

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

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An Illustrative Example

Let us consider a C program that checks some input against a given password by comparing it by 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
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10 0000	Rejected in 3 rd iteration
11 0000	Rejected in 2 nd iteration

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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

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

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Timing Security

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

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

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

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

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

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IF-HIGH

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

Debranch Semantics: The Basics

DEB-ASSN-TRUE

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

DEB-ASSN-FALSE

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

Debranch Semantics: IFs

DEB-IF-HIGH

$$\frac{\begin{array}{c} e_1 \mid \mu \Downarrow_{\ell} T_3, n_1^{k_{\ell}} \quad e_1 \mid \mu \Downarrow_{pc} T_4, n_1^{k_{pc}} \quad k_{\ell} \not\sqsubseteq \ell \quad n_1 \& n = n' \quad !n_1 \& n = n'' \\ \text{debranch}(c_1, n', \ell) \mid \mu \Downarrow_{k_{pc}} T_1 \mid \mu' \quad \text{debranch}(c_2, n'', \ell) \mid \mu' \Downarrow_{k_{pc}} T_2 \mid \mu'' \end{array}}{\text{debranch}(\text{if } e_1 \text{ then } c_1 \text{ else } c_2, n, \ell) \mid \mu \Downarrow_{pc} \langle T_1, T_2, T_3, T_4, \text{DEB-IF-HIGH} \rangle \mid \mu''}$$

DEB-IF-LOW

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

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

- LEAN4 (2013)
- 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) {pc: Level} (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.
  = reflexivity.
  = reflexivity.
  = specialize (IHe1 _ _ _ _ X1 X0_1).
    specialize (IHe2 _ _ _ _ X2 X0_2).
    rewrite → IHe1.
    rewrite → IHe2.
    reflexivity.
Qed.
```

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- During December, I spent some time in IIT Delhi with Prof Vaishnavi Sundararanjan and started properly working with theorem provers.
- After this, I got extremely anxious about my **proofs and theorems being incorrect.**

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Learning Proofs

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- 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 by example is difficult: "The proof is trivial", or "The proof follows simply from induction on x ".

Intuition

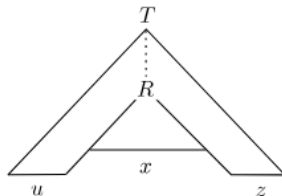
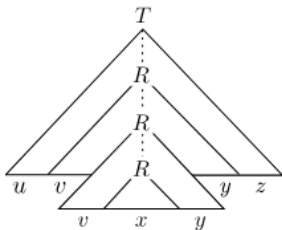
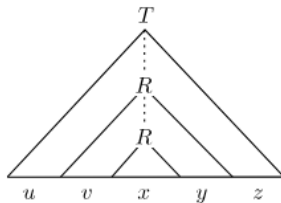
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- This is bad. Spending time on things obvious by intuition, may hamper the **non-obvious** things.
- This is good. It allows for stronger guarantees. **As a student, by default, your intuition is non-existent or bad.**

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