FaCT: A DSL for Timing-Sensitive Computation

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MIT 6.888 Fall 2020
Based on slides from Sunjay Cauligi
Goal: Constant-Time Code

- Constant-time code: timing is independent of secrets
  - Variable-time instruction
  - Memory accesses
  - Conditional branches
  - Early termination

```c
if (sec)
   x = a;
} else {
   x = b;
}
```
Motivation: Constant-Time Code is Messy

- Existing techniques include using bitmasks, CMOVs, ORAM, etc.
- The problem:
  - Manually optimized code is messy/unreadable/difficult to reason about correctness
  - Automatically obfuscated code incurs high performance overhead

```c
if (sec)
    x = a;
else {
    x = b;
}
x = (sec & a) | (~mask & b)

(sec) CMOV x = a
(!sec) CMOV x = b
```

Rane et. al. Raccoon: closing digital side-channels through obfuscated execution. SEC’15
Threat Model

• Attacker can observe execution time of target programs

• Not concretely stated in the paper
  • Instruction execution “trace” should be independent from secrets

• However, execution time is determined by micro-arch states
  • Thus, miss a computer architecture model, characterized by which kinds of instructions can leak information and which can not, e.g., arithmetic instructions
Overview

• A DSL for writing readable constant-time code

• Transform **secret control flow** to constant-time
  • Transform code that leaks secret via early return, conditional branch
  • Reject programs that leak secret via memory accesses, loop iterations, variable-time instructions

• Ensure transformations can be performed safely
A DSL Trade-offs Among

An example:
To address the imprecision problem of static information flow analysis, remove pointers and disallow recursive typed references.
Strengths (Potential Long-term Impacts)

- Provide a great abstraction
  - For SW developers, easy to write constant-time programs
  - For compiler developers, use different techniques to achieve the constant-time goal
    - *ctselect* compiles to a series of bitmasks or the CMOV instruction on x86_64
    - For HW people, performance optimization for execution on public data

- Well-defined typing systems for information flow tracking and formal verification

- A user study to show how easy to write programs using FaCT
A Controversial Contribution

• Reject programs that leak secret via memory accesses, loop iterations, variable-time instructions
  • Put the pressure on programmers. What about AES? Is it really a good trade-off?
  • How much time is spent on manually fixing these problems?

```plaintext
O(1)

x = buffer[secret_index];
```

```plaintext
O(n)

for (uint32 i = 0 to len buffer) {
    if (i == secret_index) {
        x = buffer[i];
    }
}
```
Limitations/Questions

• Impacts of compiler optimizations of FaCT generated code
  • Security evaluation using deduct is not sufficient
  • More information about generated binary sizes may help reason about the performance improvements

• It would be helpful to elaborate more on the trade-offs/reasons for picking the specific design choice in the paper
FaCT Technique Details
Explicit Secrecy and Information Flow Tracking

• How to handle \( st(sec\_val, \ pub\_addr) \)?

```c
secret uint32 decrypt(
    secret uint32 key,
    public uint32 msg)
{
    if (key > 40) {
        ...
    }
    ...
    ...
}

secret uint32 decrypt(
    secret uint32 key,
    public uint32 msg)
{
    if (key > 40) {
        ...
    }
    ...
    ...
}
```
Type system detects leaks via...

- Conditional branches
- Early termination
- Function side effects
- Memory access patterns
- Direct assignment
- ...

FaCT transforms these

FaCT disallows these
Transform Secret Conditionals

```plaintext
if (s) {
  x = 40;
} else {
  x = 19;
  y = x + 2;
}
```

```plaintext
x = -s & 40 | (s-1) & x;
```

```plaintext
x = (s-1) & 19 | -s & x;
```

```plaintext
y = (s-1) & (x + 2) | -s & y;
```
if (s) {
    return 40;
}

if (!done) {
    rval = 40;
    done = true;
}

rval = (-s & (done-1)) & 40 | ...

done = (-s & (done-1)) & true | ...
void foo(secret mut uint32 x) {
    x = 5;
}
...
if (sec) {
    foo(x);
}

void foo(secret mut uint32 x, secret bool callCtx) {
    x = ctselect(callCtx, 5, x);
}
...
foo(x, sec);
Unsafe transformations

What if $j > \text{len arr}$?

**Out of bounds** access!

Check for out-of-bounds accesses; Solve constraints using Z3
Porting code to FaCT

• Rewrite the whole library
• Rewrite a function (and callees)
• Rewrite a chunk of code
Real Code Needs Escape Aatches

• **Declassify** secrets to public
  • secretbox:
    ```
    if (!declassify(crypto_verify(...))
    return false;
    ```

• TLS:
  ```
  b = pmac[declassify(i)];
  ```

• **Assume** constraints for solver
  • Function preconditions
  • Invariants for mutable variables

• **Extern** function declarations
  • OpenSSL: AES + SHA1 implementations
Performance Evaluation

- Optimized with **same optimization flags**
- **Empirically tested** to be constant-time

![Graph showing % Overhead for donna, secretbox, ssl3, and TLS](image)
Understanding constant-time code

Task 1
message encoding

Task 2
long division

Mean score

+7.5%

+25%
Writing constant-time code

Task 3
secret memzero
+27%

Task 4
padding check
+9.4%

Task 5
padding removal
+42%

# Correct submissions

C  FaCT
C  FaCT
C  FaCT

C  FaCT
Discussion Questions on HW/SW

• Given modern computers have execution units that may not be constant time (specifically division), even a static flow of instructions may not execute with constant total time. What would it take to make sure said execution units operate in a constant time? Division is rare in crypt, so maybe just avoiding it altogether?

• What other processor optimizations exist that will make constant-time operation hard or impossible?

• If a given piece of code is made timing-insensitive, is it possible for power side-channels to still be present?
Discussion Questions on Code Transformation

• Would a lower level solution to the constant time problem be more effective?

• Could we further extend such constant-time reasoning to the optimizer to formally verify the entire compilation flow?

• Is there a more efficient way for the front-end compiler to operate than return statements -> conditionals and then conditionals -> constant time code?
Discussion Questions on Usage

• Are there any cryptographic constructs which are unable to be expressed in FaCT?

• Has there been any further user studies done? If so, what have they shown? If not, what could we expect to see?

• How well do secrets propagate through the type system in practice? For example, if I as an inexperienced cryptographer produce a cipher where I mark my salt, my key, and my plaintext as secret, is this sufficient? Is it overkill?