Decision Procedures for Vulnerability Analysis

Journées du GDR GPL 2021

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Formal Verification

Formal verification aims to prove or disprove the correctness of a system with respect to a certain specification or property

Used in a growing number of contexts

- Cryptographic protocols
- Electronic hardware
- Software source code

Core concept: $\mathcal{M} \models \mathcal{P}$

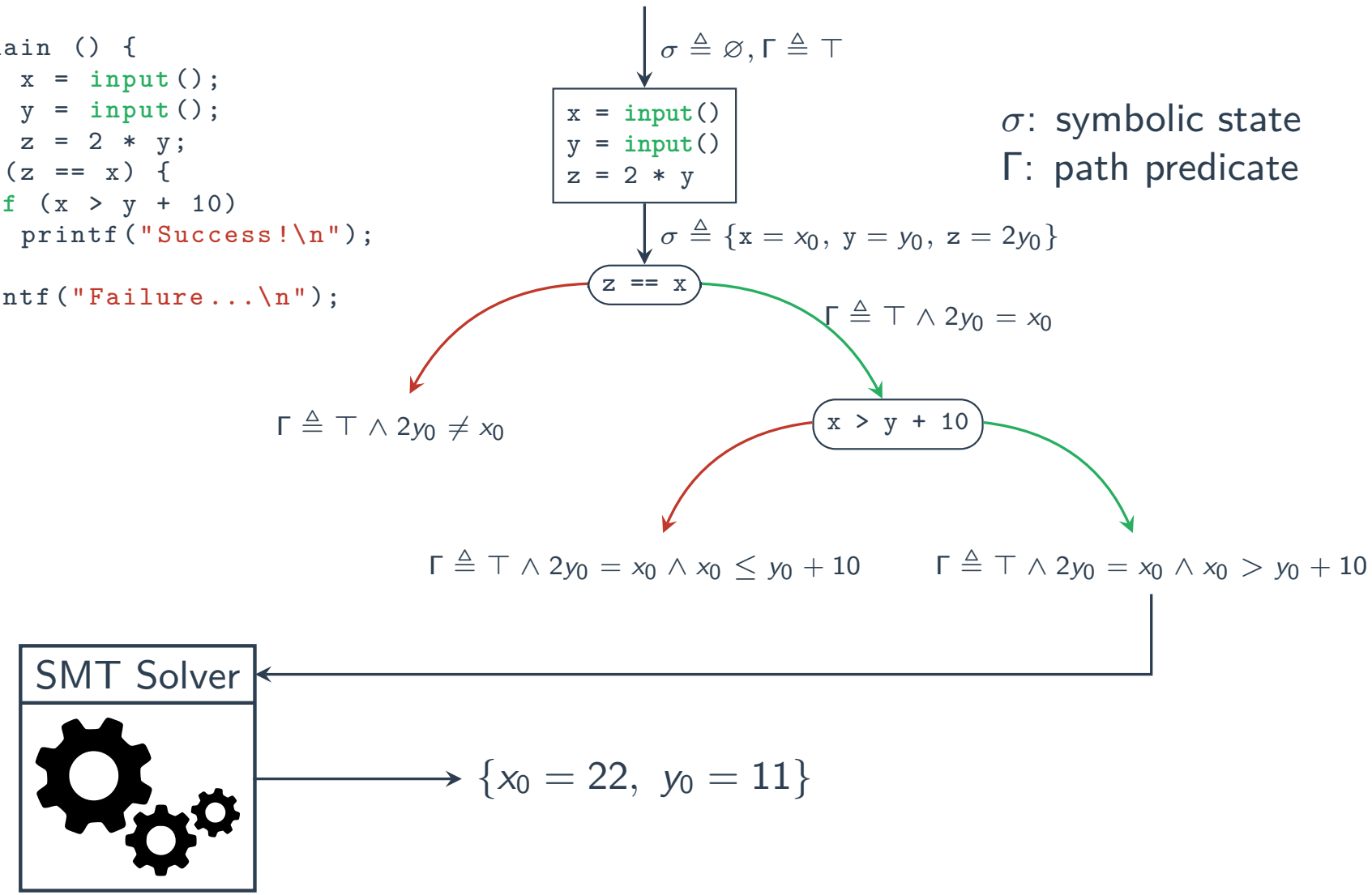
- $\mathcal{M}$: the model of the system
- $\mathcal{P}$: the property to be checked
- $\models$: the algorithmic check

Some automated software verification techniques:

- Abstract Interpretation
- Bounded Model Checking (BMC)
- Symbolic Execution (SE) — BINSEC

Symbolic Execution

```
int main () {
  int x = input();
  int y = input();
  int z = 2 * y;
  if (z == x) {
    if (x > y + 10)
      printf("Success!\n");
  }
  printf("Failure...\n");
}
```



Limitations and Successes

Symbolic Execution suffers several limitations...

- Path explosion
- Memory model
- Constraint solving
- Interactions with the environment

...but still leads to several successful applications

SAGE, P.Godefroid et al.

$\Rightarrow$ x86 instruction level SE

KLEE, C.Cadar et al.

$\Rightarrow$ LLVM bytecode level SE

It is now a question of applying it to vulnerability analysis

Motivating Example

```c
#define SIZE

void get_secret (char secr[]) {
// Retrieve the secret
}

void read_input (char src[], char dst[]) {
  int i = 0;
  while (src[i]) {
    dst[i] = src[i];
    i++;
  }
}

int validate (char secr[], char inpt[]) {
  int b = 1;
  for (int i = 0; i < SIZE; i++) {
    b &= secr[i] == inpt[i];
  }
  return b;
}
```

```c
int main (int argc, char *argv[]) {
  char secr[SIZE];
  char inpt[SIZE];

  if (argc != 2) return 0;

  get_secret(secr);
  read_input(argv[1],inpt);

  if (validate(secr, inpt)) {
    printf("Success!\n");
  }
  else {
    printf("Failure...\n");
  }
}
```

Motivating Example

```c
#define SIZE

void get_secret (char secr[]) {
// Retrieve the secret
}

void read_input (char src[], char dst[]) {
  int i = 0;
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  char secr[SIZE];
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  if (argc != 2) return 0;

  get_secret(secr);
  read_input(argv[1],inpt);

  if (validate(secr, inpt)) {
    printf("Success!\n");
  }
  else {
    printf("Failure...\n");
  }
}
```

Goal

Find an input such that the execution reach the “Success!” branch

Motivating Example

```c
#define SIZE

void get_secret (char secr[]) {
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void read_input (char src[], char dst[]) {
  int i = 0;
  while (src[i]) {
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int main (int argc, char *argv[]) {
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  char inpt[SIZE];

  if (argc != 2) return 0;

  get_secret(secr);
  read_input(argv[1],inpt);

  if (validate(secr, inpt)) {
    printf("Success!\n");
  }
  else {
    printf("Failure...\n");
  }
}
```

$\exists i.\exists s.\exists m_0.\exists p_0.$

i: input $\quad m$: memory

s: secret $\quad p$: stack pointer

$$p_1 \triangleq p_0 - \texttt{SIZE}$$
$$p_2 \triangleq p_1 - \texttt{SIZE}$$
$$m_1 \triangleq m_0\,[p_1 \,..\, p_1 + \texttt{SIZE} - 1] \leftarrow s$$
$$m_2 \triangleq m_1\,[p_2 \,..\, p_2 + N - 1] \leftarrow i$$

$$m_2\,[p_1 \,..\, p_1 + \texttt{SIZE} - 1] = m_2\,[p_2 \,..\, p_2 + \texttt{SIZE} - 1]$$

Binary-Level Semantics

$$
\begin{aligned}
&\exists i.\exists s.\exists m_0.\exists p_0.\\
&\quad p_1 \triangleq p_0 - \texttt{SIZE}\\
&\quad p_2 \triangleq p_1 - \texttt{SIZE}\\
&\quad m_1 \triangleq m_0\,[p_1 \,..\, p_1 + \texttt{SIZE} - 1] \leftarrow s\\
&\quad m_2 \triangleq m_1\,[p_2 \,..\, p_2 + N - 1] \leftarrow i\\
&m_2\,[p_1 \,..\, p_1 + \texttt{SIZE} - 1] = m_2\,[p_2 \,..\, p_2 + \texttt{SIZE} - 1]
\end{aligned}
$$

oversimplified formula!

The real formula is about 2130 reads and 456 writes

Binary-Level Semantics

$$
\begin{aligned}
&\exists i.\exists s.\exists m_0.\exists p_0.\\
&\quad p_1 \triangleq p_0 - \texttt{SIZE}\\
&\quad p_2 \triangleq p_1 - \texttt{SIZE}\\
&\quad m_1 \triangleq m_0\,[p_1 \,..\, p_1 + \texttt{SIZE} - 1] \leftarrow s\\
&\quad m_2 \triangleq m_1\,[p_2 \,..\, p_2 + N - 1] \leftarrow i\\
&m_2\,[p_1 \,..\, p_1 + \texttt{SIZE} - 1] = m_2\,[p_2 \,..\, p_2 + \texttt{SIZE} - 1]
\end{aligned}
$$

oversimplified formula!

The real formula is about 2130 reads and 456 writes

Unrolling-based verification techniques (BMC, SE)

- may produce huge formulas
- with a high number of reads and writes

In some extreme cases, solvers may spend hours on these formulas

ASPack case study: 293 000 reads, 58 000 writes

$\Rightarrow$ 24 hours of resolution !

Security Is Not Safety

Sending the formula to a solver:

$$\Rightarrow \left\{ s_{[0\,..\,\texttt{SIZE}-1]} = 0, i_{[0\,..\,\texttt{SIZE}-1]} = 0, \ldots \right\}$$

"If the secret is 0, then you can choose 0 as an input."

Sure, that is true...
but a false positive in practice

- the secret will not likely be 0

$\Rightarrow$ the execution will not reach the "Success" branch

Security Is Not Safety

Sending the formula to a solver:

$\Rightarrow \left\{ s_{[0\,..\,\texttt{SIZE}-1]} = 0, i_{[0\,..\,\texttt{SIZE}-1]} = 0, \ldots \right\}$

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- the secret will not likely be 0

$\Rightarrow$ the execution will not reach the "Success" branch

Threat models make security $\neq$ safety

A better formalization:

- We do not have control over s, m_0 and p_0
- These variables should be universally quantified

$\Rightarrow$ This is where the problems begin...

- Symbolic Execution (SE)
  - under-approximation verification technique
  - heavily relies on SMT solvers
- Application to vulnerability analysis
  - requires to move from source analysis to binary analysis
  - modeling threat models introduces universal quantifiers
- Problems
  - finding a model for a $\forall$-formula is difficult
  - going low-level significantly increases formula size

  $\Rightarrow$ The Death of SMT Solvers

Section 1

Model Generation for Quantified Formulas: A Taint-Based Approach

Overview

- Challenge
  - Deal with quantified-formulas and model generation
  - Notoriously hard! (undecidable)
- Existing approaches
  - Complete but costly for very specific theories
  - Incomplete but efficient for UNSAT/UNKNOWN
  - Costly or too restricted for model generation
- Our proposal
  - SAT/UNKNOWN and model generation
  - Incomplete but efficient, generic, theory independent
  - Reuse state-of-the-art solvers as much as possible

Published in Computer Aided Verification 30th, Oxford, UK, 2018 [CAV18]

Presented in Approches Formelles dans l'Assistance au Développement de Logiciels, Grenoble, France, 2018 [AFADL18]

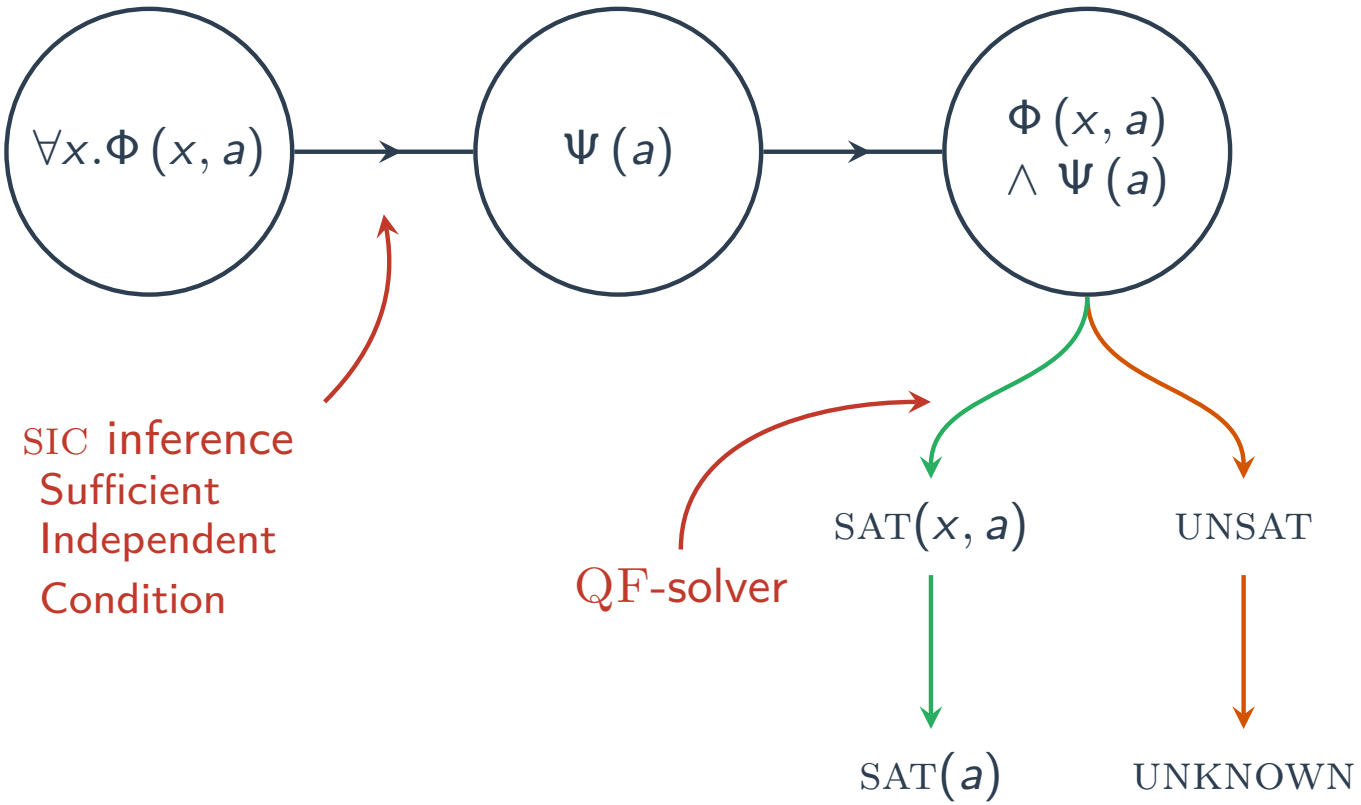
Toy Example

```
int main () {
  int a = input ();
  int b = input ();

  int x = rand ();

  if (a * x + b > 0) {
    analyze_me();
  }
  else {
    ...
  }
}
```

We propose a way to infer such conditions

- Quantified reachability condition: $\forall x.ax + b > 0$
- Generalizable solutions of $ax + b > 0$ have to be independent from `x`
  - A bad solution: $a = 1 \wedge x = 1 \wedge b = 0$
  - A good solution: $a = 0 \wedge x = 1 \wedge b = 1$
- The constraint $a = 0$ is the independence condition
- Quantifier-free reachability condition: $(ax + b > 0) \wedge (a = 0)$

Our Proposal in a Nutshell



Sufficient Independence Condition (SIC)

Sufficient Independence Condition (SIC)

A SIC for a formula $\Phi(\boldsymbol{x}, \boldsymbol{a})$ with regard to $\boldsymbol{x}$ is a formula $\Psi(\boldsymbol{a})$ such that $\Psi(\boldsymbol{a}) \models (\forall \boldsymbol{x}.\forall \boldsymbol{y}.\Phi(\boldsymbol{x}, \boldsymbol{a}) \Leftrightarrow \Phi(\boldsymbol{y}, \boldsymbol{a}))$.

formula indep.

- If $\Phi \triangleq ax + b > 0$ then $a = 0$ is a $\text{SIC}_{\Phi,x}$.
- If $\Delta \triangleq (t[a] \leftarrow b)[c]$ then $a = c$ is a $\text{SIC}_{\Delta,t}$.
- $\bot$ is always a SIC, but a useless one...

Model generalization

- Let $\Phi(\boldsymbol{x}, \boldsymbol{a})$ a formula and $\Psi(\boldsymbol{a})$ a $\text{SIC}_{\Phi,\boldsymbol{x}}$.
- If there exists an interpretation $\{\mathtt{x}, \mathtt{a}\}$ such that $\{\mathtt{x}, \mathtt{a}\} \models \Psi(\boldsymbol{a}) \wedge \Phi(\boldsymbol{x}, \boldsymbol{a})$, then $\{\mathtt{a}\} \models \forall \boldsymbol{x}.\Phi(\boldsymbol{x}, \boldsymbol{a})$.

Weakest Independence Condition (WIC)

A WIC for a formula $\Phi(\boldsymbol{x}, \boldsymbol{a})$ with regard to $\boldsymbol{x}$ is a $\text{SIC}_{\Phi,\boldsymbol{x}}$ Π such that, for any other $\text{SIC}_{\Phi,\boldsymbol{x}}$ Ψ, $\Psi \models \Pi$.

- Both SIC $a = 0$ and $a = c$ presented earlier are WIC.
- $\Omega \triangleq \forall \boldsymbol{x}.\forall \boldsymbol{y}.(\Phi(\boldsymbol{x}, \boldsymbol{a}) \Leftrightarrow \Phi(\boldsymbol{y}, \boldsymbol{a}))$ is always a $\text{WIC}_{\Phi,\boldsymbol{x}}$, but involves quantifiers
- A formula Π is a $\text{WIC}_{\Phi,\boldsymbol{x}}$ if and only if $\Pi \equiv \Omega$.

Model specialization

- Let $\Phi(\boldsymbol{x}, \boldsymbol{a})$ a formula and $\Pi(\boldsymbol{a})$ a $\text{WIC}_{\Phi,\boldsymbol{x}}$.
- If there exists an interp. $\{\mathtt{a}\}$ such that $\{\mathtt{a}\} \models \forall \boldsymbol{x}.\Phi(\boldsymbol{x}, \boldsymbol{a})$, then $\{\mathtt{x}, \mathtt{a}\} \models \Pi(\boldsymbol{a}) \wedge \Phi(\boldsymbol{x}, \boldsymbol{a})$ for any valuation $\mathtt{x}$ of $\boldsymbol{x}$.

Taint-based SIC inference

Function `inferSIC(Φ,x)`:

Input: Φ a formula and x a set of targeted variables

Output: Ψ a $\mathrm{SIC}_{\Phi,x}$

either Φ *is a constant*
return $\top$

either Φ *is a variable* v
return $v \notin x$

either Φ *is a function* $f\,(\phi_1, .., \phi_n)$
Let $\psi_i \triangleq \texttt{inferSIC}\,(\phi_i, x)$ for all $i \in \{1, .., n\}$
Let $\Psi \triangleq \texttt{theorySIC}\,(f, (\phi_1, .., \phi_n), (\psi_1, .., \psi_n), x)$
return $\Psi \vee \bigwedge_i \psi_i$

syntactic part

a and b indep$_x$ $\rightsquigarrow$ $f\,(a, b)$ indep$_x$

semantic part

a indep$_x$ and $a = 0$ $\rightsquigarrow$ $a \cdot * $ indep$_x$

Taint-based SIC inference

Proposition

- If $\texttt{theorySIC}(f, \phi_i, \psi_i, \boldsymbol{x})$ computes a $\mathrm{SIC}_{f(\phi_i),\boldsymbol{x}}$, then $\texttt{inferSIC}(\Phi, \boldsymbol{x})$ computes a $\mathrm{SIC}_{\Phi,\boldsymbol{x}}$.

Function `inferSIC(`Φ`,`$\boldsymbol{x}$`)`**:**

Input: Φ a formula and $\boldsymbol{x}$ a set of targeted variables

Output: Ψ a $\mathrm{SIC}_{\Phi,\boldsymbol{x}}$

either Φ *is a constant*
  return $\top$

either Φ *is a variable* v — syntactic part
  return $v \notin \boldsymbol{x}$

a and b indep$_{\boldsymbol{x}}$ $\rightsquigarrow$ $f\,(a, b)$ indep$_{\boldsymbol{x}}$

either Φ *is a function* $f\,(\phi_1, .., \phi_n)$

Let $\psi_i \triangleq \texttt{inferSIC}\,(\phi_i, \boldsymbol{x})$ for all $i \in \{1, .., n\}$

Let $\Psi \triangleq \texttt{theorySIC}\,(f, (\phi_1, .., \phi_n), (\psi_1, .., \psi_n), \boldsymbol{x})$

return $\Psi \vee \bigwedge_i \psi_i$ — semantic part

a indep$_{\boldsymbol{x}}$ and $a = 0$ $\rightsquigarrow$ $a \cdot * $ indep$_{\boldsymbol{x}}$

theorySIC defined as a recursive function

$$
\begin{aligned}
(a \Rightarrow b)^\bullet &\triangleq (a^\bullet \wedge a = \bot) \vee (b^\bullet \wedge b = \top) \\
(a \wedge b)^\bullet &\triangleq (a^\bullet \wedge a = \bot) \vee (b^\bullet \wedge b = \bot) \\
(a \vee b)^\bullet &\triangleq (a^\bullet \wedge a = \top) \vee (b^\bullet \wedge b = \top) \\
(\mathsf{ite}\, c\, a\, b)^\bullet &\triangleq (c^\bullet \wedge \mathsf{ite}\, c\, a^\bullet\, b^\bullet) \vee (a^\bullet \wedge b^\bullet \wedge a = b)
\end{aligned}
$$

$$
\begin{aligned}
(a_n \wedge b_n)^\bullet &\triangleq (a_n^\bullet \wedge a_n = 0_n) \vee (b_n^\bullet \wedge b_n = 0_n) \\
(a_n \vee b_n)^\bullet &\triangleq (a_n^\bullet \wedge a_n = 1_n) \vee (b_n^\bullet \wedge b_n = 1_n) \\
(a_n \times b_n)^\bullet &\triangleq (a_n^\bullet \wedge a_n = 0_n) \vee (b_n^\bullet \wedge b_n = 0_n) \\
(a_n \ll b_n)^\bullet &\triangleq (b_n^\bullet \wedge b_n \geq n)
\end{aligned}
$$

$$
\begin{aligned}
((a\,[i] \leftarrow e)\,[j])^\bullet &\triangleq (\mathsf{ite}\ (i = j)\ e\ (a\,[j]))^\bullet \\
&\triangleq ((i = j)^\bullet \wedge (\mathsf{ite}\ (i = j)\ e^\bullet\ (a\,[j])^\bullet)) \\
&\quad \vee (e^\bullet \wedge (a\,[j])^\bullet \wedge (e = a\,[j])) \\
&\triangleq (i^\bullet \wedge j^\bullet \wedge (\mathsf{ite}\ (i = j)\ e^\bullet\ (a\,[j])^\bullet)) \\
&\quad \vee (e^\bullet \wedge (a\,[j])^\bullet \wedge (e = a\,[j]))
\end{aligned}
$$

Experimental Evaluation

Boolector: an efficient QF-solver for bitvectors and arrays

Best approaches

		Z3	Btor•	Btor• ▷ Z3
SMT-LIB	SAT	261	399	485
	# UNSAT	165	N/A	165
	UNKNOWN	843	870	619
	total time	270 150	350	94 610
BINSEC	SAT	953	1042	1067
	# UNSAT	319	N/A	319
	UNKNOWN	149	379	35
	total time	64 761	1 152	1 169

GRUB example

	Z3	Btor•
SAT	1	**540**
# UNSAT	42	N/A
UNKNOWN	852	355
total time	159 765	**16 732**

Complementarity with existing solvers (SAT instances)

		CVC4•	Z3•	Btor•
SMT-LIB	CVC4	-10 +168 [252]		-10 +325 [409]
	Z3		-119 +224 [485]	-86 +224 [485]
BINSEC	CVC4	-25 +28 [979]		-25 +116 [1067]
	Z3		-25 +114 [1067]	-25 +114 [1067]

solver•: solver enhanced with our method

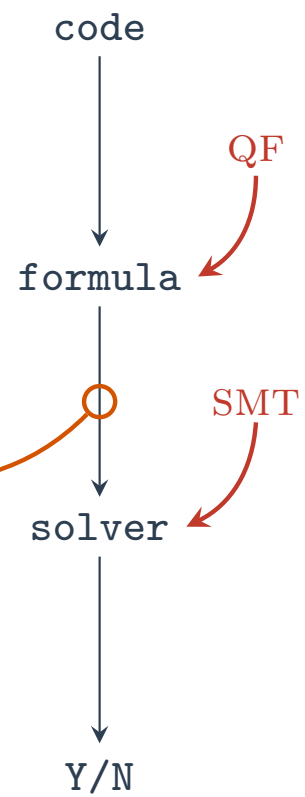
Section 2

Arrays Made Simpler: An Efficient, Scalable and Thorough Preprocessing

Overview

- Challenge
  - Array theory useful for modelling memory or data structures...
  - ...but a bottleneck for resolution of large formulas (BMC, SE)
- Existing approaches
  - General decision procedures for the theory of arrays
  - Dedicated handling of arrays inside tools
- Our proposal
  - FAS, an efficient simplification for array theory

  $\Rightarrow$ Improves existing solvers



Published in Logic for Programming, Artificial Intelligence and Reasoning, Awassa, Ethiopia, 2018 [LPAR18]

Presented in Journées Francophones des Langages Applicatifs, Banyuls-sur-Mer, France, 2018 [JFLA18]

Array Theory

Two basic operations on arrays

- Reading in a at index $i \in \mathcal{I}$: $a[i]$
- Writing in a an element $e \in \mathcal{E}$ at index $i \in \mathcal{I}$: $a[i] \leftarrow e$

$$\cdot[\cdot] : \text{Array } \mathcal{I}\ \mathcal{E} \to \mathcal{I} \to \mathcal{E}$$
$$\cdot[\cdot] \leftarrow \cdot : \text{Array } \mathcal{I}\ \mathcal{E} \to \mathcal{I} \to \mathcal{E} \to \text{Array } \mathcal{I}\ \mathcal{E}$$

$$\text{ROW-axiom: } \forall a\, i\, j\, e.\, (a[i] \leftarrow e)[j] = \begin{cases} e & \text{if } i = j \\ a[j] & \text{otherwise} \end{cases}$$

Prevalent in software analysis

- Modelling memory
- Abstracting data structure (map, queue, stack...)

Hard to solve

- NP-complete
- Read-Over-Write (ROW) may require case-splits

Arrays in Practice

Unrolling-based verification techniques (BMC, SE)

- may produce huge formula
- high number of reads and writes

In some extremes cases, solvers may spend hours on these formulas

> Without proper simplification,
> array theory might become a bottleneck for resolution

What should we simplify ? Read-Over-Write (ROW)!

ROW Simplification

An example coming from binary analysis

$\texttt{esp}_0 : \texttt{BitVec16}$
$\texttt{mem}_0 : \texttt{Array BitVec16 BitVec16}$

$\texttt{assert}\,(\texttt{esp}_0 > 61440)$
$\texttt{mem}_1 \triangleq \texttt{mem}_0\,[\texttt{esp}_0 - 16] \leftarrow 1415$
$\texttt{esp}_1 \triangleq \texttt{esp}_0 - 64$
$\texttt{eax}_0 \triangleq \texttt{mem}_1\,[\texttt{esp}_1 + 48]$
$\texttt{assert}\,(\texttt{mem}_1\,[\texttt{eax}_0] = 9265)$

$\rightsquigarrow$

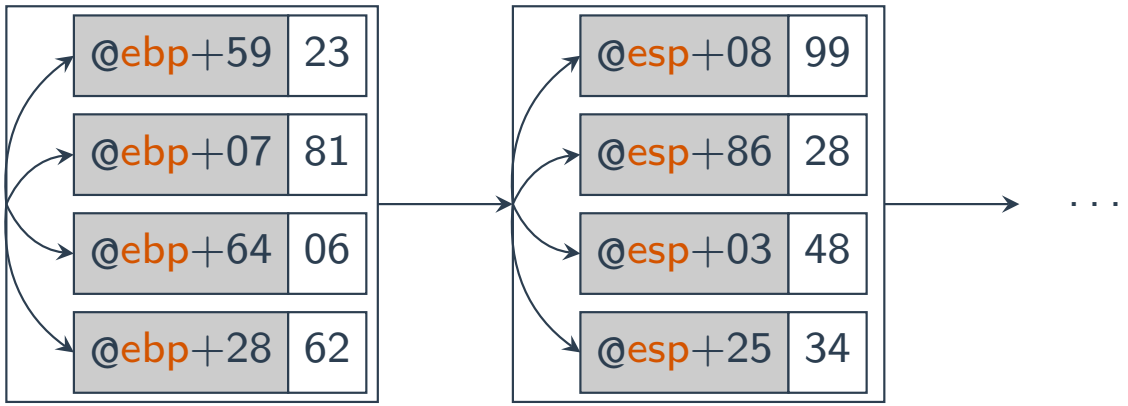
$\texttt{esp}_0 : \texttt{BitVec16}$
$\texttt{mem}_0 : \texttt{Array BitVec16 BitVec16}$

$\texttt{assert}\,(\texttt{esp}_0 > 61440)$
$\texttt{assert}\,(\texttt{mem}_0\,[1415] = 9265)$

These simplifications depend on two factors

- The equality check procedure
  verify that $\texttt{esp}_1 + 48 = \texttt{esp}_0 - 16$
  $\Rightarrow$ **precise reasoning**: base normalization + abstract domains
- The underlying representation of an array
  remember that $\texttt{mem}_1\,[\texttt{esp}_1 + 48] = 1415$
  $\Rightarrow$ **scalability** issue: list-map representation

Improving scalability: list-map representation



How to update

Given a write of e at index i

- Is i *comparable* with indices of elements in the head?
- If so add (i, e) in this map
- Else add a new head map containing only (i, e)

How to simplify ROW

Given a read at index j

- Is j *comparable* with indices of elements in the head?
- If so, look for (i, e) with $i{=}j$
  - if succeeds then return e
  - else recurse on next map
- Else stop

Precise reasoning: base normalization and abstract domains

Propagate "variable+constant" terms

- If $y \triangleq z + 1$ then $x \triangleq y + 2 \rightsquigarrow x \triangleq z + 3$
- Together with associativity, commutativity...

$\Rightarrow$ Reduce the number of bases

Associate to every indices i an abstract domain $i^\sharp$

- If $i^\sharp \sqcap j^\sharp = \bot$ then $(a\,[i] \leftarrow e)\,[j] = a\,[j]$
- Integrated in the list-map representation

$\Rightarrow$ Prove disequality between different bases

Impact of the Simplification: Medium-Size Formulas

- 6,590 x 3 medium-size formulas from static SE
- TIMEOUT = 1,000 seconds

		simpl. time	#TIMEOUT and resolution time						#ROW
			Boolector		Yices		Z3		
concrete	default	61	0	163	2	69	0	872	**866,155**
	FAS	85	0	94	2	68	0	244	**1,318**
	FAS-itv	111	0	94	2	68	0	224	1,318
interval	default	65	0	**2,584**	2	465	31	155,992	866,155
	FAS	99	0	2,245	2	487	25	126,806	531,654
	FAS-itv	118	0	**755**	2	140	14	37,269	205,733
symbolic	default	61	0	6,173	3	1,961	**65**	305,619	866,155
	FAS	91	0	6,117	3	1,965	66	158,635	531,654
	FAS-itv	111	0	4,767	2	1,108	**43**	80,569	295,333

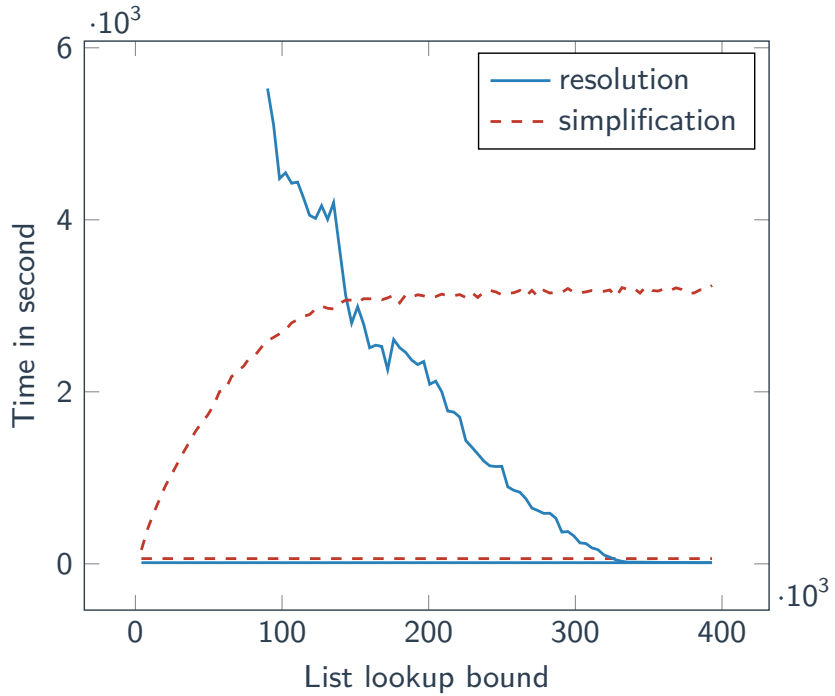
Impact of the Simplification: Very Large Formulas

- 29 x 3 very large formulas from dynamic SE
- TIMEOUT = 1,000 seconds

		simpl. time	#TIMEOUT and resolution time						#ROW
			Boolector		Yices		Z3		
concrete	default	44	10	159	4	1,098	26	3.33	**1,120,798**
	FAS-list	**1,108**	8	845	4	198	10	918	456,915
	FAS	196	8	820	4	196	10	922	456,915
	FAS-itv	210	4	654	1	12	4	1,120	**0**
interval	default	44	12	131	12	**596**	**27**	0.19	1,120,798
	FAS-list	222	12	129	12	595	26	236	657,594
	FAS	231	12	129	12	597	26	291	657,594
	FAS-itv	237	12	58	12	**28**	**19**	81	651,449
symbolic	default	40	12	1,522	12	1,961	27	0.13	1,120,798
	FAS-list	187	11	1,199	12	2,018	26	486	657,594
	FAS	194	11	1,212	12	2,081	26	481	657,594
	FAS-itv	200	11	1,205	12	2,063	26	416	657,594

Focus on Specific Case: the ASPack Example

- Huge formula obtained from the ASPack packing tool
- 293 000 ROWs
- 24 hours of resolution!



Using FAS

- #ROW reduced to 2 467
- 14 sec for resolution
- 61 sec for preprocessing

Using list representation

- Same result with a bound of 385 024 and beyond...
- ...but 53 min preprocessing

Section 3

Get Rid of False Positives with Robust Symbolic Execution

Overview

- Symbolic Execution (SE)
  - under-approximation verification technique
  - heavily relies on SMT solvers
  - should be exempt of false positives
- In practice, false positives exist
  - misspecified abstractions, initial state...
  - some *ad hoc* workarounds, no real solution
- Our proposal: Robust Symbolic Execution
  - distinguish between controlled and uncontrolled inputs
  - robust solutions are independent of uncontrolled inputs
  - practical application of [CAV18] and [LPAR18]

Presented in Journées Francophones des Langages Applicatifs, Les Rousses, France, 2019 [JFLA19]

Motivating Example Remembered

```c
#define SIZE

void get_secret (char secr[]) {
// Retrieve the secret
}

void read_input (char src[], char dst[]) {
  int i = 0;
  while (src[i]) {
    dst[i] = src[i];
    i++;
  }
}

int validate (char secr[], char inpt[]) {
  int b = 1;
  for (int i = 0; i < SIZE; i++) {
    b &= secr[i] == inpt[i];
  }
  return b;
}
```

```c
int main (int argc, char *argv[]) {
  char secr[SIZE];
  char inpt[SIZE];

  if (argc != 2) return 0;

  get_secret(secr);
  read_input(argv[1],inpt);

  if (validate(secr, inpt)) {
    printf("Success!\n");
  }
  else {
    printf("Failure...\n");
  }
}
```

$\exists i.\exists s.\exists m_0.\exists p_0.$

i: input $\quad m$: memory

s: secret $\quad p$: stack pointer

$$p_1 \triangleq p_0 - \texttt{SIZE}$$
$$p_2 \triangleq p_1 - \texttt{SIZE}$$
$$m_1 \triangleq m_0\,[p_1 \,..\, p_1 + \texttt{SIZE} - 1] \leftarrow s$$
$$m_2 \triangleq m_1\,[p_2 \,..\, p_2 + N - 1] \leftarrow i$$

$$m_2\,[p_1 \,..\, p_1 + \texttt{SIZE} - 1] = m_2\,[p_2 \,..\, p_2 + \texttt{SIZE} - 1]$$

Robust Symbolic Execution in Practice

$$
\begin{aligned}
&\exists i.\exists s.\exists m_0.\exists p_0.\\
&\quad p_1 \triangleq p_0 - \texttt{SIZE}\\
&\quad p_2 \triangleq p_1 - \texttt{SIZE}\\
&\quad m_1 \triangleq m_0\,[p_1 \,..\, p_1 + \texttt{SIZE} - 1] \leftarrow s\\
&\quad m_2 \triangleq m_1\,[p_2 \,..\, p_2 + N - 1] \leftarrow i\\
&m_2\,[p_1 \,..\, p_1 + \texttt{SIZE} - 1] = m_2\,[p_2 \,..\, p_2 + \texttt{SIZE} - 1]
\end{aligned}
$$

Sending the formula to a solver:

$\Rightarrow \left\{ s_{[0\,..\,\texttt{SIZE}-1]} = 0, i_{[0\,..\,\texttt{SIZE}-1]} = 0, \ldots \right\}$

- This is a false positive

A better formalization: Robust SE

- We do not have control over s, m_0 and p_0
- These variables should be universally quantified

Robust Symbolic Execution in Practice

$$
\begin{aligned}
&\exists i.\forall s.\forall m_0.\forall p_0.\\
&\quad p_1 \triangleq p_0 - \texttt{SIZE}\\
&\quad p_2 \triangleq p_1 - \texttt{SIZE}\\
&\quad m_1 \triangleq m_0\,[p_1 \,..\, p_1 + \texttt{SIZE} - 1] \leftarrow s\\
&\quad m_2 \triangleq m_1\,[p_2 \,..\, p_2 + N - 1] \leftarrow i\\
&m_2\,[p_1 \,..\, p_1 + \texttt{SIZE} - 1] = m_2\,[p_2 \,..\, p_2 + \texttt{SIZE} - 1]
\end{aligned}
$$

Problems:

- finding a model for a $\forall$-formula is difficult
- going low-level significantly increases formula size

$\Rightarrow$ The Death of SMT Solvers

Robust Symbolic Execution in Practice

$$\exists i.\ \exists s.\ \exists m_0.\ \forall p_0.$$
$$p_1 \triangleq p_0 - \texttt{SIZE}$$
$$p_2 \triangleq p_1 - \texttt{SIZE}$$
$$m_1 \triangleq m_0\,[p_0 - \texttt{SIZE}\,..\,p_0 - 1] \leftarrow s$$
$$m_2 \triangleq m_1\,[p_0 - 2 \cdot \texttt{SIZE}\,..\,p_0 - 2 \cdot \texttt{SIZE} + N - 1] \leftarrow i$$
$$i[0\,..\,\texttt{SIZE} - 1] = i[\texttt{SIZE}\,..\,2 \cdot \texttt{SIZE} - 1]$$
$$\wedge\ N \geq 2 \cdot \texttt{SIZE}$$

Problems:

- finding a model for a $\forall$-formula is difficult [CAV18]
- going low-level significantly increases formula size [LPAR18]

$\Rightarrow$ ~~The Death of SMT Solvers~~

For example with $\texttt{SIZE} = 8$,

- input `abcdefghabcdefgh` leads to the "Success!" branch
- buffer overflow in `read_input`

Experimental Evaluation

- set of `crackme` challenges
- compare true and false positives

	SE robust		
	true positives	false positives	UNKNOWN
Boolector	N/A	N/A	24
CVC4	5	**0**	19
Yices	N/A	N/A	24
Z3	7	**0**	17

	SE classic		
	true positives	false positives	UNKNOWN
Boolector	**12**	11	1
CVC4	7	9	8
Yices	7	11	6
Z3	**12**	12	0

	SE robust + elim.		
	true positives	false positives	UNKNOWN
Boolector	**12**	**0**	12
CVC4	7	**0**	17
Yices	7	**0**	17
Z3	**12**	**0**	12

Back to 28: GRUB2 Authentication Bypass

- Original version: press Backspace 28 times to get a rescue shell
- Case study: same vulnerable code turned into a `crackme` challenge

- SE classic:
  incorrect solution
- SE robust:
  solvers TIMEOUT

- SE robust + elim.:
  correct solution in 80s
- SE robust + elim. + simpl.:
  correct solution in 30s

Section 4

Conclusion

Summary

- Symbolic Execution (SE)
  - under-approximation verification technique
  - heavily relies on SMT solvers
- Application to vulnerability analysis
  - requires to move from source analysis to binary analysis
  - modeling threat models introduces universal quantifiers
- Problems
  - finding a model for a $\forall$-formula is difficult
  - going low-level significantly increases formula size

  $\Rightarrow$ The Death of SMT Solvers

Contributions

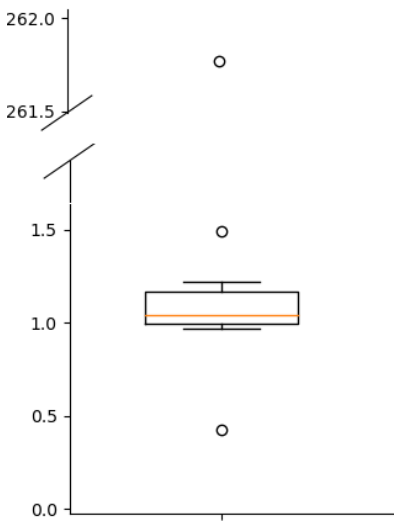
1. Model Generation for Quantified Formulas
   - Proposed a novel and generic taint-based approach
   - Proved its correctness and its efficiency
   - Presented an implementation for arrays and bit-vectors
   - Evaluated on SMT-LIB and formulas generated by Symbolic Execution
2. Arrays Made Simpler
   - Presented FAS, a simplification dedicated to the theory of arrays
   - Geared at eliminating ROW, based on a dedicated data structure, original simplifications and low-cost reasoning
   - Evaluated in different settings on very large formulas
3. Robust Symbolic Execution
   - Highlighted the problem of false positives in classic Symbolic Execution
   - Introduced formally the framework of Robust Symbolic Execution
   - Implemented a proof of concept in the binary analyser BINSEC

New Results

Guillaume Girol, B. Farinier, and S. Bardin.
Not all bugs are created equal, but robust reachability can tell the difference.
In *CAV 2021, Virtual, July 18-24, 2021.*

- Formal definition of Robust Reachability, application to SE and BMC
- Adaptation of standard optimizations to Robust Reachability
- Evaluation against 46 reachability problems including CVE replays and CTFs

	SE	BMC	RSE	RSE+	RBMC
Correct	30	22	37	44	32
False positive	16	14			
Inconclusive			7		1
Resource exhaustion		10	2	2	13



- Universal quantification of formulas has a cost, but not so high.
- RSE+ (robust SE with path merging) is 15% slower than SE in median, but with large outliers.