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

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Outline

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 ;
}
```

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

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

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Let us say our μ is $x \rightarrow \mathit{true}^L$, $y \rightarrow \mathit{true}^M$, $z \rightarrow \mathit{true}^H$, 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.

Expression Semantics

CONST

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

VAR

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

OPER

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

Command Semantics

The Basics

SKIP

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

ASSN

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

SEQ

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

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IF-HIGH

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$$\frac{\textsf{debranch}(c_1, n, pc) \mid \mu \Downarrow_k T_1 \mid \mu' \qquad \begin{array}{c} e \mid \mu \Downarrow_{pc} T, n^k \\ \textsf{debranch}(c_2, !n, pc) \mid \mu' \Downarrow_k T_2 \mid \mu'' \end{array} \qquad k \not\sqsubseteq pc}{\textsf{if } e \textsf{ then } c_1 \textsf{ else } c_2 \mid \mu \Downarrow_{pc} \langle T, T_1, T_2, \texttt{IF}-\texttt{HIGH} \rangle \mid \mu''}$$

Debranch Semantics: The Basics

DEB-ASSN-TRUE

$$\frac{e \mid \mu \Downarrow_{pc} T_1, n^k \qquad x \mid \mu \Downarrow_{pc} T_2, n_1^{k_1}}{\mathsf{debranch}(x := e, (true), \ell) \mid \mu \Downarrow_{pc} \langle T_1, T_2, \mathtt{DEB} - \mathtt{ASSN_x} \rangle \mid \mu, x \mapsto n^k}$$

DEB-ASSN-FALSE

$$\frac{e \mid \mu \Downarrow_{pc} T_1, n^k \qquad x \mid \mu \Downarrow_{pc} T_2, n_1^{k_1}}{\mathsf{debranch}(x := e, (false), \ell) \mid \mu \Downarrow_{pc} \langle T_1, T_2, \mathtt{DEB} - \mathtt{ASSN_x} \rangle \mid \mu, x \mapsto n_1^k}$$

Debranch Semantics: IFs

DEB-IF-HIGH

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

DEB-IF-LOW

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

ITPs

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

- LEAN4 (2013)
- 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 comparitively 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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- 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 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".

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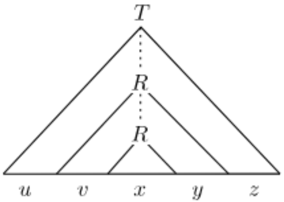

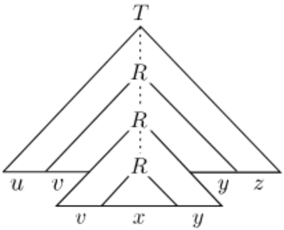

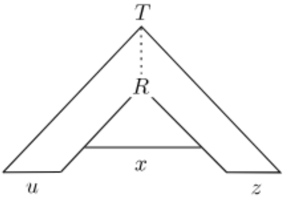

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- This is bad. Spending time on things obvious by intuition, may hamper the non-obvious things.
- This is good. It allows for stronger guarantees. As a student, by default, your intuition is non-existent or bad.

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- 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!