

Mechanical Specification and Verification for Mitigating Timing-based Side Channel Leaks

Aniket Mishra

[2025-12-18 Thu]

Outline

- 1 Fall-Through Semantics for Mitigating Timing-based Side Channel Leaks
- 2 Interactive Theorem Proving - What's the Fuss About?
- 3 Mechanical Specification and Verification for Mitigating Timing-based Side Channel Leaks
- 4 Interactive Theorem Proving - An Undergraduate Perspective

An Illustrative Example

Let us consider a C program that checks some input against a given password by comparing it character by character.

```
bool matchpwd ( int * input , size_t n ) {  
    if ( n != pwd_length ) return false;  
    for ( int i = 0; i < n ; i ++) {  
        if ( input [ i ] != pwd [ i ]) return false ;  
    }  
    return true ;  
}
```

An Exploit

Let's say the password is **101010**, an exploit may look like the following.

Example (An Attack Trace)

000000 Rejected in 1st iteration

An Exploit

Let's say the password is **101010**, an exploit may look like the following.

Example (An Attack Trace)

000000	Rejected in 1 st iteration
100000	Rejected in 3 rd iteration

An Exploit

Let's say the password is **101010**, an exploit may look like the following.

Example (An Attack Trace)

000000	Rejected in 1 st iteration
100000	Rejected in 3 rd iteration
110000	Rejected in 2 nd iteration

An Exploit

Let's say the password is **101010**, an exploit may look like the following.

Example (An Attack Trace)

000000	Rejected in 1 st iteration
100000	Rejected in 3 rd iteration
110000	Rejected in 2 nd iteration
101000	Rejected in 5 th iteration

An Exploit

Let's say the password is **101010**, an exploit may look like the following.

Example (An Attack Trace)

000000	Rejected in 1 st iteration
100000	Rejected in 3 rd iteration
110000	Rejected in 2 nd iteration
101000	Rejected in 5 th iteration
101100	Rejected in 4 th iteration

An Exploit

Let's say the password is **101010**, an exploit may look like the following.

Example (An Attack Trace)

000000	Rejected in 1 st iteration
100000	Rejected in 3 rd iteration
110000	Rejected in 2 nd iteration
101000	Rejected in 5 th iteration
101100	Rejected in 4 th iteration
101010	Password accepted!

Threat Model

Thus, given an adversary that can execute the program under security label ℓ .

Threat Model

Thus, given an adversary that can execute the program under security label ℓ .

Data Security

The adversary can view the state of the memory, but values that are high relative to ℓ are invisible.

Threat Model

Thus, given an adversary that can execute the program under security label ℓ .

Data Security

The adversary can view the state of the memory, but values that are high relative to ℓ are invisible. As an example, let us take $L \sqsubseteq M \sqsubseteq H$ and let us take $\ell = M$.

Let us say our μ is $x \rightarrow \text{true}^L$, $y \rightarrow \text{true}^M$, $z \rightarrow \text{true}^H$, then the adversary's view of the memory is:

Threat Model

Thus, given an adversary that can execute the program under security label ℓ .

Data Security

The adversary can view the state of the memory, but values that are high relative to ℓ are invisible. As an example, let us take $L \sqsubseteq M \sqsubseteq H$ and let us take $\ell = M$.

Let us say our μ is $x \rightarrow \text{true}^L$, $y \rightarrow \text{true}^M$, $z \rightarrow \text{true}^H$, then the adversary's view of the memory is:

$x \rightarrow \text{true}^L$, $y \rightarrow \text{true}^M$, $z \rightarrow *$

Threat Model

Thus, given an adversary that can execute the program under security label ℓ .

Data Security

The adversary can view the state of the memory, but values that are high relative to ℓ are invisible. As an example, let us take $L \sqsubseteq M \sqsubseteq H$ and let us take $\ell = M$.

Let us say our μ is $x \rightarrow \text{true}^L$, $y \rightarrow \text{true}^M$, $z \rightarrow \text{true}^H$, then the adversary's view of the memory is:

$x \rightarrow \text{true}^L$, $y \rightarrow \text{true}^M$, $z \rightarrow *$

Timing Security

The adversary has exact knowledge of when and where each memory access takes place during a program's execution.

Expression Semantics

CONST

$$\frac{}{n \mid \mu \Downarrow_{pc} \langle \text{CONST} \rangle, n^{pc}}$$

VAR

$$\frac{\mu(x) = n^k}{x \mid \mu \Downarrow_{pc} \langle \text{VAR}_x \rangle, n^{pc \sqcup k}}$$

OPER

$$\frac{e_1 \mid \mu \Downarrow_{pc} T_1, n_1^{k_1} \quad e_2 \mid \mu \Downarrow_{pc} T_2, n_2^{k_2} \quad n = n_1 \oplus n_2}{e_1 \oplus e_2 \mid \mu \Downarrow_{pc} \langle T_1, T_2, \text{OPER}_{\oplus} \rangle, n^{k_1 \sqcup k_2}}$$

Command Semantics

The Basics

SKIP

$$\frac{}{\text{skip} \mid \mu \Downarrow_{pc} \langle \text{SKIP} \rangle \mid \mu}$$

ASSN

$$\frac{e \mid \mu \Downarrow_{pc} T, n^k}{x := e \mid \mu \Downarrow_{pc} \langle T, \text{ASSN}_x \rangle \mid \mu, x \mapsto n^k}$$

SEQ

$$\frac{c_1 \mid \mu \Downarrow_{pc} T_1 \mid \mu' \quad c_2 \mid \mu' \Downarrow_{pc} T_2 \mid \mu''}{c_1; c_2 \mid \mu \Downarrow_{pc} \langle T_1, T_2, \text{SEQ} \rangle \mid \mu''}$$

Command Semantics

The Basics

SKIP

$$\frac{}{\text{skip} \mid \mu \Downarrow_{pc} \langle \text{SKIP} \rangle \mid \mu}$$

ASSN

$$\frac{e \mid \mu \Downarrow_{pc} T, n^k}{x := e \mid \mu \Downarrow_{pc} \langle T, \text{ASSN}_x \rangle \mid \mu, x \mapsto n^k}$$

SEQ

$$\frac{c_1 \mid \mu \Downarrow_{pc} T_1 \mid \mu' \quad c_2 \mid \mu' \Downarrow_{pc} T_2 \mid \mu''}{c_1; c_2 \mid \mu \Downarrow_{pc} \langle T_1, T_2, \text{SEQ} \rangle \mid \mu''}$$

IF-HIGH

IF-HIGH

$$\frac{\text{debranch}(c_1, n, pc) \mid \mu \Downarrow_k T_1 \mid \mu' \quad \text{debranch}(c_2, !n, pc) \mid \mu' \Downarrow_k T_2 \mid \mu'' \quad k \not\subseteq pc}{\text{if } e \text{ then } c_1 \text{ else } c_2 \mid \mu \Downarrow_{pc} \langle T, T_1, T_2, \text{IF-HIGH} \rangle \mid \mu''}$$

Debranch Semantics: The Basics

DEB-ASSN-TRUE

$$\frac{e \mid \mu \Downarrow_{pc} T_1, n^k \quad x \mid \mu \Downarrow_{pc} T_2, n_1^{k_1}}{\text{debranch}(x := e, (\text{true}), \ell) \mid \mu \Downarrow_{pc} \langle T_1, T_2, \text{DEB-ASSN}_x \rangle \mid \mu, x \mapsto n^k}$$

DEB-ASSN-FALSE

$$\frac{e \mid \mu \Downarrow_{pc} T_1, n^k \quad x \mid \mu \Downarrow_{pc} T_2, n_1^{k_1}}{\text{debranch}(x := e, (\text{false}), \ell) \mid \mu \Downarrow_{pc} \langle T_1, T_2, \text{DEB-ASSN}_x \rangle \mid \mu, x \mapsto n_1^k}$$

Debranch Semantics: IFs

DEB-IF-HIGH

$$\frac{e_1 \mid \mu \Downarrow_{\ell} T_3, n_1^{k_{\ell}} \quad e_1 \mid \mu \Downarrow_{pc} T_4, n_1^{k_{pc}} \quad k_{\ell} \not\sqsubseteq \ell \quad n_1 \& \& n = n' \quad !n_1 \& \& n = n''}{\text{debranch}(c_1, n', \ell) \mid \mu \Downarrow_{k_{pc}} T_1 \mid \mu' \quad \text{debranch}(c_2, n'', \ell) \mid \mu' \Downarrow_{k_{pc}} T_2 \mid \mu''}$$

$$\text{debranch}(\text{if } e_1 \text{ then } c_1 \text{ else } c_2, n, \ell) \mid \mu \Downarrow_{pc} \langle T_1, T_2, T_3, T_4, \text{DEB - IF - HIGH} \rangle \mid \mu''$$

DEB-IF-LOW

$$c = \left\{ \begin{array}{ll} \text{debranch}(c_1, n, \ell) & \text{if } n_1 = \text{true} \\ \text{debranch}(c_2, n, \ell) & \text{otherwise} \end{array} \right\} \quad \frac{e_1 \mid \mu \Downarrow_{\ell} T_1, n_1^k \quad c \mid \mu \Downarrow_{pc} T_2 \mid \mu' \quad k \sqsubseteq \ell}{\text{debranch}(\text{if } e_1 \text{ then } c_1 \text{ else } c_2, n, \ell) \mid \mu \Downarrow_{pc} \langle T_1, T_2, \text{DEB - IF - LOW} \rangle \mid \mu'}$$

ITPs

Interactive Theorem Provers have been around for quite a while. However, they have been facing a lot of very *recent* adoption.

- LEAN4 (2013)
- FStar (2011)
- Agda (1999)
- Coq/Rocq (1989/2025)
- Isabelle (1986)
- Automath (1967)

Expressing Mathematical Structures

```
Inductive NAT :=  
| NAT_zero  
| NAT_succ (n: NAT).  
  
Inductive EQ {A: Type} : A → A → Type :=  
| EQ_refl (x: A) : EQ x x.  
  
Inductive EXISTS {A: Type} (P: A → Type) :=  
| EXISTS_intro (witness: A) (proof: P witness) : EXISTS P.  
  
Definition All_numbers_are_reflexively_equal  
  : ∀ (n: NAT), EQ n n := λ n ⇒ EQ_refl n.  
  
Theorem All_numbers_are_reflexively_equal' : ∀ (n: NAT), EQ n n.  
Proof.  
  (** Assuming some n. *)  
  intros n.  
  (** The theorem holds by definition of EQ. *)  
  constructor.  
Qed.
```

Why Bother?

The most important thing that we get from these systems is **trust**.

- **Manual verification** can be error-prone and time-consuming.
- With a theorem prover, the implementation of the core system is comparatively very **small**.
- With this base, it is much easier to **trust results** (although there are caveats we will discuss later).

Expressing Grammars

```
(** An expression is either a primitive, a variable, or a binary operation. *)
Inductive Expression :=
| PrimitiveExpression (prim: Primitive)
| VarExpression (x: Var)
| BinOpExpression (binop: BinOp) (e1 e2: Expression).

(** The commands in our language are:
+ Skip, corresponding to a NO-OP
+ Assignments
+ Sequences (ie. perform c1 then c2)
+ Conditionals
+ While Loops
*)
Inductive Command : Type :=
| SkipCommand
| AssnCommand (x: Var) (e: Expression)
| SeqCommand (c1 c2: Command)
| IfCommand (e: Expression) (c1 c2: Command)
| WhileCommand (e: Expression) (c: Command)
```

Expressing Semantics

```
(** * [Language: Semantics *)  
  
(* Described here is the expression semantics. There is not much of interest to talk about here. *)  
Inductive ExpressionBigStep  
  {binop_eval: BinOp → Primitive → Primitive → Primitive}  
  {rel: Level → Level → Type}  
  {latticeProof: JoinSemiLattice rel} : Expression → MemStore → Level → TimingList → Primitive → Level → Type :=  
| ConstBigStep (prim: Primitive) {mu: MemStore}  
  : ExpressionBigStep (PrimitiveExpression prim) mu pc (SingleTiming CONST) prim pc  
  
| VarBigStep(x: Var) (mu: MemStore) (pc j: Level) (joinProof: Join rel pc (snd (mu x)) j)  
  : ExpressionBigStep (VarExpression x) mu pc (SingleTiming (VAR x)) (fst (mu x)) j  
  
| OperBigStep (oper: BinOp) {mu: MemStore} {e1 e2: Expression} {pc k1 k2 joinK1k2: Level} {T1 T2: TimingList} {n1 n2: Primitive}  
  (p1: ExpressionBigStep e1 mu pc T1 n1 k1)  
  (p2: ExpressionBigStep e2 mu pc T2 n2 k2)  
  (joinProof: Join rel k1 k2 joinK1k2)  
  : ExpressionBigStep (BinOpExpression oper e1 e2) mu pc (T1 , T2 , (SingleTiming (OPER oper))) (binop_eval oper n1 n2) joinK1k2.
```

Expressing Invariants

```
Lemma ExpressionTimSec {binop_eval: BinOp → Primitive → Primitive → Primitive}
  {rel: Level → Level → Type}
  {latticeProof: JoinSemilattice rel}:
  ∀ {e: Expression} {pc1 pc2 k1 k2: Level} {mu1 mu2: MemStore} {n1 n2: Primitive} {T1 T2: TimingList},
    @ExpressionBigStep binop_eval rel latticeProof e mu1 pc1 T1 n1 k1 →
    @ExpressionBigStep binop_eval rel latticeProof e mu2 pc2 T2 n2 k2 →
    (T1 = T2).

Proof.
  intros. dependent induction e; dependent destruction X0; dependent destruction X.
   $\vdash$  reflexivity.
   $\vdash$  reflexivity.
  specialize (IHe1  $\vdash$   $\dots$  X1 X0-1).
  specialize (IHe2  $\vdash$   $\dots$  X2 X0-2).
  rewrite  $\rightarrow$  IHe1.
  rewrite  $\rightarrow$  IHe2.
  reflexivity.

Qed.
```

Why Did I Bother?

- I started working on this project during the first semester of my second year. I was taking Discrete Math **at the same time!**

Why Did I Bother?

- I started working on this project during the first semester of my second year. I was taking Discrete Math **at the same time!**
- During December, I spent some time in IIT Delhi with Prof. Vaishnavi Sundararajan and started properly working with theorem provers.

Why Did I Bother?

- I started working on this project during the first semester of my second year. I was taking Discrete Math **at the same time!**
- During December, I spent some time in IIT Delhi with Prof. Vaishnavi Sundararajan and started properly working with theorem provers.
- After this, I got extremely anxious about my **proofs and theorems being incorrect**.

Learning to write Rocq vs Learning to write Proofs

Learning Rocq

- Well documented and maintained by a team of highly qualified researchers/engineers.

Learning to write Rocq vs Learning to write Proofs

Learning Rocq

- Well documented and maintained by a team of highly qualified researchers/engineers.
- Wonderful widely available resources for learning ([Software Foundations](#)).

Learning to write Rocq vs Learning to write Proofs

Learning Rocq

- Well documented and maintained by a team of highly qualified researchers/engineers.
- Wonderful widely available resources for learning ([Software Foundations](#)).
- At the end of the day, it is a programming language!
Possibility of [transfer](#).

Learning to write Rocq vs Learning to write Proofs

Learning Rocq

- Well documented and maintained by a team of highly qualified researchers/engineers.
- Wonderful widely available resources for learning ([Software Foundations](#)).
- At the end of the day, it is a programming language!
Possibility of [transfer](#).

Learning Proofs

- Universally accepted resources do not exist (as far as I know).

Learning to write Rocq vs Learning to write Proofs

Learning Rocq

- Well documented and maintained by a team of highly qualified researchers/engineers.
- Wonderful widely available resources for learning (Software Foundations).
- At the end of the day, it is a programming language! Possibility of transfer.

Learning Proofs

- Universally accepted resources do not exist (as far as I know).
- Discrete Math courses often focus on already existing/well-studied structures.

Learning to write Rocq vs Learning to write Proofs

Learning Rocq

- Well documented and maintained by a team of highly qualified researchers/engineers.
- Wonderful widely available resources for learning ([Software Foundations](#)).
- At the end of the day, it is a programming language!
Possibility of [transfer](#).

Learning Proofs

- Universally accepted resources do not exist (as far as I know).
- Discrete Math courses often focus on [already existing/well-studied structures](#). But (from what I know), not as much work in [defining and using your own](#).



Learning to write Rocq vs Learning to write Proofs

Learning Rocq

- Well documented and maintained by a team of highly qualified researchers/engineers.
- Wonderful widely available resources for learning ([Software Foundations](#)).
- At the end of the day, it is a programming language!
Possibility of [transfer](#).

Learning Proofs

- Universally accepted resources do not exist (as far as I know).
- Discrete Math courses often focus on [already existing/well-studied structures](#). But (from what I know), not as much work in [defining and using your own](#).



Intuition

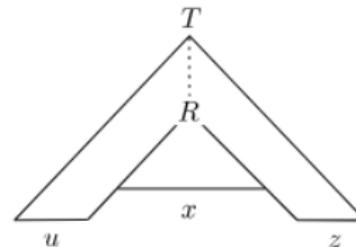
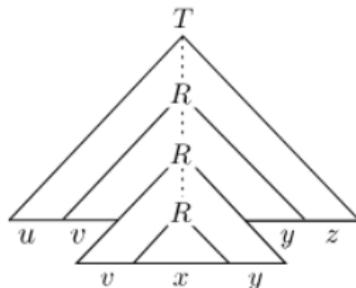
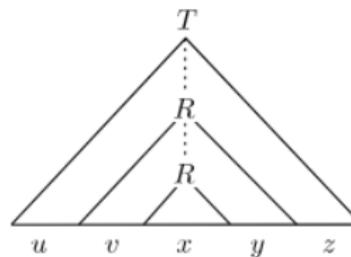
Intuition plays a big role in proofs.

Intuition

Intuition plays a big role in proofs. Take for example the pumping lemma for context free grammars.

Intuition

Intuition plays a big role in proofs. Take for example the pumping lemma for context free grammars.



Intuition in ITPs

- There is **almost no room** for intuition in ITPs.

Intuition in ITPs

- There is **almost no room** for intuition in ITPs.
- This is bad. Spending time on things obvious by intuition, may hamper the **non-obvious** things.

Intuition in ITPs

- There is **almost no room** for intuition in ITPs.
- This is bad. Spending time on things obvious by intuition, may hamper the **non-obvious** things.
- This is good. It allows for stronger guarantees.

Intuition in ITPs

- There is **almost no room** for intuition in ITPs.
- This is bad. Spending time on things obvious by intuition, may hamper the **non-obvious** things.
- This is good. It allows for stronger guarantees. **As a student, by default, your intuition is non-existent or bad.**

Costs and Caveats

Costs and Caveats

- Error in specification.

Costs and Caveats

- Error in **specification**.
- **Bugs** in prover-software. Possibility of **breaking updates**.

Costs and Caveats

- Error in **specification**.
- **Bugs** in prover-software. Possibility of **breaking updates**.
- Benefits from **abstractions**.

Costs and Caveats

- Error in **specification**.
- **Bugs** in prover-software. Possibility of **breaking updates**.
- Benefits from **abstractions**.
- Strictness can cause difficulty in **iteration**.

Concluding

That's all! Thank you for attending my talk. I am part of a student club called ,\ AMBDA. at IIT Gandhinagar where we like to work on interesting things in PLT along with organising talks to cultivate interest in PLT. Let me know if you are interested in knowing more!
You can also contact me at
<mailto:aniket.mishra@iitgn.ac.in>.