TANA: Address-based Side-Channel Leakages Quantification

Qinkun Bao

Address-based Side Channels

```
unsigned char key = input();
// 4 bits information
unsigned char temp = key/2;
if (temp == 0xb)
// branch 0 takes 2s
else
// branch 1 takes 1s
```

Secret-dependent control-flow transfers

```
T[1024];
// Lookup tables with 64 entries
index = key % 64;
temp = T[index]
// Secret-dependent memory access
```

Secret-dependent memory accesses

Side-channel Vulnerability Detections

Software countermeasures:

- Find vulnerabilities
- Fix vulnerabilities

Existing works:

- False positives
  - e.g., 2248 potential leakages for RSA in OpenSSL, 1510 of them were dismissed
- Report many unsensitive leakages

Our Objective: Identify and quantify address-based side-channels precisely.

An example

```
unsigned char k1, k2;
...
t1 = T[k1 % 8];       // Leakage 1
if(k1 > 127)          // Leakage 2
    A();
if(k2 + k1 > 127)     // Leakage 3
    B();
```

An attacker:
1. knows which element the code read
2. knows if the code runs A(), B()

Leakage	1	2	3	1,2	1,3	2,3
Leaked (bits)	3	1	1	4	4	2

Overview

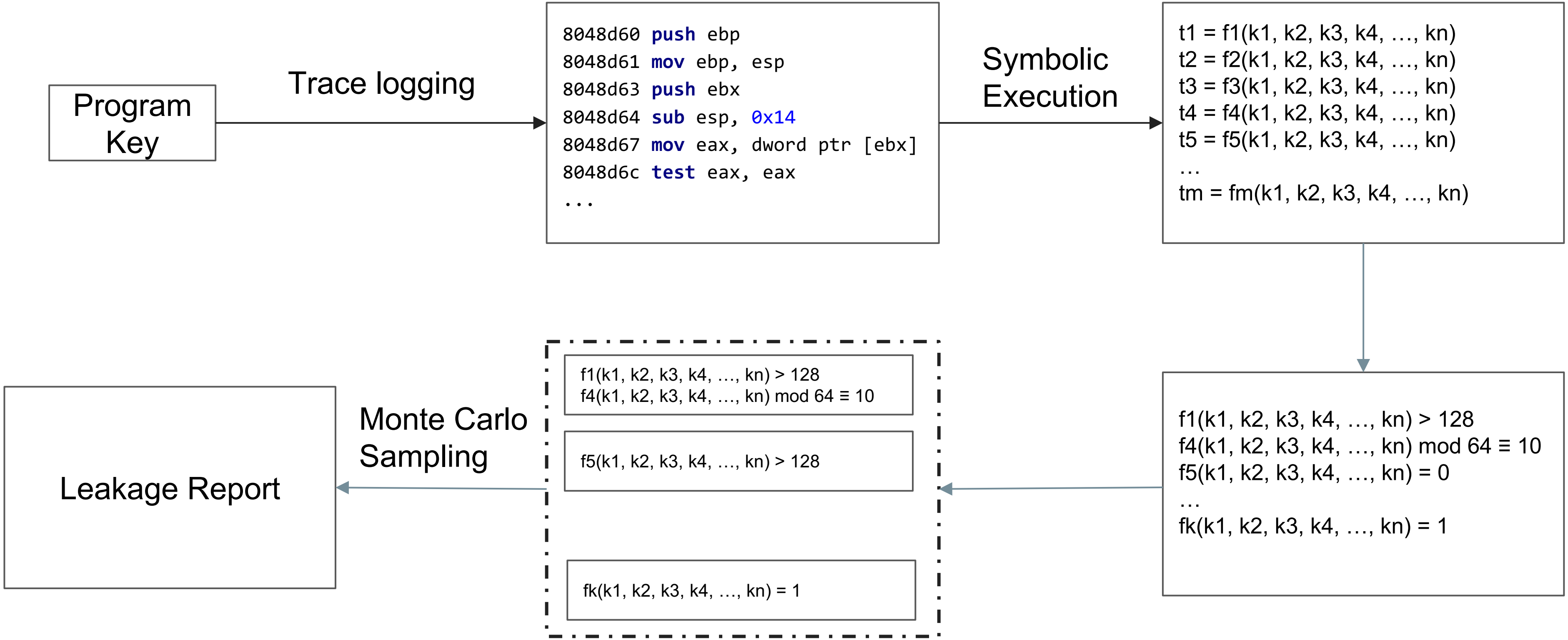


Figure 1. TANA architecture

Challenges

- Information Leakage Definition
  - Shannon entropy and mutual information
  - Number of different observations
- Leakage Dependence
  - Real-world applications may have multiple information leakages sites
  - Some leakages are dependent
- Scalability
  - We want to quantify information leakages in real-world applications
  - e.g. AES implementations have thousands of lines -> 1 million instructions
  - The performance is important

Challenge 1: Information Leakage Definition

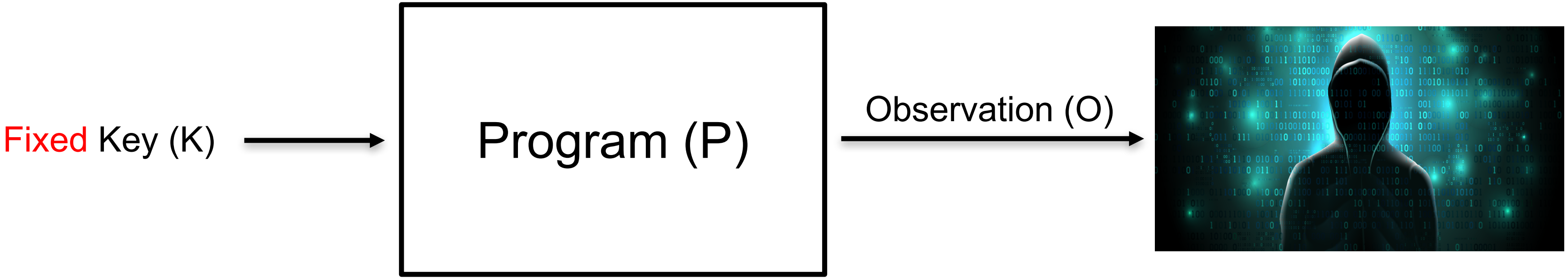


Figure 2. Observation Model

Observations:

1. Secret-dependent control-flow
2. Secret-dependent memory access

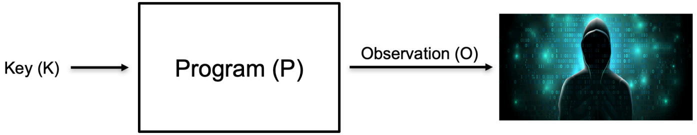
Previous Information Leakage Definition

Mutual Information (MI):

$$\mathrm{MI} = \mathrm{I}(\mathrm{K};\mathrm{O}) = \mathrm{H}(\mathrm{O}) - \mathrm{H}(\mathrm{K}|\mathrm{O}) = \mathrm{H}(\mathrm{O}) = \sum_{\mathrm{o_i} \in \mathrm{O}} \mathrm{P}(\mathrm{o_i})\log_2 \mathrm{P}(\mathrm{o_i})$$

Maximal Leakage (ML):

$$\mathrm{ML} = \log_2 |\mathrm{O}|$$




```c
unsigned char key = input();
// key = [0 ... 255]
if(key = 128)
   A(); // branch 1
else if (key < 64)
   B(); // branch 2
else if (key < 128)
   C(); // branch 3
else
   D(); // branch 4
```

Branch	1	2	3	4
Possibility	$\frac{1}{256}$	$\frac{64}{256}$	$\frac{63}{256}$	$\frac{128}{256}$

$$MI = \frac{1}{256}log_2\frac{1}{256} + \frac{64}{256}log_2\frac{64}{256} + \frac{63}{256}log_2\frac{63}{256} + \frac{128}{256}log_2\frac{128}{256} = 1.7bits$$

$$ML = log_2 4 = 2bits$$

Challenge 1: Information Definition

```
// Dummy password checker
unsigned char key = input();
// key = [0 ... 255]
if(key = 128)
   A(); // branch 1
else if (key < 64)
   B(); // branch 2
else if (key < 128)
   C(); // branch 3
else
   D(); // branch 4
```

Suppose an attacker knows the code run branch 1, then he knows the key equals to 128.

Mutual Information: 1.7 bits
Max Leakage: 2 bits

Problem: Both methods neglect the input key and give an "average" estimate.

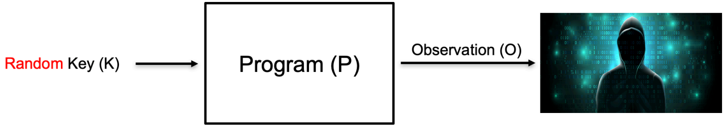


Figure 3

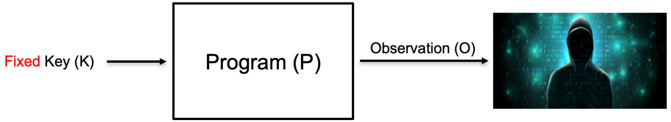


Figure 4

Challenge 1: Information Leakage Definition

Definition. *Given a program P with the input set K, an adversary has the observation o when the input k ∈ K. We denote it as*

$$P(k) = 0$$

The leakage L_{ko} *based on the observation is*

$$L_{ko} = \ log_2|K| - log_2|K^o|$$

where

$$K_o = \{k' \mid k' \in K \ and \ P(k') = o\}$$

Basic idea: counting the number of observations that have the same memory-access pattern.

```
// Dummy password checker
unsigned char key = input();
// key = [0 ... 255]
if(key = 128)
   A(); // branch 1
else if (key < 64)
   B(); // branch 2
else if (key < 128)
   C(); // branch 3
else
   D(); // branch 4
```

Example:

$$|K| = 256 \quad |K_1| = 1 \quad |K_2| = 64$$

$$L_{ko1} = \ log_2 256 \ - \ log_2 1 \ = 8 \ bits$$

$$L_{ko2} = \ log_2 256 \ - \ log_2 64 \ = 2 \ bits$$

Challenge 2: Leakage Dependence

- Suppose one program has two leakage sites A and B.
  - Independent Leakage
  - Mutual Exclusive Leakage
  - Dependent Leakage

```
unsigned char k1, k2, t1, t2;
t1 = k1 + 2*k2;
t2 = 2*k1 - k2;
if(t2 + t1 > 127)  // Leakage A
    A();
if(t2 - t1 > 0)    // Leakage B
    B();
```

Leakage A:

$$\begin{cases} 0 \leq k_1 \\ k_1 \leq 255 \\ 3k_1 + k_2 > 127 \end{cases}$$

Leakage B:

$$\begin{cases} 0 \leq k_2 \\ k_2 \leq 255 \\ k_1 - 3k_2 > 0 \end{cases}$$

Leakage A and B :

$$\begin{cases} 0 \leq k_1 \\ k_1 \leq 255 \\ 3k_1 + k_2 > 127 \\ k_1 - 3k_2 > 0 \end{cases}$$

if $L_{(k1k2)A} + L_{(k1+k2)B} = L_{(k1+k2)AB}$,
then A and B are independent

Challenge 3: Scalability

We want to quantify information leakages from real-world applications.

The performance suffers from the following aspects:

- Symbolic Execution
    - IR explosion
- Monte Carlo Sampling
    - #P problem

Challenge 3: Scalability (Symbolic Execution)

- Why symbolic execution (SE) is slow?
- Path Explosion ✔
- Constraint Solving ✔
- Intermediate Languages (IR) ?

Why symbolic execution uses IR?

- Support many architecture platform.
  - X86, ARM, MIPS
- Easy to implement
  - X86, more than 1000 instructions
  - Side effects

test eax, eax →

```
STR  R_EAX:32,       , V_00:32
STR  0:1,            , R_CF:1
AND  V_00:32,  ff:8, V_01:8
SHR  V_01:8,    7:8, V_02:8
SHR  V_01:8,    6:8, V_03:8
XOR  V_02:8, V_03:8, V_04:8
SHR  V_01:8,    5:8, V_05:8
SHR  V_01:8,    4:8, V_06:8
XOR  V_05:8, V_06:8, V_07:8
XOR  V_04:8, V_07:8, V_08:8
SHR  V_01:8,    3:8, V_09:8
SHR  V_01:8,    2:8, V_10:8
XOR  V_09:8, V_10:8, V_11:8
SHR  V_01:8,    1:8, V_12:8
XOR  V_12:8, V_01:8, V_13:8
XOR  V_11:8, V_13:8, V_14:8
XOR  V_08:8, V_14:8, V_15:8
AND  V_15:8,    1:1, V_16:1
NOT  V_16:1,         , R_PF:1
STR     0:1,         , R_AF:1
EQ  V_00:32,   0:32, R_ZF:1
SHR V_00:32,  1f:32, V_17:32
AND    1:32,V_17:32, V_18:32
EQ     1:32,V_18:32, R_SF:1
STR     0:1,         , R_OF:1
```

Solution: instruction-level symbolic execution

QSYM: A Practical Concolic Execution Engine Tailored for Hybrid Fuzzing. Insu Yun, Sangho Lee, Meng Xu, Yeongjin Jang, and Taesoo Kim.In Proceedings of the 27th USENIX Security Symposium (Security 2018),Baltimore, MD, August 2018.

Challenge 3: Scalability (Monte Carlo Sampling)

- The problem is #P-Hard.
- The number of satisfying assignments might be exponentially small.
  - e.g., $F(K) = \begin{cases} k_1 = 1 \\ 120 < k_2 < 123 \\ k_3 = 3 \\ k_4 = 4 \\ k_5 = 5 \end{cases}$ $\quad k_1, k_2, k_3, k_4, k_5 \in [0, 255]$

Total search space: 2^{40}
Only two satisfying assignments

Solution: Markov chain Monte Carlo Sampling

Implementation

- 15k LoC of C++11
- Trace Collection
  - Intel Pin Tool
- Symbolic Execution
  - Arithmetic, bitwise, logical, control-transfer
  - Not support: AVX, floating number, AES-NI
- Information Leakage Sampling

Evaluation (Not finished)

- Real-world cryptosystems:
  - OpenSSL 0.9.7 1.1.1
  - mbedTLS 2.5 2.15
  - Libjpeg
- Performance
  - CacheD 5 hours
  - 30s found 8 secret-dependent memory access for the DES in mbedTLS 2.5

Summary

Identify and quantify address-based side-channels leakages precisely

- A trace-based method that models each leakage site with math formulas.
- We quantify the information leakages based on the number of secrets that satisfy the constrain.
- Most of leakages found by recent works are hard to exploited. (Need to be confirmed)