Static Analysis using Abstract Interpretation

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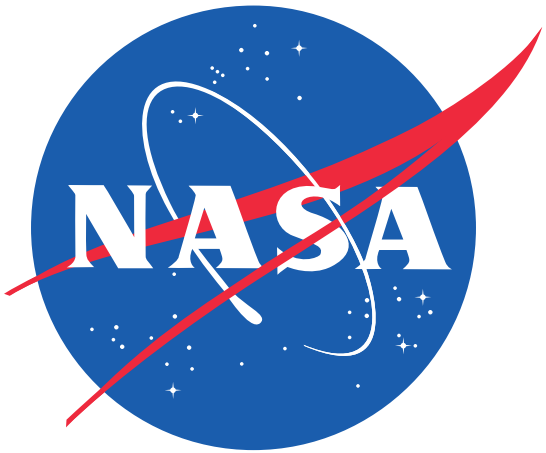
NASA Ames Research Center, California



STINGER
GHAFFARIAN
TECHNOLOGIES

Syllabus

Software development

- Software represent more than half of the development cost of an aircraft
- Regulated by international standards (DO-178 rev. B/C)

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- Tests
  - Expensive because run on a special hardware
  - Can miss bugs
  - Slow
- Solution : use static analysis
- NASA V&V program

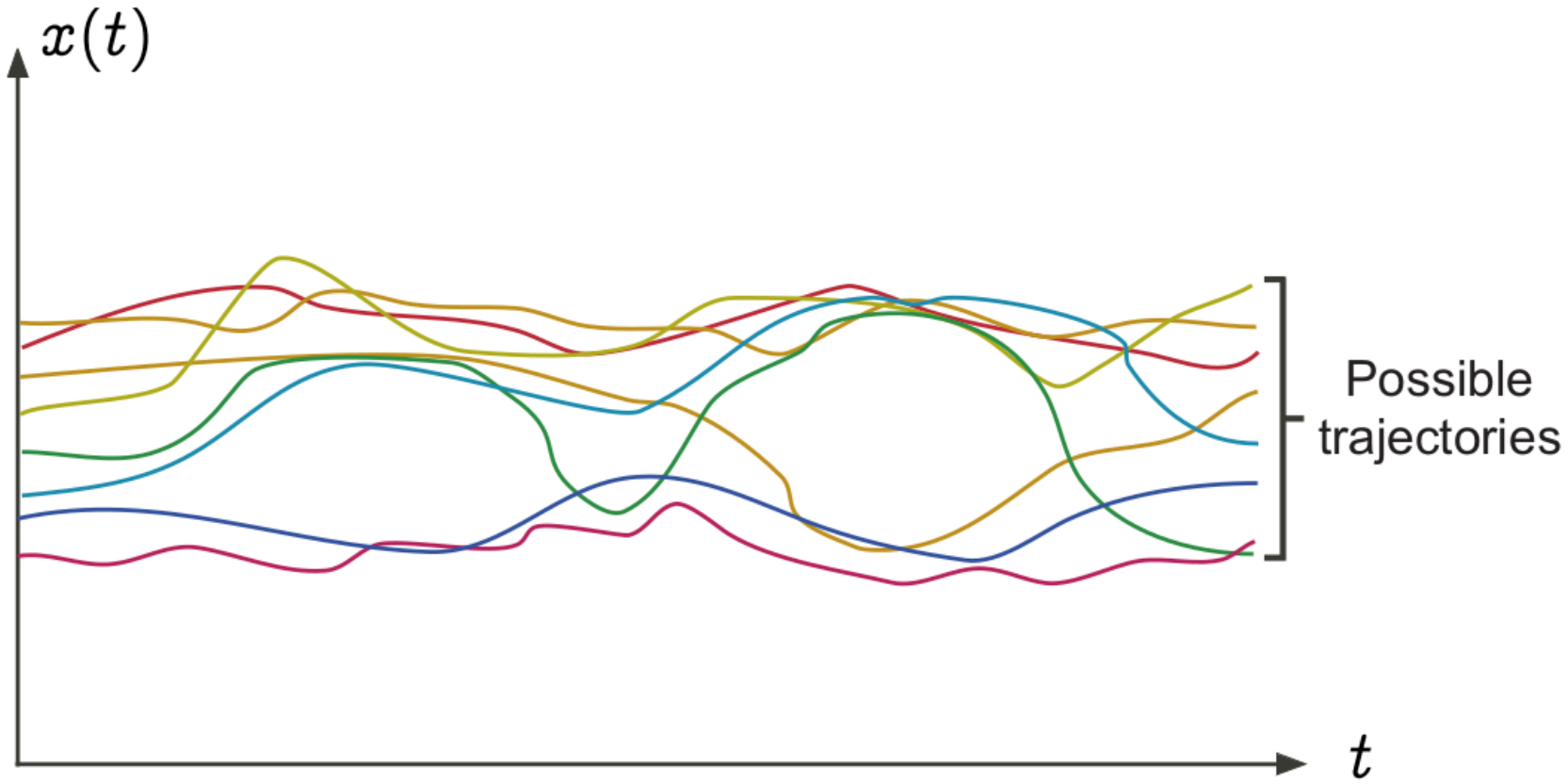
Safety properties

- Main objectives : no runtime errors
  - buffer overflow
  - null dereference
  - division by zero
  - integer overflow
- Harder objectives :
  - assertions (pre/post invariants)
  - termination
- certified => soundness is required
- abstract interpretation is a good candidate
- runtime errors can be security vulnerabilities !

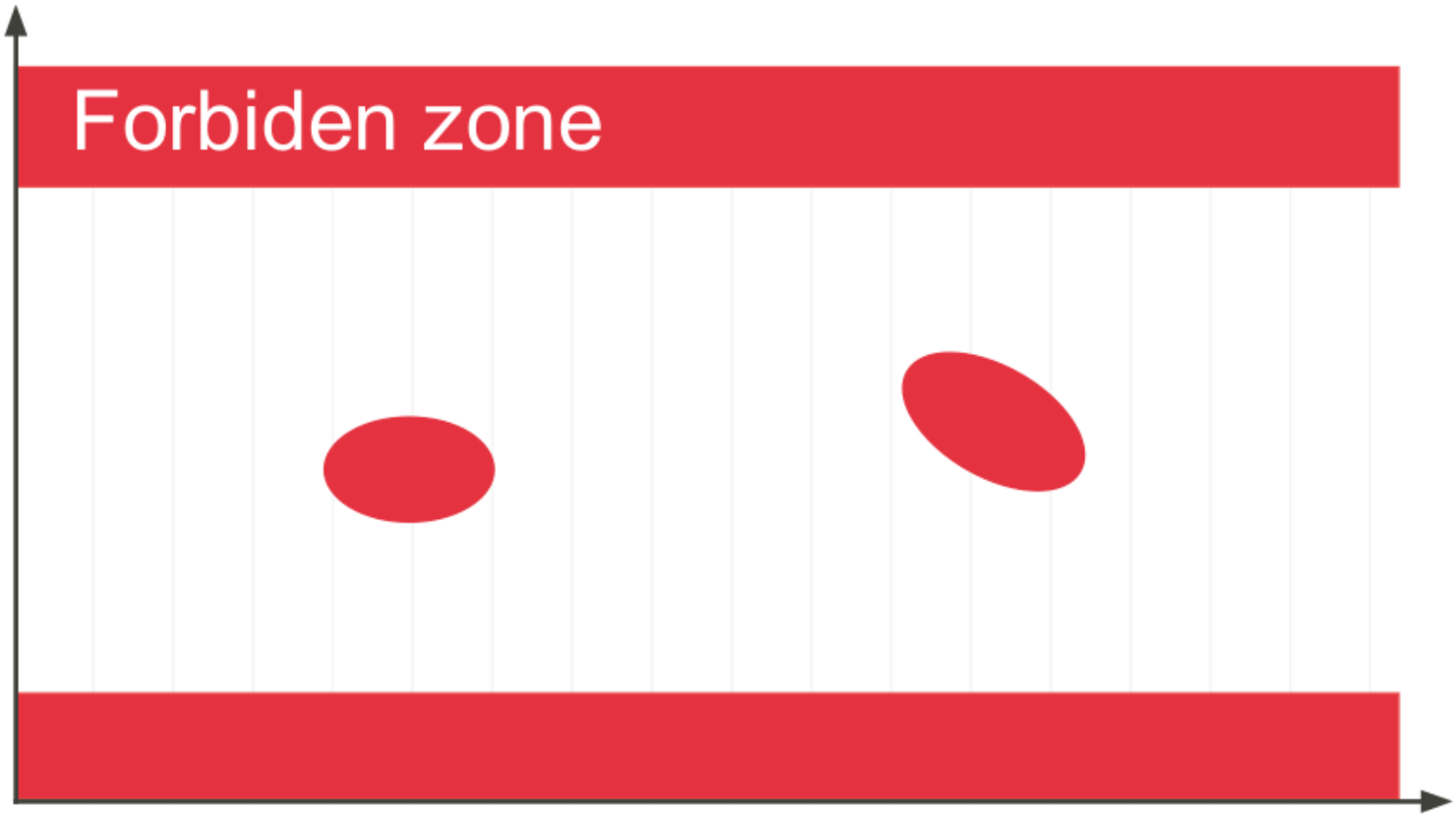
Abstract Interpretation

- based on the concrete semantics of your program
- automatic formal proof
- sound approximation of reachable states

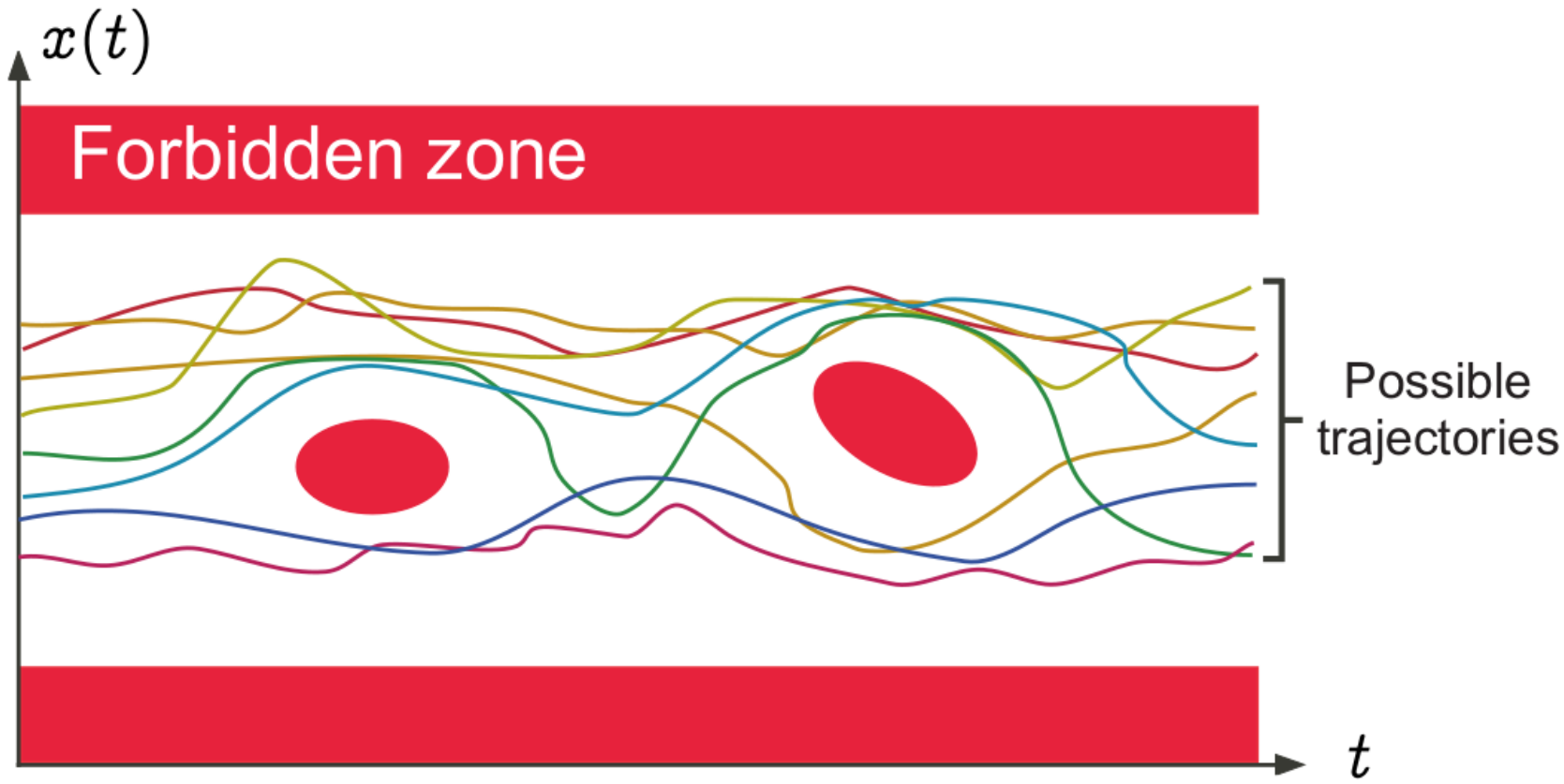
Abstract Interpretation



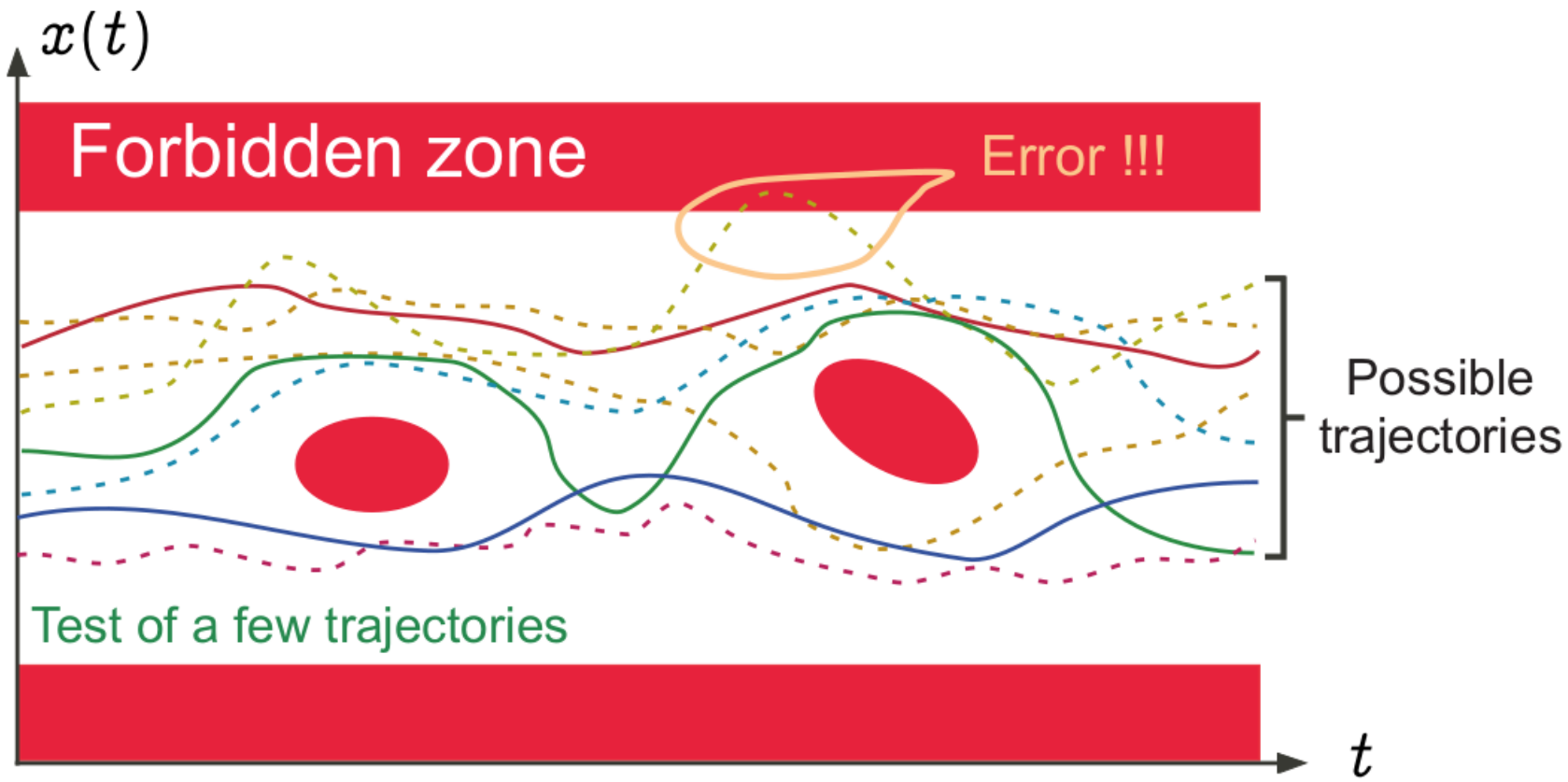
$semantics(P)$



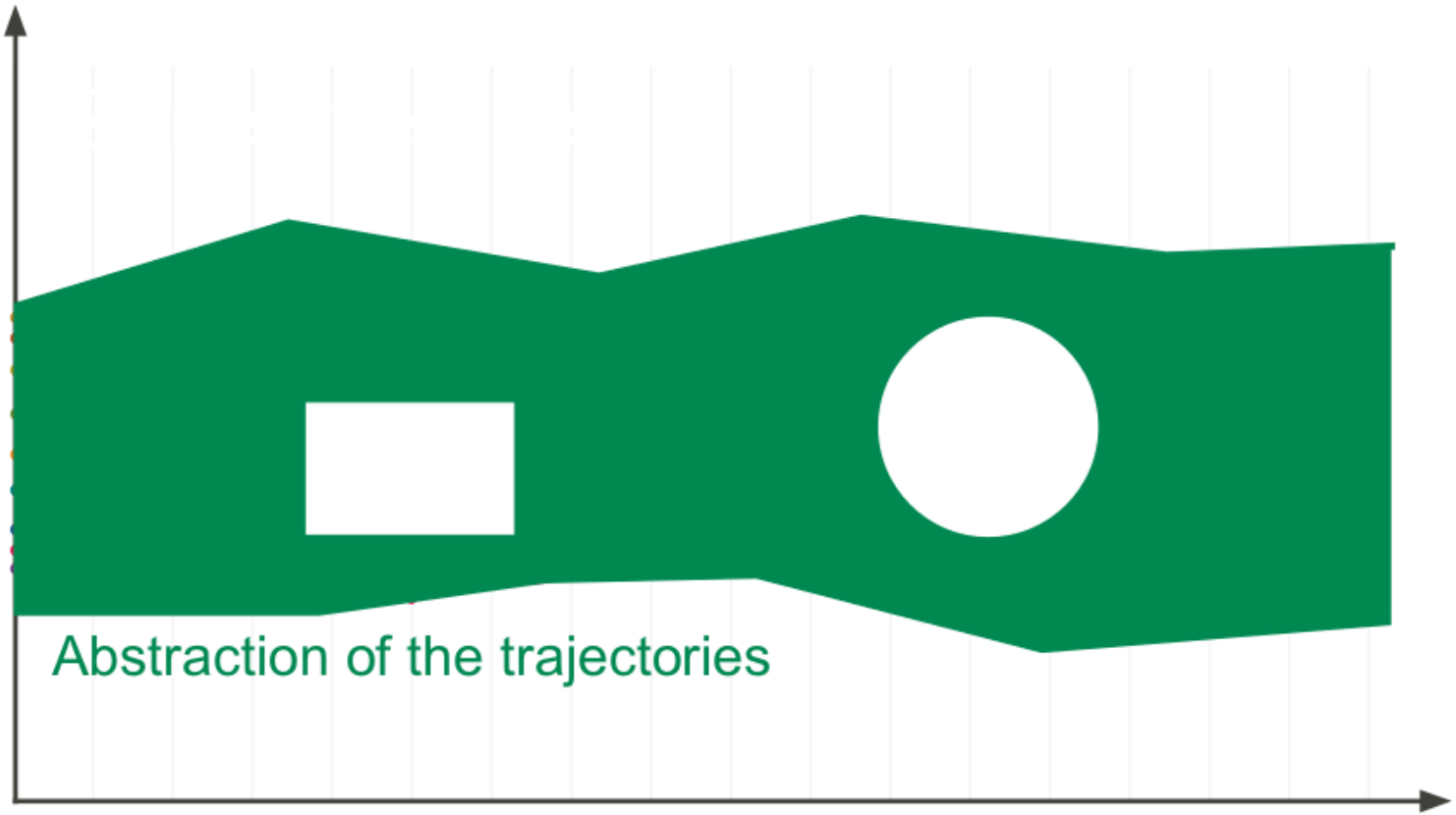
$specification(P)$



$$\mathit{semantics}(P) \subseteq \mathit{specification}(P)$$

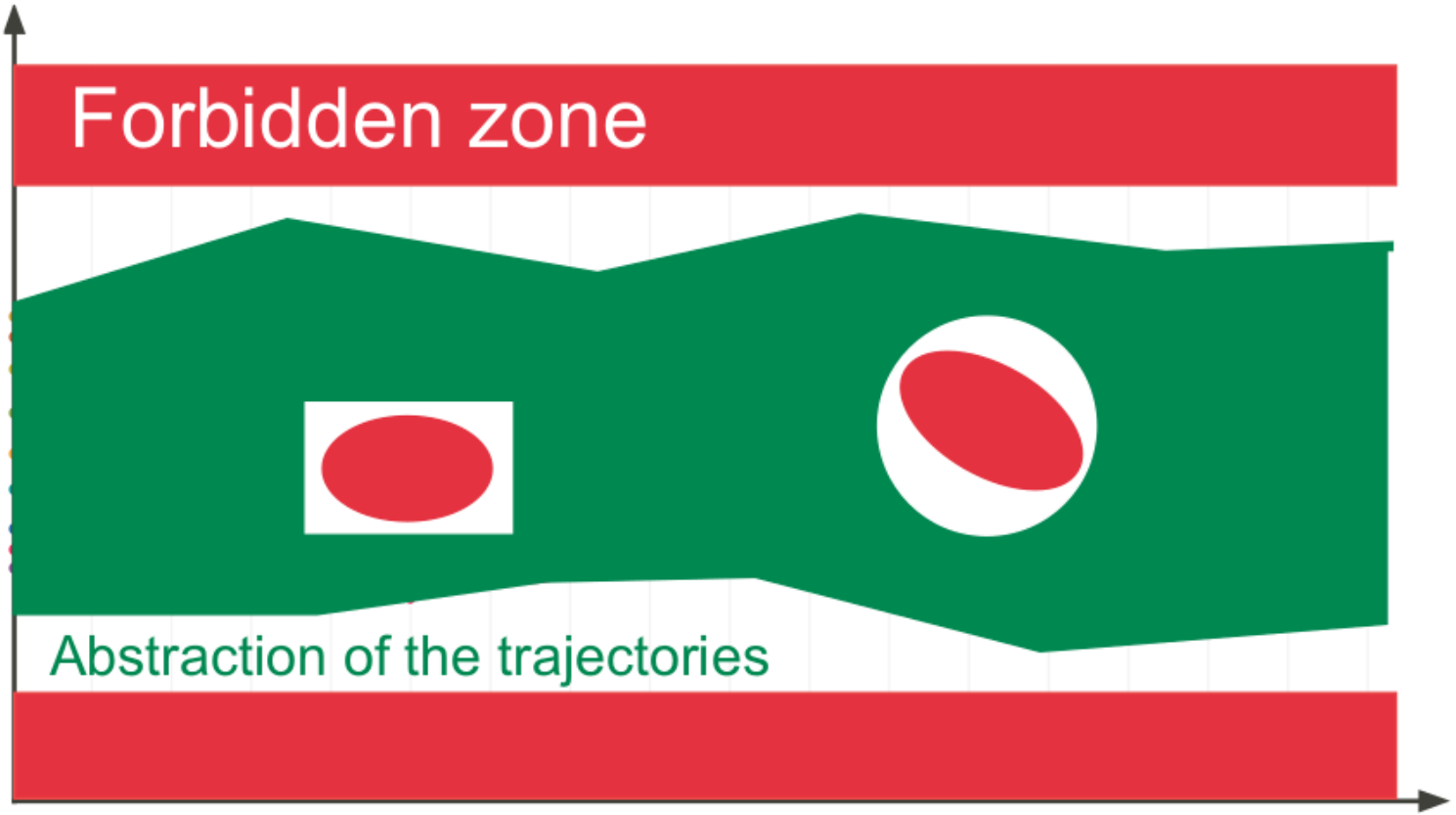


Using testing



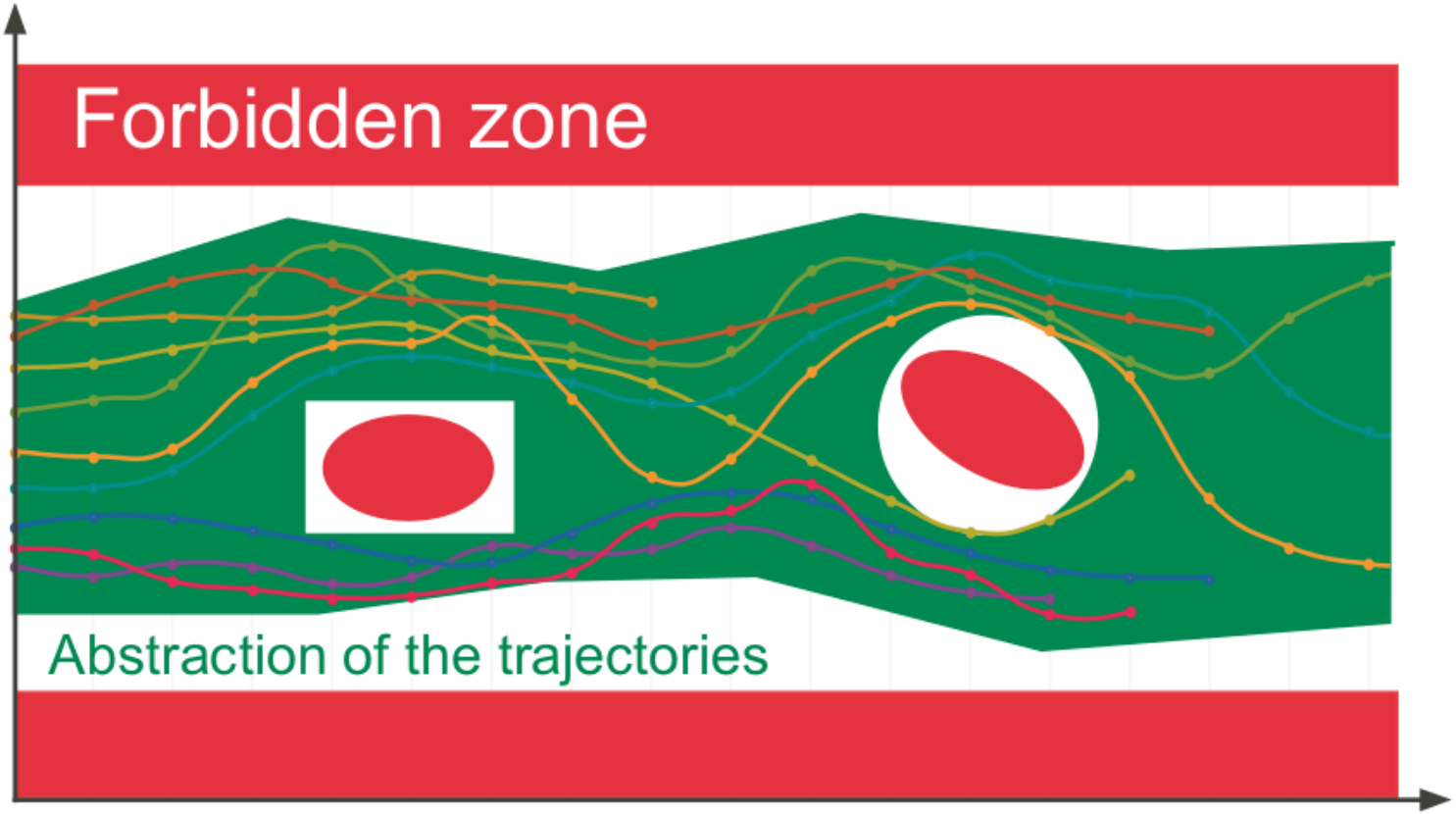
$abstraction(P)$

Abstract Interpretation



$$abstraction(P) \subseteq specification(P)$$

Abstract Interpretation



$$\mathit{semantics}(P) \subseteq \mathit{abstraction}(P) \subseteq \mathit{specification}(P)$$

Reminder

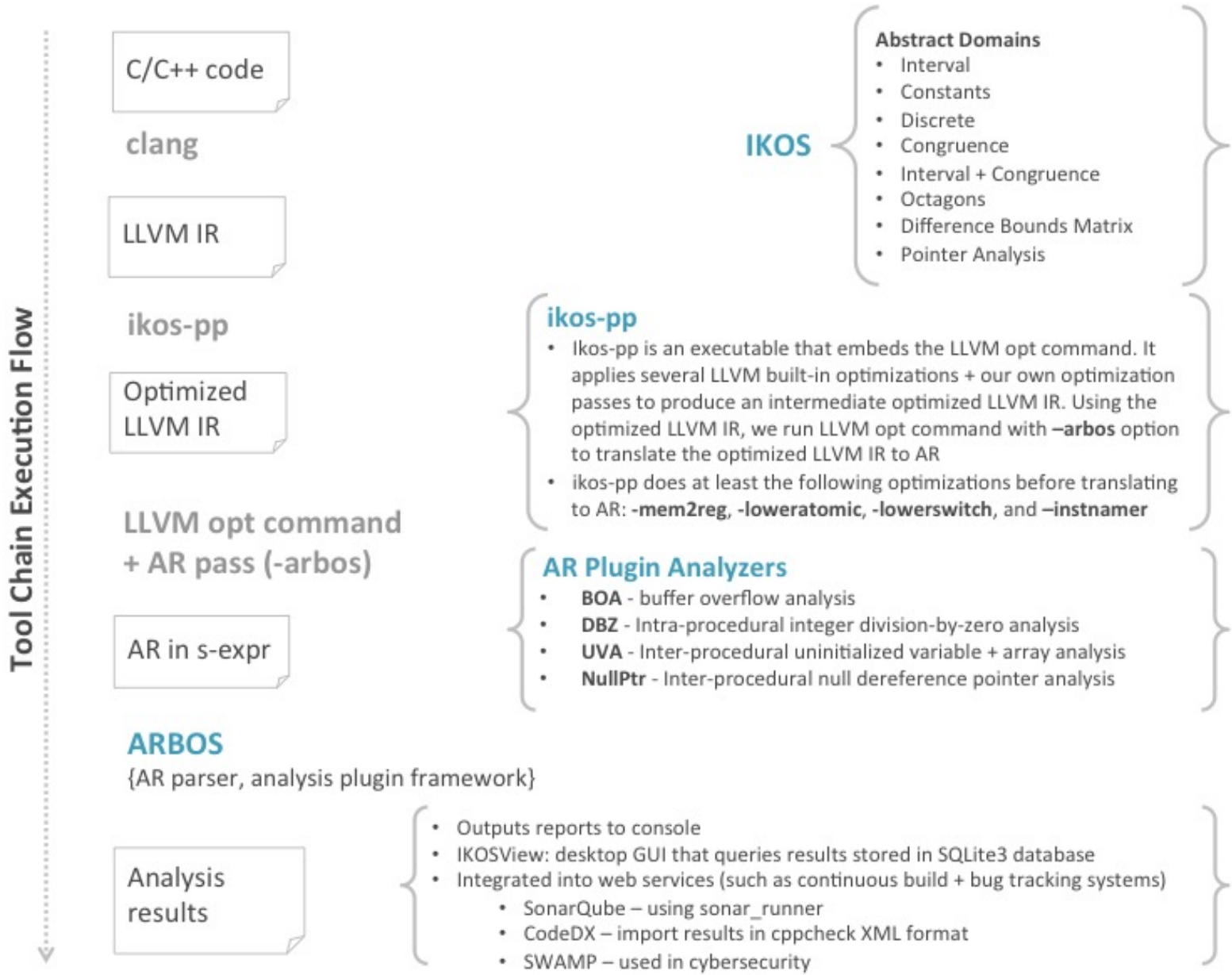
- Thank you Pierre Loïc Garoche

Syllabus

The IKOS project

- Inference Kernel for Open Static Analyzers
- C++ library for abstract interpretation
- C/C++ static analyzer
- Target embedded systems
- Analyses :
  - Buffer overflow
  - Division by zero
  - Null dereference
  - Uninitialized variables
  - Prover
- `https://ti.arc.nasa.gov/opensource/ikos/`

Toolchain


Tool Chain Execution Flow
C/C++ code
clang
LLVM IR
ikos-pp
Optimized LLVM IR
LLVM opt command + AR pass (-arbos)
AR in s-expr
ARBOS
{AR parser, analysis plugin framework}
Analysis results
IKOS
Abstract Domains
Interval
Constants
Discrete
Congruence
Interval + Congruence
Octagons
Difference Bounds Matrix
Pointer Analysis
ikos-pp
Ikos-pp is an executable that embeds the LLVM opt command. It applies several LLVM built-in optimizations + our own optimization passes to produce an intermediate optimized LLVM IR. Using the optimized LLVM IR, we run LLVM opt command with –arbos option to translate the optimized LLVM IR to AR
ikos-pp does at least the following optimizations before translating to AR: -mem2reg, -loweratomic, -lowerswitch, and –instnamer
AR Plugin Analyzers
BOA - buffer overflow analysis
DBZ - Intra-procedural integer division-by-zero analysis
UVA - Inter-procedural uninitialized variable + array analysis
NullPtr - Inter-procedural null dereference pointer analysis
Outputs reports to console
IKOSView: desktop GUI that queries results stored in SQLite3 database
Integrated into web services (such as continuous build + bug tracking systems)
SonarQube – using sonar_runner
CodeDX – import results in cppcheck XML format
SWAMP – used in cybersecurity

LLVM

- Low Level Virtual Machine
- Compiler Infrastructure
- Generic assembly language
- Allow language independent optimization

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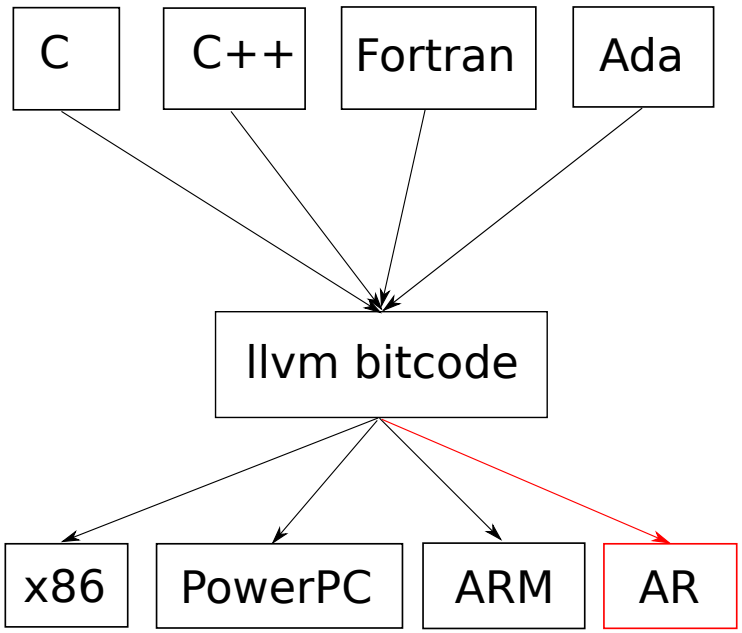
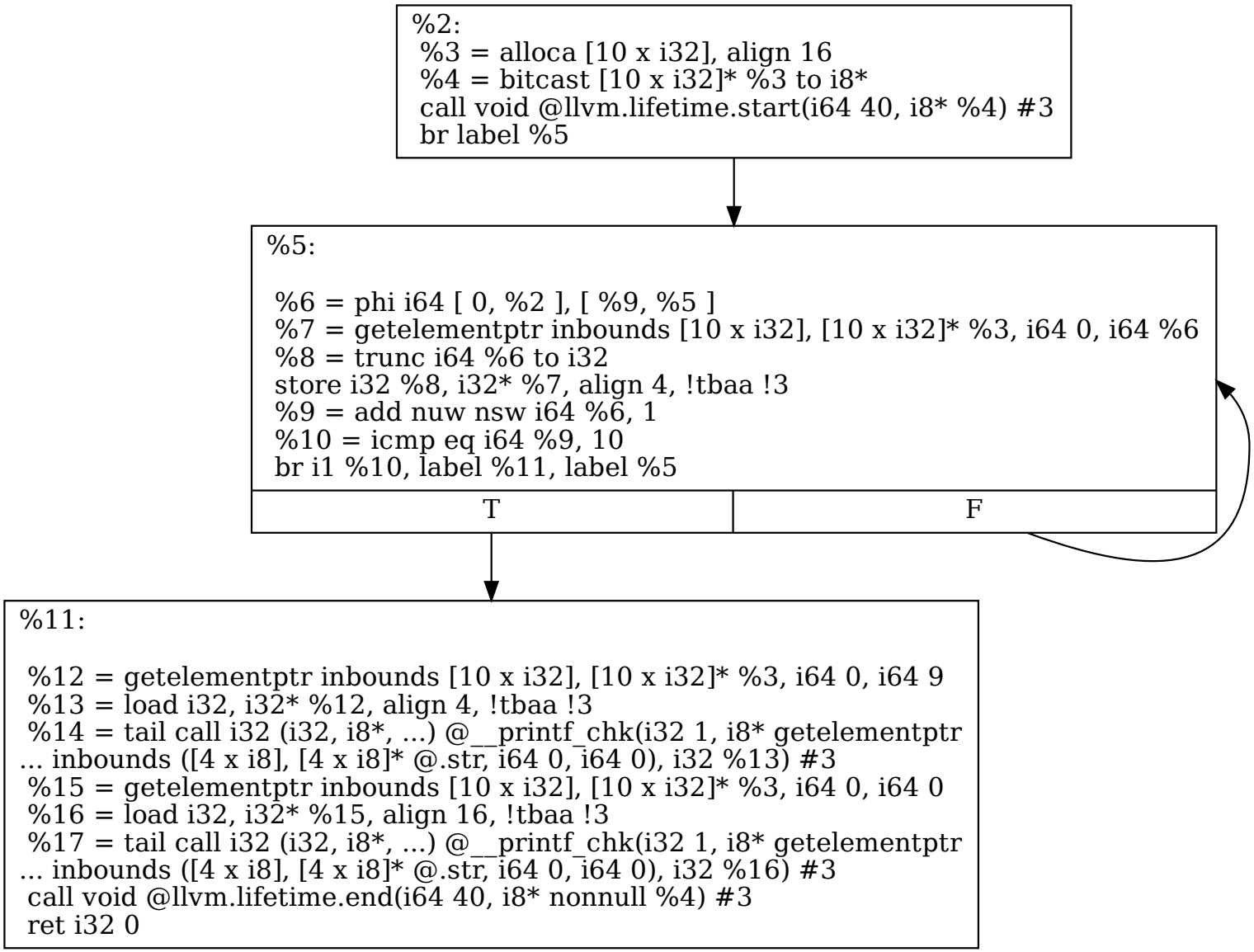


$ cat test.c

```c
#include <stdio.h>

int main(int argc, char** argv) {
  int a[10];
  int i;
  for (i = 0; i < 10; i++) {
    a[i] = i;
  }
  printf("%d\n", a[i - 1]);
  printf("%d\n", a[0]);
  return 0;
}
```

$ clang -c -emit-llvm -O1 -o test.bc test.c
$ opt -S test.bc

```
define i32 @main(i32, i8** nocapture readnone) local_unnamed_addr #0 {
  %3 = alloca [10 x i32], align 16
  %4 = bitcast [10 x i32]* %3 to i8*
  call void @llvm.lifetime.start(i64 40, i8* %4) #3
  br label %5

; <label>:5:                                        ; preds = %5, %2
  %6 = phi i64 [ 0, %2 ], [ %9, %5 ]
  %7 = getelementptr inbounds [10 x i32], [10 x i32]* %3, i64 0, i64 %6
  %8 = trunc i64 %6 to i32
  store i32 %8, i32* %7, align 4
  %9 = add nuw nsw i64 %6, 1
  %10 = icmp eq i64 %9, 10
  br i1 %10, label %11, label %5

; <label>:11:                                       ; preds = %5
  %12 = getelementptr inbounds [10 x i32], [10 x i32]* %3, i64 0, i64 9
  %13 = load i32, i32* %12, align 4
  %14 = tail call i32 (i32, i8*, ...) @__printf_chk(i32 1,
          i8* getelementptr inbounds ([4 x i8], [4 x i8]* @.str, i64 0, i64 0), i32 %13) #3
  %15 = getelementptr inbounds [10 x i32], [10 x i32]* %3, i64 0, i64 0
  %16 = load i32, i32* %15, align 16
  %17 = tail call i32 (i32, i8*, ...) @__printf_chk(i32 1,
          i8* getelementptr inbounds ([4 x i8], [4 x i8]* @.str, i64 0, i64 0), i32 %16) #3
  call void @llvm.lifetime.end(i64 40, i8* nonnull %4) #3
  ret i32 0
}
```

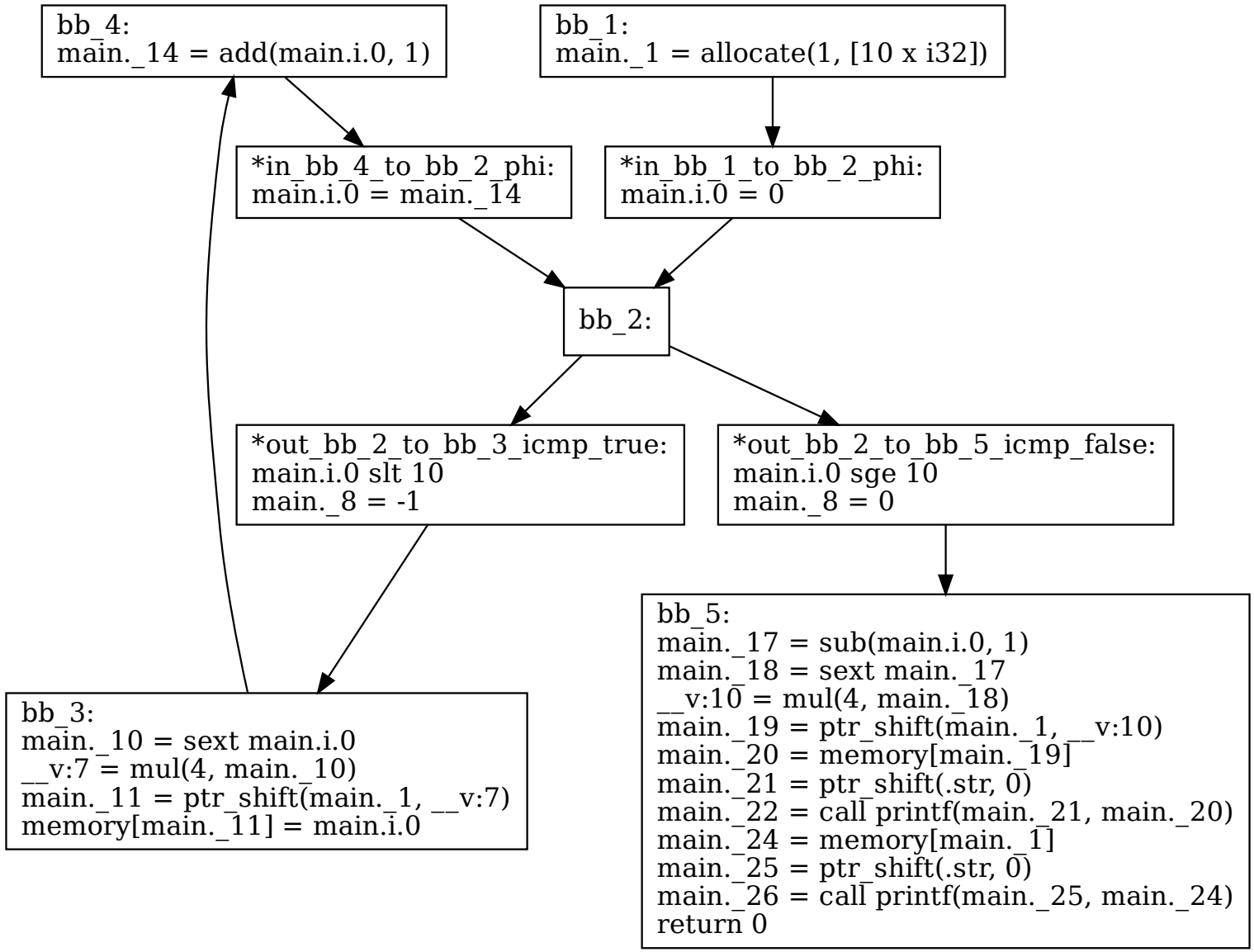

%2:
%3 = alloca [10 x i32], align 16
%4 = bitcast [10 x i32]* %3 to i8*
call void @llvm.lifetime.start(i64 40, i8* %4) #3
br label %5
%5:
%6 = phi i64 [0, %2], [%9, %5]
%7 = getelementptr inbounds [10 x i32], [10 x i32]* %3, i64 0, i64 %6
%8 = trunc i64 %6 to i32
store i32 %8, i32* %7, align 4, !tbaa !3
%9 = add nuw nsw i64 %6, 1
%10 = icmp eq i64 %9, 10
br i1 %10, label %11, label %5
T
F
%11:
%12 = getelementptr inbounds [10 x i32], [10 x i32]* %3, i64 0, i64 9
%13 = load i32, i32* %12, align 4, !tbaa !3
%14 = tail call i32 (i32, i8*, ...) @__printf_chk(i32 1, i8* getelementptr
... inbounds ([4 x i8], [4 x i8]* @.str, i64 0, i64 0), i32 %13) #3
%15 = getelementptr inbounds [10 x i32], [10 x i32]* %3, i64 0, i64 0
%16 = load i32, i32* %15, align 16, !tbaa !3
%17 = tail call i32 (i32, i8*, ...) @__printf_chk(i32 1, i8* getelementptr
... inbounds ([4 x i8], [4 x i8]* @.str, i64 0, i64 0), i32 %16) #3
call void @llvm.lifetime.end(i64 40, i8* nonnull %4) #3
ret i32 0

IKOS-PP

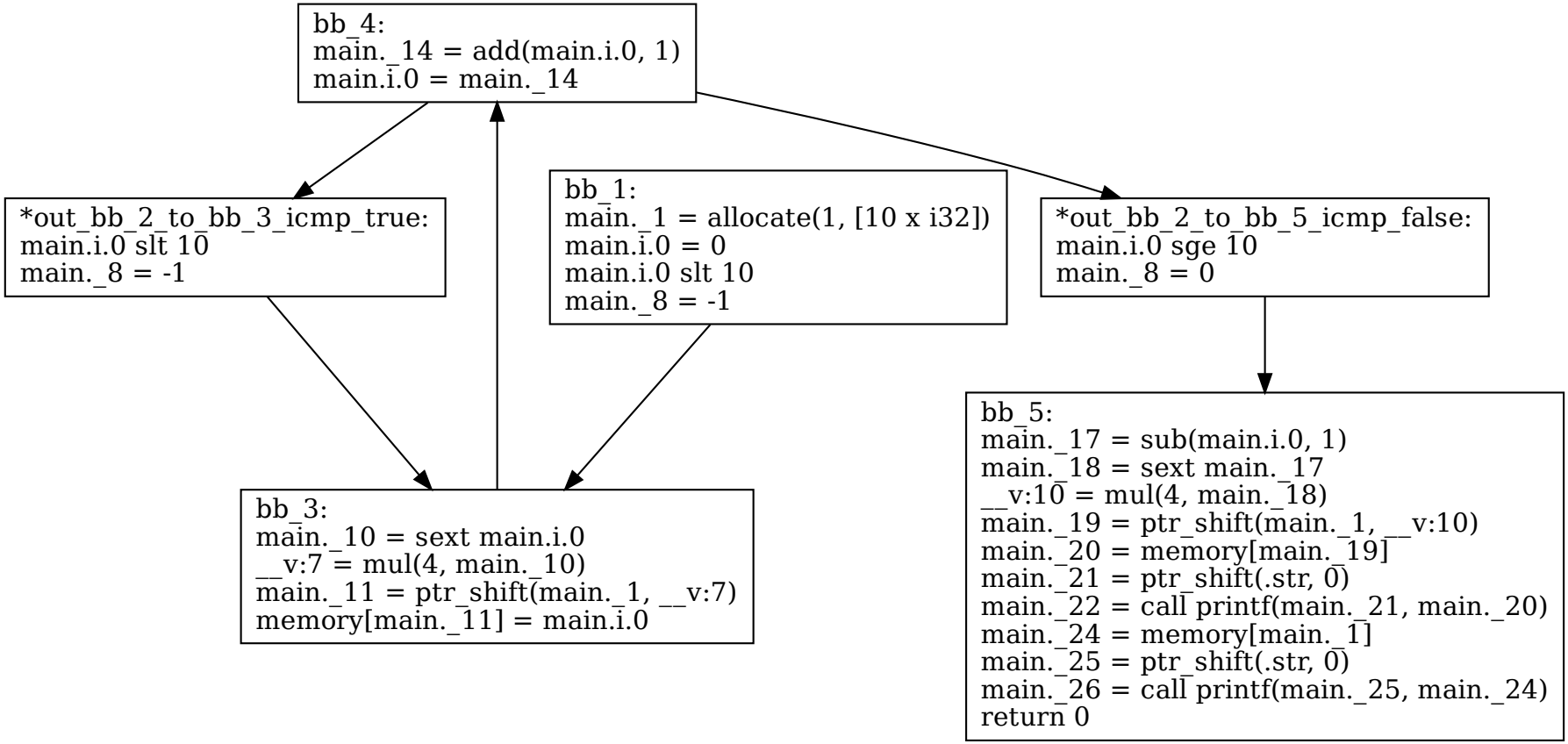
- IKOS pre-processor
- Run llvm optimization passes :
  - mem2reg : SSA Form
  - globaldce : Dead Code Elimination
  - globalopt : Global Variable Optimizer
  - simplifycfg : Control Flow Graph Optimizer
  - scalarrepl : Scalar Replacement of Aggregates
  - sccp : Sparse Conditional Constant Propagation
  - loop-simplify : Canonical Form for Loops
  - lcssa : Loop Closed SSA Form
  - loop-deletion : Dead Loop Elimination
  - lowerinvoke : Lower Invoke Instructions
  - lowerswitch : Lower Switch Instructions
- Run home made llvm passes :
  - Lower Global Variable Initialization
  - Lower Constant Expressions
  - Lower Select Instructions
  - Name Values

- Abstract Representation
- Major differences with llvm :
  - Branching instructions are translated into assertions
  - Memory instructions are byte oriented
  - Some instructions are removed
- Translation from llvm to AR using a llvm pass
- Text representation using s-expressions

```
($function
 ($name ($main)) ($ty (!8))
 ($params ($p ($name ($main.arg_1)) ($ty (!9))) ($p ($name ($main.arg_2)) ($ty (!10))))
 ($local_vars ($local_var ($var ($name ($main._1)) ($ty (!11)))))
 ($code
   ($entry ($bb_1)) ($exit ($bb_5)) ($unreachable) ($ehresume)
   ($basicblocks
     ($basicblock ($name ($bb_1))
       ($instructions
         ($allocate ($dest ($cst ($localvariableref ($name ($main._1)) ($ty (!11)))))
                    ($alloca_ty (!12)) ($array_size ($cst ($constantint ($val (#1)) ($ty (!9)))))
                    ($debug ($srcloc ($line (#-1)) ($col (#-1)) ($file (!2)))))
       )
     )
     ($basicblock
       ($name ($*in_bb_1_to_bb_2_phi))
       ($instructions
         ($assign ($lhs ($var ($name ($main.i.0)) ($ty (!9))))
                  ($rhs ($cst ($constantint ($val (#0)) ($ty (!9)))))
                  ($debug ($srcloc ($line (#6)) ($col (#10)) ($file (!13)))))
       )
     )
     [...]
   )
   ($trans
     ($edge ($bb_1) ($*in_bb_1_to_bb_2_phi))
     ($edge ($*in_bb_1_to_bb_2_phi) ($bb_2))
     ($edge ($bb_2) ($*out_bb_2_to_bb_3_icmp_true))
     ($edge ($bb_2) ($*out_bb_2_to_bb_5_icmp_false))
     ($edge ($*in_bb_4_to_bb_2_phi) ($bb_2))
     [...]
   )
 )
)
```


bb_4:
main._14 = add(main.i.0, 1)
bb_1:
main._1 = allocate(1, [10 x i32])
*in_bb_4_to_bb_2_phi:
main.i.0 = main._14
*in_bb_1_to_bb_2_phi:
main.i.0 = 0
bb_2:
*out_bb_2_to_bb_3_icmp_true:
main.i.0 slt 10
main._8 = -1
*out_bb_2_to_bb_5_icmp_false:
main.i.0 sge 10
main._8 = 0
bb_3:
main._10 = sext main.i.0
__v:7 = mul(4, main._10)
main._11 = ptr_shift(main._1, __v:7)
memory[main._11] = main.i.0
bb_5:
main._17 = sub(main.i.0, 1)
main._18 = sext main._17
__v:10 = mul(4, main._18)
main._19 = ptr_shift(main._1, __v:10)
main._20 = memory[main._19]
main._21 = ptr_shift(.str, 0)
main._22 = call printf(main._21, main._20)
main._24 = memory[main._1]
main._25 = ptr_shift(.str, 0)
main._26 = call printf(main._25, main._24)
return 0

- Load an Abstract Representation file (*.ar*) and apply passes
- Similar to llvm *opt* command
- IKOS passes :
  - ps-opt : Optimize pointer shift statements
  - branching-opt : Optimize the Control Flow Graph
  - inline-init-gv : Inline initialization of global variables in main
  - unify-exit-nodes : Unify exit nodes
  - analyzer : Analyzer pass


bb_4:
main._14 = add(main.i.0, 1)
main.i.0 = main._14
*out_bb_2_to_bb_3_icmp_true:
main.i.0 slt 10
main._8 = -1
bb_1:
main._1 = allocate(1, [10 x i32])
main.i.0 = 0
main.i.0 slt 10
main._8 = -1
*out_bb_2_to_bb_5_icmp_false:
main.i.0 sge 10
main._8 = 0
bb_3:
main._10 = sext main.i.0
__v:7 = mul(4, main._10)
main._11 = ptr_shift(main._1, __v:7)
memory[main._11] = main.i.0
bb_5:
main._17 = sub(main.i.0, 1)
main._18 = sext main._17
__v:10 = mul(4, main._18)
main._19 = ptr_shift(main._1, __v:10)
main._20 = memory[main._19]
main._21 = ptr_shift(.str, 0)
main._22 = call printf(main._21, main._20)
main._24 = memory[main._1]
main._25 = ptr_shift(.str, 0)
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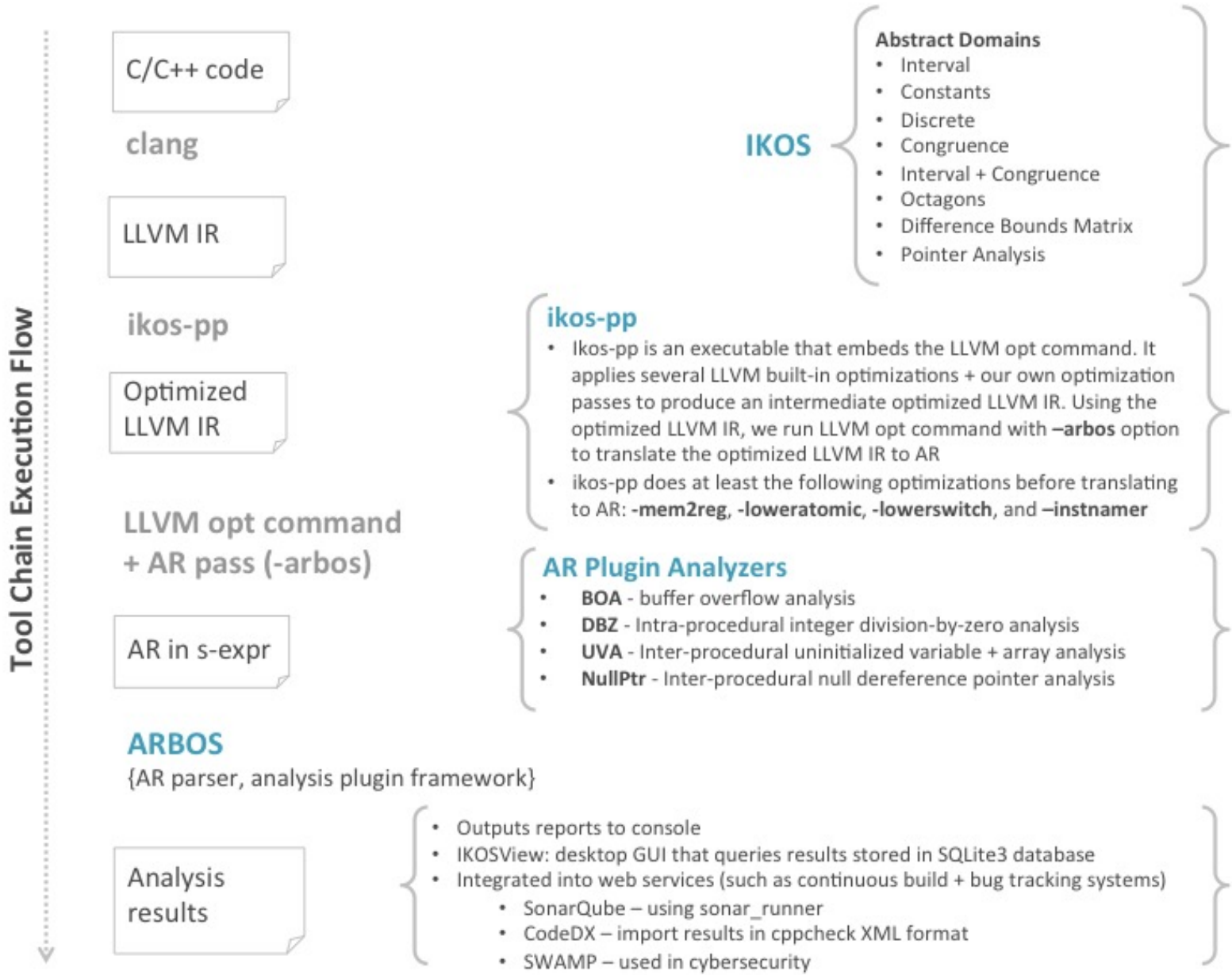
Analyzer

- Liveness analysis
- Pointer analysis
- Memory analysis combining :
  - Numerical analysis
  - Pointer analysis
  - Uninitialized variable analysis
  - Null pointer analysis
- Checkers :
  - buffer overflow
  - division by zero
  - null dereference
  - uninitialized variables
  - assertion prover
- Store results in a SQLite database

Report

- The toolchain is launched via a python script
- Generate reports in different formats :
  - Console (gcc style)
  - JSON
  - XML
  - etc.
- Output database reusable (using *ikos-render*)

Toolchain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LLVM opt command + AR pass (-arbos)
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Integrated into web services (such as continuous build + bug tracking systems)
SonarQube – using sonar_runner
CodeDX – import results in cppcheck XML format
SWAMP – used in cybersecurity

Demo

Demo.

Aeroquad - The Open Source Quadcopter

- Code size :
  - lines of code : 167k
  - bitcode instructions : 4634
- Time stats :
  - arbos : 1 min 51.888 sec
  - ikos-pp : 0.126 sec
  - llvm-to-ar : 0.898 sec
- Summary :
  - number of checks : 2908
  - number of unreachable checks : 46 (1.6%)
  - number of safe checks : 2688 (92.4%)
  - number of definite unsafe checks : 0
  - number of warnings : 174 (5.9%)

Aeroquad - The Open Source Quadcopter

- Writes at specific addresses :

```
*(0x42) = x;
```

- False positives on loops with casts :

```
for (byte axis = 0; axis < 3; axis++) {
  accelSample[axis] = 0;
}
```

- Tricky array indexing :

```
static byte receiverPin[6] =
  {2, 5, 6, 4, 7, 8};
pinData[receiverPin[channel]].edge =
  FALLING_EDGE;
```

Paparazzi - Autopilot System for UAV

- Code size :
  - lines of code : 23k
  - bitcode instructions : 4436
- Time stats :
  - arbos : 1 min 2.930 sec
  - ikos-pp : 0.132 sec
  - llvm-to-ar : 1.111 sec
- Summary :
  - number of checks : 2372
  - number of unreachable checks : 352 (14.8%)
  - number of safe checks : 2020 (85.2%)
  - number of definite unsafe checks : 0
  - number of warnings : 0

GEN2

- Code size :
  - lines of code : 13k
  - bitcode instructions : 5340
- Time stats :
  - arbos : 2 min 16.161 sec
  - ikos-pp : 0.199 sec
  - llvm-to-ar : 1.358 sec
- Summary :
  - number of checks : 3121
  - number of unreachable checks : 0
  - number of safe checks : 3028 (97.1%)
  - number of definite unsafe checks : 0
  - number of warnings : 93 (2.9%)

MNAV

- Code size :
  - lines of code : 159k
  - bitcode instructions : 2145
- Time stats :
  - arbos : 12.950 sec
  - ikos-pp : 0.056 sec
  - llvm-to-ar : 0.468 sec
- Summary :
  - number of checks : 430
  - number of unreachable checks : 17 (3.9%)
  - number of safe checks : 330 (76.7%)
  - number of definite unsafe checks : 0
  - number of warnings : 83 (19.3%)

CASS

- Time stats :
  - arbos : 1 day 2 hour 17.463 sec
  - ikos-pp : 13.234 sec
  - llvm-to-ar : 24.431 sec
- Summary :
  - number of checks : 254452
  - number of unreachable checks : 33300 (13.0%)
  - number of safe checks : 172521 (67.8%)
  - number of definite unsafe checks : 0
  - number of warnings : 48631 (19.1%)

Results

FLTz - flight simulator with OpenGL displays

- Code size :
  - lines of code : 91k
  - bitcode instructions : 14501
- Time stats :
  - arbos : 5 day 9 hour 27 min 41.459 sec
  - ikos-pp : 25.211 sec
  - llvm-to-ar : 1 min 2.661 sec
- Summary :
  - number of checks : 1302470
  - number of unreachable checks : 72409 (5.5%)
  - number of safe checks : 153312 (11.7%)
  - number of definite unsafe checks : 19 (0.001%)
  - number of warnings : 1076730 (82.6%)

Syllabus

Liveness analysis

- Mark *live* and *dead* variables after each basic block
- Dataflow analysis
- Used to clean up variables in the abstract domain
- Problem for relationnal domains

Liveness analysis - Algorithm

- Kill - Gen algorithm
- $GEN[b]$: set of variables used in b before any assignment
- $KILL[b]$: set of variables that are assigned in b

Liveness analysis - Algorithm

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- $GEN[b]$: set of variables used in b before any assignment
- $KILL[b]$: set of variables that are assigned in b

- $GEN[stmt : y \leftarrow f(x_1, \cdots, x_n)] = \{x_1, ..., x_n\}$
- $KILL[stmt : y \leftarrow f(x_1, \cdots, x_n)] = \{y\}$

Liveness analysis - Algorithm

- Kill - Gen algorithm
- $GEN[b]$: set of variables used in b before any assignment
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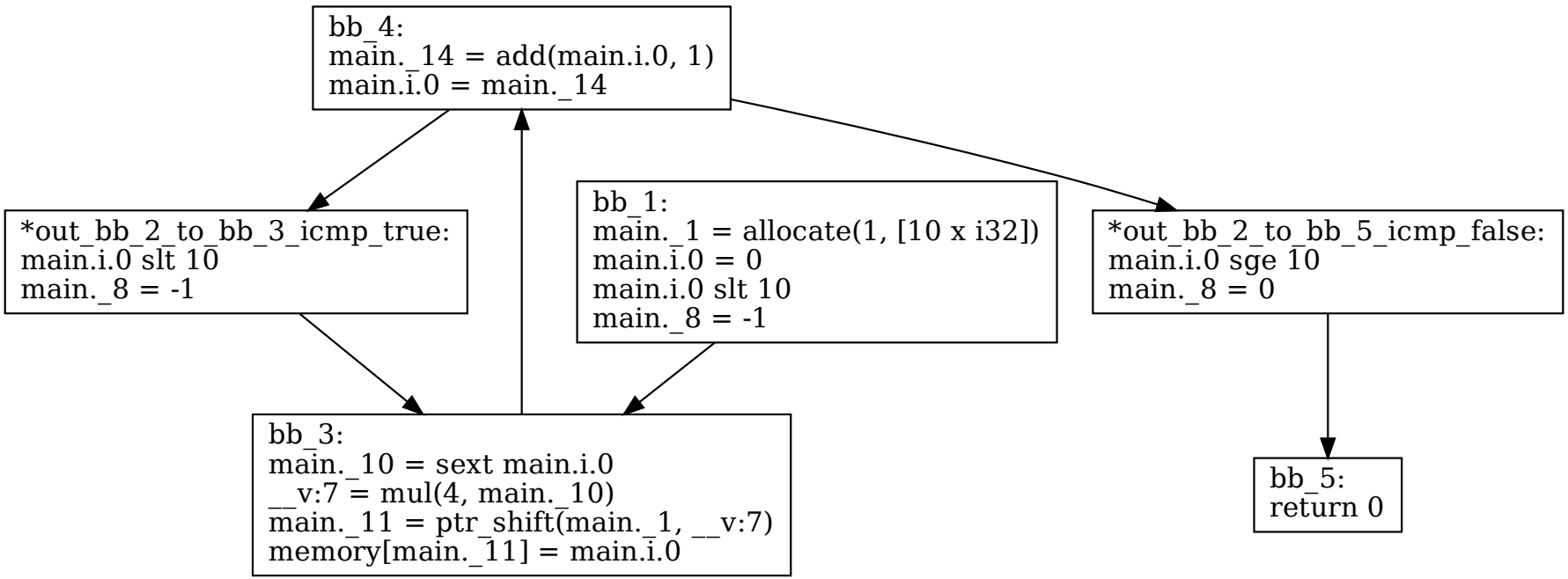
- $KILL[stmt : y \leftarrow f(x_1, \cdots, x_n)] = \{y\}$

- $LIVE_{in}[b] = GEN[b] \cup (LIVE_{out}[b] - KILL[b])$
- $LIVE_{out}[b] = \bigcup_{p \in succ[b]} LIVE_{in}[p]$
- $LIVE_{out}[final] = \emptyset$

Liveness analysis - Example



Pointer analysis

- Pointer analysis : What memory locations can a pointer expression refer to ?
- Alias analysis : Are two pointers refering to the same locations ?
- Intraprocedural vs Interprocedural
- Flow sensitive vs Flow insensitive
- Context sensitive vs Context insensitive

Pointer analysis - Model

- How to model memory locations ?
- Global variables : use symbolic names (e.g, g)
- Local variables : use symbolic names (e.g, $main.x$)
- Dynamically allocated memory : use symbolic names ?
  - Problem : potentially unbounded locations (think about a loop)
  - Solution : use symbolic names with an instruction counter (e.g, $blk(l, \lambda)$)

Pointer analysis - Andersen's algorithm

- Andersen's pointer analysis
- For each pointer p, we call T_p the set of memory locations pointed by p
- Goal : find T_p for each pointer p
- Idea : view pointer assignments as subset constraints
- Complexity : $O(n^3)$, worst case $O(n^4)$

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- For each pointer p, we call T_p the set of memory locations pointed by p
- Goal : find T_p for each pointer p
- Idea : view pointer assignments as subset constraints
- Complexity : $O(n^3)$, worst case $O(n^4)$

- $p = \&x \Leftrightarrow T_p \supseteq \{x\}$
- $p = q + o \Leftrightarrow T_p \supseteq T_q$
- $p = *q \Leftrightarrow T_p \supseteq *T_q \Leftrightarrow \forall x \in T_q, T_p \supseteq O(x)$
- $*p = q \Leftrightarrow *T_p \supseteq T_q \Leftrightarrow \forall x \in T_p, O(x) \supseteq T_q$

Pointer analysis - Andersen's algorithm

- Andersen's pointer analysis
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- How to solve the constraints system ? A fix point, of course !

Pointer analysis - Andersen's algorithm

Example :

- $p = \&a$
- $q = \&b$
- $*p = q$
- $r = \&c$
- $s = p$
- $t = *p$
- $*s = r$

Example :

- $p = \&a \Leftrightarrow T_p \supseteq \{a\}$
- $q = \&b \Leftrightarrow T_q \supseteq \{b\}$
- $*p = q \Leftrightarrow *T_p \supseteq T_q$
- $r = \&c \Leftrightarrow T_r \supseteq \{c\}$
- $s = p \Leftrightarrow T_s \supseteq T_p$
- $t = *p \Leftrightarrow T_t \supseteq *T_p$
- $*s = r \Leftrightarrow *T_s \supseteq T_r$

Exercice : solve it !

Solution :

- $T_p = \{a\}$
- $T_q = \{b\}$
- $T_r = \{c\}$
- $T_s = \{a\}$
- $T_t = \{b, c\}$
- $O(a) = \{b, c\}$
- $O(b) = \emptyset$
- $O(c) = \emptyset$

Pointer analysis - Steensgaard's algorithm

- Steensgaard's pointer analysis
- Idea : view pointer assignments as equality constraints

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Pointer analysis - Steensgaard's algorithm

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- Question : Is it more or less precise ? Why ?
- Question : Complexity ?

Pointer analysis - Steensgaard's algorithm

- Steensgaard is less precise than Andersen's algorithm
- Each equality constraint is equivalent to 2 inclusion constraints
- Steensgaard's constraints system include Andersen's constraints
- Think fix point : once you reached Andersen's system fix point solution, you will keep growing to satisfy equality constraints
- Complexity : $O(nlog(n))$ (process each constraint once using union-find)

Solution :

- $T_p = T_s = \{a\}$
- $T_q = T_t = T_r = O(a) = \{b, c\}$
- $O(b) = \emptyset$
- $O(c) = \emptyset$

Pointer analysis - IKOS

- IKOS uses Andersen's approach
- Based on Arnaud Venet's paper : « A Scalable Nonuniform Pointer Analysis for Embedded Programs », SAS 2004
- Compute points-to set (Andersen) and offset (Intervals) for each pointer
- $\mathbb{D}^{\#} = \mathbb{P} \rightarrow (\mathbb{A} \cup \{\top\}) \times \mathbb{I}$
- Interprocedural
- Flow insensitive
- Context insensitive

Memory analysis

- Memory analysis (also called Value analysis) based on a reduced domain product of :
  - Numerical domain for integers (by default, intervals)
  - Pointer domain
  - Null pointer domain
  - Uninitialized variable domain
  - Floating points are currently ignored
- Based on Antoine Mine's paper : « Field-Sensitive Value Analysis of Embedded C Programs with Union Types and Pointer Arithmetics », LCTES'06
- Interprocedural
- Context sensitive

Memory analysis - Pointer domain

- Pointer abstract domain
- $\mathbb{D}_p^\# = \mathbb{V} \to (\mathbb{A} \cup \{\top\}) \times \mathbb{I}$
- Pointwise order $\sqsubseteq_p^\#$, Pointwise union $\sqcup_p^\#$
- $(\mathbb{D}_p^\#, \sqsubseteq_p^\#, \sqcup_p^\#)$ is a lattice
- Galois connection (α_p, γ_p) with the concrete semantics
- Reduction with the previous flow-insensitive pointer analysis

- Abstract operations :
  - $[\![p = \&x]\!]^{\#}(\rho) = \rho\ [p \rightarrow (\{x\}, [0, 0])]$
  - $[\![p = q + o]\!]^{\#}(\rho) = \rho\ [p \rightarrow (\mathit{addresses}(\rho(q)), \mathit{offsets}(\rho(q)) + o]$
  - $[\![*p = q]\!]^{\#}(\rho) = \rho$
  - $[\![p = *q]\!]^{\#}(\rho) = \rho\ [p \rightarrow (\top,]-\infty, +\infty[)]$

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  - $[\![*p = q]\!]^{\#}(\rho) = \rho$
  - $[\![p = *q]\!]^{\#}(\rho) = \rho\ [p \rightarrow (\top,]-\infty, +\infty[)]$
- Question : $[\![p == q]\!]^{\#}(\rho) = ?$
- Question : $[\![p \neq q]\!]^{\#}(\rho) = ?$

Memory analysis - Null pointer domain

- Null pointer abstract domain
- $D_n = \{\bot, \mathit{Null}, \mathit{NonNull}, \top\}$
- $\mathbb{D}_n^\# = \mathbb{V} \to D_n$
- $\bot \sqsubseteq_n^\# \mathit{Null}$, $\bot \sqsubseteq_n^\# \mathit{NonNull}$, $\mathit{Null} \sqsubseteq_n^\# \top$, $\mathit{NonNull} \sqsubseteq_n^\# \top$
- $\mathit{Null} \sqcup_n^\# \mathit{NonNull} = \top$
- $(\mathbb{D}_n^\#, \sqsubseteq_n^\#, \sqcup_n^\#)$ is a lattice
- Galois connection (α_n, γ_n) with the concrete semantics

Memory analysis - Uninitialized variable domain

- Uninitialized variable abstract domain
- $D_u = \{\bot, \mathit{Init}, \mathit{Uninit}, \top\}$
- $\mathbb{D}_u^\# = \mathbb{V} \to D_u$
- $\bot \sqsubseteq_u^\# \mathit{Init}$, $\bot \sqsubseteq_u^\# \mathit{Uninit}$, $\mathit{Init} \sqsubseteq_u^\# \top$, $\mathit{Uninit} \sqsubseteq_u^\# \top$
- $\mathit{Init} \sqcup_u^\# \mathit{Uninit} = \top$
- $(\mathbb{D}_u^\#, \sqsubseteq_u^\#, \sqcup_u^\#)$ is a lattice
- Galois connection (α_u, γ_u) with the concrete semantics

Memory analysis - Memory model

- Question : how to model the memory ?
- LLVM is low level, a byte representation is necessary
- The C language is not type safe and is very permissive on casts

Memory analysis - Memory model

- Question : how to model the memory ?
- LLVM is low level, a byte representation is necessary
- The C language is not type safe and is very permissive on casts

We need to model correctly the following code :

```
uint64_t x = 1;
uint32_t* p = (uint32_t*)&x;
p += 1;
uint32_t y = *p;
```

By the way, what is y's value ?

Memory model from « Formalizing the LLVM Intermediate Representation for Verified Program Transformations », POPL 2012

$$\begin{array}{rl} \text{Memory cell mc} = & \mid \text{mb}(\mathit{size}, \mathit{byte}) \\ & \mid \text{mptr}(\mathit{blk}, \mathit{offset}, \mathit{index}) \\ & \mid \text{muinit} \end{array}$$

- Memory state $= (N, B, C)$
- N : next block id
- $B = \mathbb{Z}^+ \to \mathbb{Z}^+$: block id to block size (bytes)
- $C = \mathbb{Z}^+ \times \mathbb{Z}^+ \to \mathbb{MC}$: (block id, offset in bytes) to memory cell

Example :

```
int* p = (int*) malloc(sizeof(int) + sizeof(int*));
*p = 0x01020304;
int** q = (int**)(p + 1);
*q = p + 2;
```

Example :

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```

blk id	offset	memory cell
0	0	mb(32, 4)
0	1	mb(32, 3)
0	2	mb(32, 2)
0	3	mb(32, 1)
0	4	mptr(l, 8, 0)
0	5	mptr(l, 8, 1)
0	6	mptr(l, 8, 2)
0	7	mptr(l, 8, 3)

By the way, what architecture could it be ?

Memory analysis - Memory abstract domain

- Memory abstract domain
- Based on Antoine Mine's paper : « Field-Sensitive Value Analysis of Embedded C Programs with Union Types and Pointer Arithmetics », LCTES'06
- Idea : abstract memory using cells : $C(\mathit{address}, \mathit{offset}, \mathit{size})$
- Each cell is considered as a variable in the underlying abstract domain
- Cells may overlap
- $\mathbb{C} = \mathbb{A} \rightarrow \mathbb{Z}^+ \times \mathbb{Z}^+$
- $\mathbb{D}^{\#}_{\mathit{mem}} = \mathbb{C} \times \mathbb{D}^{\#}_{\mathit{underlying}}$
- In IKOS, $\mathbb{D}^{\#}_{\mathit{underlying}} = \mathbb{D}^{\#}_{\mathit{num}} \times \mathbb{D}^{\#}_{\mathit{ptr}} \times \mathbb{D}^{\#}_{\mathit{null}} \times \mathbb{D}^{\#}_{\mathit{unini}}$
- Pointwise partial order, Pointwise union

- Abstract operations : forward to $\mathbb{D}^{\#}_{underlying}$, except memory read and write.
- Memory write :
  - set to $\bot$ if p is null or uninitialized
  - $(points\_to, offset) = \rho(p)$
  - $cells = realize\_write(points\_to, offset)$
  - $\forall c \in cells$, $strong\_update(c, rhs)$ or $weak\_update(c, rhs)$
- Memory read :
  - set to $\bot$ if p is null or uninitialized
  - $(points\_to, offset) = \rho(p)$
  - $cells = realize\_read(points\_to, offset)$
  - $\forall c \in cells$, $strong\_update(lhs, c)$ or $weak\_update(lhs, c)$

Example :

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int* p = (int*) malloc(sizeof(int) + sizeof(int*));
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```
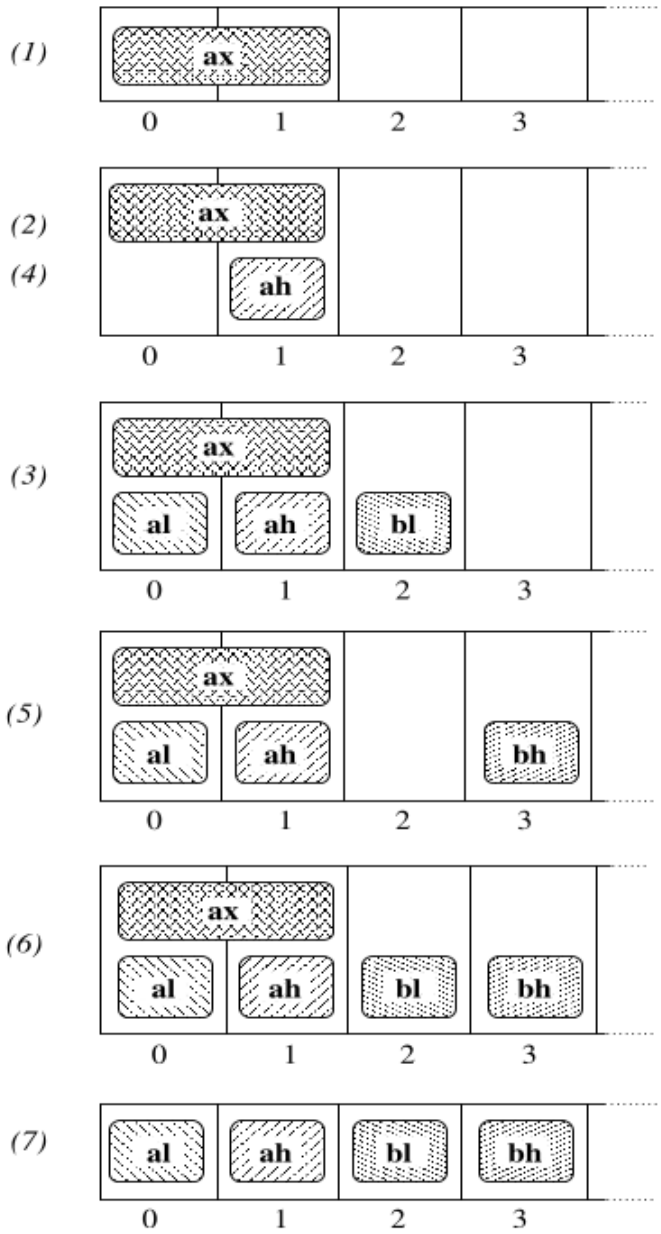

Abstract value at the end :

$(malloc \rightarrow \{\{0,4\},\{4,4\}\})$
$(C(malloc,0,4) \rightarrow [0x01020304, 0x01020304])$
$(C(malloc,4,4) \rightarrow (malloc,[8,8]),$
$\quad p \rightarrow (malloc,[0,0]),$
$\quad q \rightarrow (malloc,[4,4]))$
$(C(malloc,4,4) \rightarrow NonNull, p \rightarrow NonNull, q \rightarrow NonNull)$
$(C(malloc,0,4) \rightarrow Init, C(malloc,4,4) \rightarrow Init, p \rightarrow Init, q \rightarrow Init))$

```
static union {
  struct { uint8 al, ah, bl, bh, ... } b;
  struct { uint16 ax, bx, ... } w;
} regs;
regs.w.ax = X; // (1)
if (!regs.b.ah) { // (2)
  regs.b.bl = regs.b.al; // (3)
} else { // (4)
  regs.b.bh = regs.b.al; // (5)
}
// (6)
regs.b.al = X; // (7)
```

Memory analysis - Memory abstract domain



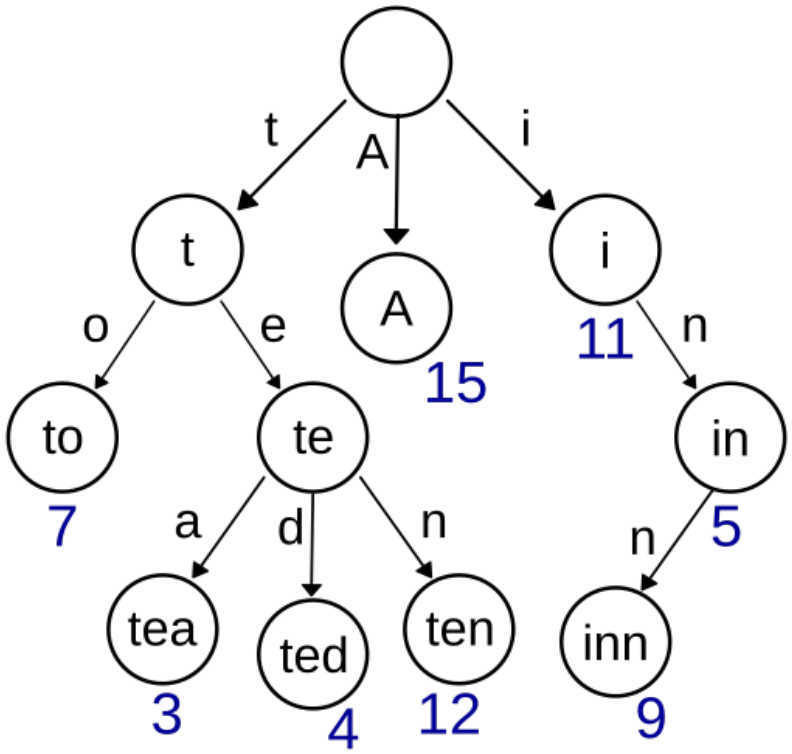
Property checking

- Last step : check for properties at each statement location
- Checkers :
  - buffer overflow : $0 <= \mathit{offset}$ and $\mathit{offset} + \mathit{read\_size} <= \mathit{buffer\_size}$
  - division by zero : $\mathit{divisor} \neq 0$
  - null dereference : $p \neq \mathit{Null}$
  - uninitialized variable : $v \neq \mathit{Uninit}$
  - prover : $v \neq 0$

Syllabus

Abstract domains implementation

- Separate domain ($\mathbb{V} \to \mathbb{D}$) are implemented with patricia trees
- Insertion and removal in $O(log(n))$
- Merge in $O(n)$
- Transformation in $O(n)$
- Very cheap union !



Analyzing C++

Analyzing C++ is very tricky :

- Heavy chains of function calls because of templates
- The libc++ needs to be modeled
- Need to be precise on pointers for virtual method calls
- Handle exceptions

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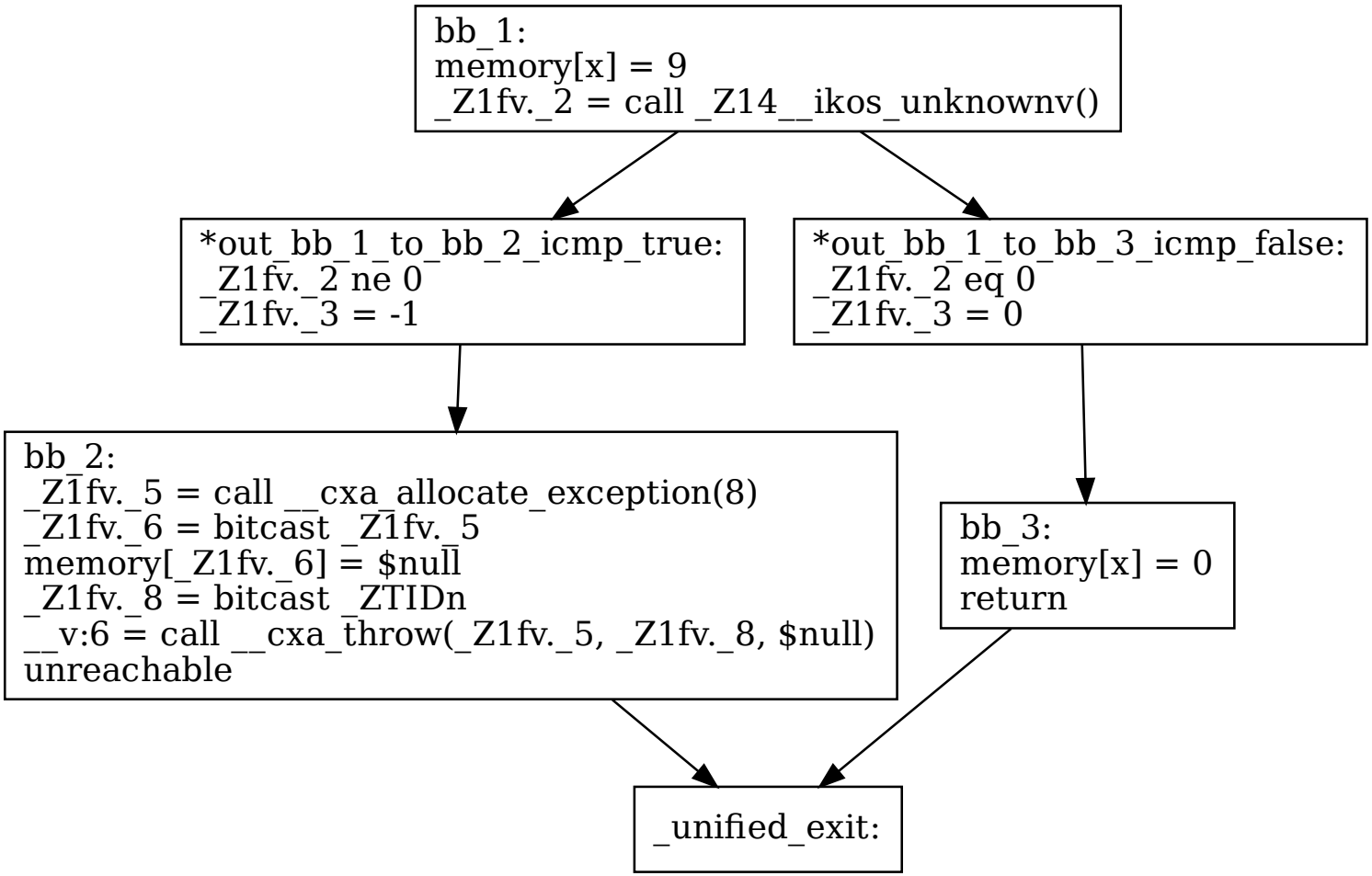
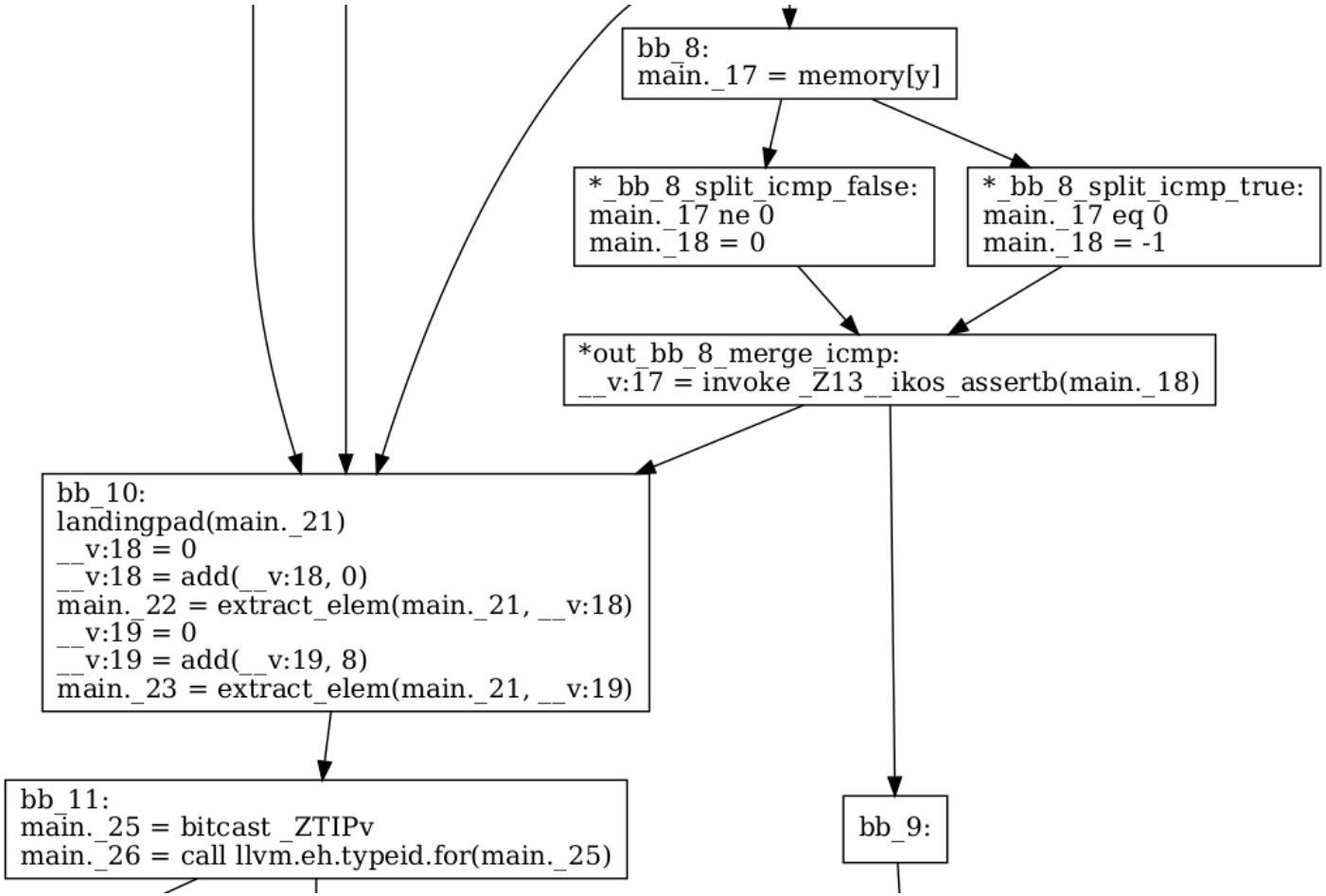
Work in progress !

Exception handling



Exception handling



Exception handling

- $\mathbb{D}^{\#}_{exc} = \mathbb{D}^{\#} \times \mathbb{D}^{\#}$
- $[\![throw(e)]\!]^{\#}(N, E) = (\bot, N \cup E)$
- $[\![landingpad(e)]\!]^{\#}(N, E) = (E, \bot)$
- $[\![v = x]\!]^{\#}(N, E) = ([\![v = x]\!]^{\#}(N), E)$
- $(N_1, E_1) \sqcup^{\#} (N_2, E_2) = (N_1 \cup N_2, E_1 \cup E_2)$

Relational abstract domains

- Intervals are very imprecise for loops with a non-deterministic bound
- Solution : use a weakly-relational domain, such as the DBM domain
- Based on Antoine Mine's paper : «A New Numerical Abstract Domain Based on Difference-Bound Matrices », PADO, 155-172, 2001.

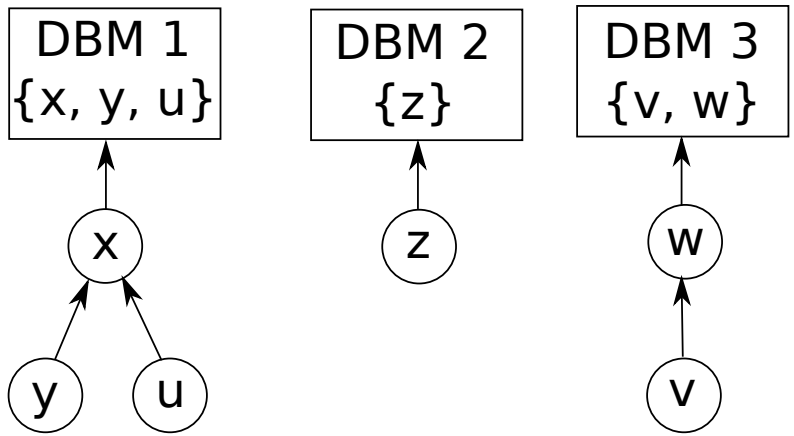
- Difference-Bound Matrices
- Weakly-relational abstract domain

$$\begin{bmatrix} 0 & m_{0,1} & m_{0,2} & \dots & m_{0,n} \\ m_{1,0} & 0 & m_{1,2} & \dots & m_{1,n} \\ m_{2,0} & m_{2,1} & 0 & \dots & m_{2,n} \\ \dots & \dots & \dots & \dots & \dots \\ m_{n,0} & m_{n,1} & m_{n,2} & \dots & 0 \end{bmatrix}$$

- $m_{i,j} \in \mathbb{Z} \cup \{+\infty\}$
- $v_i - v_j \leq m_{j,i}$
- $v_0 = 0$, thus $v_i \in [-m_{i,0}, m_{0,i}]$
- Abstract operations require normalization
- normalization :
  $v_i - v_k \leq m_{k,i}$ and
  $v_k - v_j \leq m_{j,k} \Rightarrow$
  $v_i - v_j \leq m_{k,i} + m_{j,k}$
- cost $O(n^3)$, n number of variables

Variable packing

- Idea : keep a list of DBMs, where each DBM contains variables that are related to each other.
- Union-Find structure to dynamically infer relations among variables
- Normalization cost $O(n)$, n number of DBMs



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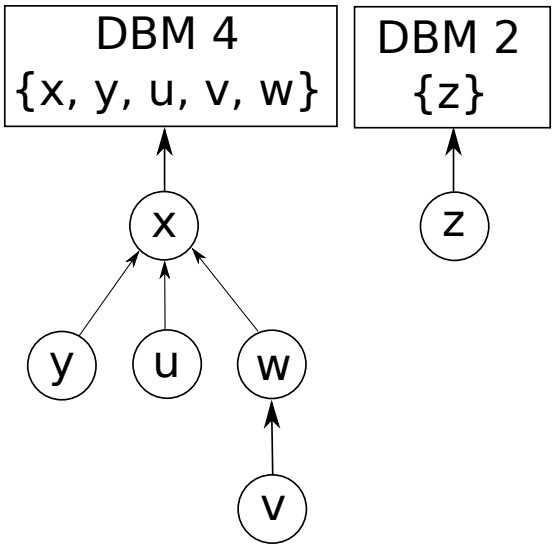


Variable packing - Tests

Pointer analysis using function summarization.

File	DBMs	Size	Var Packing	Size
astree-ex	1.01s	36	0.13s	7
test-1	0.13s	27	0.03s	4
test-1-unsafe	0.13s	27	0.02s	4
test-10	0.03s	10	0.02s	4
test-10-unsafe	0.03s	11	0.02s	4
paparazzi-microjet	3241.14s	611	158.50s	88
gen2	> 5h	?	7817.42s	367
aeroquad-servo	78.12s	71	1.33s	14
aeroquad-new	86.18s	65	0.76s	5
cornell	447.06s	226	2.64s	6
sporesate2-spore-pl	895.45s	?	10.29s	19

Other ideas

- Group variables depending on heuristics
- Use the gauge domain

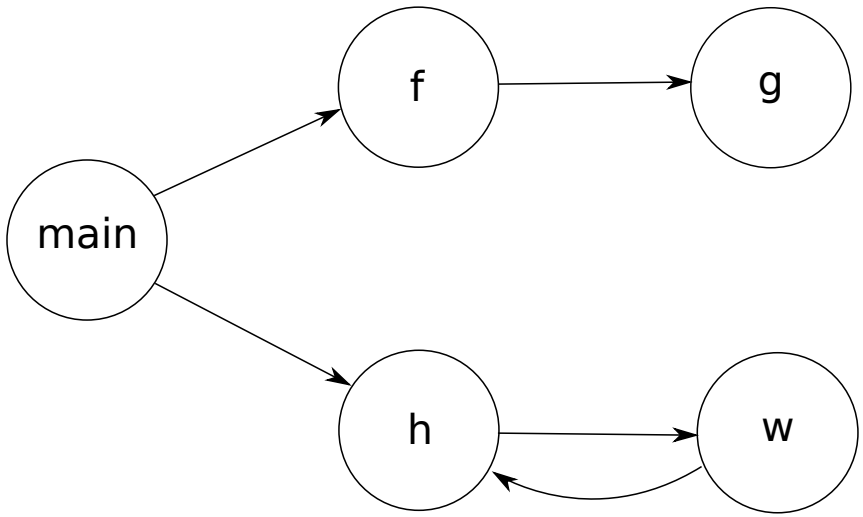
Other ideas

- Group variables depending on heuristics
- Use the gauge domain

Work in progress !

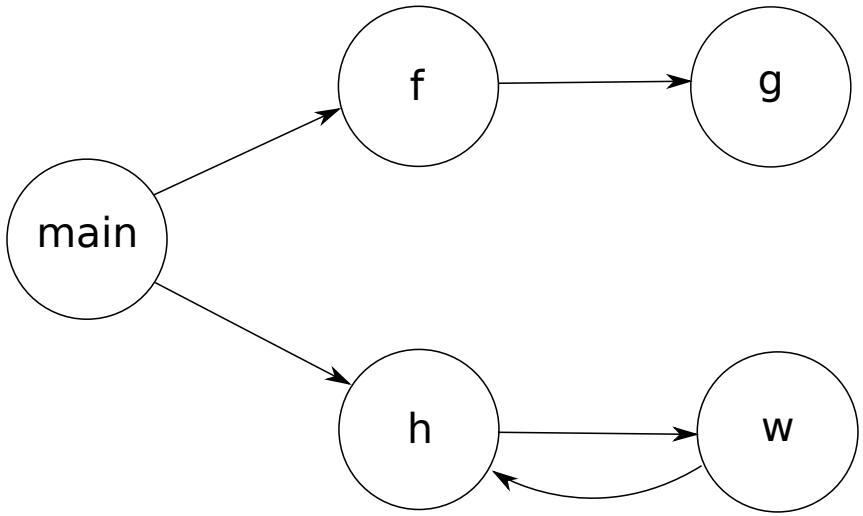
Function summarization

- IKOS uses dynamic inlining
- Idea : analyse each function only once to build a summary



Function summarization : Call graph analysis

- Problem : call graph cycle



Function summarization : Call graph analysis

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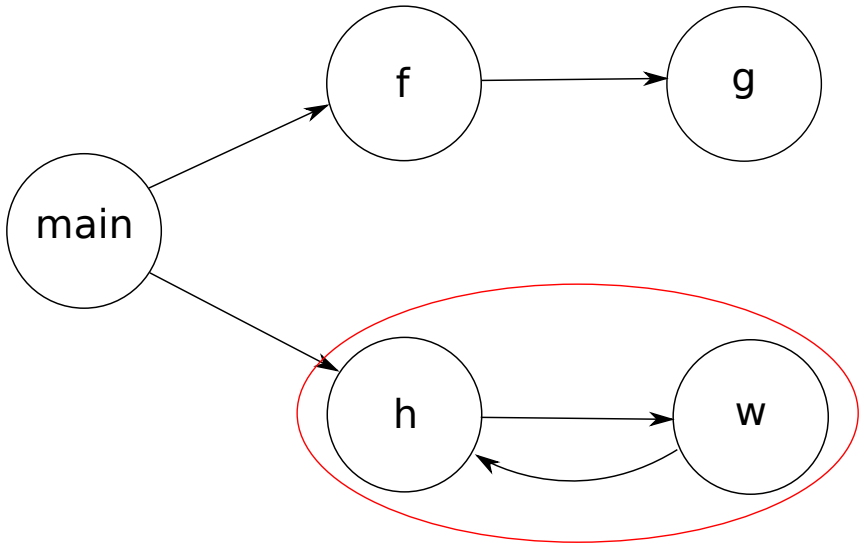

- Strongly connected component analysis
- Topological order
- Bottom-up analysis (from the leaves to the root)
- Top-down analysis (from the root to the leaves)

Function summarization : Memory analysis

- Need a way to express the effect of a function call on the memory
- More particularly on global variables and pointer parameters
- Relation between the input memory state and the output memory state
- Idea : Introduce *input cells* and *output cells*

$$x = x + 1 \Leftrightarrow \mathit{Cell}\{x, 0, 4, \mathit{Out}\} = \mathit{Cell}\{x, 0, 4, \mathit{In}\} + 1$$

Function summarization : Tests

Buffer overflow analysis using function summarization

File	Inlining	Summaries	Warnings	Errors	Lines
astree-ex	0.36s	0.57s	2/2	0/0	22 (1)
test-1	0.14s	0.16s	0/0	0/0	22 (1)
test-1-unsafe	0.13s	0.18s	0/0	2/2	22 (1)
test-10	0.10s	0.13s	**0/2**	0/0	20 (3)
paparazzi	**154.03s**	**110.09s**	0/0	0/0	24650 (199)
gen2	307.66s	$>$ 3h	195/ ?	0/ ?	22030 (82)

Integer overflow

- Problem : llvm integer types are signedness agnostic
- Because most instructions are signedness agnostic : add, sub, mul, etc.
- How to be be sound and precise ?
  - Intervals with infinite precision : imprecise or unsound
  - Suppose integers are unsigned : imprecise
  - Suppose integers are signed : imprecise
  - Wrapped intervals : Jorge Navas's paper « Signedness-Agnostic Program Analysis : Precise Integer Bounds for Low-Level Code »
  - Domain product : unsigned and signed

Syllabus

Conclusion

Thank you. Questions ?