensive computations.

\(\Rightarrow\) Means: dataflow IR, static analyses, optimisations, simulation.

Christophe Alias, Laure Gonnord, Matthieu Moy
http://www.ens-lyon.fr/LIP/CASH/
Outline

Motivations
Static analyses, examples
Static analysis of software, how?

Abstract Interpretation 101

Abstract Interpretation for optimising compilers
Example 1: a scalable analysis for pointers
Example 2: array bound check elimination
Impact on compiler optimisation pathes

Conclusion
Software needs safety and performance

- For safety-critical systems . . .
- and general purpose systems!
Software needs safety and performance

• For safety-critical systems . . .
• and general purpose systems!

▶ Programs crash because of array out-of-bounds accesses, complex pointer behaviour, . . .
Software guarantees, how?

- Development processes: coding rules, ... 
- Testing: do not cover all cases.
- Proof assistants: expensive.

▶ Static analysis of programs.
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Goal: safety 1/2

Prove that (some) memory accesses are safe:

```c
int main () {
    int v[10];
    v[0]=0; ✓
    return v[20]; ✗
}
```

▶ This program has an illegal array access.
Goal: safety 2/2

Prove program correctness/absence of functional bug:

```c
void find_mini (int a[N], int l, int u){
    unsigned int i=l;
    int b=a[l]
    while (i <= u){
        if(a[i]<b) b=a[i] ;
        i++ ;
    }
    // here b = min(a[l..u])
}
```

This program finds the minimum of the sub-array.
Enable loop parallelism:

```c
void fill_array (char *p){
    unsigned int i;
    for (i=0; i<4; i++)
        *(p + i) = 0 ;
    for (i=4; i<8; i++)
        *(p + i) = 2*i ;
}
```

The two regions do not overlap.
Goal: performance 2/2

Enable code motion:

```c
void code_motion(int* p1, int* p2, int* p){
    // ...
    while (p2 > p1){
        a = *p;
        *p2 = 4;
        p2 --;
    }
}
```

If \( p \) and \( p_2 \) do not alias, then \( a=*p \) is invariant.

Hoisting this instruction saves one load per loop.
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Conclusion
Proving non trivial properties of software

- Basic idea: software has **mathematically defined behaviour**.
- **Automatically** prove properties.

Acceptable Behaviours

Program

(verify) No crash

(compile) Optimisable
There is no free lunch

i.e. no magical static analyser. It is impossible to prove interesting properties:

• automatically
• exactly
• on unbounded programs
There is no free lunch
i.e. no magical static analyser. It is impossible to prove interesting properties:

- automatically
- exactly with false positives!
- on unbounded programs

▷ **Abstract Interpretation** = conservative approximations.
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Conclusion
Computing (inductive) invariants

\[ \{ x \in \mathbb{N}, 0 \leq x \leq 100 \} \text{ is the most precise invariant in control point loop.} \]
Problems and solution

We want to:

- Compute infinite sets.
- In finite time.

How?

- Approximate sets (abstract domains), compute in this abstract world.
- Extrapolate (widening).
Main ingredient: abstract values

Idea: represent values of variables:

$$R_{pc} \in \mathcal{P}(\mathbb{N}^d)$$

by a **finite computable superset** $R^\#_{pc}$:

And compute such **abstract values** for each control point.

How? mimic the program operations

$$\mathbb{N}^d \times pcs \rightarrow \mathbb{N}^d \times pcs$$

by their abstract versions.

There is also this magical widening stuff, let’s forget it in this talk
Example (Pagai, Verimag)

```c
int main(int argc, char** argv){
    int x, y;
    x = 1;
    y = 2;
    /* reachable */
    /* invariant: */
    3-2*y+x = 0
    5-y >= 0
    -2+y >= 0
    /*
    while (x<8){
        x = x+2;
        y = y+1;
    }
    /* reachable */
    return 0;
}
```

see http://pagai.forge.imag.fr
Other famous AI tools

- Frama-C: “Evolved Value Analysis”.
- Astree: originally designed for safety critical C Compiled from Scade (synchronous programming).
- Polyspace (Mathworks).
Complexity in Abstract Interpretation

**Classical** abstract interpretation analyses:
- Information attached to \((\text{block}, \text{variables})\).
- A new information is computed after each statement.
- Abstract operations are sometimes costly.

- For the polyhedral abstract domain, the complexity is \(3\text{EXP}\).
Challenges in Abstract Interpretation

- Precision of the abstract domain.
- Thousands, millions of lines of code to analyze.
- Static analyzers and compilers are complex programs (that also have bugs).

Growing need for simple specialized analyses that scale
Credo: future of Abstract Interpretation

- Focus more on applicability, and less on expressivity.
- Scale and demonstrate that it scales.
- For general-purpose programs.

and use techniques from other communities (optimization, model-checking, logic, rewriting)
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Safe compilation?

- **Correct-by-construction** non-optimising compilers: Lustre, Scade.
- Translation validation: specialized proof of the generated code.
- Compcert.

▶ An evolution toward more trustable compilers. But what about code optimisation?
Motivation

Classical analyses (and optimisation) inside (production) compilers:

- Apart from classical dataflow algorithm, often **syntactic**.
- Usual abstract-interpretation based algorithms are too costly.
- Expressive algorithms: rely on “high level information”.

Need for safe and precise quasi linear-time algorithms at low-level.
Illustrations in the rest of the talk.
Motivation

Classical analyses (and optimisation) inside (production) compilers:

- Apart from classical dataflow algorithm, often **syntactic**.
- Usual abstract-interpretation based algorithms are too costly.
- Expressive algorithms: rely on “high level information”.
  - Need for safe and precise quasi linear-time algorithms at **low-level**.
  - Illustrations in the rest of the talk.
Some contributions

- Abstract domains/iteration strategies for numerical invariants [SAS11], [OOPSLA14].
- Applications to memory analysis [OOPSLA14], just in time compilers [WST14].
- Pointer analysis with “sparse” abstract interpretation [CGO16] [CGO17] [SCP17].

Collaborations with M. Maalej, F. Pereira and his team at UFMG, Brasil
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Conclusion
void partition(int *v, int N) {
    int i, j, p, tmp;
    p = v[N/2];
    for (i = 0, j = N - 1;; i++, j--) {
        while (v[i] < p) i++;
        while (p < v[j]) j--;
        if (i >= j)
            break;
        tmp = v[i];
        v[i] = v[j];
        v[j] = tmp;
    }
}
void partition(int *v, int N) {
    int i, j, p, tmp;
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        while (v[i] < p) i++;
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        if (i >= j)
            break;
        tmp = v[i];
        v[i] = v[j];
        v[j] = tmp;
    }
}

• Range information is not sufficient to disambiguate \( v[i] \) and \( v[j] \).

• We need to propagate relational information.
Our setting for scaling analyses

**Classical** abstract interpretation analyses:
- Information attached to \((block, variable)\).
- A new information is computed after each statement.

Sparse analyses ⇒ **Static Single Information (SSI)**

**Property [Ana99]:**
- Attach information to variables.
- The information must be invariant throughout the live range of the variable.

▶ A simple assignment breaks SSI!
▶ Work on suitable intermediate representations
Scaling analyses: program representation 1/2

Static Single Assignment (SSA) form: each variable is defined/assigned once.

```c
void partition(int *v, int N) {
    int i, j, p, tmp;
    p = v[N/2];
    for (i = 0, j = N - 1;; i++, j--) {
        while (v[i] < p) i++;
        ...
    }
}
```
Scaling analyses: program representation 1/2

Static Single Assignment (**SSA**) form: each variable is defined/assigned once.

```c
void partition(int *v, int N) {
    int i, j, p, tmp;
    p = v[N/2];
    for (i = 0, j = N - 1;; i++, j--) {
        while (v[i] < p) i++;
        ...
    }
}
```

▶ Sparse storage of **value** information (one value range per variable name).
Within SSA form, tests information cannot be propagated!

```c
void partition(int *v, int N) {
    ...
    if (i >= j)
        break;
    tmp = v[i];
    v[i] = v[j];
}
```

- \( i \geq j \) is invariant nowhere.
- The \( \sigma \) renaming (e-SSA) enables to propagate “\( i_F < j_F \)”. 

\[
\begin{align*}
     i_F &= \sigma(i) \\
     j_F &= \sigma(j) \\
     v_i &= v + i_F \\
     tmp &= *v_i \\
     v_j &= v + j_F \\
     *v_i &= *v_j \\
    ...
\end{align*}
\]
Scaling analyses: relational information

Recall the SSI setting:

- Information must be invariant throughout the live range of the variable. ✓
- Attach information to variables (and not blocks).

Work on semi-relational domains, for instance:

- Parametric ranges [OOPSLA14] \( x \mapsto [0, N + 1] \)
- Pentagons [LF10]: \( x \mapsto \{u, t\} \) means \( u, t \leq x \).
Contributions on static analyses for pointers

(with Maroua Maalej) [CGO16, CGO17, SCP17]

• A new sequence of static analyses for pointers.
• Based on semi-relational sparse abstract domains:
  • In CGO’16: $p \mapsto \text{loc} + [a, b]$.
  • In CGO’17: adaptation of Pentagons.
• Implemented in LLVM.
• Used as oracles for a common pass called AliasAnalysis.
• Experimental evaluation on classical benchmarks.
• Comparison with LLVM basic alias analysis.
• Our sraa outperforms basicaa in the majority of the tests.
• The combination outperforms each of these analyses separately in every one of the 100 programs.
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Contribution [OOPSLA’14]

• A technique to prove that (some) memory accesses are safe:
  • Less need for additional guards.
  • Based on abstract interpretation.
  • Precision and cost compromise.

• Implemented in LLVM-compiler infrastructure:
  • Eliminate 50% of the guards inserted by AddressSanitizer
  • SPEC CPU 2006 17% faster
A bit on sanitizing memory accesses

Different techniques: but all have an overhead.

Ex: Address Sanitizer

- Shadow every memory allocated: 1 byte \(\rightarrow\) 1 bit (allocated or not).
- Guard every array access: check if its shadow bit is valid.
  - Slows down SPEC CPU 2006 by 25%  
  - We want to remove these guards.
Green Arrays: a set of sparse analyses 1/2

1. int main(int argc, char** argv) {
2.   int size = argc + 1;
3.   char* buf = malloc(size);
4.   unsigned index = 0;
5.   scanf("%u", &index);
6.   if (index < argc) {
7.     buf[index] = 0;
8.   }
9.   return index;
10. }

Any address from buf + 0 to buf + argc is safe!

Inside the branch index is at least 0 and at most argc-1

We know that "argc - 1" is less than argc

As long as we do not have integer overflows!
Symbolic Range Analysis:
finds the lower and upper values that variables can assume

Symbolic Region Analysis:
finds the lower and upper values that a pointer can address

Integer Overflow Analysis:
Which arithmetic operations can overflow?

Any address from buf + 0 to buf + argc is safe!

Inside the branch index is at least 0 and at most argc-1

We know that " argc - 1" is less than argc

As long as we do not have integer overflows!
Experimental setup

• **Implementation:** LLVM + AddressSanitizer

• **Benchmarks:** SPEC CPU 2006 + LLVM test suite

• **Machine:** Intel(R) Xeon(R) 2.00GHz, with 15,360KB of cache and 16GB or RAM

• **Baseline:** Pentagons
  
  – Abstract interpretation that combines "less-than" and "integer ranges".†

  ```c
  int i = 0;
  unsigned j = read();
  if (...)  
    i = 9;
  if (j < i)  
    ...
  
  P(j) = (less than \{i\}, [0, 8])
  
Percentage of bound checks removed

The higher, the better.
Pentagons: 27%.
GreenArrays: 43%
Runtime improvement

The lower the bar, the faster. Time is normalized to AddressSanitizer without bound-check elimination. Average speedup: Pentagons = 9%. GreenArrays = 16%.
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Some comments on the methodology

LLVM compiler:

- comes with a test infrastructure and benchmarks.
- analysis and optimisation passes log information.
- you can add your own pass, but **where?**

```
clang -c -emit-llvm $1 -o $name.bc
opt -mem2reg -instnamer $name.bc -o $name.rbc
sage-opt -load $lib_path/$ssify.so -break-crit-edges -ssify -set 1000 $name.rbc -o $name.rbc
```

- Evaluating the impact of a given analysis is a **nightmare!**
Loop invariant code motion (LICM):

```c
void code_motion(int* p1, int *p2, int *p){
    // ...
    while(p2 > p1){
        a = *p;
        *p2 = 4;
        p2 --;
    }
}
```

- If \( p \) and \( p_2 \) do not alias, then \( a = *p \) is invariant.
### Impact of our analyses (excerpt) 2/2

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</table>

More in Maroua Maalej’s thesis.
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Summary

Static analyses for compilers:

- Application domain: code optimisation.
- Adaptation of abstract interpretation algorithms inside this particular context.
- Algorithmic and compilation techniques to scale.
- Future work: more relational domains (and data structures).
Take home message

- Code optimisation are good applications for static analyses/formal methods!
- They have to be thought in terms of scaling as well as precision.
- Sparse analyses are the key but they still have to be invented/redesigned.
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