A journey on static analyses of programs

From code verification to code optimisation

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Plan

Motivations

Abstract Interpretation for compilers

Scalable analyses for pointers

Code analysis for binaries

Impact on compiler optimisation passes

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, . . .

Goal : safety - ex

Prove that (some) memory accesses are safe :

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

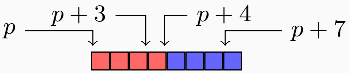
- This program has an illegal array access.

Goal : performance -ex

Enable loop parallelism :

```
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 ;
}
```

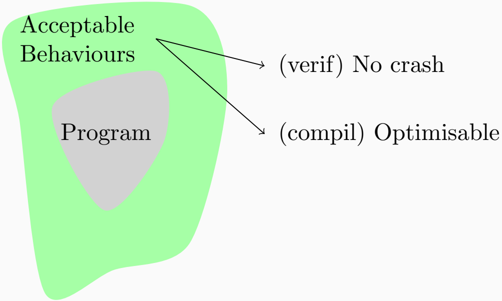
Parallel loops



- The two regions do not overlap.

Proving non trivial properties of software

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



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

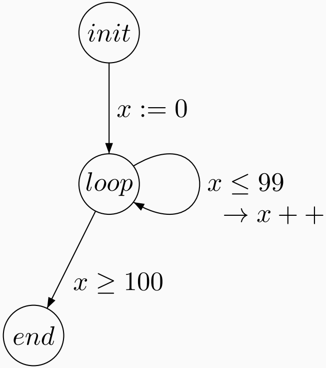
i.e. no magical static analyser. It is ~~im~~possible to prove interesting properties :

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

▶ **Abstractions** = conservative approximations.

Plan

Computing (inductive) invariants



- $\{x \in \mathbb{N}, 0 \leq x \leq 100\}$ is the most precise invariant in control point `loop`.

Problems and solution

We want to :

- Compute infinite sets.
- In finite time.

▶ How ?

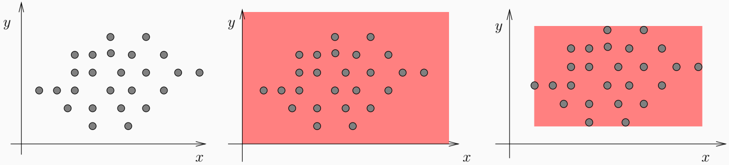
- Approximate sets (abstract domains), compute in this abstract world.
- Extrapolate (widening).

Main ingredient : abstract values

Idea : represent values of variables :

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

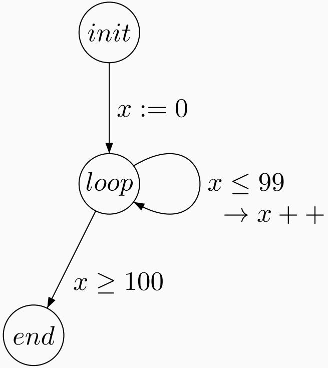
by a **finite computable superset** $R^\sharp_{pc}$:



- And compute such **abstract values** for *each control point*.
- How ? mimic the program operations by their abstract versions.

There is also this magical widening stuff, let's forget it in this talk

Computing (inductive) invariants with intervals



- **ex :** Propagate range information

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;
}
```

Challenges in Abstract Interpretation

- More data structures : pointers, arrays, ...
- 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**

Memory Analyses
Focus on expressivity - scalability - compilers.

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" information that is usually absent in the low level program representations adopted by compilers.

▶ 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].
- Polyhedral analysis on **binary code** [VMCAI19]

Collaborations with M. Maalej, F. Pereira and his team at UFMG, Brasil

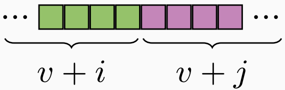
+ with C. Ballagria, J. Forget, Lille

Plan

Pointer analysis : motivating example

```
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;
  }
}
```

v[i] = *(v+i)



Motivating example - LLVM version

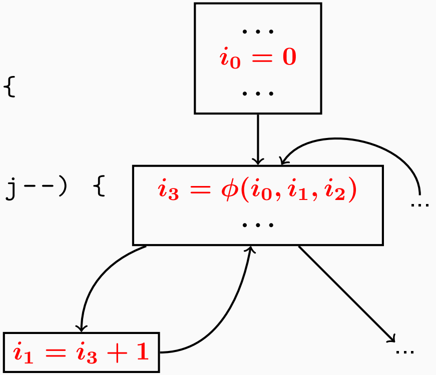
```
for.cond:                          ; preds = %for.inc, %entry
  %i.0 = phi i32 [ 0, %entry ], [ %inc18, %for.inc ]
  %j.0 = phi i32 [ %sub, %entry ], [ %dec19, %for.inc ]
  br label %while.cond

while.cond:                        ; preds = %while.body, %for.cond
  %i.1 = phi i32 [ %i.0, %for.cond ], [ %inc, %while.body ]
  %idxprom1 = sext i32 %i.1 to i64
  %arrayidx2 = getelementptr inbounds i32* %v, i64 %idxprom1
  %1 = load i32* %arrayidx2, align 4
  %cmp = icmp slt i32 %1, %0
  br i1 %cmp, label %while.body, label %while.end
```

- On a perdu une partie du contrôle (et les tableaux)

Scaling analyses : program representation (simpl.) 1/2

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

```
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).

Our setting for scaling analyses

Classical abstract interpretation analyses :

- Information attached to $(\textit{block}, \textit{variable})$.
- A new information is computed after each statement.

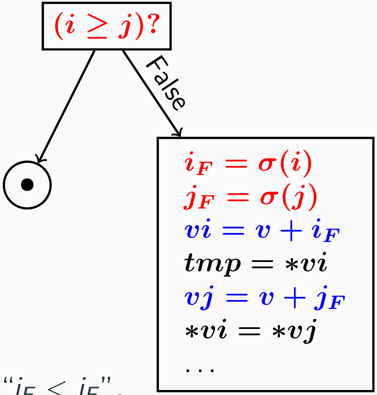
Sparse analyses $\Rightarrow$ **Static Single Information (SSI) Property :**

- Attach information to variables.
- The information must be invariant throughout the live range of the variable.

▶ Work on suitable intermediate representations.

But, in our analysis, range information is not sufficient to disambiguate `v[i]` and `v[j]`
Within **SSA** form, tests/relational information cannot be propagated !

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



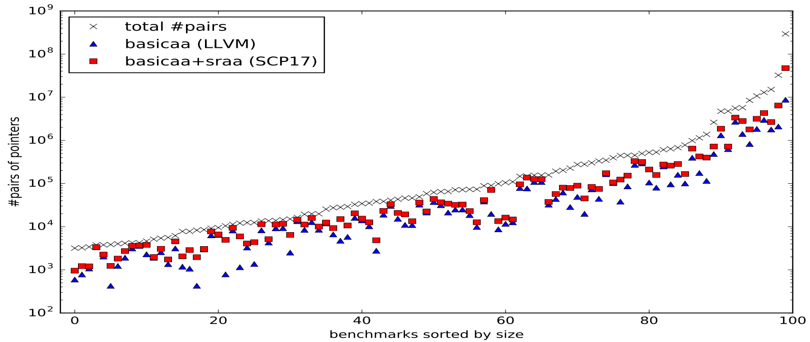
- $i \geq j$ is invariant nowhere in classical SSA.
- The σ renaming (**e-SSA**) enables to propagate "$i_F < j_F$".

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 : $p \mapsto loc + [a, b]$.
  - In CGO'17 : adaptation of Pentagons.
- Implemented in LLVM.
- Used as oracles for a common pass called `AliasAnalysis`.
- Experimental evaluation on classical benchmarks.

Experimental results [SCP17]



- 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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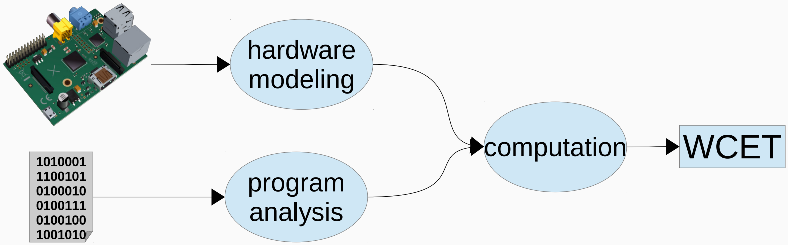
Context, Contribution

Real-time systems, scheduling needs precise worst-case execution time evaluation : **on the binary**.



- A new abstract interpretation on binary with polyhedra.

Slides from C. Ballabriga.

Analysing binary is difficult

No control, no variable, no type, only data locations.

- Look for memory accesses in the binary code
- Not always obvious that 2 accesses refer to the same data location

Aliasing example (Pseudo-Assembly)

```
SET     r1, #42
ADD     r4, sp, #8
STORE   r1, [r4 - #4]
...
LOAD    r3, [sp + #4]
ADD     r3, r3, #1
```

- LOAD and STORE access the same statically-unknown address

A taste of the abstract analysis

Abstract state shape : $(P(values), \text{register mapping}, \text{mem mapping})$.

- A memory value is represented by the dereferencing of a polyhedra variable
- The "memory mapping" encode (de)references

```
SET     r3 , #42
STORE   r3 , [sp + #4]
```

▶ Here : $(\langle x_3 = 42, x_4 = x_5 + 4 \rangle, \{r_3 : x_3, sp : x_5\}, \{x_4 : x_3\})$

Experimental evaluation

- We developed a prototype called *Polymalys*
  - Implements the approach in C++
  - Is a plugin for OTAWA
  - OTAWA is an open-source modular tool for WCET static analysis
- OTAWA handles :
  - ELF binary loading
  - CFG reconstruction
  - Architecture-independent instruction abstraction

Evaluation : benchmarks

			Bounded loops				Time (ms)	
Bench	*LoC*	*Loops*	Polymalys	*SWEET*	*Pagai*	*oRange*	Polymalys	*Pagai*
crc	16	1	1	1	1	1	150	40
fibcall	22	1	1	1	1	1	230	50
janne_complex	26	2	1	2	1	1	870	140
expint	56	3	3	2	3	3	850	9140
matmult	84	5	5	5	5	5	3640	1380
fdct	149	2	2	2	2	2	12450	2150
jfdctint	165	3	3	3	3	3	10920	1960
fir	189	2	2	2	2	1	11630	390
edn	198	12	12	12	9	12	25190	15660
ns	414	4	4	4	4	4	1740	380
gemver	186	10	10	N/A	10	10	12136	6029
covariance	138	11	11	N/A	11	11	7248	836
correlation	168	13	13	N/A	N/A	13	9129	25062
nussinov	143	8	8	N/A	8	8	7272	2811
floyd-warshall	112	7	7	N/A	2	7	2904	468

- We ran the tools on Mäalardalen and Polybench
- Strength of our tool in this comparison :
  - Works on binary
  - Tends to better estimate loop bounds
  - Reasonable analysis time, guaranteed to terminate

Plan

Evaluating analyses in LLVM

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
sage-opt -stats -load $lib_path/$python_so -load $lib_path/$sage_so -load $lib_path/$sra_so -load $lib_path/$rbaa_so -lo
ad $lib_path/$licm2_so -range-based-aa -aa-eval -no-aa -tbaa -targetlibinfo -basicaa -notti -verify -simplifycfg -domtre
e -sroa -lower-expect -targetlibinfo -no-aa -tbaa -basicaa -notti -ipsccp -globalopt -deadargelim -domtree -instcombine
-simplifycfg -basiccg -prune-eh -inline-cost -inline -functionattrs -argpromotion -sroa -domtree -lazy-value-info -jump-
threading -correlated-propagation -simplifycfg -domtree -instcombine -tailcallelim -simplifycfg -reassociate -domtree -l
oops -loop-simplify -lcssa -loop-rotate -licm2 -loop-unswitch -instcombine -scalar-evolution -loop-simplify -lcssa -indv
ars -loop-idiom -loop-deletion -loop-unroll -memdep -mldst-motion -domtree -memdep -range-based-aa -gvn -view-cfg -memde
p -memcpyopt -sccp -domtree -instcombine -lazy-value-info -jump-threading -correlated-propagation -domtree -memdep -dse
-range-based-aa -adce -simplifycfg -domtree -instcombine -barrier -domtree -loops -loop-simplify -lcssa -branch-prob -bl
ock-freq -scalar-evolution -loop-vectorize -instcombine -scalar-evolution -slp-vectorizer -simplifycfg -domtree -instcom
bine -loops -loop-simplify -lcssa -scalar-evolution -loop-unroll -strip-dead-prototypes -globaldce -constmerge -verify $
name.rbc -o $name.opt.rbc
```

▶ Evaluating the impact of a given analysis is a **nightmare** !

Impact on our alias analysis on LLVM code motion 1/2

Loop invariant code motion (LICM) :

hoist!

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

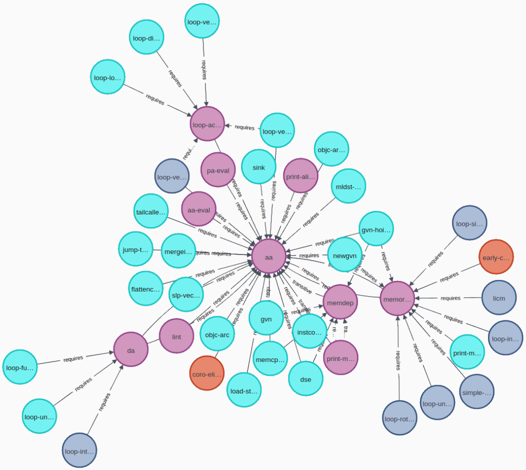
- If p and p_2 do not alias, then a=*p is invariant.

Impact of our analyses (excerpt) 2/2

Program	#Inst	#moved	
		O3	O3+our analysis (CGO16)
fixoutput	369	1	**5**
compiler	3515	0	0
bison	15645	165	**179**
archie-client	5939	0	0
TimberWolfMC	98792	1287	**1447**
allroots	574	0	0
unix-smail	5435	3	3
plot2fig	3217	3	3
bc	10632	18	**19**
yacr2	6583	144	**190**
ks	1368	8	**11**
cfrac	7353	5	**6**
espresso	50751	301	**398**
gs	55281	20	X

More in Maroua Maalej's thesis.

Understanding LLVM internals



⇝ charting the compiler. Figure from S. Michelland. More in the CAPESA project

Summary

Static analyses for compilers :

- Adaptation of abstract interpretation algorithms inside this particular context (**internal representations**).
- Algorithmic and compilation techniques to scale.
- Future work : more relational domains (and data structures), more applications, continue work on binary. . .