Side-Channel Attacks and Non-Interference

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Outline

- Last week:
  - Safety and correctness bugs in cryptographic implementations
  - Introduction to the F* proof assistant

- Today:
  - Side-channel attacks
  - Establishing non-interference in implementations

Leaking Secrets

secret s, key k

m <- encrypt(k, s)

send m

Assumption: **k is secret**

Implementation:

print(k)

let m = encrypt(k, s) in

send(m)

Indirectly Leaking Secrets

```
if k = 0xDEADBEEF then
  print(foo)
else
  print(bar)
let m = encrypt(k, s) in
send(m)
```

Leaking Information through Observations

```
let verify_pwd(string msg, string pwd) =
  if msg.length <> pwd.length then return false
  for (k = 0; k < msg.length; k ++) {
    if msg[k] <> pwd[k] then return false
  }
  return true
```

Possible attack:

- Measure execution time
- *Observe* longer execution time when msg has the same length as pwd
- *Observe* longer execution time when msg and pwd match on the first k characters

Side-Channel Attacks

- A ***side-channel attack*** exploits *physical observations* due to running a program to *infer information* about secrets
  - Execution time
  - Power consumption
  - Cache patterns
  - Keyboard sounds
  - …

- Can leak cryptographic keys, plaintexts, state information, …

Timing Attacks [Kocher, CRYPTO' 96]

- First published side-channel attack on cryptography
- Focuses on modular exponentiation
- Able to find fixed Diffie-Hellman exponents, factor RSA keys, …
- Let's look at this on RSA

Background on RSA [Rivest, Shamir, Adleman, 78]

- Public-key encryption algorithm (can also be used for signing)
- Relies on a public key (N, e), and a private key d
- N is the product of two large prime numbers p and q
- e and d are related through $ed = 1 \bmod (p - 1)(q - 1)$
- Security relies on p and q being unknown to the attacker (i.e., factoring large numbers is hard)

RSA Encryption

- Public key *(N, e),* private key *d,* plaintext *M*
- Encryption: Ciphertext is $M^e \; mod \; N$
- Decryption: We receive a ciphertext *C.* We return $C^d \; mod \; N$

- Correctness: For any plaintext M, decrypt(encrypt(M)) == M
  Mathematically: $(M^e)^d \; mod \; N = M \; mod \; N$
  Proof relies on Fermat's little theorem

- Can also be used for signing:
  - Send $\left(M, M^d \; mod \; N\right)$
  - Anybody can check that $(M^d)^e \; mod \; N = M \; mod \; N$

Timing Attack on RSA

- Attacker goal: Guess private key *d*
- Attacker capabilities: Can query decryption for any ciphertext C

$C^d \ mod \ N$ implementation (assume d contains w bits):

x = 1

for k = 0 to w – 1 do

    if d[k] = 1 then x = xC mod N

    x = x^2 mod N

return x

Timing Attack on RSA

x = 1

for k = 0 to w – 1 do

  if d[k] = 1 then x = xC mod N

  x = x^2 mod N

return x

Example: Take d = 10 (binary: 1010)

(Iteration 0): d[0] = 0

  x = x^2 mod N // = 1 mod N

(Iteration 1): d[1] = 1

  x = xC mod N // = C mod N

  x = x^2 mod N // = C^2 mod N

(Iteration 2): d[2] = 0

  x = x^2 mod N // = C^4 mod N

(Iteration 3): d[3] = 1

  x = xC mod N // = C^5 mod N

  x = x^2 mod N // = C^{10} mod N

Timing Attack on RSA

```
x = 1
for k = 0 to w – 1 do
    if d[k] = 1 then x = xC mod N
    x = x^2 mod N
return x
```

- Attacker goal: Guess d[0]
- Assumption: y mod N is slower for some values of y
  - Ex: When y >= N depending on mod impl

Attack:

- Call decrypt with two ciphertexts C_1, C_2, such that $C_1^2 < N$ <= C_2^2
- If execution times differ, then d[0] = 1, else d[0] = 0
- In practice, statistical analysis with a family of C_1, C_2 to account for noise, network delay, …

Timing attack on RSA

```
for k = 0 to w – 1 do
    if d[k] = 1 then x = xC mod N
    x = x^2 mod N
return x
```

- Assume d[0], … d[k-1] are known
- Attacker goal: Guess d[k]
- Assumption: y mod N is slower when N <= y

Attack:

- The attacker can compute the first k iterations for any ciphertext C
- Call decrypt with two ciphertexts C_1, C_2, such that $x_1^2 < N$ <= x_2^2 where x_1, x_2 are intermediate results after k iterations for C_1, C_2
- If execution times differ, then d[k] = 1, else d[k] = 0

Timing Attack on RSA

- Recursively applying this methodology, we can guess all bits of *d*
- Original results:
  - 128-bit key could be broken with about 10,000 samples (4 bits/sec)
  - 512-bit key coud be broken in a few minutes with ~350,000 measurements
- Further attacks on optimized RSA implementations intended to circumvent timing attacks also shown effective

  Remote Timing Attacks are Practical, Brumley and Boneh, USENIX’ 03

Cache-based Side Channel Attacks

- Exploit timing differences due to accesses to memory caches
- Especially demonstrated on the AES block cipher

Bernstein, D. J. (2005). *Cache-timing attacks on AES.*

Osvik, D. A., Shamir, A., & Tromer, E. (2006). *Cache attacks and countermeasures: the case of AES.*

Bonneau, J., & Mironov, I. (2006). *Cache-collision timing attacks against AES.*

Tromer, E., Osvik, D. A., & Shamir, A. (2010). *Efficient cache attacks on AES, and countermeasures*

Background on AES

- Block cipher: transforms a fixed-size plaintext (128 bits) into a ciphertext using a secret key *k*
    - Many encryption modes to support arbitrary-sized plaintexts (AES-GCM, AES-CTR, …)
- Initially, xor plaintext with key
- Followed by several rounds of encryption operating on a state of 16 bytes

$$\begin{matrix} p_0 & p_4 & p_8 & p_{12} \\ p_1 & p_5 & p_9 & p_{13} \\ p_2 & p_6 & p_{10} & p_{14} \\ p_3 & p_7 & p_{11} & p_{15} \end{matrix} \xrightarrow{\text{AES Rounds}} \begin{matrix} c_0 & c_4 & c_8 & c_{12} \\ c_1 & c_5 & c_9 & c_{13} \\ c_2 & c_6 & c_{10} & c_{14} \\ c_3 & c_7 & c_{11} & c_{15} \end{matrix}$$

AES Round

Several Successive Transformations:

$$\begin{matrix} p_0 & p_4 & p_8 & p_{12} \\ p_1 & p_5 & p_9 & p_{13} \\ p_2 & p_6 & p_{10} & p_{14} \\ p_3 & p_7 & p_{11} & p_{15} \end{matrix}$$

$$\downarrow$$

- Substitute bytes through affine transformation (SubBytes)

$$\begin{matrix} p'_0 & p'_4 & p'_8 & p'_{12} \\ p'_1 & p'_5 & p'_9 & p'_{13} \\ p'_2 & p'_6 & p'_{10} & p'_{14} \\ p'_3 & p'_7 & p'_{11} & p'_{15} \end{matrix}$$

$$\downarrow$$

- Different shifts in each row (ShiftRows)

$$\begin{matrix} p'_0 & p'_4 & p'_8 & p'_{12} \\ p'_5 & p'_9 & p'_{13} & p'_1 \\ p'_{10} & p'_{14} & p'_2 & p'_6 \\ p'_{15} & p'_3 & p'_7 & p'_{11} \end{matrix}$$

$$\downarrow$$

- Apply linear transformation to each column (MixColumns):

$$\begin{matrix} p''_0 & p''_4 & p''_8 & p''_{12} \\ p''_1 & p''_5 & p''_9 & p''_{13} \\ p''_2 & p''_6 & p''_{10} & p''_{14} \\ p''_3 & p''_7 & p''_{11} & p''_{15} \end{matrix}$$

- Xor with (a derived sub)key (AddRoundKey): $c_i = p''_i \oplus k_i$

Optimized AES Round

- The first three transformations (SubBytes, ShiftRows, MixColumns) only depend on the input state
- The result can be precomputed for all p_i , and stored in tables T_k.

Optimized AES round:

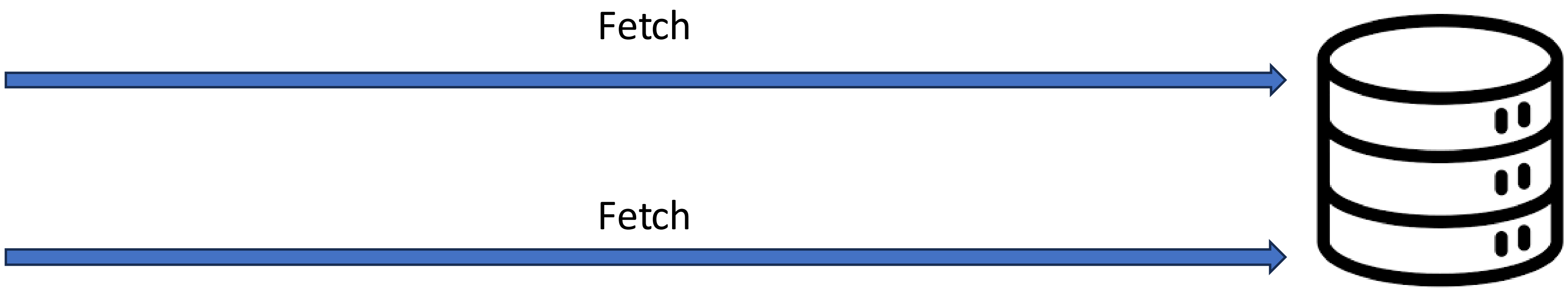
$$\begin{matrix} x_0 & x_4 & x_8 & x_{12} \\ x_1 & x_5 & x_9 & x_{13} \\ x_2 & x_6 & x_{10} & x_{14} \\ x_3 & x_7 & x_{11} & x_{15} \end{matrix} \Rightarrow \begin{matrix} T_0[x_0] \oplus T_1[x_5] \oplus T_2[x_{10}] \oplus T_3[x_{15}] \oplus \{k_0, k_1, k_2, k_3\} \\ T_0[x_4] \oplus T_1[x_9] \oplus T_2[x_{14}] \oplus T_3[x_3] \oplus \{k_4, k_5, k_6, k_7\} \\ T_0[x_8] \oplus T_1[x_{13}] \oplus T_2[x_2] \oplus T_3[x_7] \oplus \{k_8, k_9, k_{10}, k_{11}\} \\ T_0[x_{12}] \oplus T_1[x_1] \oplus T_2[x_6] \oplus T_3[x_{11}] \oplus \{k_{12}, k_{13}, k_{14}, k_{15}\} \end{matrix}$$

Cache Model (Simplified)

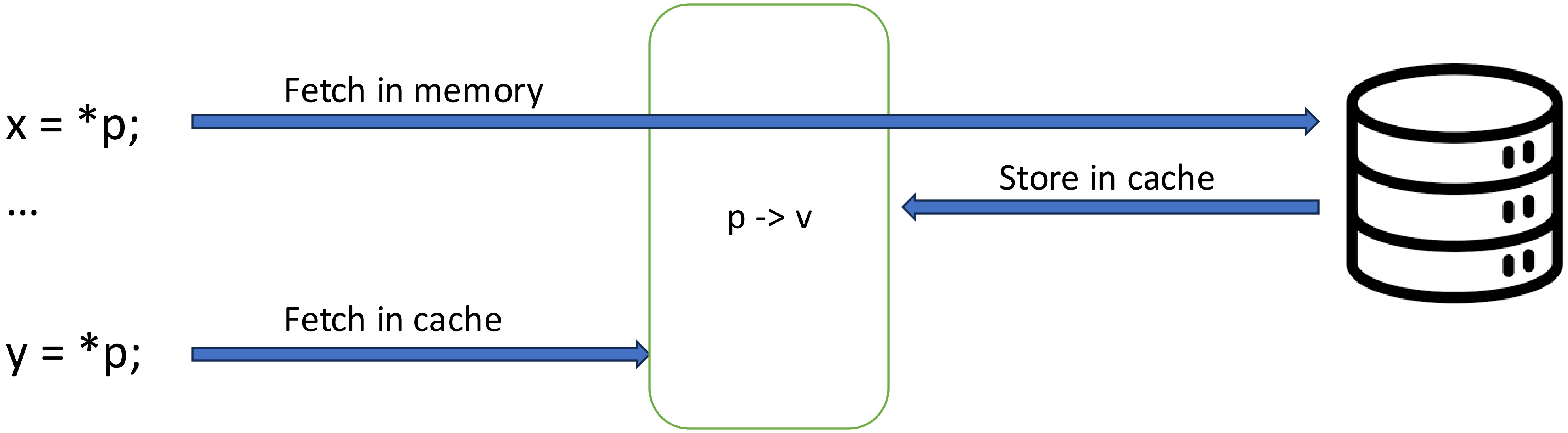
x = *p;

…

y = *p;



Cache Model (Simplified)



- Accesses to the cache are faster than to main memory
- Storage in the cache is smaller than memory
- When the cache is full, storing a new value removes older mappings

AES First Round Cache Attack

- For the first round, the inputs x_i are equal to $p_i \oplus k_i$
- We are accessing memory at address $T_k[x_i]$
- The attacker controls input *p*
- We access $T_0[x_0], T_0[x_4], T_0[x_8], T_0[x_{12}]$
- If (e.g.) $x_0 = x_4$, execution time is lower as $T_0[x_4]$ is stored in cache when accessing $T_0[x_0]$
- Trying different samples, we can find values of p_0, p_4, such that $x_0 = p_0 \oplus k_0 = x_4 = p_4 \oplus k_4$
- We can determine the value of $k_0 \oplus k_4$

AES Cache-Based Attacks

- Similar attacks allow to infer more information about the key, leading to key retrieval
- Omitted details
  - Attacker needs to control the initial state of the cache
  - Cache does not allow to reason about lower bits of accessed addresses
  - Other computations can lead to timing differences
- There exists technical solutions for all of this

Speculative Side-Channel Attacks: Spectre

```
if (0 <= x < a.length) {
  i = a[x];
  r = b[i];
}
```

- Assume that all values in *a* are in [0; b.length[
- Can this code lead to a buffer overflow?

- In theory, no, all accesses are in bound, but…

CPU Branch Prediction

- CPU instruction pipeline: Fetch, Decode, Execute, Access Memory, Write results in registers
- Modern CPUs anticipate and start executing next instructions early
- When branching occur, CPUs “guess” which branch is most likely to start the instruction pipeline
- When wrong, rollback to earlier CPU state
- Problem: Rollback does not include the entire microarchitectural state, e.g., cache state

Speculative Side-Channel Attacks: Spectre

```
if (0 <= x < a.length) {
  i = a[x];
  r = b[i];
}
```

- Run program with x = a.length + n
- CPU predicts that the if branch will be taken
- Pre-executes the two memory accesses
- When rolling back, the cache contains a mapping for *i*

- Attack:
  - Train branch predictor for if branch
  - Pick *n* such that a[a.length + n] contains a secret
  - Launch a cache side channel attack to infer i

Physical Side-Channel Attacks

- Similar attacks exploit the power consumption or electromagnetic leakage.
- Ex: Power consumption of a given instruction is correlated to the number of bits set in its operands (Hamming weight model)
- Infer information about secrets manipulated by the program
- Require some access to the device

Recent Physical Side-Channel Attacks

Video-Based Cryptanalysis: Extracting Cryptographic Keys from Video Footage of a Device's Power LED, Nassi et al., 2023

- **Core idea:**
  - Direct access to device is not needed, a video of its use might be enough
  - The power consumption of a device affects the brightness of its power LED
  - In some cases, this is sufficient to launch a remote power-based side-channel attack

- Today: Focus on *digital* side-channel attacks

Non-Interference [Goguen-Meseguer, 82]

- Goal: We want to ensure that *secret data* does not impact *public observations* available to an attacker

- Information-flow property based on *secrecy labels*:
  - High (H) == Secret data
  - Low (L) == Public data

- High-level idea: There is no flow from high data to low data

Non-Interference, Formally

For a given program *p*,

$\forall\ (s_1\ s_2 \colon state)$,

$s_{1|\,L} = s_{2|\,L} \Rightarrow$ // States agree on low values

$s_1 \rightarrow_p^* s_1' \Rightarrow$ // Executing *p* in s_1 yields s_1'

$s_2 \rightarrow_p^* s_2' \Rightarrow$ // Executing *p* in s_2 yields s_2'

$s_{1|\,L}' = s_{2|\,L}'$ // Results agree on low values

Non-Interference Example

if x = 1 then y := 1 else y := 0

- If x : H, y : H: No low values, non-interference
- If x : L, y : L: Initial agreement on x, non-interference
- If x : L, y : H: Initial agreement on x, non-interference
- If x : H, y : L: Observing the result of y leaks information about x

- Goal: Statically ensure noninterference

Non-Interference by Typing [Volpano et al., 96]

$$
\begin{array}{lll}
(\textit{expressions}) & e ::= & x \mid l \mid n \mid e + e' \mid e - e' \mid e = e' \mid e < e' \\
(\textit{commands}) & c ::= & e := e' \mid c; c' \mid \textbf{if } e \textbf{ then } c \textbf{ else } c' \mid \\
 & & \textbf{while } e \textbf{ do } c \mid \textbf{letvar } x := e \textbf{ in } c
\end{array}
$$

$$
\begin{array}{lll}
(\textit{data types}) & \tau ::= & s \\
(\textit{phrase types}) & \rho ::= & \tau \mid \tau\ \textit{var} \mid \tau\ \textit{cmd}
\end{array}
$$

- Data types *s* are security labels (in our case, H and L)
- Each expression and command is annotated with a security label

Typing Judgement

$$\lambda; \gamma \vdash p : \rho$$

- λ is a memory store: It associates to each *location* its security label
- γ is a variable environment: It maps variables to their type
- Under this context, this judgement gives program p the type ρ

Typing Rules

$$(\textsc{int}) \qquad \lambda; \gamma \vdash n : \tau$$

$$(\textsc{var}) \qquad \lambda; \gamma \vdash x : \tau\ var \qquad \text{if } \gamma(x) = \tau\ var$$

$$(\textsc{varloc}) \qquad \lambda; \gamma \vdash l : \tau\ var \qquad \text{if } \lambda(l) = \tau$$

$$(\textsc{r-val}) \qquad \frac{\lambda; \gamma \vdash e : \tau\ var}{\lambda; \gamma \vdash e : \tau}$$

Typing Rules

$$(\textsc{arith}) \qquad \frac{\begin{array}{l}\lambda; \gamma \vdash e : \tau, \\ \lambda; \gamma \vdash e' : \tau\end{array}}{\lambda; \gamma \vdash e + e' : \tau}$$

$$(\textsc{assign}) \qquad \frac{\begin{array}{l}\lambda; \gamma \vdash e : \tau \ var, \\ \lambda; \gamma \vdash e' : \tau\end{array}}{\lambda; \gamma \vdash e := e' : \tau \ cmd}$$

Typing Rules

(COMPOSE)
$$\frac{\lambda; \gamma \vdash c : \tau\ cmd, \quad \lambda; \gamma \vdash c' : \tau\ cmd}{\lambda; \gamma \vdash c; c' : \tau\ cmd}$$

(IF)
$$\frac{\lambda; \gamma \vdash e : \tau, \quad \lambda; \gamma \vdash c : \tau\ cmd, \quad \lambda; \gamma \vdash c' : \tau\ cmd}{\lambda; \gamma \vdash \textbf{if}\ e\ \textbf{then}\ c\ \textbf{else}\ c' : \tau\ cmd}$$

(WHILE)
$$\frac{\lambda; \gamma \vdash e : \tau, \quad \lambda; \gamma \vdash c : \tau\ cmd}{\lambda; \gamma \vdash \textbf{while}\ e\ \textbf{do}\ c : \tau\ cmd}$$

Typing Example

if x = 1 then y := 1 else y := 0

Assume that x : H var, y : H var

Goal : Give this program the type *H cmd*

Typing Example

Goal: x: H var, y: H var ⊢ if x = 1 then y := 1 else y := 0 : *H cmd*

$$(\text{IF})\quad \frac{\begin{array}{l}\lambda;\gamma \vdash e : \tau,\\ \lambda;\gamma \vdash c : \tau\ cmd,\\ \lambda;\gamma \vdash c' : \tau\ cmd\end{array}}{\lambda;\gamma \vdash \textbf{if}\ e\ \textbf{then}\ c\ \textbf{else}\ c' : \tau\ cmd}$$

Need to prove

- x: H var, y : H var ⊢ x = 1 : H
- x: H var, y : H var ⊢ y := 1 : H cmd
- x: H var, y : H var ⊢ y := 0 : H cmd

Typing Example

Goal: x: H var, y: H var ⊢ x = 1 : H

$$(\text{ARITH}) \quad \frac{\lambda; \gamma \vdash e : \tau, \quad \lambda; \gamma \vdash e' : \tau}{\lambda; \gamma \vdash e + e' : \tau}$$

Need to prove

- x: H var, y : H var ⊢ 1 : H
- x: H var, y : H var ⊢ x : H

$$(\text{INT}) \quad \lambda; \gamma \vdash n : \tau$$

$$(\text{VAR}) \quad \lambda; \gamma \vdash x : \tau \ var \quad \text{if } \gamma(x) = \tau \ var$$

$$(\text{R-VAL}) \quad \frac{\lambda; \gamma \vdash e : \tau \ var}{\lambda; \gamma \vdash e : \tau}$$

Typing Example

Goal: x: H var, y : H var ⊢ y := 1 : *H cmd*

$$(\text{ASSIGN}) \quad \frac{\lambda; \gamma \vdash e : \tau\ var, \quad \lambda; \gamma \vdash e' : \tau}{\lambda; \gamma \vdash e := e' : \tau\ cmd}$$

Need to prove

- x: H var, y : H var ⊢ y : H var $\quad (\text{VAR}) \quad \lambda; \gamma \vdash x : \tau\ var \quad \text{if } \gamma(x) = \tau\ var$
- x: H var, y : H var ⊢ 1 : H $\quad (\text{INT}) \quad \lambda; \gamma \vdash n : \tau$

Label Subtyping

- The type system is sufficient when *x* and *y* have the same label
- What about x : L var, y : H var ?

$$(\text{IF}) \quad \frac{\begin{array}{l}\lambda; \gamma \vdash e : \tau, \\ \lambda; \gamma \vdash c : \tau\ cmd, \\ \lambda; \gamma \vdash c' : \tau\ cmd\end{array}}{\lambda; \gamma \vdash \mathbf{if}\ e\ \mathbf{then}\ c\ \mathbf{else}\ c' : \tau\ cmd}$$

- The If rule requires the condition and the commands to have the same label!

Label Subtyping

$$(\textsc{base}) \quad \frac{\tau \leq \tau'}{\vdash \tau \subseteq \tau'} \qquad\qquad (\textsc{subtype}) \quad \frac{\lambda; \gamma \vdash p : \rho, \quad \vdash \rho \subseteq \rho'}{\lambda; \gamma \vdash p : \rho'}$$

- We consider that label L is "lower" than label H
- Models that a public value can always be hidden as secret

- Given x = 0 : L, this allows us to derive x = 0 : H

Label Subtyping

$$(\text{CMD}^{-}) \qquad \frac{\vdash \tau \subseteq \tau'}{\vdash \tau' \; cmd \subseteq \tau \; cmd}$$

- Different variance compared to expression rule
- Intuitively: If a program is "secure" in a context which might depend on secret data, then it is also in a less privileged context
- Alternative proof: y := 1 : H cmd => y := 1 : L cmd

Exercises

- For the following programs, either give a typing derivation showing non-interference, or explain why the program does not typecheck

- x: L var, y: H var ⊢ while (x < 10) do (x := x + 1; y := y + 1)

- x: H var, y: L var ⊢ while (x < 10) do
  if y = 2 then x := x + 1 else x := x + 2

Back to Digital Side-Channels

- The typing approach so far avoids indirect leaks, e.g., by observing public values
- However, it allows typechecking if key = … then x = …, which leaks the key by observing the timing of the attack

- Need to extend formalism beyond leaking values!

Instrumenting Semantics

- Previously: $s_1 \rightarrow_p^* s_1'$
- We record traces containing all branching and memory accesses

(Trace) l ::= ε | Branch (b) . l | Access(n) . l

$$s_1 \rightarrow_p^* s_1', l_1$$

When executing *if b then p else p' ,* we record Branch(b)

When executing a[n], we record Access(n)

Non-Intereference with Observations

For a given program *p*,

$$\forall\ (s_1\ s_2 \colon state),$$

$$s_{1|\,L} = s_{2|\,L} \Rightarrow s_1 \rightarrow_p^* s_1', l_1 \Rightarrow s_2 \rightarrow_p^* s_2', l_2 \Rightarrow$$

$$s'_{1|\,L} = s'_{2|\,L} \wedge l_1 = l_2$$

Captures that the program executes the same program paths, and performs identical memory (and hence cache) accesses for the same attacker-controlled inputs

The “Constant-Time” Programming Discipline

Cryptographic implementations must follow a “constant-time” programming discipline, which forbids

- Branching involving secrets
- Using instructions which execute in variable time with secrets (e.g., division)
- Accessing memory based on secret indices

The “Constant-Time” Programming Discipline

- Is this enough?

System-level Non-interference for Constant-time Cryptography, Barthe et al., CCS’ 14 studies this formally

- Easy programming discipline to follow?

  Jan 2024: **KyberSlash: division timings depending on secrets in Kyber software**

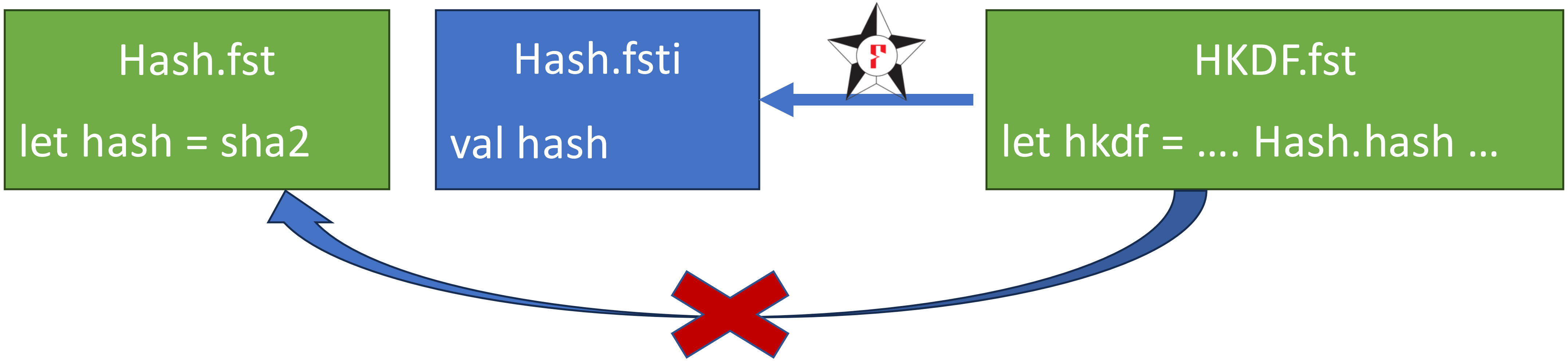
  https://kyberslash.cr.yp.to/ , https://cryspen.com/post/ml-kem-implementation/

  KyberSlash: Exploiting secret-dependent division timings in Kyber implementations, Bernstein et al., CHES’ 25

- We need tools to enforce this

Non-Interference by Typing Abstraction

- Remember from last week:



- Client modules only have access to the interface
- Underlying implementation is hidden (true for other languages supporting abstraction)

Non-Interference by Typing Abstraction

SUInt32.fsti

```
val suint32: Type          // Abstract type for secret uint32 integers

val (+) : suint32 -> suint32 -> suint32
val (*) : suint32 -> suint32 -> suint32
// Non-constant time operations are not exposed
// val (/) : suint32 -> suint32 -> suint32
```

Implementing Abstract Secret Integers

SUInt32.fst

```
let suint32 = uint32     // Underlying definition is simply standard integers

let (+) n1 n2 = n1 + n2
let (*) n1 n2 = n1 * n2
```

- Abstract type for opaque “secret integers”
- Exposes arithmetic and bitwise constant-time operations, but not comparison, division
- After extraction, compiled to standard integer, no runtime cost

Using Secret Integers

n1, n2 : suint32 // Secret integers

if n1 > n2 then … No comparison defined for secret integers

val index (b: array uint8) (i: uint32) : …

let x = b.[n1] in … Expected type uint32, got type suint32

- Can be seen as an extension of previous typing discipline

Speculative Execution

p[10]	s[5]

```
if i < 10 {
  x = p[i];
}
w[x] = 0;
```

Spectre v1-read

s[5]	p[10]

```
if i < 5 {
  s[i] =sec;
}
x = p[0];
w[x] = 0;
```

Spectre v1-write

Protecting Against Speculative Execution

```
if i < 10 {
  x = p[i];
}
w[x] = 0;
```

→

```
if i < 10 {
  fence();
  x = p[i];
}
w[x] = 0;
```

Need to insert a fence at each branch

Large overhead

Protecting Against Speculative Execution

```
if i < 10 {
  x = p[i];
}
w[x] = 0;
```

```
if i < 10 {
    x = p[i];
    protect(x);
}
w[x] = 0;
```

```
if i < 10 {
    x = p[i];
}
protect(x);
w[x] = 0;
```

Protect Semantics

- We rely on a specific variable, **ms**

y = protect(x, ms): “conditional masking”

- -1 if **ms** = -1
- no-op otherwise

Need to set ms when misspeculating: **set_ms(cond)**

- set_ms(cond) sets **ms** to -1 if cond is false
- no-op otherwise

Protecting Against Speculative Execution

```
if i < 10 {
  x = p[i];
}
w[x] = 0;
```

```
if i < 10 {
  set_ms(i < 10);
  x = p[i];
  x = protect(x, ms);
}
w[x] = 0;
```

How to ensure this protects against speculative attacks?

A Type-System for Speculative Constant-Time

[Shivakumar et al., 23]

- Type systems for constant-time had one security label, **L** or **H**

- Idea: Extend it with a pair of labels τ_n, τ_s which are either **L** or **H**

- τ_n : security label for “normal” executions
- τ_s : security label for speculative executions

Typing Rules

$$\textsc{Var}\quad \Gamma \vdash x : \Gamma(x)$$

$$\textsc{Op}\quad \frac{\Gamma \vdash e_1 : \tau_1 \qquad \Gamma \vdash e_2 : \tau_2}{\Gamma \vdash op(e_1, e_2) : \tau_1 \cup \tau_2}$$

- $\mathbf{L} \cup \mathbf{H} = \mathbf{H}, \quad \mathbf{L} \cup \mathbf{L} = \mathbf{L}, \quad \mathbf{H} \cup \mathbf{H} = \mathbf{H}$
- $(\tau_n, \tau_s) \cup (\tau_n{}', \tau_s{}') = (\tau_n \cup \tau_n{}', \tau_s \cup \tau_s{}')$

Typing Rules

$$\textsc{Const} \quad \Gamma \vdash n : (L, L)$$

$$\textsc{Sub} \quad \frac{\Gamma \vdash e : \tau \qquad \tau \leq \tau'}{\Gamma \vdash e : \tau'}$$

- $\mathbf{L \leq H}$
- $(\tau_n, \tau_s) \leq (\tau_n{}', \tau_s{}') \Leftrightarrow \tau_n \ \leq \tau_n' \ \wedge \tau_s \ \leq \tau_s{}'$

Typing Rules: Speculative Load

$$\frac{\textsc{Load} \\ \Gamma \vdash i : (L, L) \qquad \Gamma(a) = (\tau_n, \tau_s)}{\Gamma \vdash x = a[i] : \Gamma[x \leftarrow (\tau_n, H)]}$$

Typing Rules: Protect

y = protect(x, ms)

Recall: Behaviour depends on **ms!**

Conceptually, “y is protected against speculative attacks if **ms** accurately models the current state of misspeculation”

Need to keep track of the state of ms!

Typing Rules: Execution Modes

Idea: Keep track of the relationship between **ms** and misspeculation in a mode Σ

Σ := | **unk** | $\mathbf{ms}$ | $\mathbf{ms}_{|e}$

- $\mathbf{ms}$: If misspeculation, then ms = -1
- **unk:** No information about the current state
- $\mathbf{ms}_{|e}$: If misspeculation and e is true, then ms = -1

Typing Rules: Protect and Set-ms

$$\textsc{Protect}\ \frac{\Gamma' = \Gamma[y \leftarrow (\Gamma_n(x), \Gamma_n(x))]}{\mathsf{ms}, \Gamma \vdash y = \mathrm{protect}(x, \mathsf{ms}) : \mathsf{ms}, \Gamma'}$$

$$\textsc{Set-MS}\ \ \mathsf{ms}_{|e}, \Gamma \vdash \mathsf{ms} = \mathrm{set\_ms}(e) : \mathsf{ms}, \Gamma$$

Typing Rules: Load

$$\textsc{Load}\quad \frac{\Gamma \vdash i : (L, L) \qquad \Gamma(a) = (\tau_n, \tau_s)}{\Gamma \vdash x = a[i] : \Gamma[x \leftarrow (\tau_n, H)]}$$

$$\textsc{Load}\quad \frac{\Gamma \vdash i : (L, L) \qquad \Gamma(a) = (\tau_n, \tau_s)}{\boxed{\Sigma,}\Gamma \vdash x = a[i] \ \boxed{\Sigma,}\Gamma[x \leftarrow (\tau_n, H)]}$$

$$\textsc{Const-Load}\quad \frac{\text{n is constant}}{\Sigma, \Gamma \vdash x = a[n] : \Sigma, \Gamma[x \leftarrow \Gamma(a)]}$$

Typing Rules: Seq and Assign

$$\textsc{Assign}\ \frac{\Gamma \vdash e : \tau}{\Sigma, \Gamma \vdash x = e : \Sigma, \Gamma[x \leftarrow \tau]}$$

$$\textsc{Seq}\ \frac{\Sigma_0, \Gamma_0 \vdash c_1 : \Sigma_1, \Gamma_1 \qquad \Sigma_1, \Gamma_1 \vdash c_2 : \Sigma_2, \Gamma_2}{\Sigma_0, \Gamma_0 \vdash c_1;\ c_2 : \Sigma_2, \Gamma_2}$$

Typing Rules: Branching

$$\frac{\Gamma \vdash b : (L, L) \qquad \Sigma_{|b}, \Gamma \vdash c_1 : \Sigma_1, \Gamma_1 \qquad \Sigma_{|!b}, \Gamma \vdash c_2 : \Sigma_2, \Gamma_2}{\Sigma, \Gamma \vdash \texttt{if}\ b\ \texttt{then}\ c_1\ \texttt{else}\ c_2, \Sigma_1 \cap \Sigma_2, \Gamma_1 \cup \Gamma_2}\ \textsc{If}$$

- $\Sigma_{|b} = \mathbf{ms}_{|b}$ if $\Sigma = \mathbf{ms}$, otherwise **unk**
- $\Sigma_1 \cap \Sigma_2 = \Sigma_1$ if $\Sigma_1 = \Sigma_2$, otherwise **unk**

Branching Example

$\{\, \mathbf{ms} \,\}$

```
if i < 10 {
```

  $\{\, \mathbf{ms}_{\mid\, i<10} \,\}$

```
  set_ms(i < 10);
```

  $\{\, \mathbf{ms} \,\}$

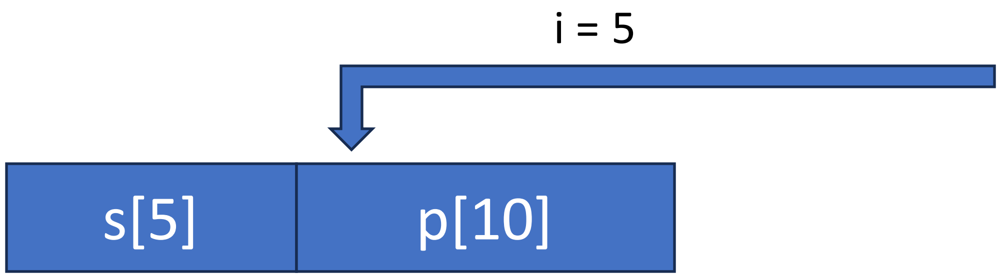
After set_ms, ms correctly models misspeculation

Can be safely used for speculative protection

Speculative Stores

- We can store a value with label τ in an array with label τ' if $\tau \leq \tau'$
- Implicit assumption: accesses are in bound

- Speculative executions break this assumption!




```
if i < 5 {
  s[i] =sec;
}
x = p[0];
w[x] = 0;
```

Typing Rules: Store

$$\frac{\textsc{Store} \quad \Gamma \vdash i : (L, L) \qquad \Gamma \vdash e : \tau \qquad \tau \leq \Gamma(a) \qquad \forall a' : \mathbf{A}, a' \neq a . \Gamma'[a'] = (\Gamma_n[a'], \tau_s)}{\Sigma, \Gamma \vdash a[i] = e : \Sigma, \Gamma'}$$

Exercises

- Starting from **ms**, either provide a typing derivation or explain typing failures for the following programs. All variables but s and sec have type **L, L**

```
if i < 10 {
  x = p[i];
}
w[x] = 0;
```

```
if i < 10 {
  s[i] = 0;
}
x = p[0];
w[x] = 0;
```

```
if i < 5 {
  s[i] = sec;
}
x = p[0];
w[x] = 0;
```

```
if i < 10 {
  ms = set_ms(i < 10);
  x = p[i];
  x = protect(x, ms);
}
w[x] = 0;
```

```
if b {
  ms = set_ms(b);
  s[3] = sec;
} else {
  ms = set_ms(!b);
}
x = p[5];
w[x] = 0;
```

```
b = i < 5;
if b {
  ms = set_ms(b);
  s[i] = sec;
} else {
  ms = set_ms(!b);
}
x = p[0];
x = protect(x, ms);
w[x] = 0;
```

Typing Limitations

- Only guarantees resistance against timing, cache-based, and speculative (with extension) side-channels
- Only provides guarantees within the semantics of the source language (C, OCaml, …)
- Compilers can reintroduce side-channels

Compiler-Induced Side Channels

```
let login() =
    x = read_passwd()
    res = check_pwd(x)
    x = 0
    return res
```

Compile

```
let login() =
    x = read_passwd()
    res = check_pwd(x)
    return res
```

Unused assignment

Password can leak after execution!

Crypto Compiler-Induced Side Channels

Assume b is secret

if b then r := x else r := y

Rewrite into constant-time version

int mask = create_mask(b);

r := (x & mask) | (y & ~mask);

```
[@@ Comment "Returns 2^64 - 1 if a = b, otherwise returns 0.
static inline uint64_t FStar_UInt64_eq_mask(uint64_t a, uint64_t b)
{
  uint64_t x = a ^ b;
  uint64_t minus_x = ~x + (uint64_t)1U;
  uint64_t x_or_minus_x = x | minus_x;
  uint64_t xnx = x_or_minus_x >> (uint32_t)63U;
  return xnx - (uint64_t)1U;
}
```

if b then r := x else r := y

LLVM COMPILER INFRASTRUCTURE : Did you mean

Avoiding Compiler-Induced Side-Channels

- Use a constant-time preserving compiler

  Formal verification of a constant-time preserving C compiler, Barthe et al., POPL' 20

  Preservation of Speculative Constant-Time by Compilation, Arranz Olmos et al., POPL' 25

  - Impressive, but heavy effort needed
  - How to reach performance of industrial compilers?
  - How to scale to variety of backends and architectures?

Avoiding Compiler-Induced Side Channels

- Analyze binary code after compilation

  Verifying constant time implementations, Almeida et al., USENIX' 16

  BINSEC/REL: Efficient Relational Symbolic Execution for Constant-Time at Binary-Level, Daniel et al., S&P' 20

- How to determine which parts of memory/registers should be secret?
- How to precisely analyze binary code, and retrieve semantic structure?

- **PhD offer:** Leverage source semantic information in verified crypto code to improve binary analysis (combination of HACL* and BINSEC)