Week 5

# An Introduction to Cyber Security – CS 573

Instructor: Dr. Edward G. Amoroso

eamoroso@tag-cyber.com

Week 5

# Required Week Five Readings

1. **"Password Authentication with Insecure Communication," Leslie Lamport https://lamport.azurewebsites.net/pubs/password.pdf**

***2.*** **Chapters 12 through 16:** ***From CIA to APT: An Introduction to Cyber Security*****, E. Amoroso & M. Amoroso**

**LinkedIn: Edward Amoroso**

Week 5

# Week 5: Authentication Protocols

# How Do Nation States Cryptanalyze Encrypted Data?
(Warm-Up Topic)

# Three Methods for Cryptanalysis

- **Ciphertext Only**
  - Cryptanalyst only has encrypted text
  - No hints or codebooks

# Three Methods for Cryptanalysis

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  - No hints or codebooks
- **Known Plaintext**
  - Cryptanalyst observes hints (no control)
  - Tiny codebook examples can be developed

# Three Methods for Cryptanalysis

- **Ciphertext Only**
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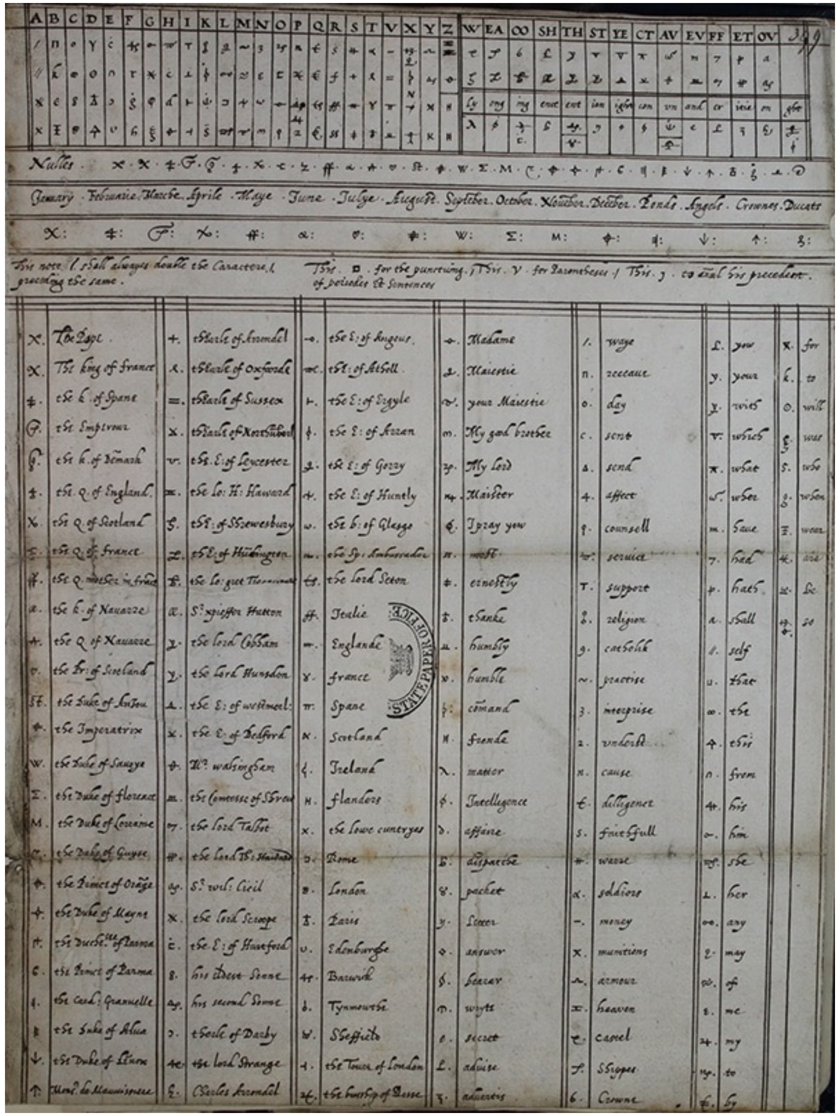
  - No hints or codebooks
- **Known Plaintext**
  - Cryptanalyst observes hints (no control)
  - Tiny codebook examples can be developed
- **Chosen Plaintext**
  - Cryptanalyst has the encryption function
  - Codebook can be developed



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# Three Methods for Cryptanalysis

- **Ciphertext Only**
  - Cryptanalyst only has encrypted text
  - No hints or codebooks
- **Known Plaintext**
  - Cryptanalyst observes hints (no control)
  - Tiny codebook examples can be developed
- **Chosen Plaintext**
  - Cryptanalyst has the encryption function
  - Codebook can be developed

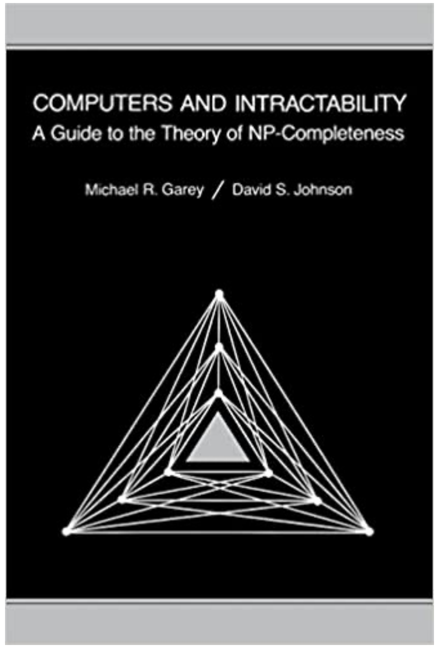
***Two requirements protect encrypted text:***

1. The encryption function must be cryptographically hard
2. The cleartext and ciphertext domains must be huge

***Two Implications:***

You must try every possible case to find the encryption function

The number of possible cases cannot feasibly be covered



COMPUTERS AND INTRACTABILITY

A Guide to the Theory of NP-Completeness

Michael R. Garey / David S. Johnson

# What is Authentication?

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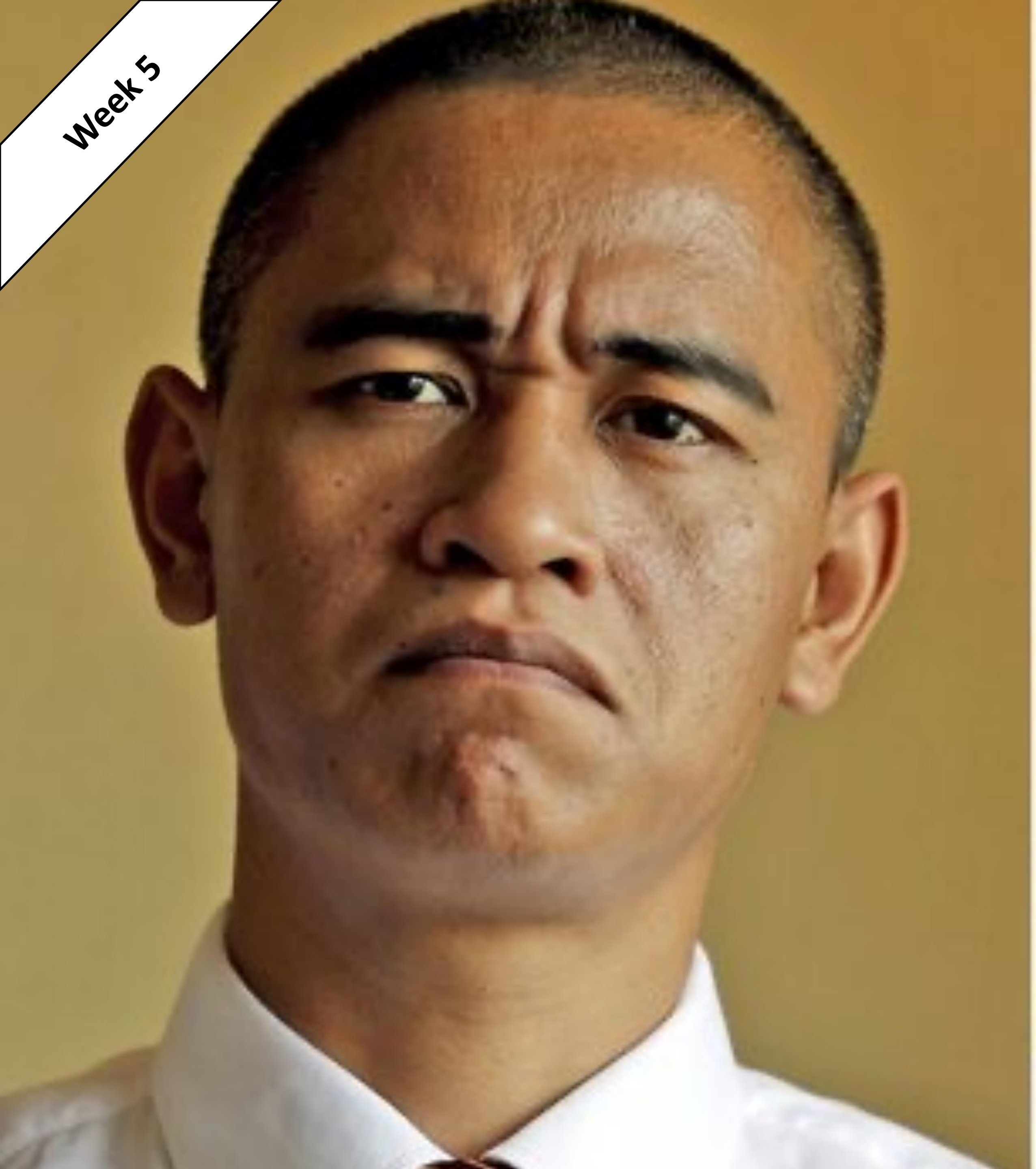

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Authentication:
Process of validating a reported identity.

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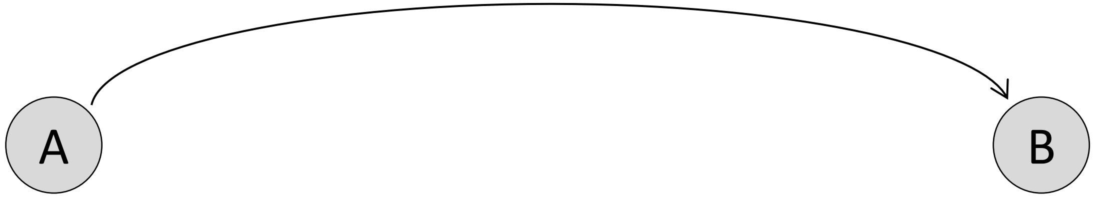
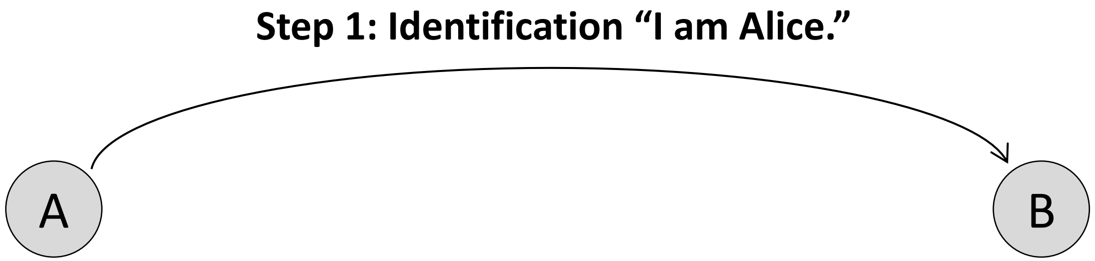
# One-Factor Authentication Schema

Step 1: Identification “I am Alice.”



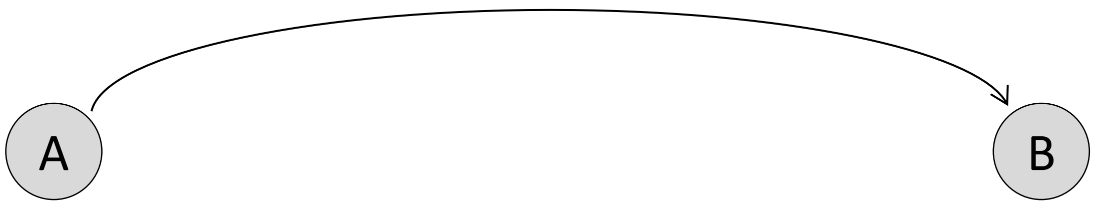
# One-Factor Authentication Schema



**Step 1: Identification "I am Alice."**

*Server Validates Client: "Client Authentication"*

# One-Factor Authentication Schema


Step 1: Identification “I am Alice.”

*Client Validates Server: “Server Authentication”*

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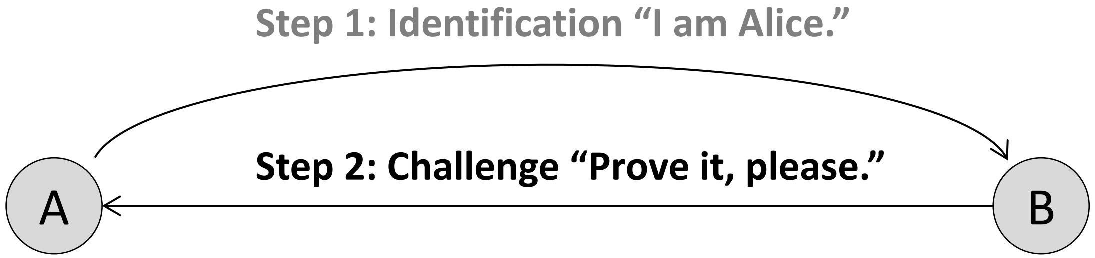
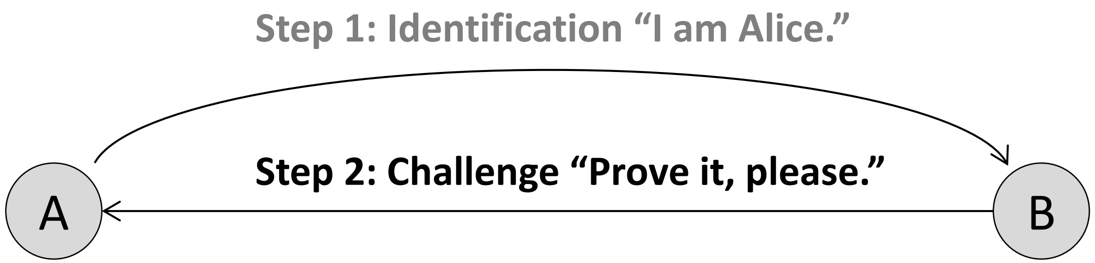
# One-Factor Authentication Schema



Step 1: Identification “I am Alice.”

Step 2: Challenge “Prove it, please.”

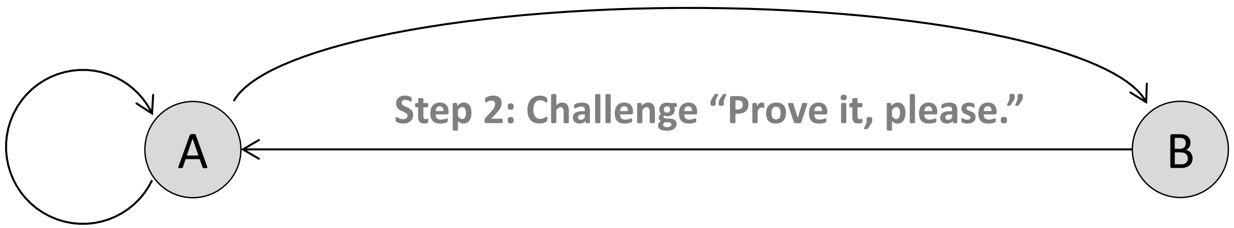
# One-Factor Authentication Schema


Step 1: Identification "I am Alice."
Step 2: Challenge "Prove it, please."
A
B

*Challenge includes tangible domain value – possible "known plaintext" attacks*

*Challenge includes no tangible domain value – likely to restrict to "ciphertext–only attacks"*

# One-Factor Authentication Schema



Step 1: Identification "I am Alice."

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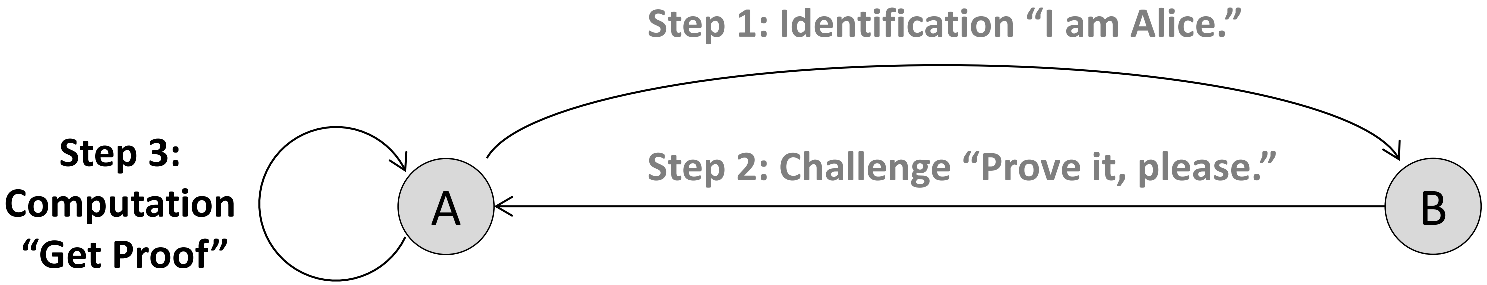
Step 3: Computation "Get Proof"

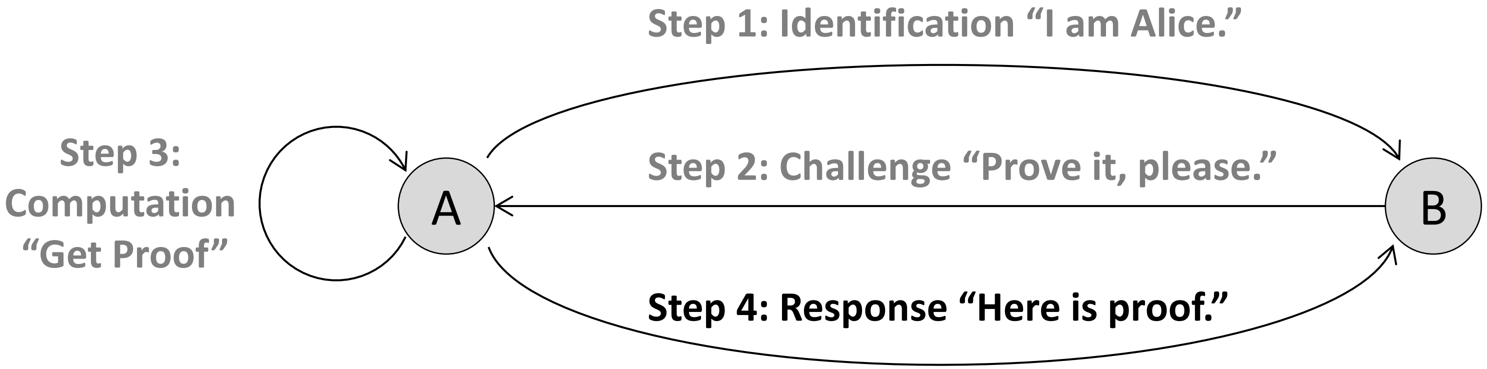
# One-Factor Authentication Schema


Step 1: Identification "I am Alice."
Step 2: Challenge "Prove it, please."
Step 3: Computation "Get Proof"
A
B

*Computation might involve simple look-up/locate process (e.g., passwords)*

*Computation might be more deliberate mathematical operation on domain value*

# One-Factor Authentication Schema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Step 4: Response "Here is proof."

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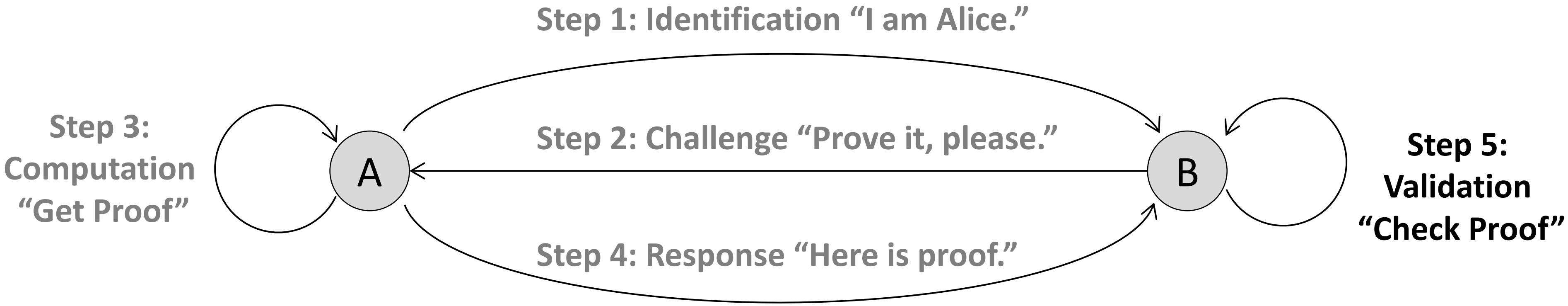
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Step 5: Validation “Check Proof”
A
B

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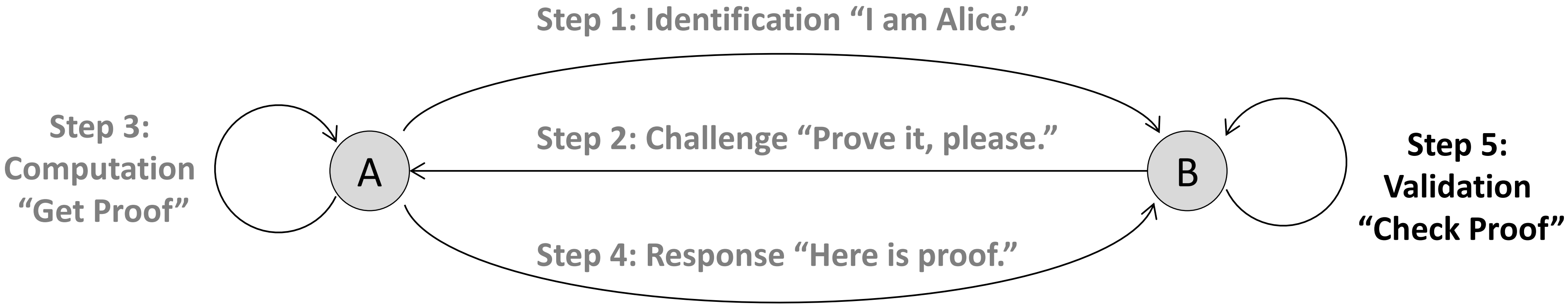
# One-Factor Authentication Schema



Step 1: Identification “I am Alice.”
Step 3:
Computation
“Get Proof”
A
Step 2: Challenge “Prove it, please.”
B
Step 5:
Validation
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Step 4: Response “Here is proof.”

*Validation might involve simple look-up/locate process (e.g., passwords)*

*Validation might be more deliberate mathematical operation on domain value*

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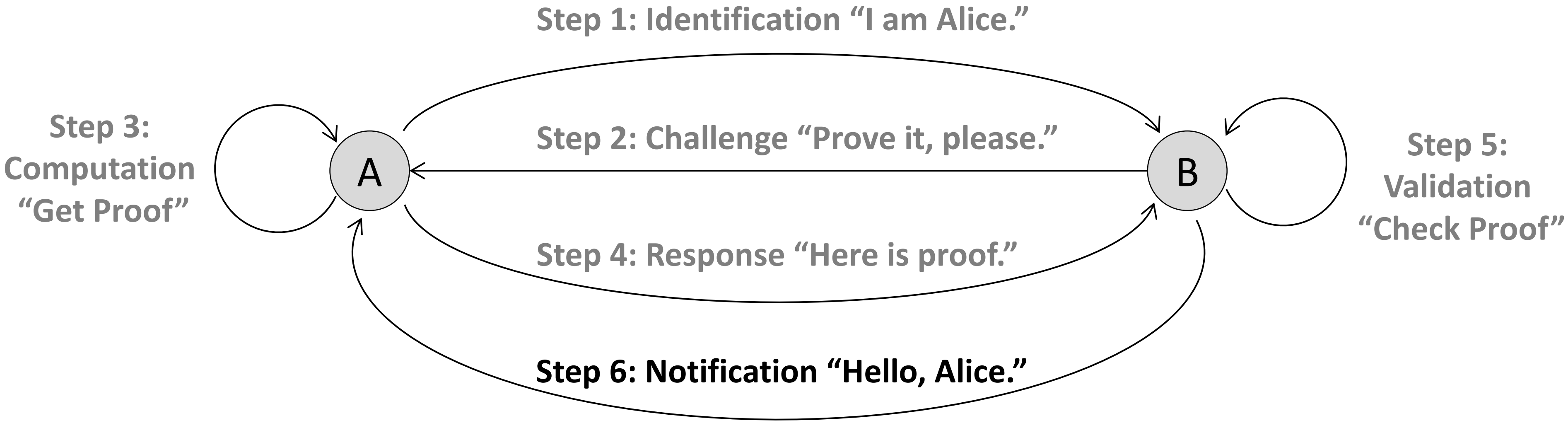
# One-Factor Authentication Schema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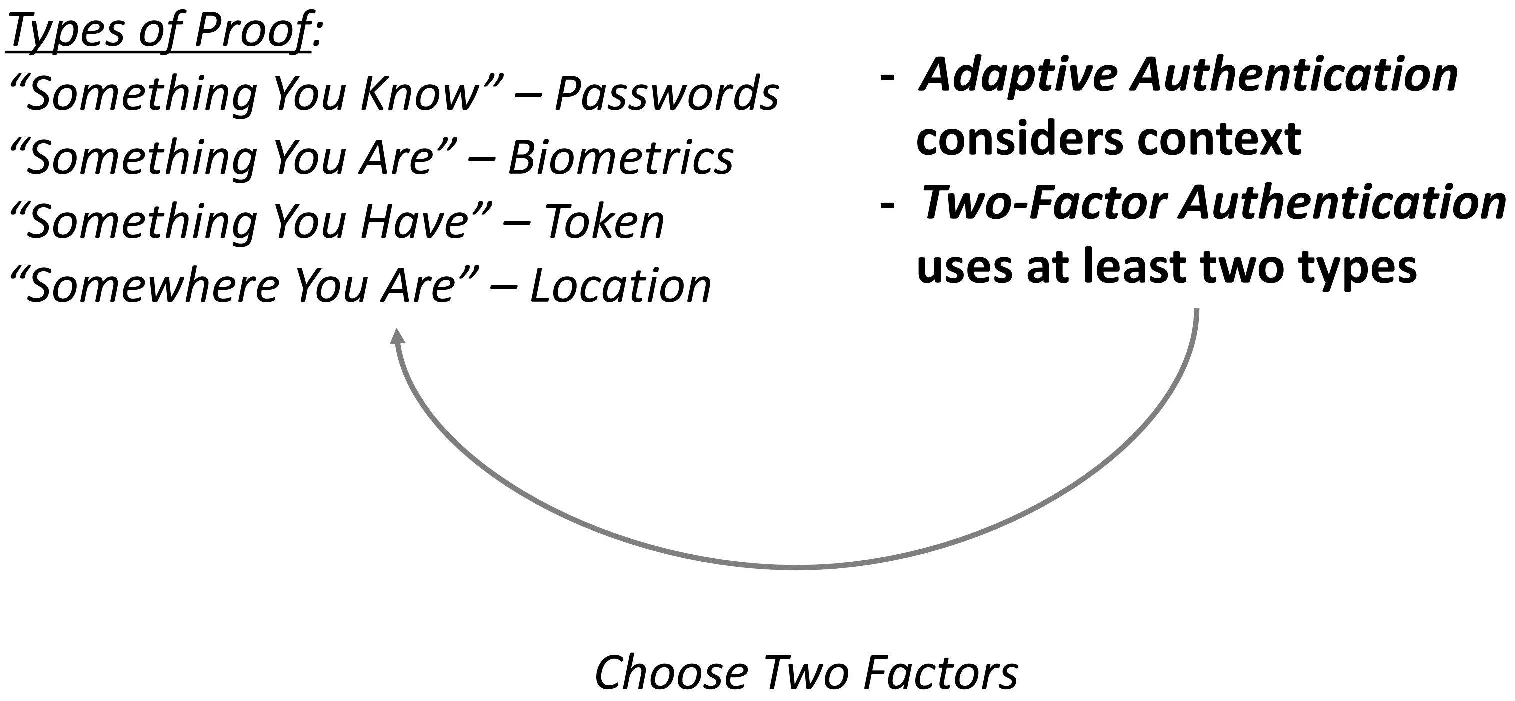
Step 6: Notification “Hello, Alice.”

# Two-Factor Authentication Schema



*<u>Types of Proof</u>:*

*“Something You Know” – Passwords*

*“Something You Are” – Biometrics*

*“Something You Have” – Token*

*“Somewhere You Are” – Location*

- ***Adaptive Authentication*** **considers context**
- ***Two-Factor Authentication*** **uses at least two types**

*Choose Two Factors*

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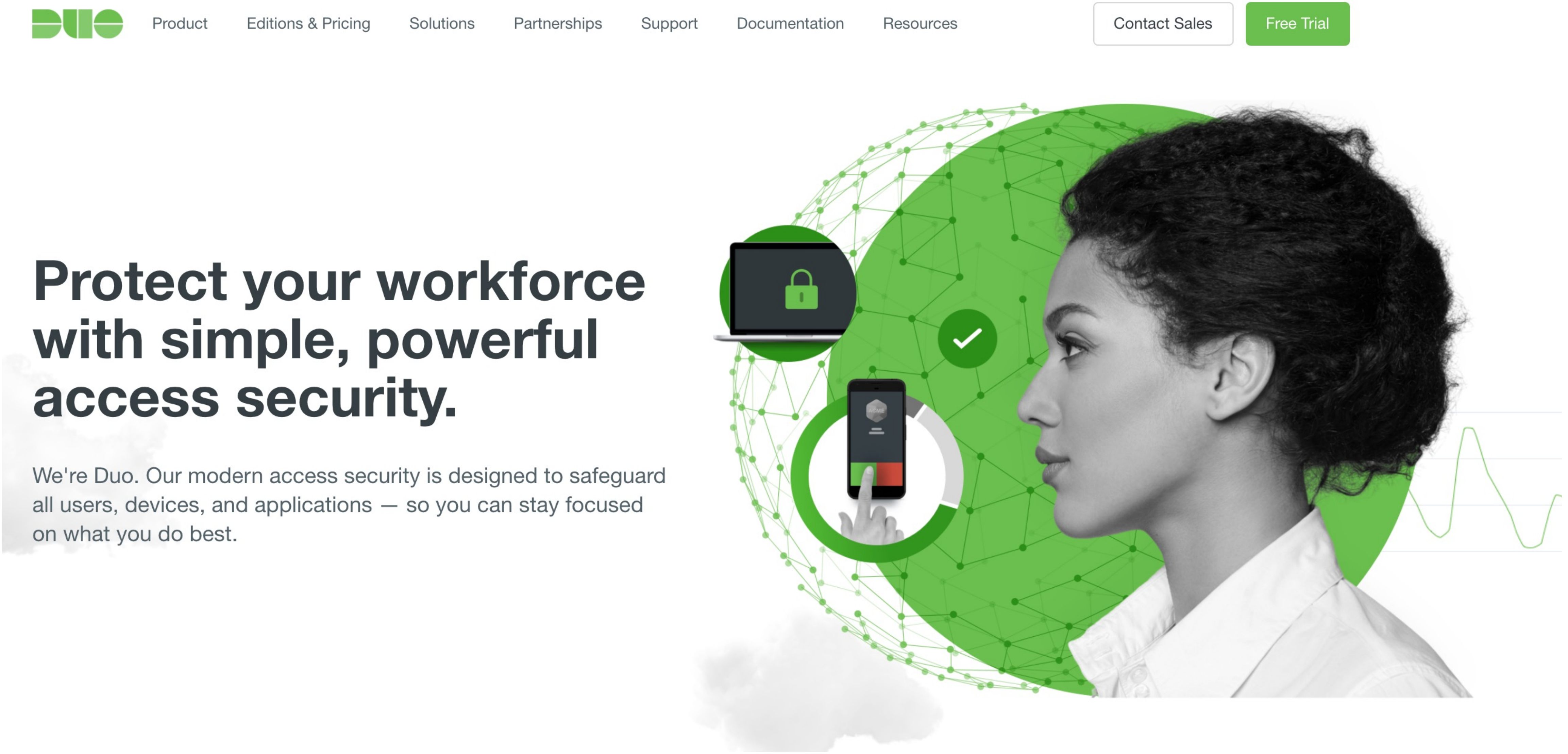
# MyStevens Two-Factor Authentication



Protect your workforce with simple, powerful access security.

We're Duo. Our modern access security is designed to safeguard all users, devices, and applications — so you can stay focused on what you do best.

# How Do Hackers Try to Bypass Authentication?

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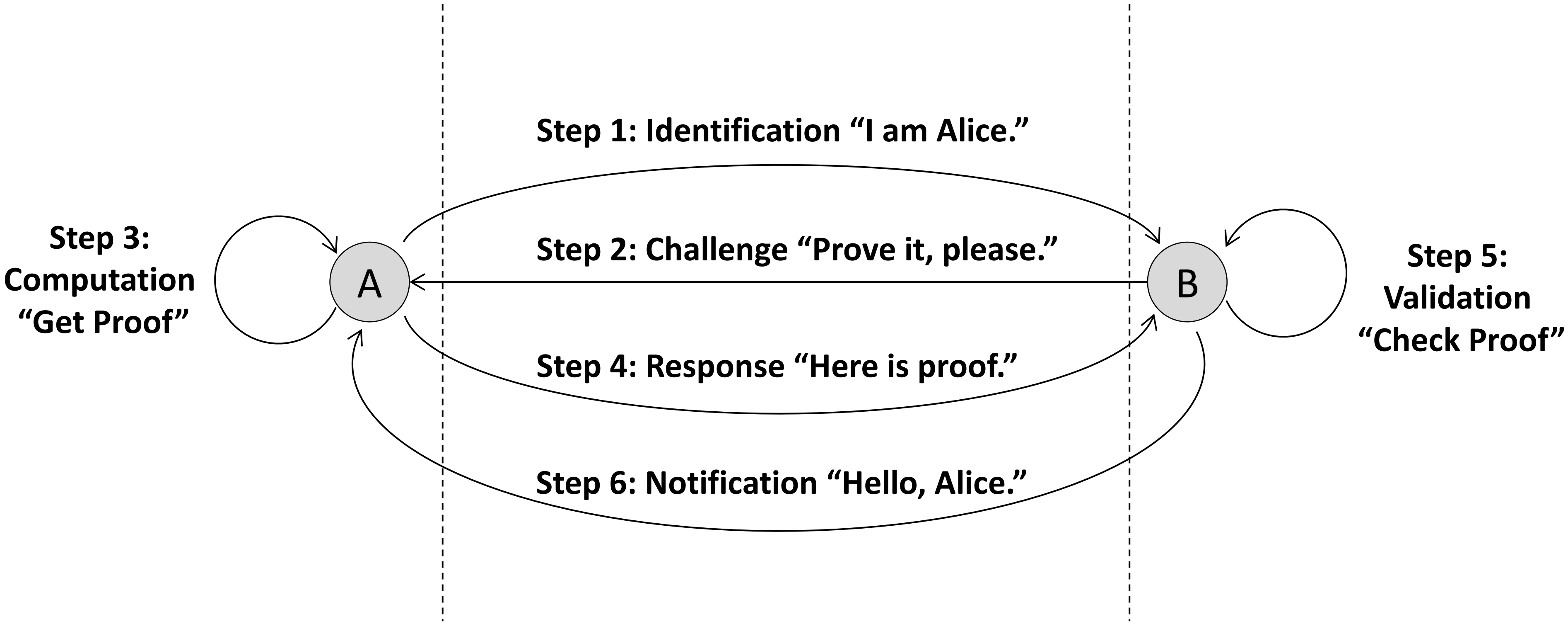
# Authentication Schema



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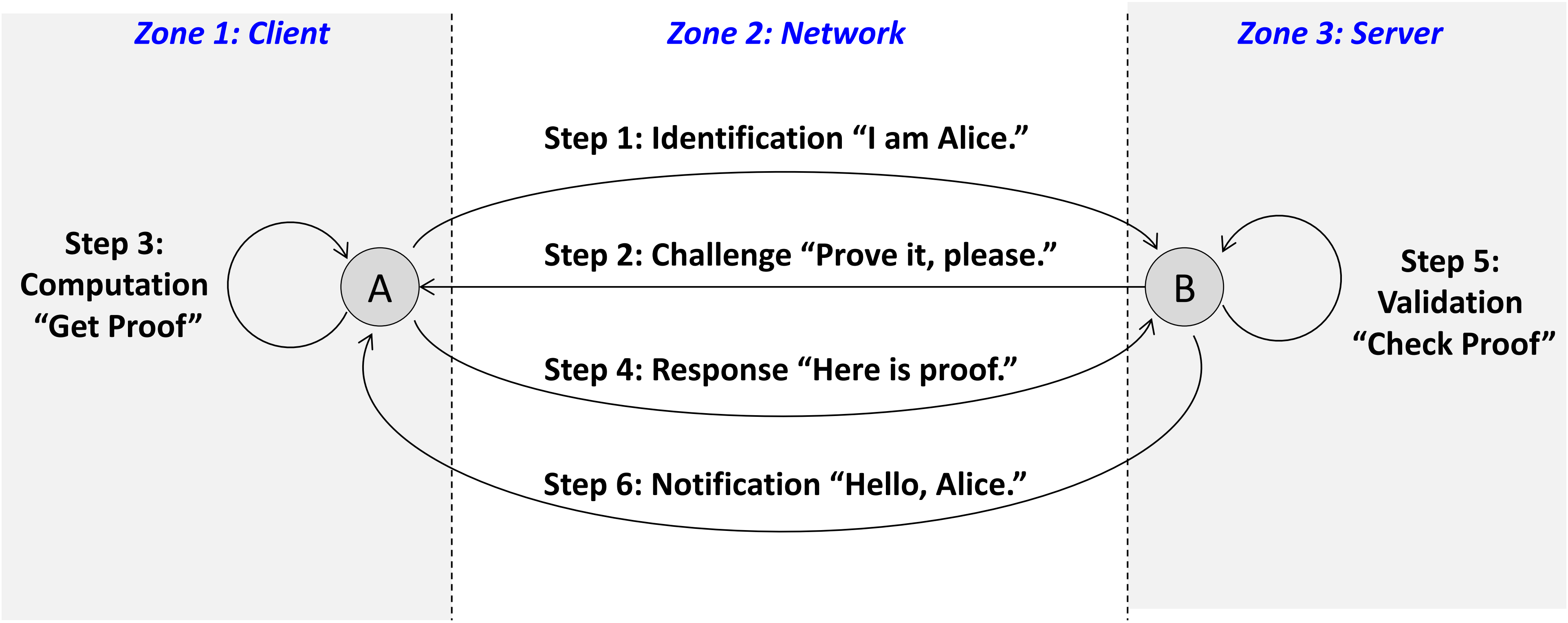
# Authentication Schema


Zone 1: Client
Zone 2: Network
Zone 3: Server
Step 1: Identification "I am Alice."
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A
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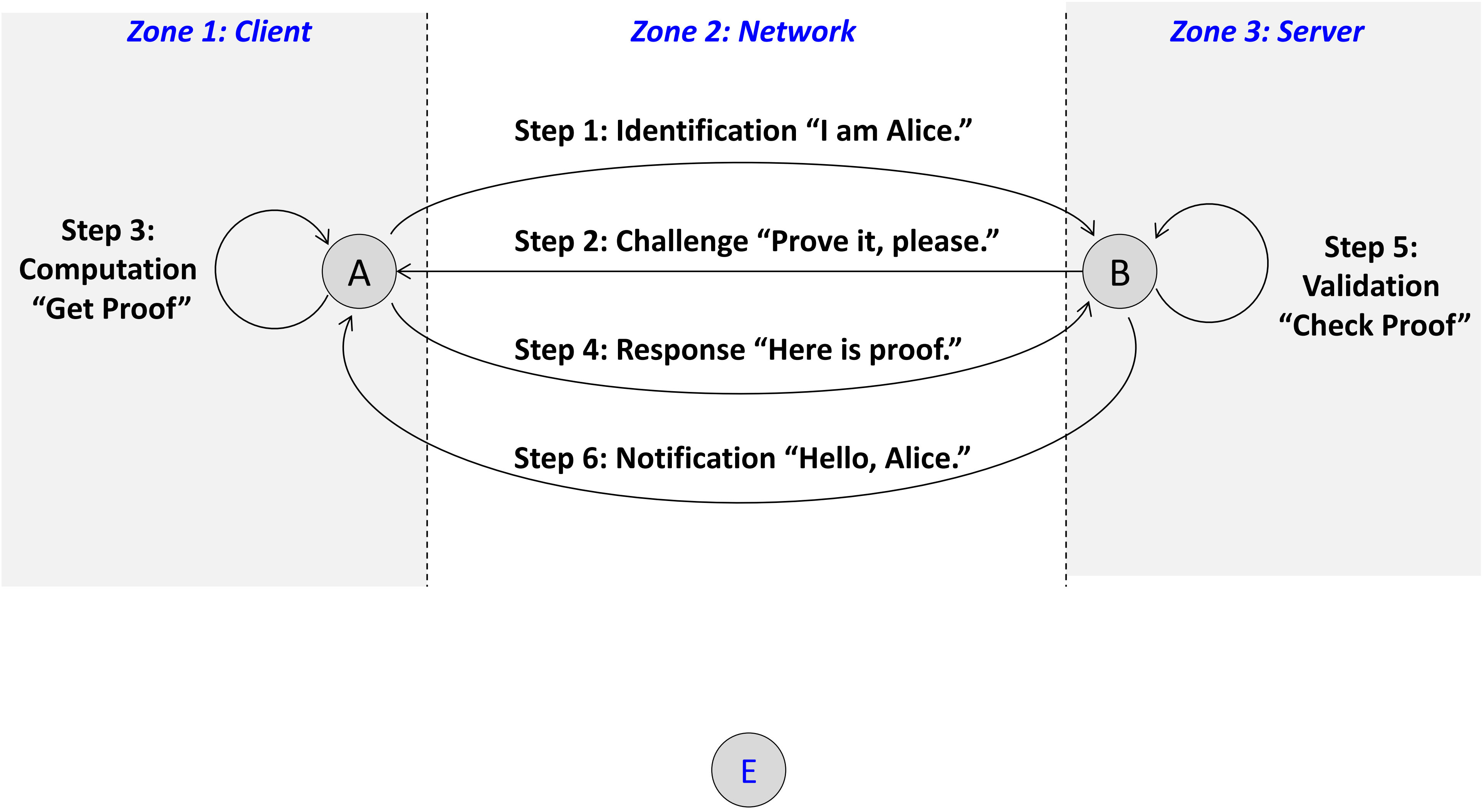
Step 6: Notification "Hello, Alice."

# Authentication Schema



*Zone 1: Client*

*Zone 2: Network*

*Zone 3: Server*

Step 1: Identification "I am Alice."

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Step 3: Computation "Get Proof"

Step 4: Response "Here is proof."

Step 5: Validation "Check Proof"

Step 6: Notification "Hello, Alice."

Eve is the Attacker

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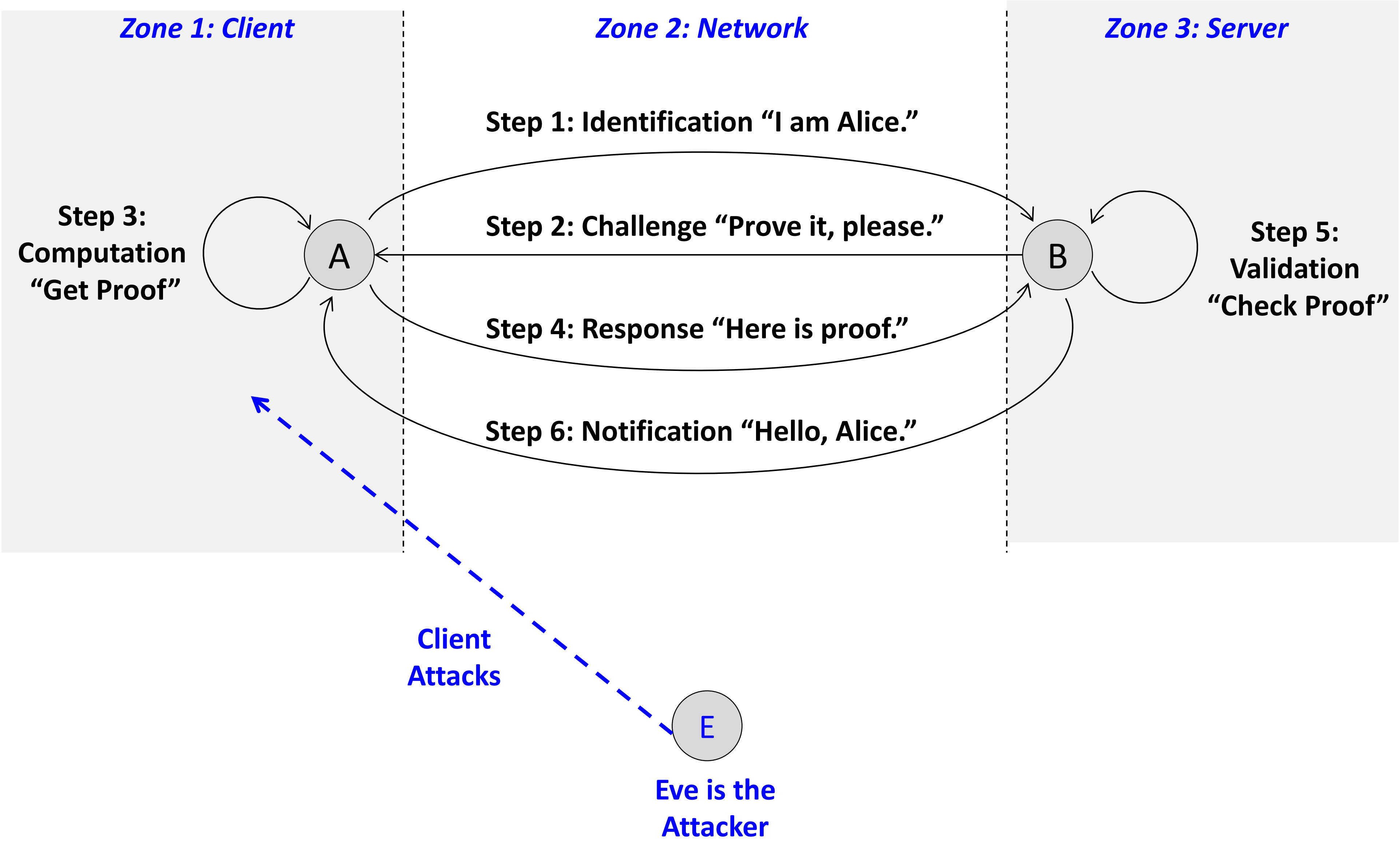
# Authentication Schema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Step 6: Notification “Hello, Alice.”
A
B
E
Client Attacks
Eve is the Attacker

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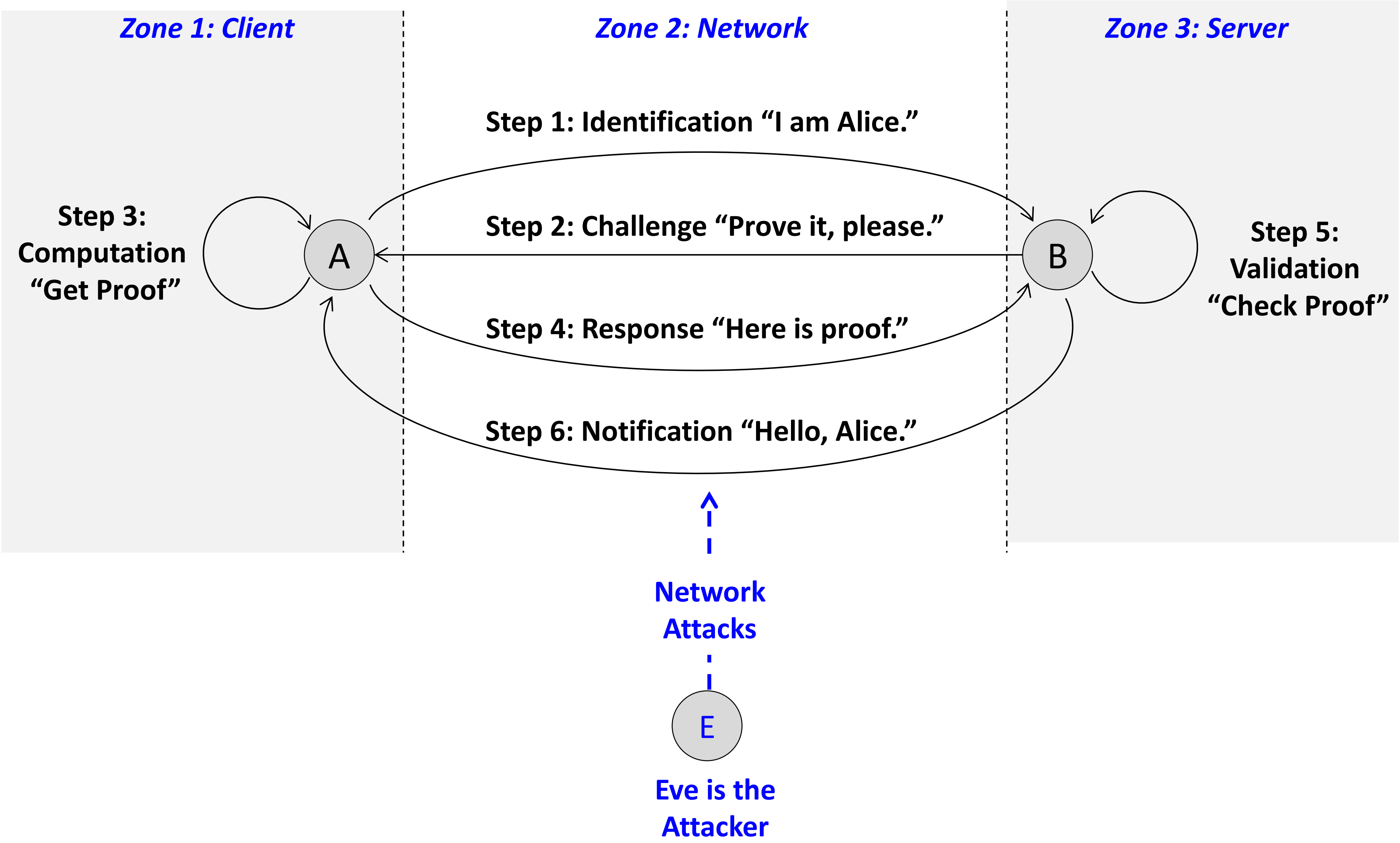
# Authentication Schema



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Step 5: Validation "Check Proof"
Step 6: Notification "Hello, Alice."
Network Attacks
E
Eve is the Attacker

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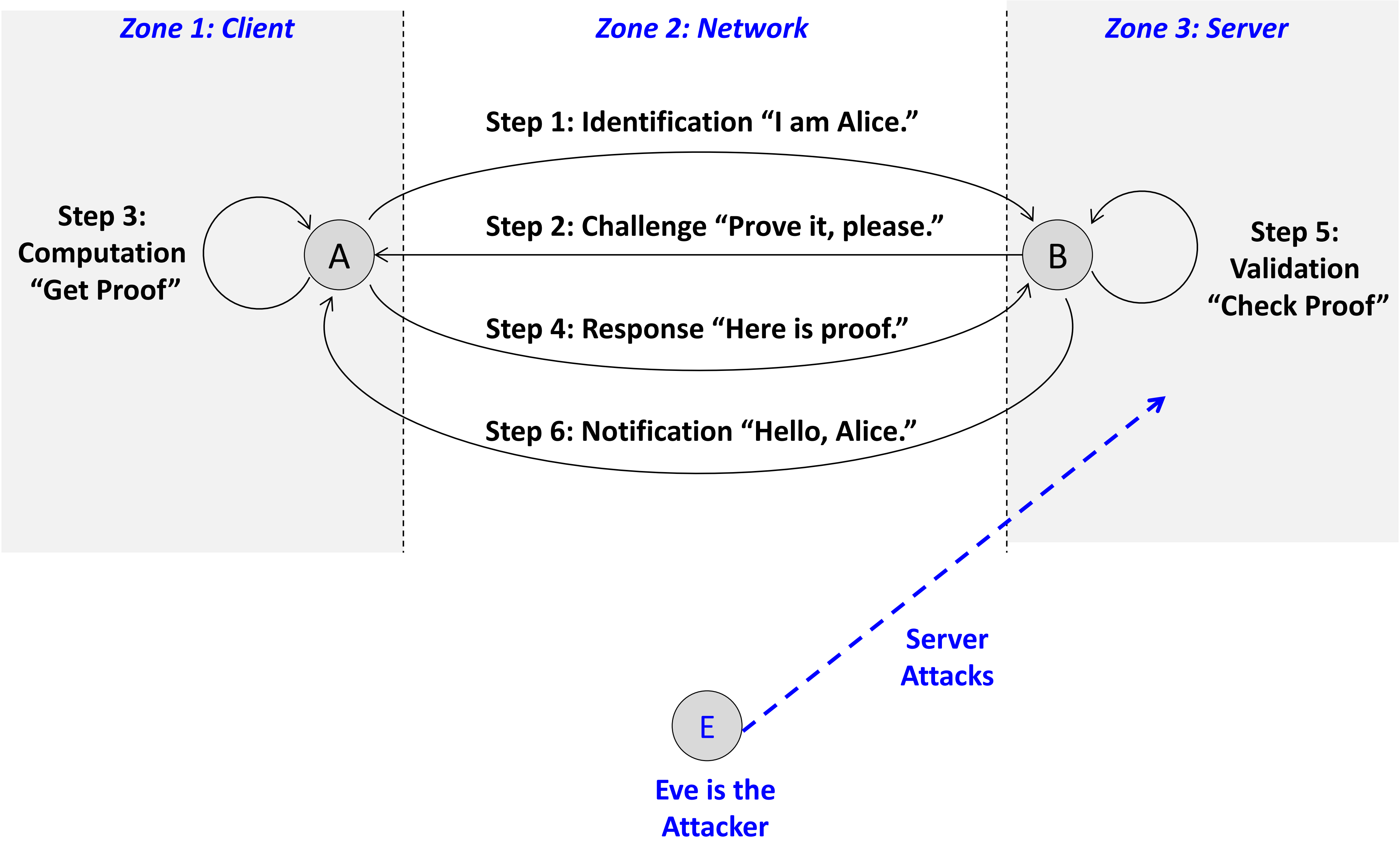
# Authentication Schema



*Zone 1: Client*

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*Zone 3: Server*

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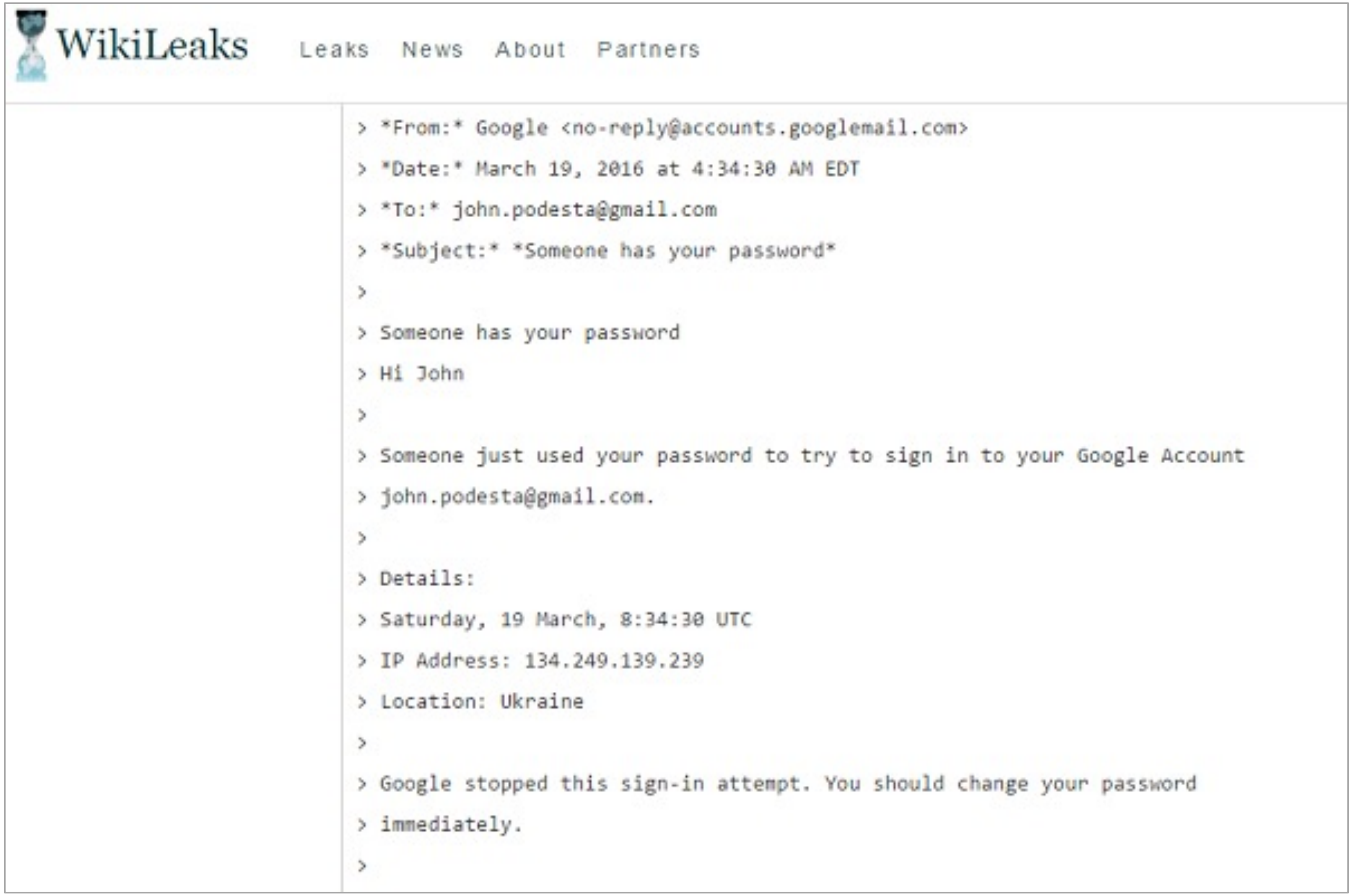
Step 6: Notification "Hello, Alice."

Server Attacks

Eve is the Attacker

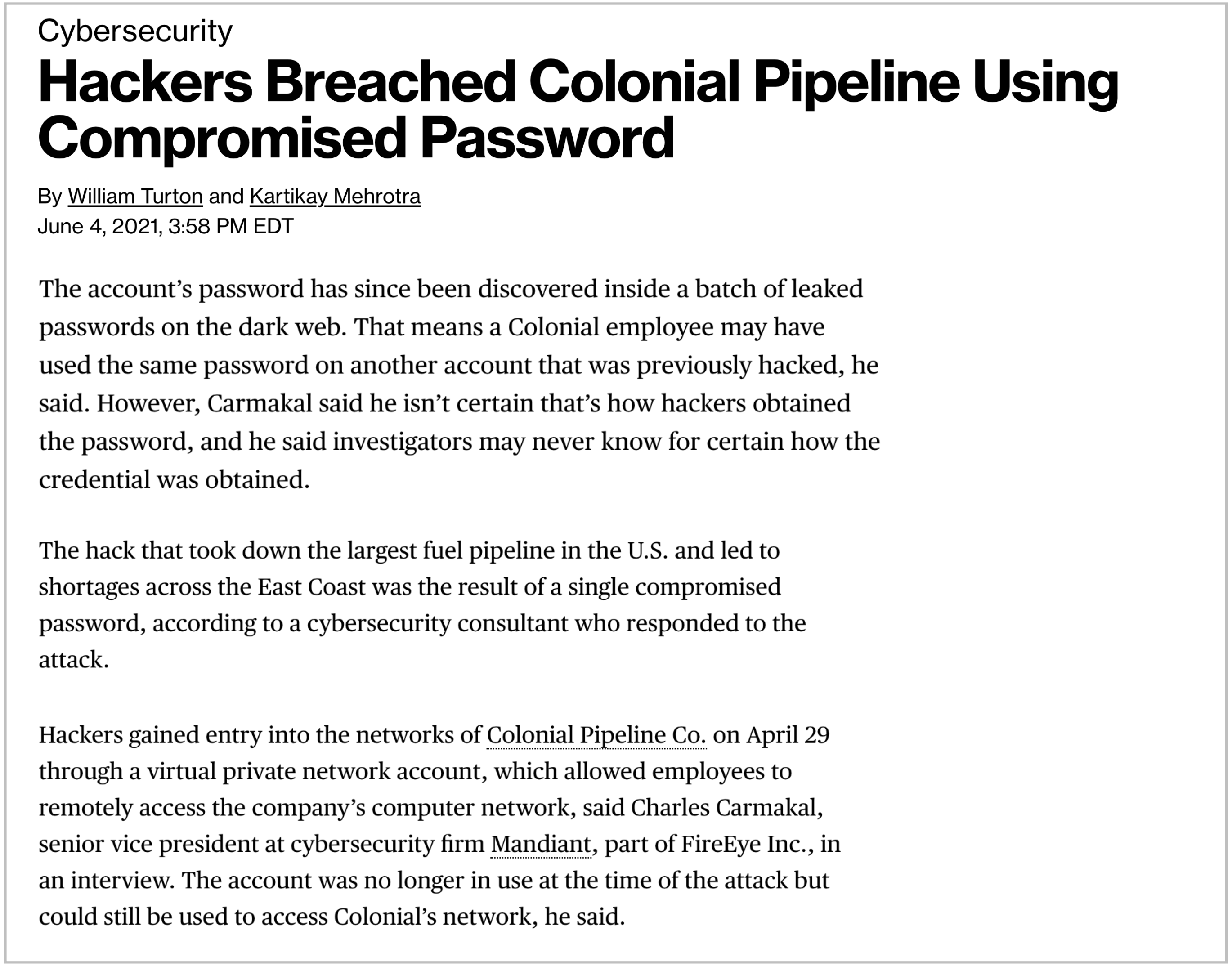
# Are Passwords Acceptable for Authentication?

# Password-Related Incident: Democratic National Committee 2016



```
> *From:* Google <no-reply@accounts.googlemail.com>
> *Date:* March 19, 2016 at 4:34:30 AM EDT
> *To:* john.podesta@gmail.com
> *Subject:* *Someone has your password*
>
> Someone has your password
> Hi John
>
> Someone just used your password to try to sign in to your Google Account
> john.podesta@gmail.com.
>
> Details:
> Saturday, 19 March, 8:34:30 UTC
> IP Address: 134.249.139.239
> Location: Ukraine
>
> Google stopped this sign-in attempt. You should change your password
> immediately.
>
```

# Password-Related Incident: Colonial Pipeline Ransomware 2021



Cybersecurity

## Hackers Breached Colonial Pipeline Using Compromised Password

By William Turton and Kartikay Mehrotra
June 4, 2021, 3:58 PM EDT

The account's password has since been discovered inside a batch of leaked passwords on the dark web. That means a Colonial employee may have used the same password on another account that was previously hacked, he said. However, Carmakal said he isn't certain that's how hackers obtained the password, and he said investigators may never know for certain how the credential was obtained.

The hack that took down the largest fuel pipeline in the U.S. and led to shortages across the East Coast was the result of a single compromised password, according to a cybersecurity consultant who responded to the attack.

Hackers gained entry into the networks of Colonial Pipeline Co. on April 29 through a virtual private network account, which allowed employees to remotely access the company's computer network, said Charles Carmakal, senior vice president at cybersecurity firm Mandiant, part of FireEye Inc., in an interview. The account was no longer in use at the time of the attack but could still be used to access Colonial's network, he said.

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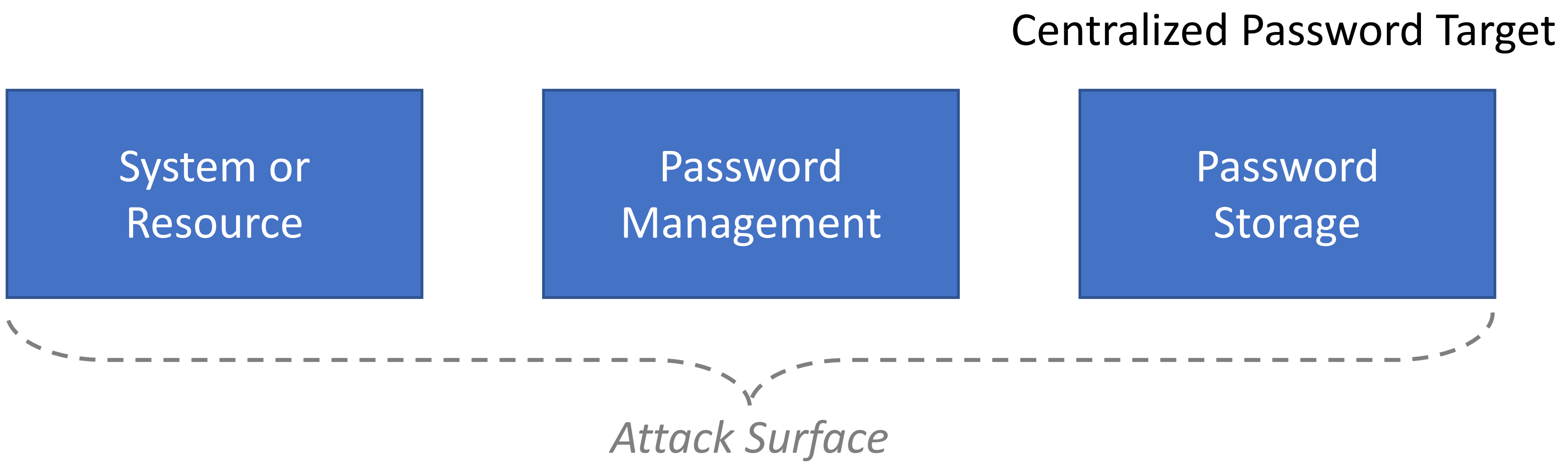
# Inherent Threat of Password Repositories



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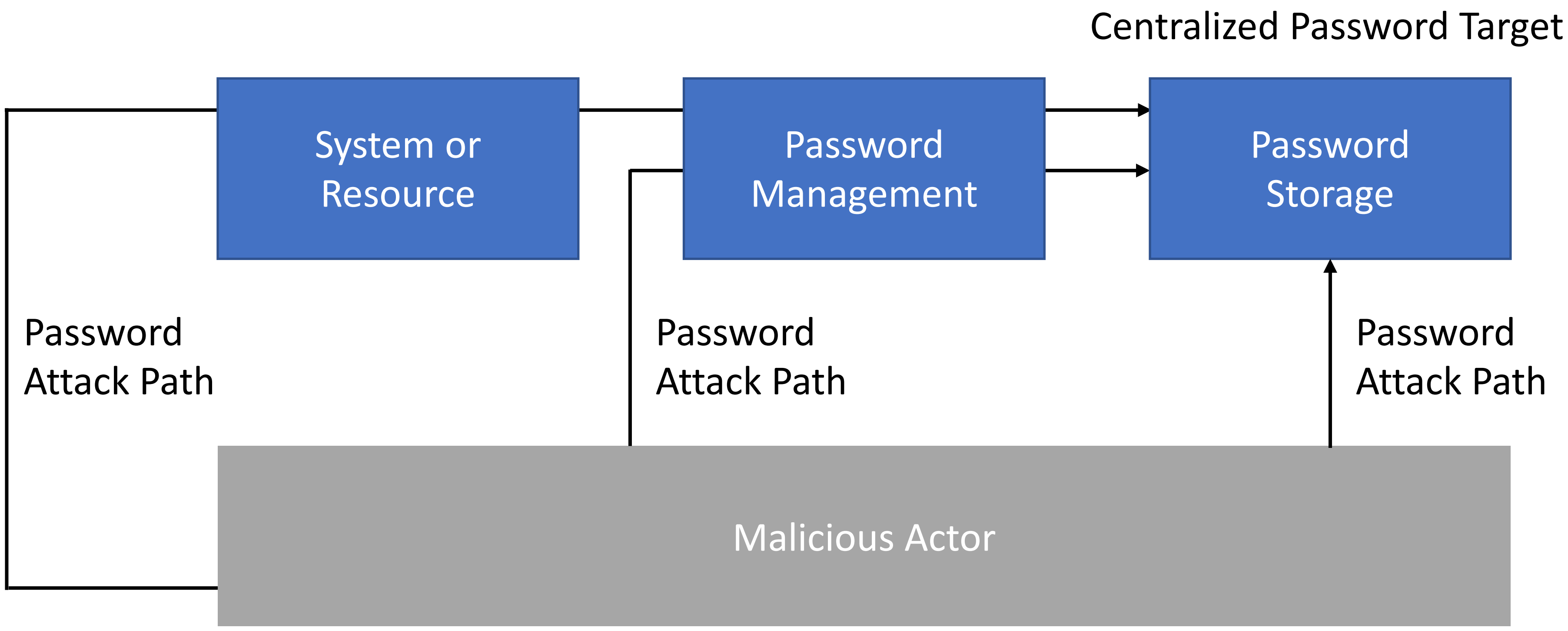
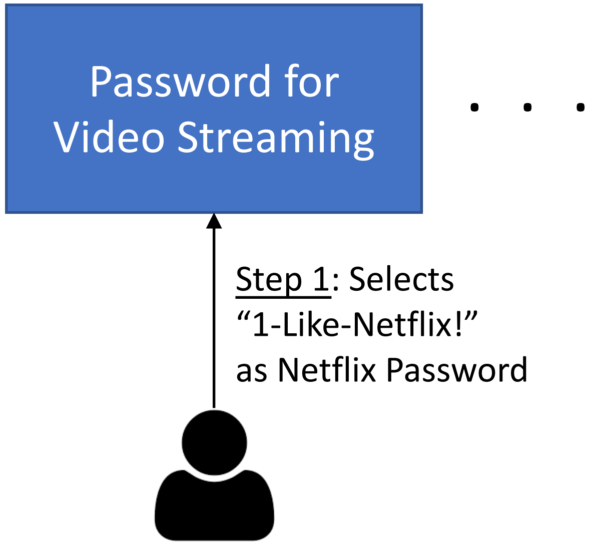
# Inherent Threat of Password Repositories



# Inherent Threat of Password Reuse

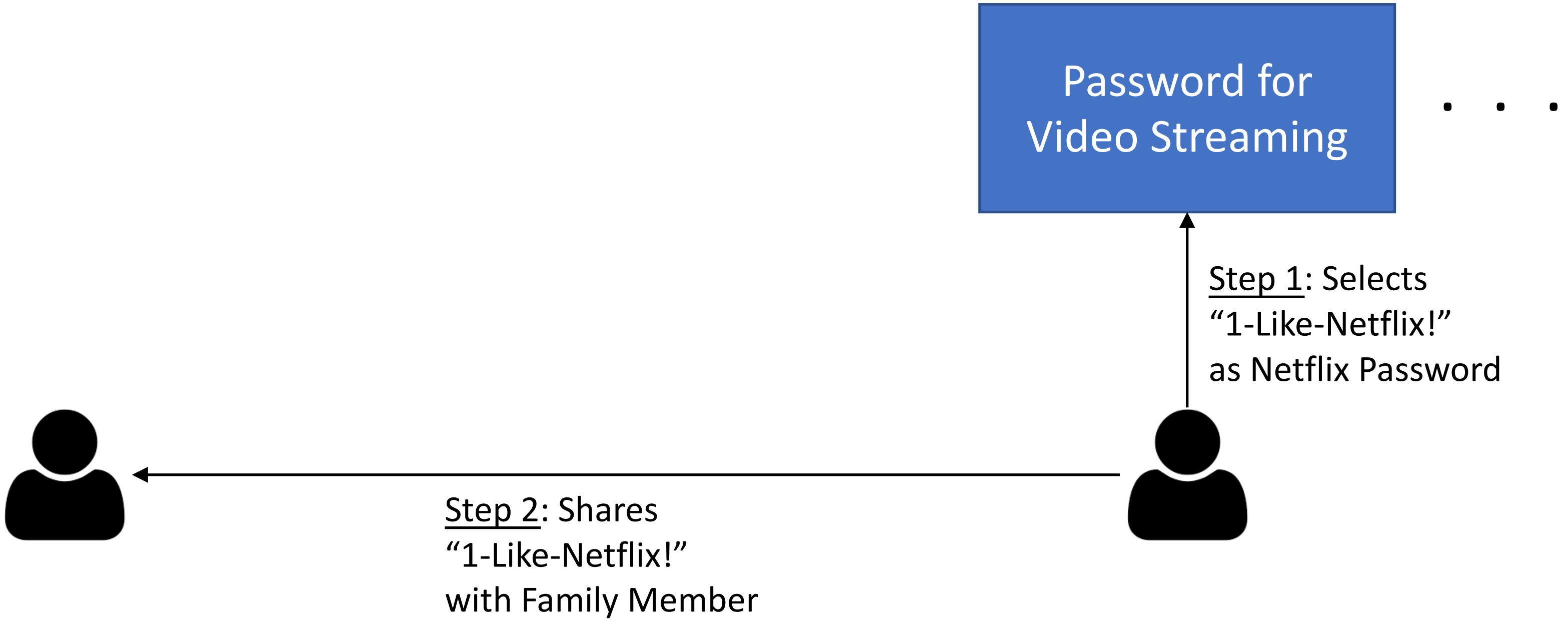


Password for Video Streaming

. . .

Step 1: Selects “1-Like-Netflix!” as Netflix Password

# Inherent Threat of Password Reuse



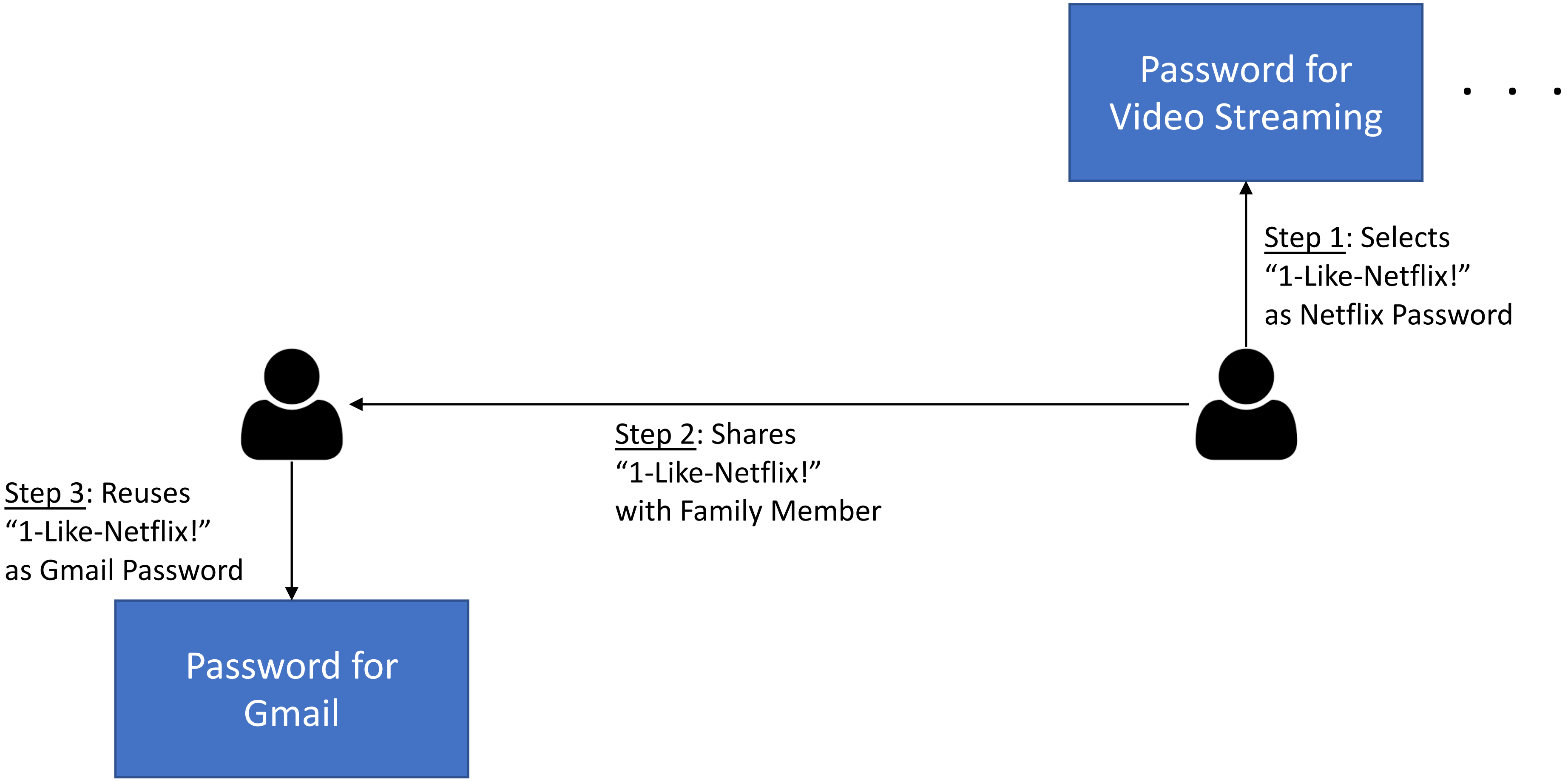
Password for Video Streaming

. . .

Step 1: Selects "1-Like-Netflix!" as Netflix Password

Step 2: Shares "1-Like-Netflix!" with Family Member

# Inherent Threat of Password Reuse



Password for Video Streaming

. . .

Step 1: Selects "1-Like-Netflix!" as Netflix Password

Step 2: Shares "1-Like-Netflix!" with Family Member

Step 3: Reuses "1-Like-Netflix!" as Gmail Password

Password for Gmail

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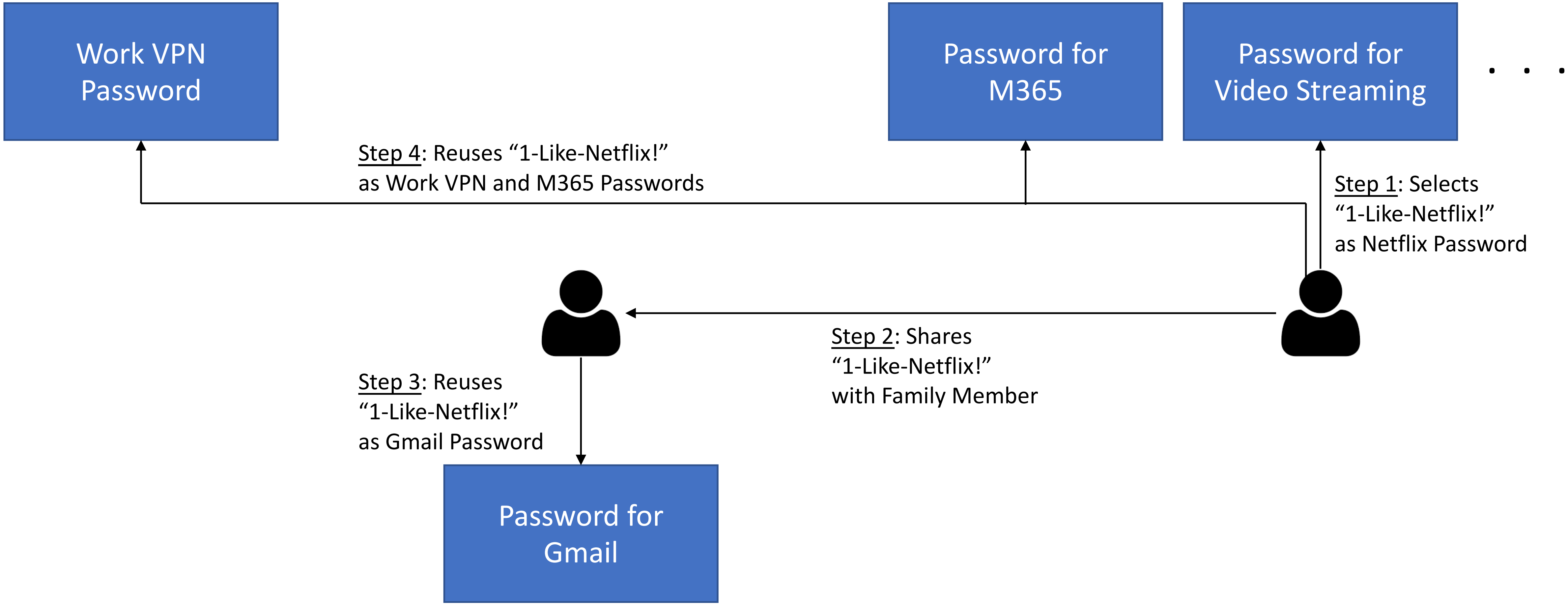
# Inherent Threat of Password Reuse



Work VPN Password

Password for M365

Password for Video Streaming

. . .

Step 1: Selects “1-Like-Netflix!” as Netflix Password

Step 2: Shares “1-Like-Netflix!” with Family Member

Step 3: Reuses “1-Like-Netflix!” as Gmail Password

Step 4: Reuses “1-Like-Netflix!” as Work VPN and M365 Passwords

Password for Gmail

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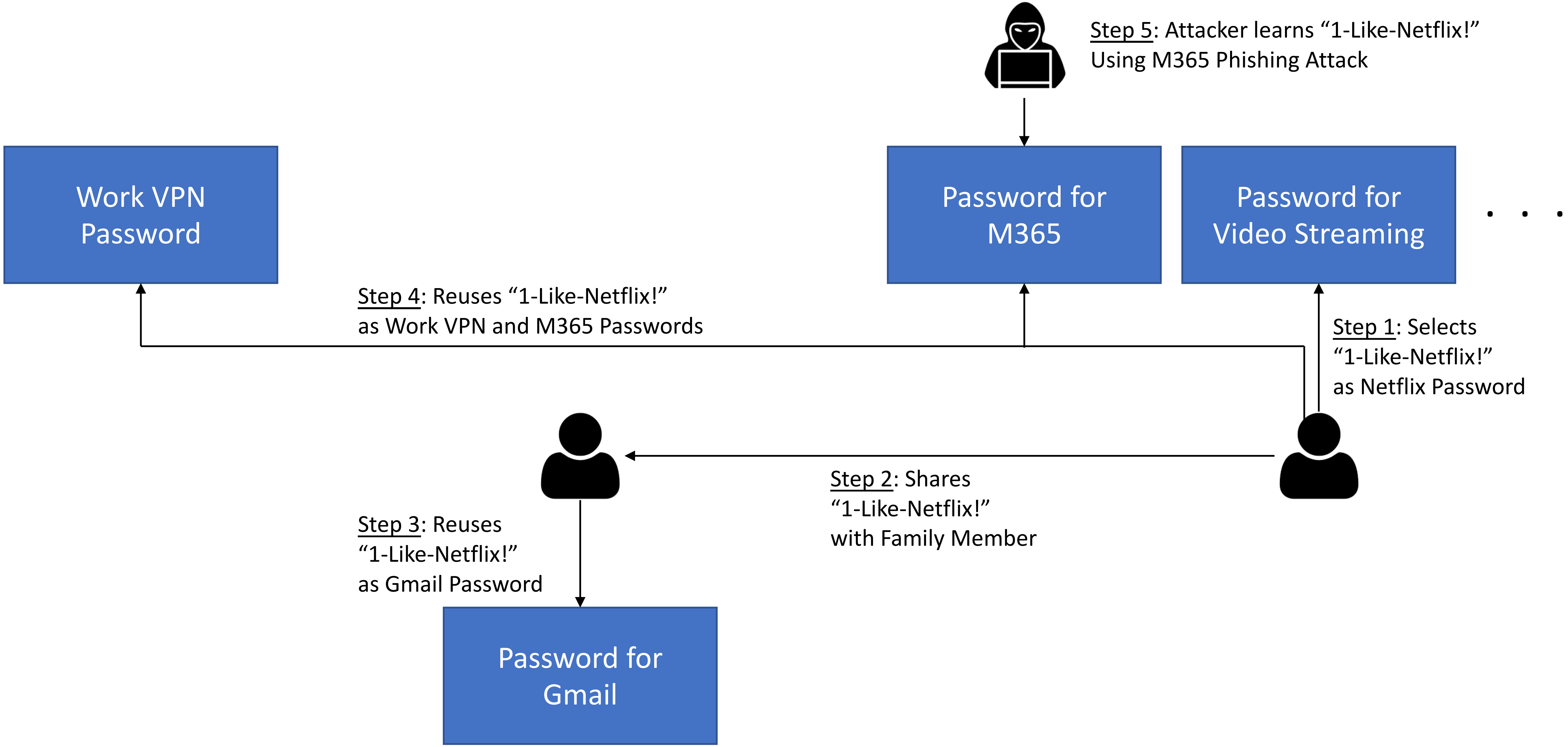
# Inherent Threat of Password Reuse



Step 5: Attacker learns “1-Like-Netflix!” Using M365 Phishing Attack
Work VPN Password
Password for M365
Password for Video Streaming
. . .
Step 4: Reuses “1-Like-Netflix!” as Work VPN and M365 Passwords
Step 1: Selects “1-Like-Netflix!” as Netflix Password
Step 2: Shares “1-Like-Netflix!” with Family Member
Step 3: Reuses “1-Like-Netflix!” as Gmail Password
Password for Gmail

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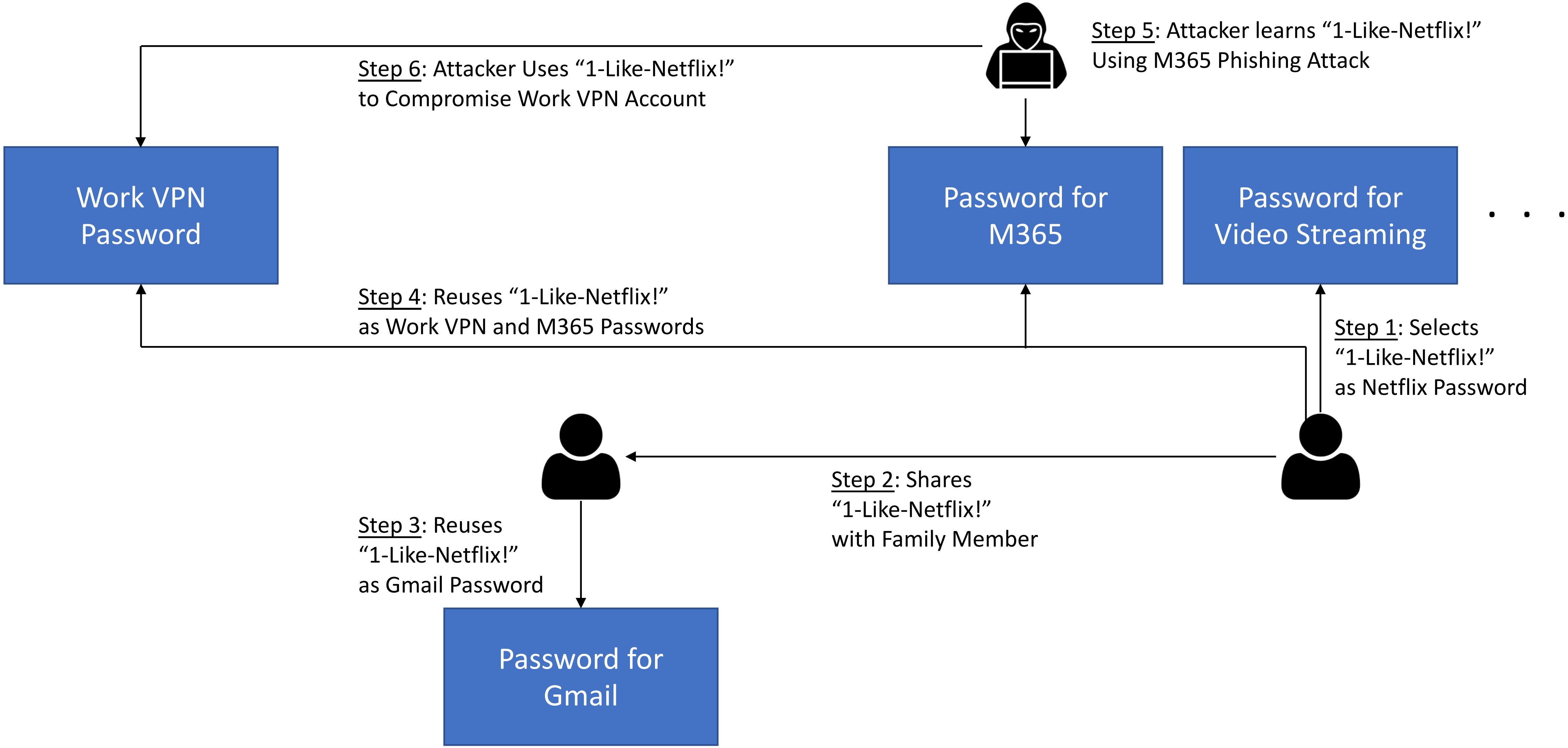
# Inherent Threat of Password Reuse



Step 5: Attacker learns “1-Like-Netflix!” Using M365 Phishing Attack

Step 6: Attacker Uses “1-Like-Netflix!” to Compromise Work VPN Account

Work VPN Password

Password for M365

Password for Video Streaming

. . .

Step 4: Reuses “1-Like-Netflix!” as Work VPN and M365 Passwords

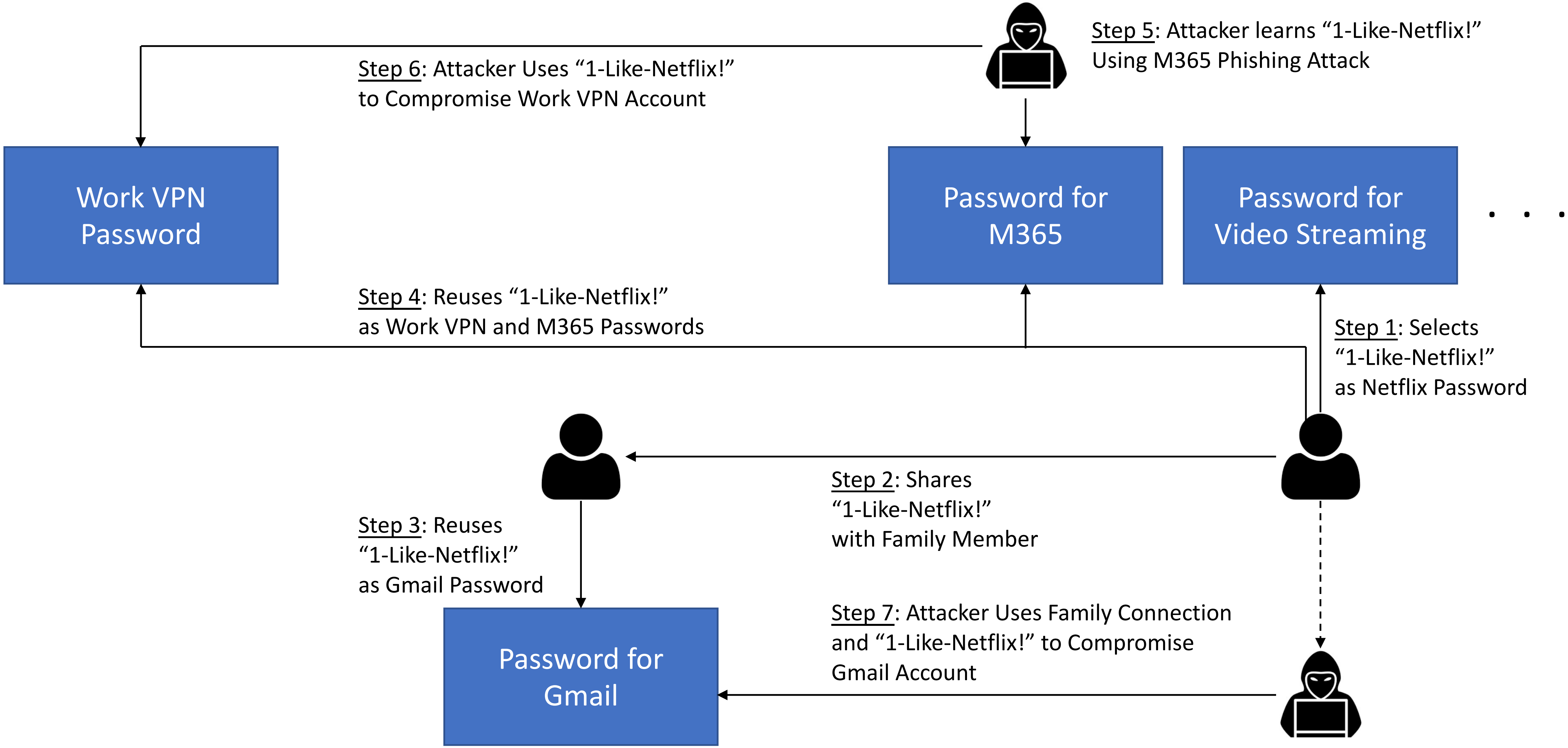
Step 1: Selects “1-Like-Netflix!” as Netflix Password

Step 2: Shares “1-Like-Netflix!” with Family Member

Step 3: Reuses “1-Like-Netflix!” as Gmail Password

Password for Gmail

# Inherent Threat of Password Reuse



Step 1: Selects "1-Like-Netflix!" as Netflix Password

Step 2: Shares "1-Like-Netflix!" with Family Member

Step 3: Reuses "1-Like-Netflix!" as Gmail Password

Step 4: Reuses "1-Like-Netflix!" as Work VPN and M365 Passwords

Step 5: Attacker learns "1-Like-Netflix!" Using M365 Phishing Attack

Step 6: Attacker Uses "1-Like-Netflix!" to Compromise Work VPN Account

Step 7: Attacker Uses Family Connection and "1-Like-Netflix!" to Compromise Gmail Account

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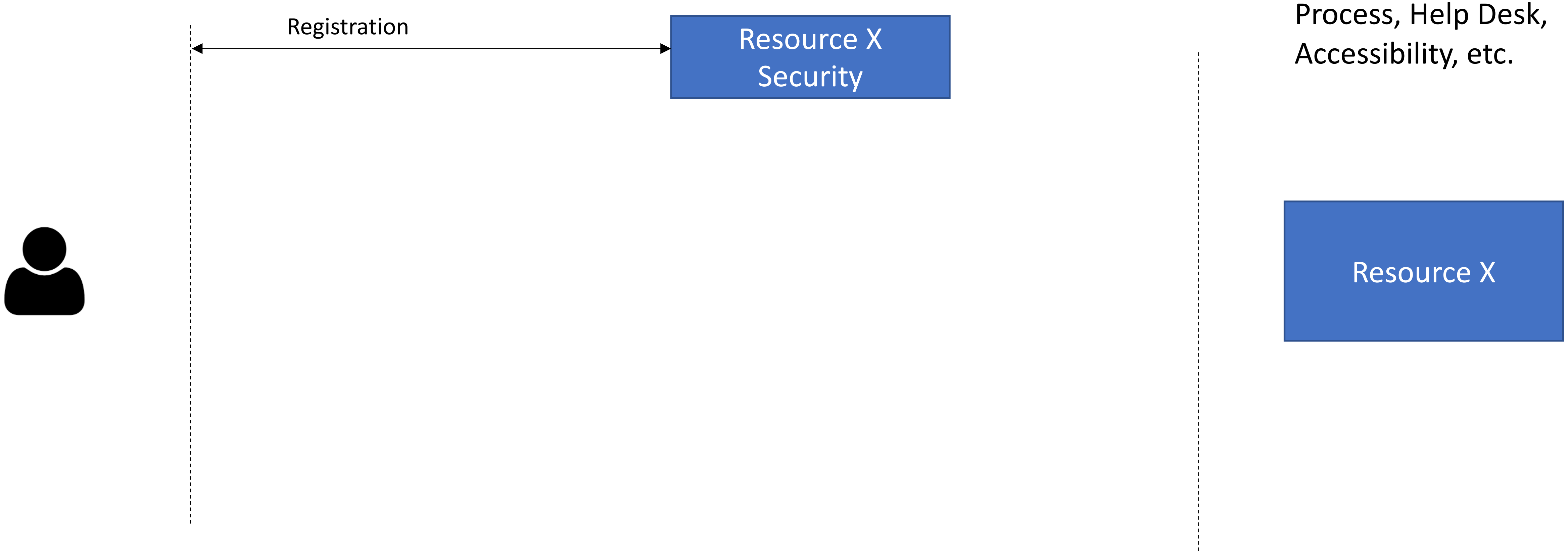
# Inherent Friction from Password Usage

**Friction:**
Process, Help Desk, Accessibility, etc.



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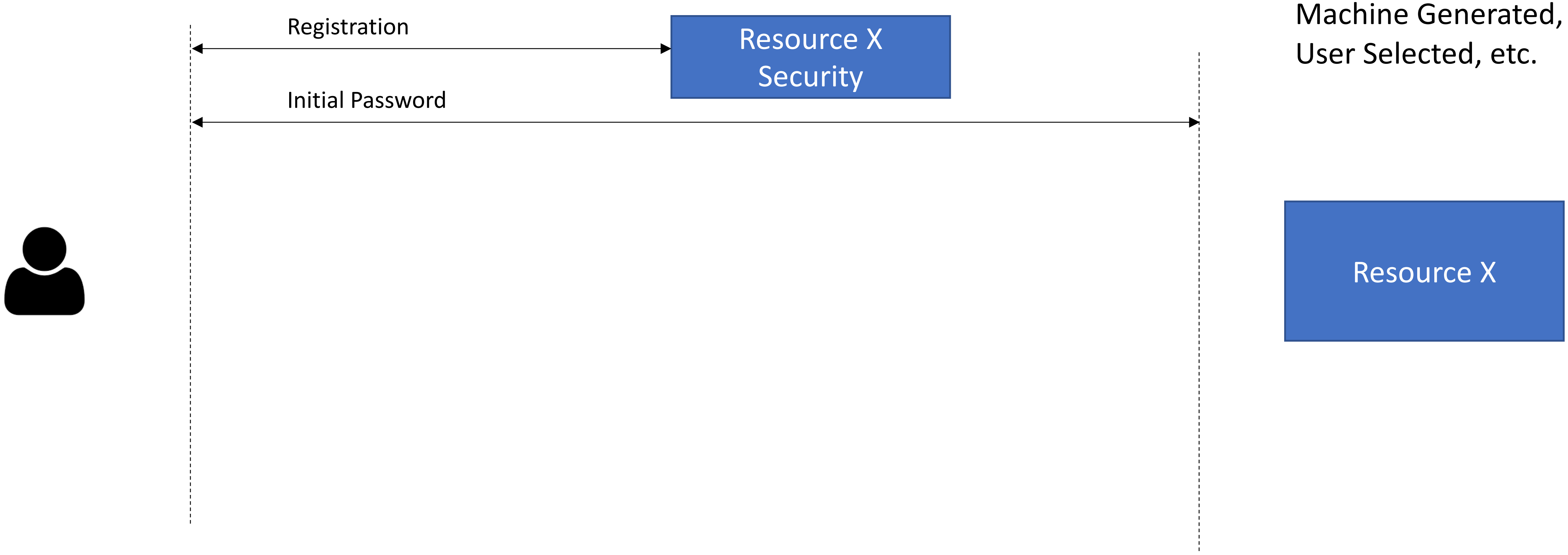
# Inherent Friction from Password Usage



**Friction:**
Machine Generated,
User Selected, etc.

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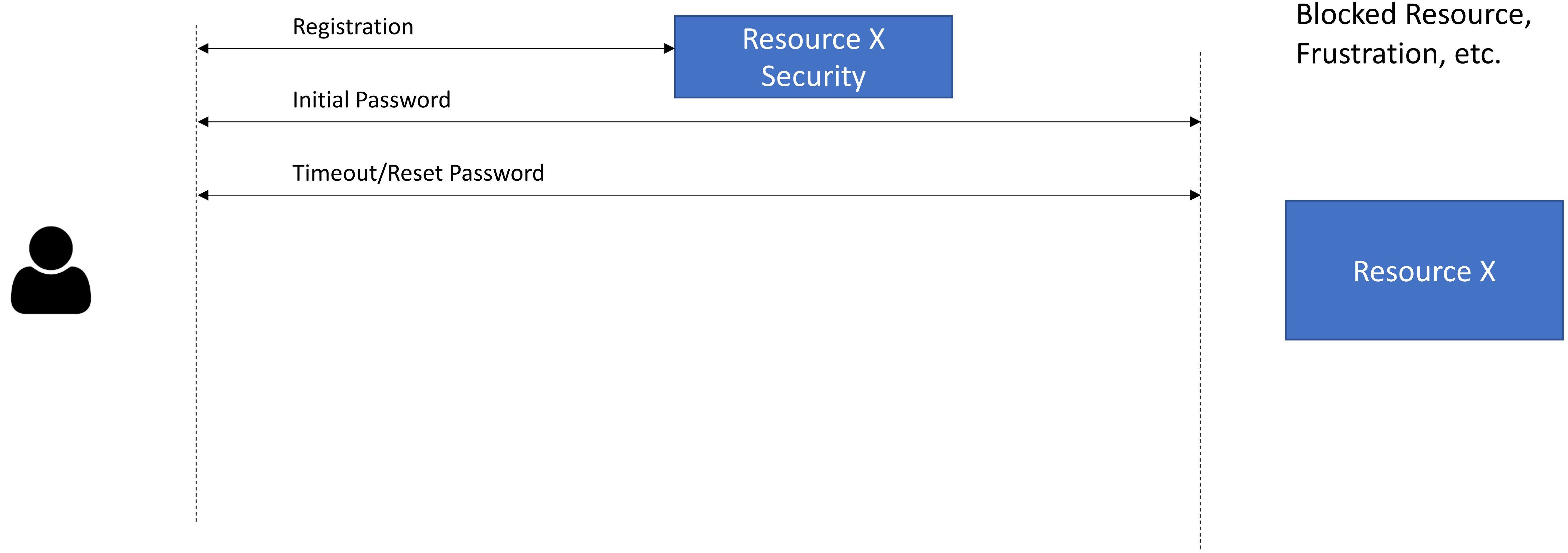
# Inherent Friction from Password Usage



**Friction:**
Blocked Resource,
Frustration, etc.

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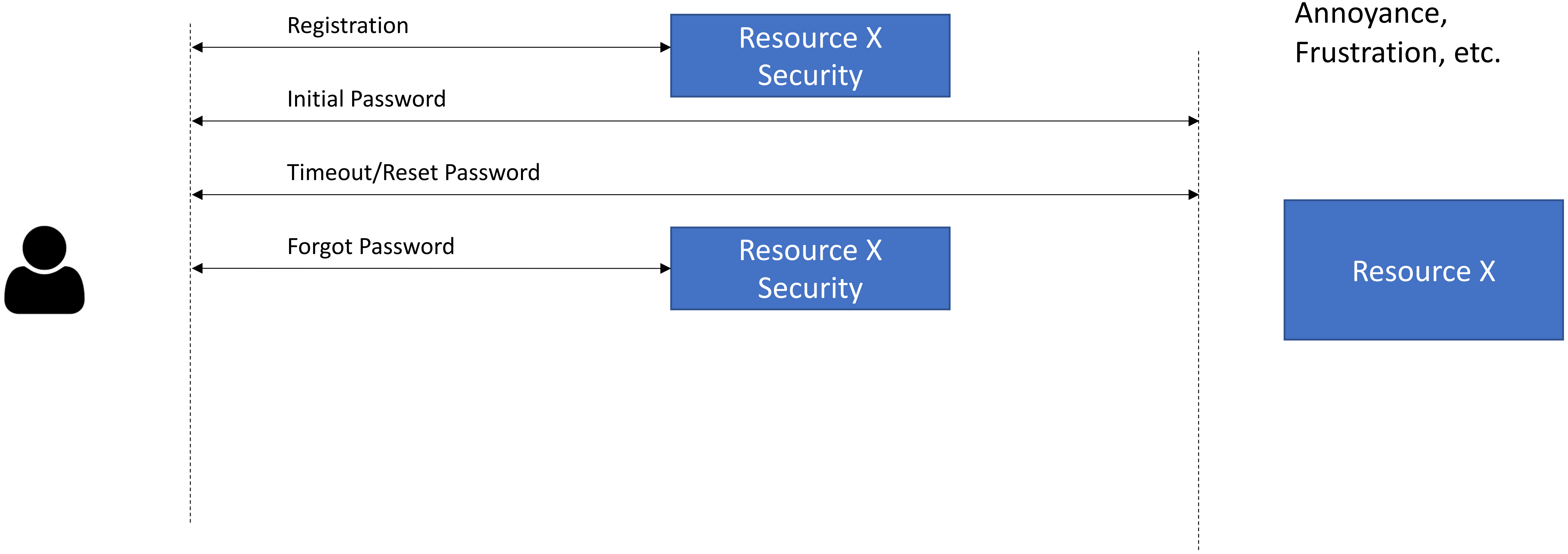
# Inherent Friction from Password Usage



**Friction:**
Annoyance,
Frustration, etc.

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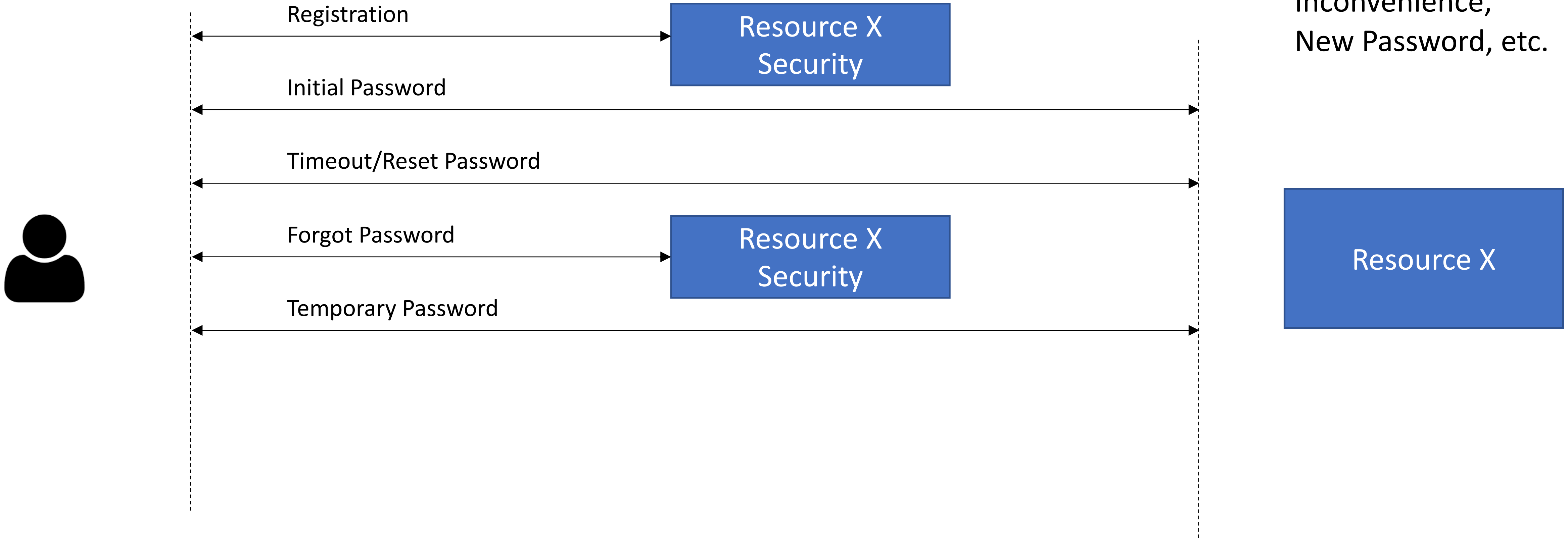
# Inherent Friction from Password Usage



**Friction:**
Inconvenience,
New Password, etc.

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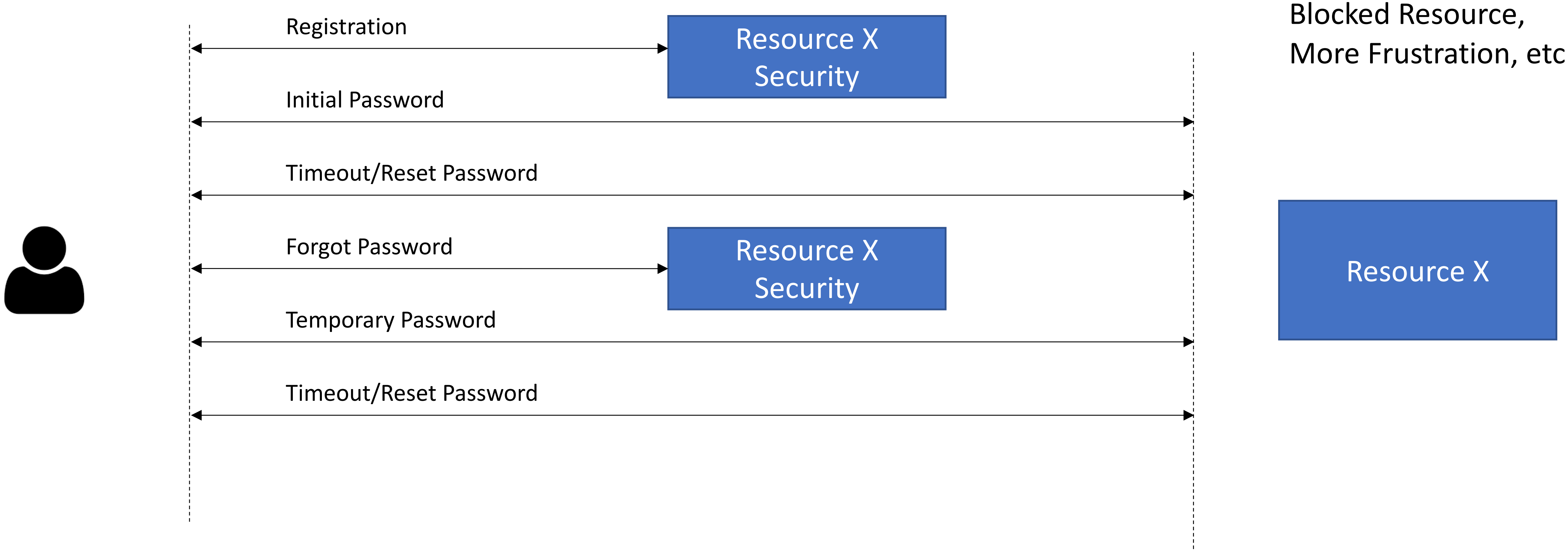
# Inherent Friction from Password Usage



**Friction:**
Blocked Resource,
More Frustration, etc.

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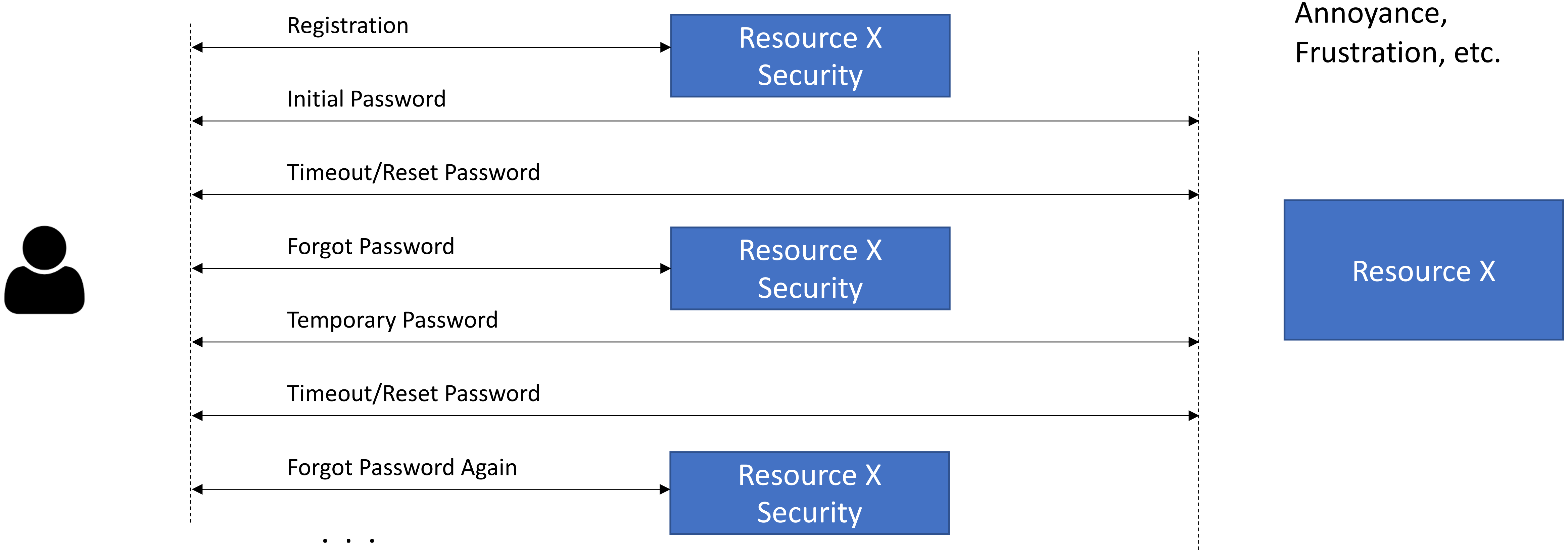
# Inherent Friction from Password Usage



**Friction:**
Annoyance,
Frustration, etc.

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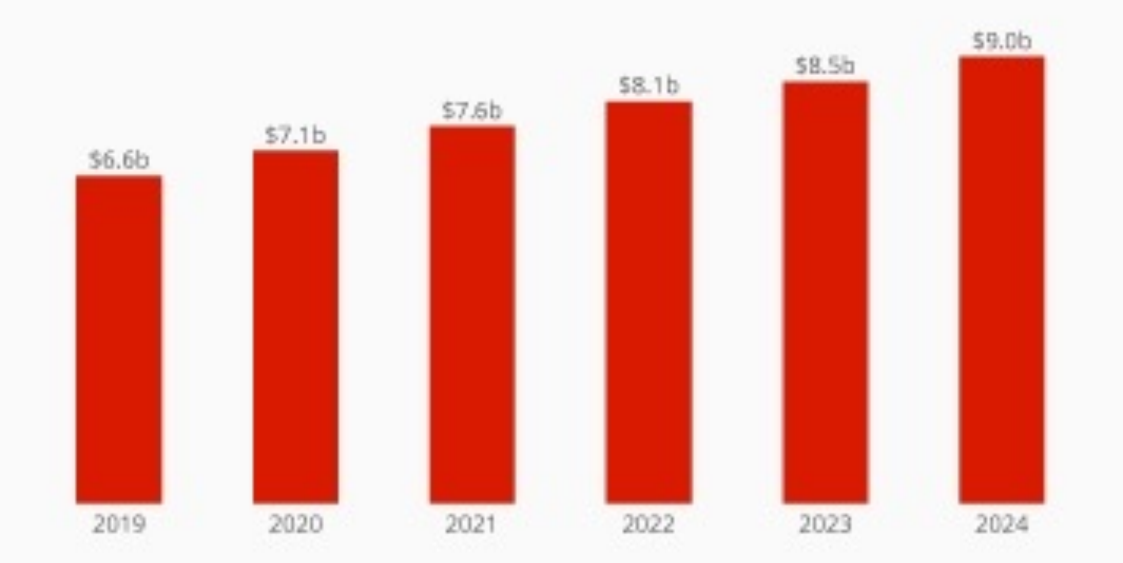
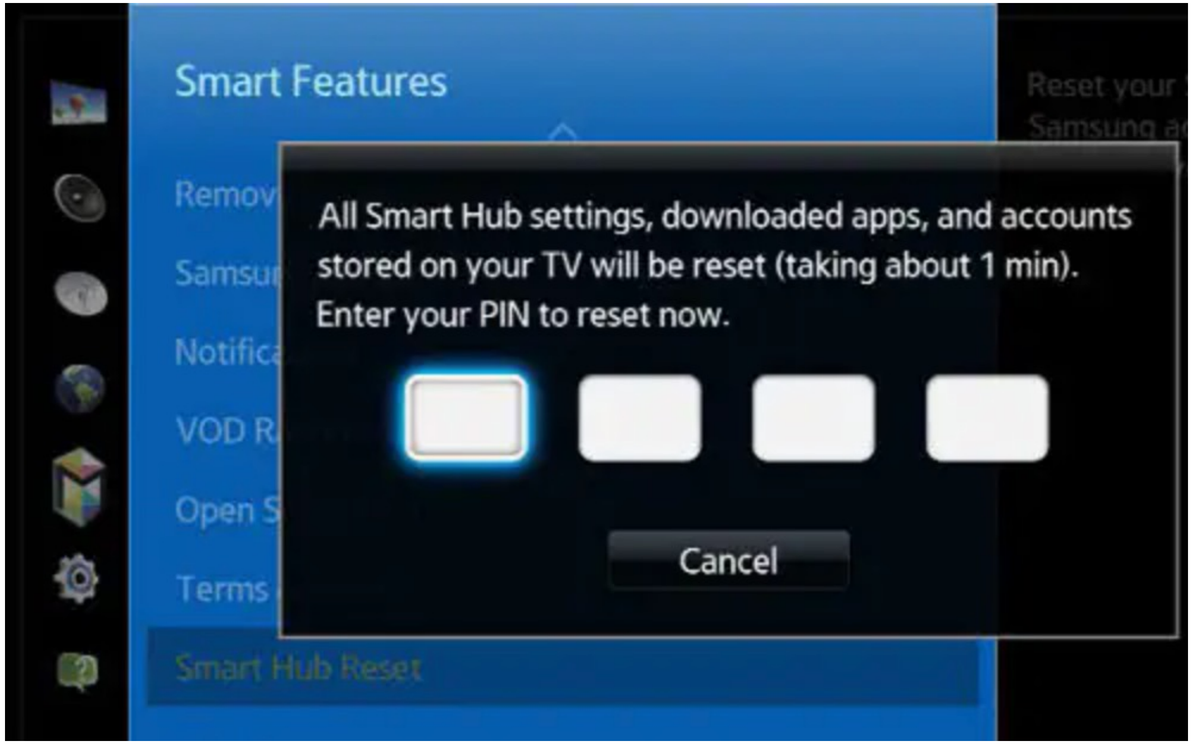
# Password Issues with Smart TV/Streaming Channels

Estimated Revenue Losses for US Pay TV Industry from Piracy and Account Sharing



Source: Statistica

https://www.statista.com/chart/19914/estimated-revenue-loss-for-the-us-pay-tv-industry-from-piracy-and-account-sharing/



All Smart Hub settings, downloaded apps, and accounts stored on your TV will be reset (taking about 1 min). Enter your PIN to reset now.

# How Did Handheld Authenticators Work?

Week 5

# Handheld Authentication Device

A

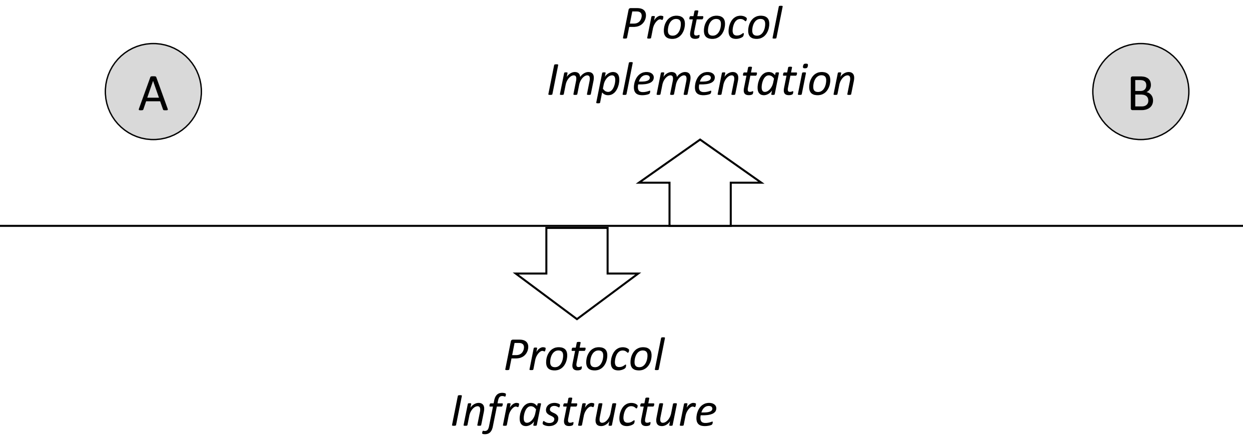
B

**Embedded Function**
**f: integer -> integer**

| *User* | *Function* |
|---|---|
| **A** | **f** |
| **C** | **f ’** |
| **G** | **f ’’** |
| **. . .** | **. . .** |

Week 5

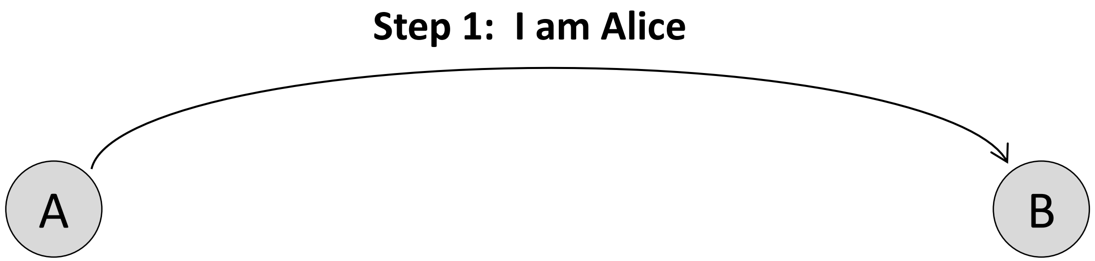
# Handheld Authentication Device



**Embedded Function**
**f: integer -> integer**

| *User* | *Function* |
|---|---|
| **A** | **f** |
| **C** | **f ’** |
| **G** | **f ’’** |
| . . . | . . . |

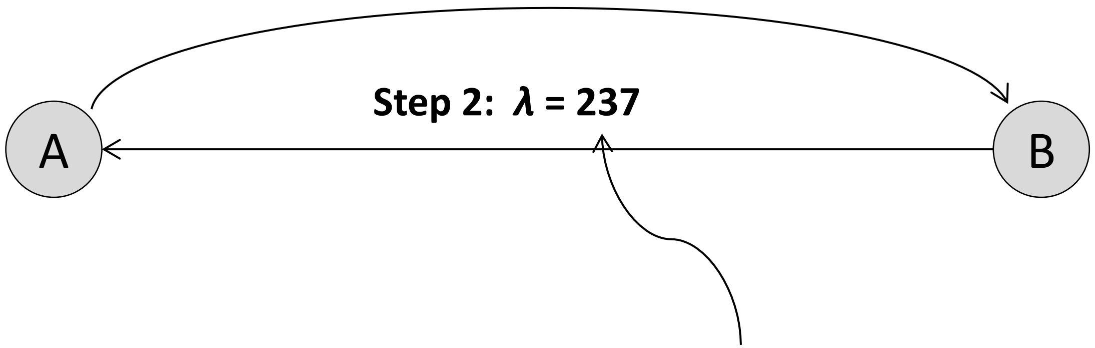
# Handheld Authentication Device


Step 1: I am Alice

**Embedded Function**
**f: integer -> integer**

| *User* | *Function* |
|---|---|
| **A** | **f** |
| **C** | **f ’** |
| **G** | **f ’’** |
| **. . .** | **. . .** |

# Handheld Authentication Device



Step 1: I am Alice

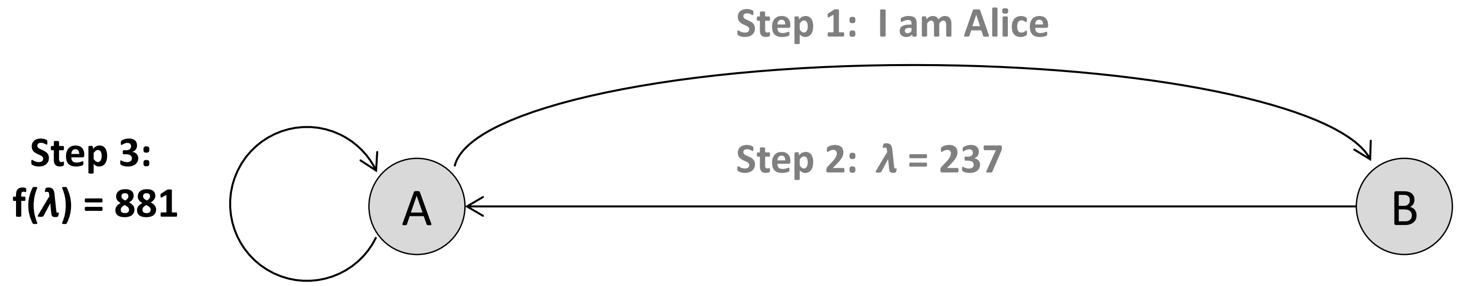
Step 2: *λ* = 237

*Randomly selected integer λ*

**Embedded Function**
**f: integer -> integer**

| *User* | *Function* |
|---|---|
| **A** | **f** |
| **C** | **f ’** |
| **G** | **f ’’** |
| . . . | . . . |

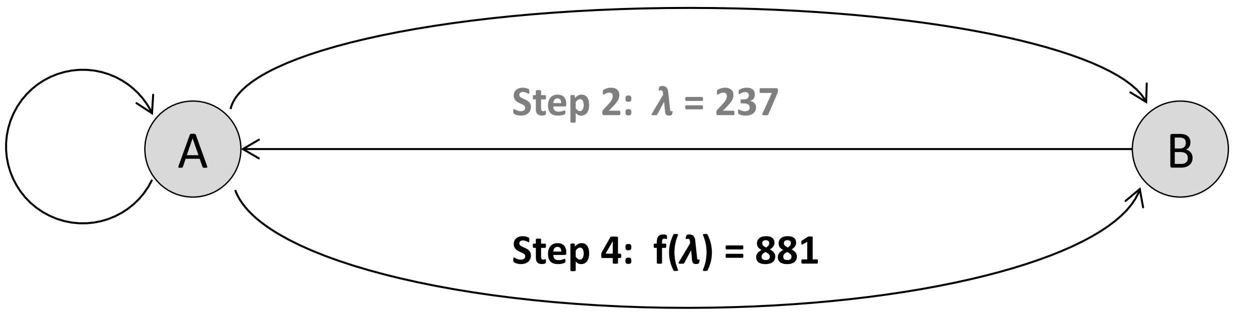
# Handheld Authentication Device



**Embedded Function**
**f: integer -> integer**

| *User* | *Function* |
|---|---|
| **A** | **f** |
| **C** | **f ’** |
| **G** | **f ’’** |
| **. . .** | **. . .** |

# Handheld Authentication Device



Step 1: I am Alice

Step 2: $\lambda$ = 237

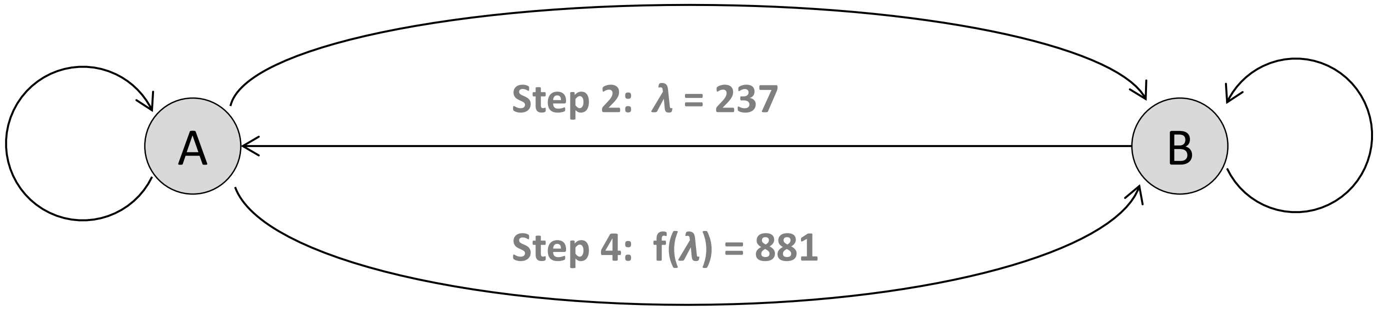
Step 3: f($\lambda$) = 881

Step 4: f($\lambda$) = 881

Embedded Function
f: integer -> integer

| *User* | *Function* |
|---|---|
| A | f |
| C | f ’ |
| G | f ’’ |
| . . . | . . . |

# Handheld Authentication Device



Step 1: I am Alice

Step 2: $\lambda$ = 237

Step 3: f($\lambda$) = 881

Step 4: f($\lambda$) = 881

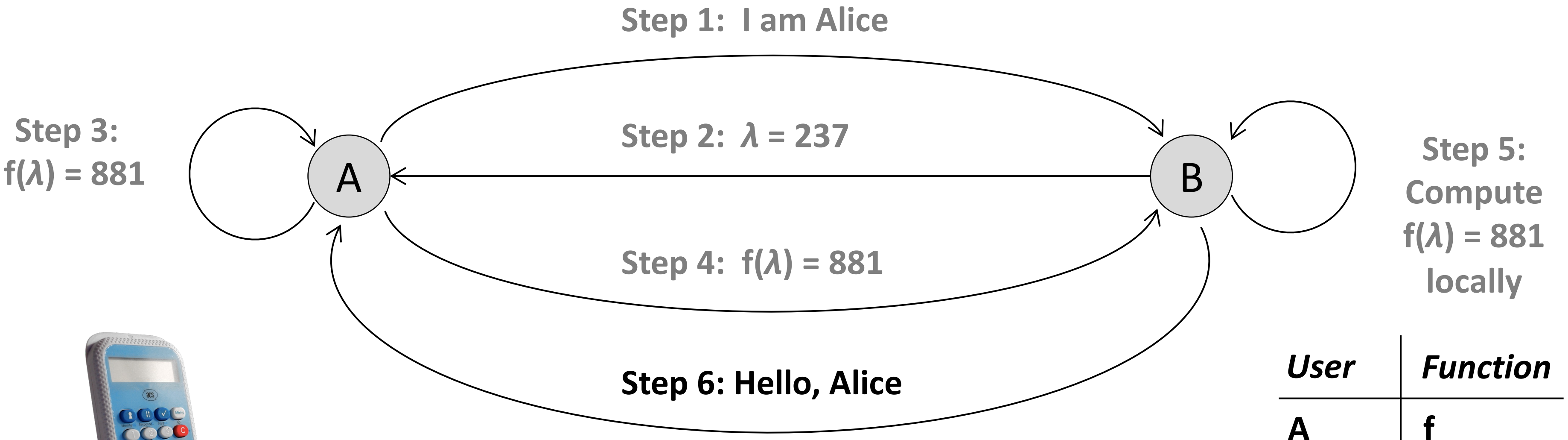
Step 5: Compute f($\lambda$) = 881 locally

Embedded Function
f: integer -> integer

| *User* | *Function* |
|---|---|
| A | f |
| C | f ’ |
| G | f ’’ |
| . . . | . . . |

Week 5

# Handheld Authentication Device

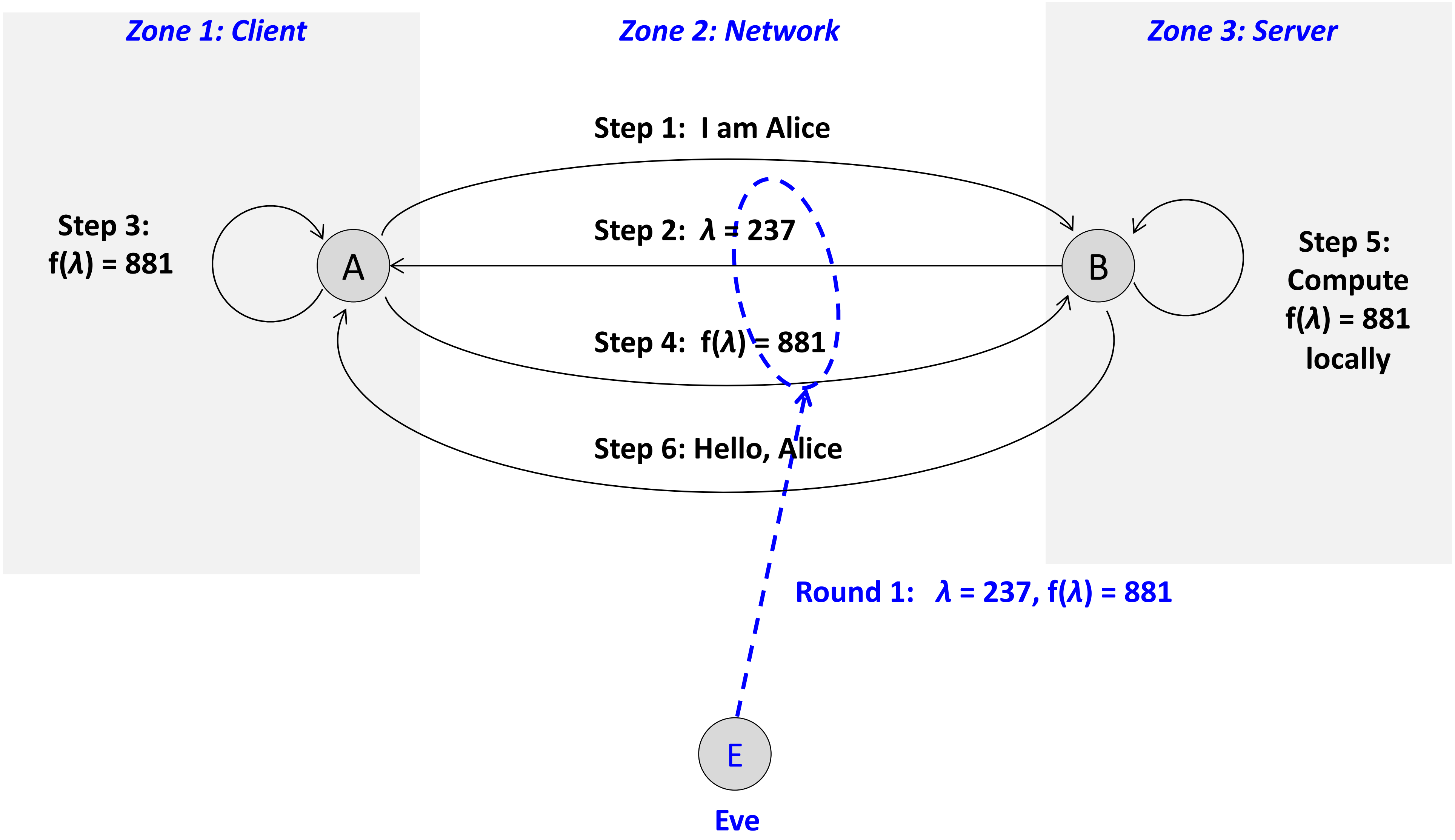


**Embedded Function**
**f: integer -> integer**

| *User* | *Function* |
|---|---|
| A | f |
| C | f ’ |
| G | f ’’ |
| . . . | . . . |

Week 5

# Handheld Authentication Device Protocol



*Zone 1: Client*

*Zone 2: Network*

*Zone 3: Server*

Step 1: I am Alice

Step 2: $\lambda$ = 237

Step 3: f($\lambda$) = 881

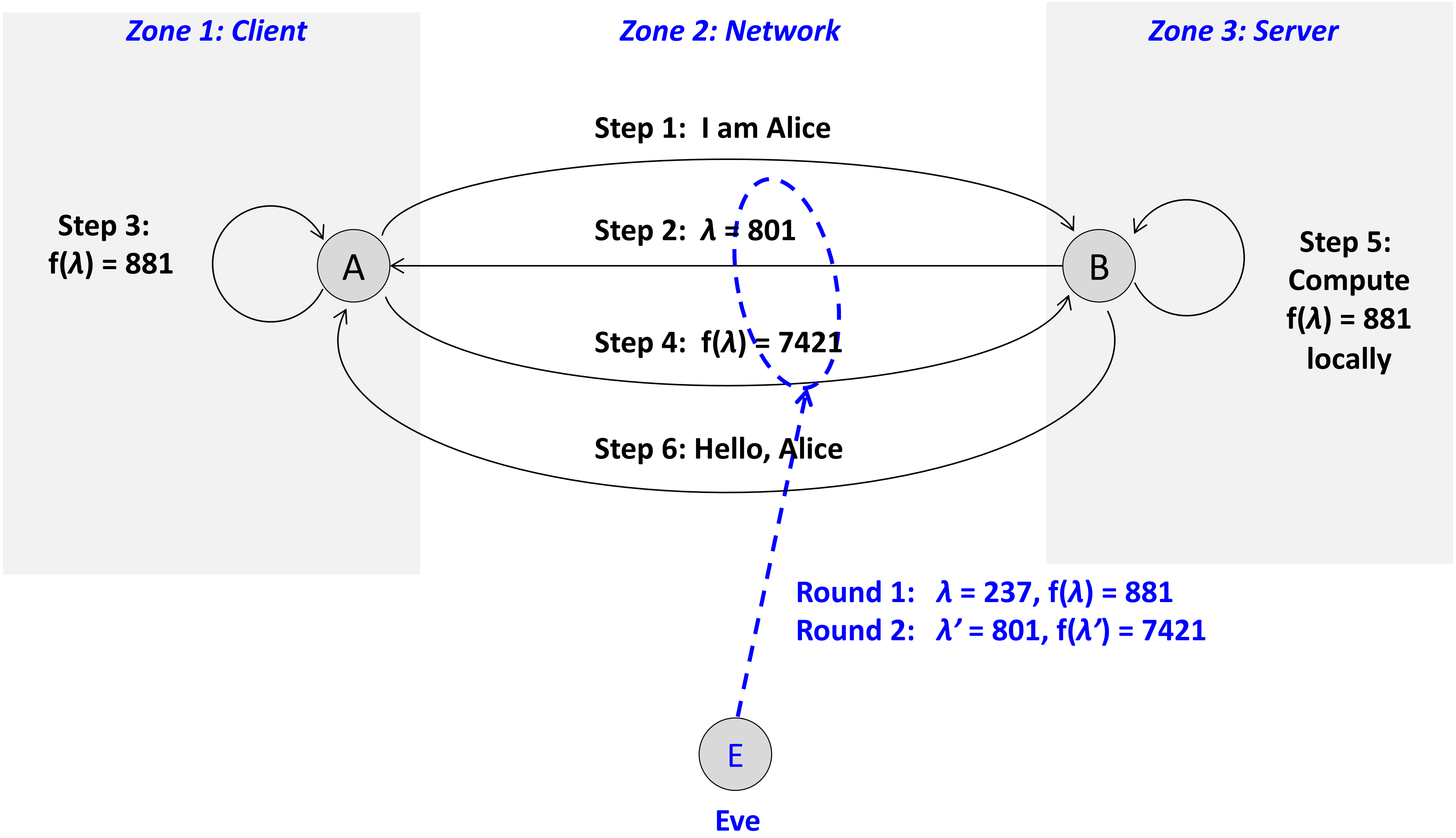
Step 4: f($\lambda$) = 881

Step 5: Compute f($\lambda$) = 881 locally

Step 6: Hello, Alice

Round 1: $\lambda$ = 237, f($\lambda$) = 881

# Handheld Authentication Device Protocol



*Zone 1: Client*

*Zone 2: Network*

*Zone 3: Server*

Step 1: I am Alice

Step 2: $\lambda$ = 801

Step 3: f($\lambda$) = 881

Step 4: f($\lambda$) = 7421

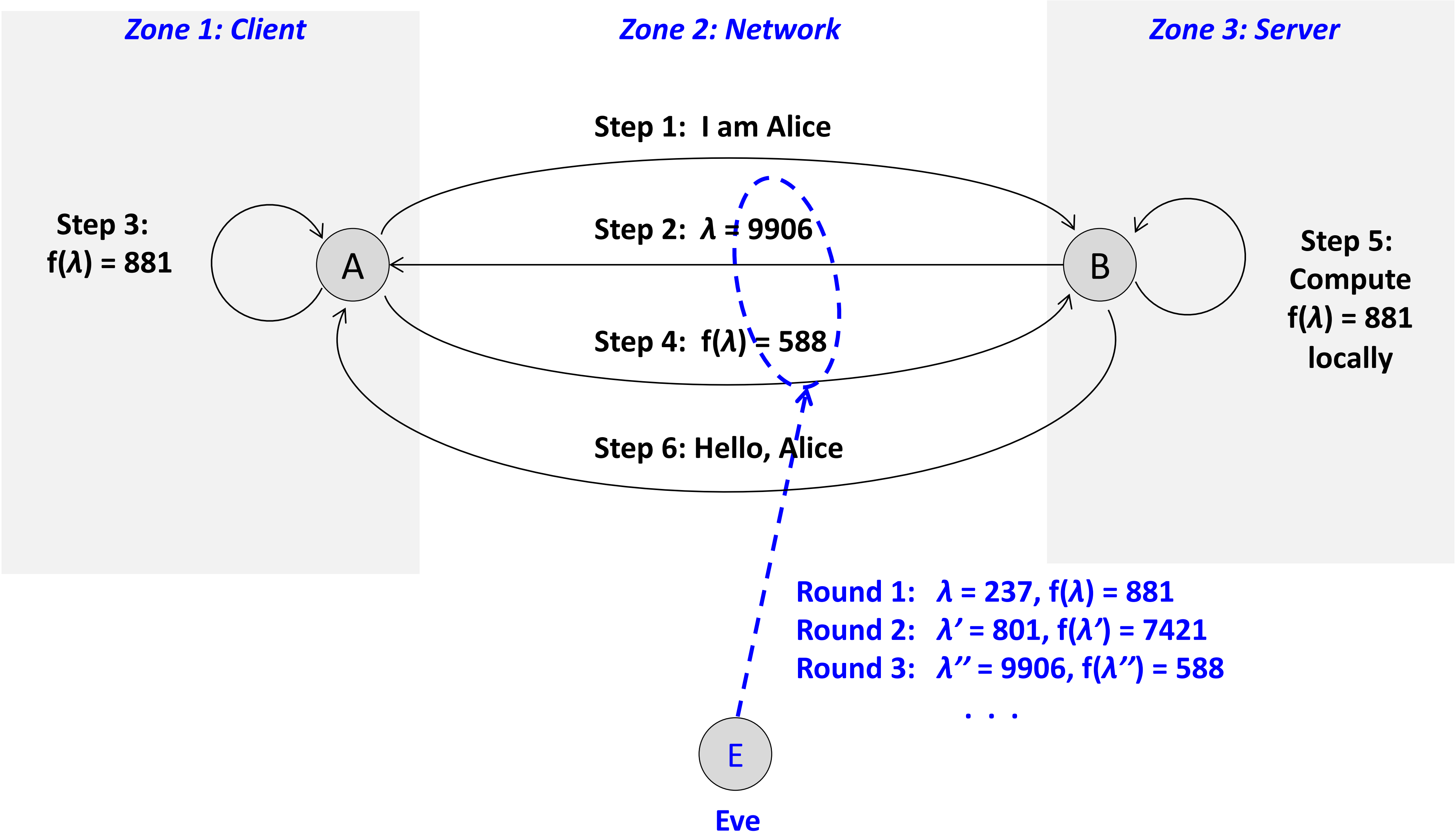
Step 5: Compute f($\lambda$) = 881 locally

Step 6: Hello, Alice

Round 1: $\lambda$ = 237, f($\lambda$) = 881
Round 2: $\lambda'$ = 801, f($\lambda'$) = 7421

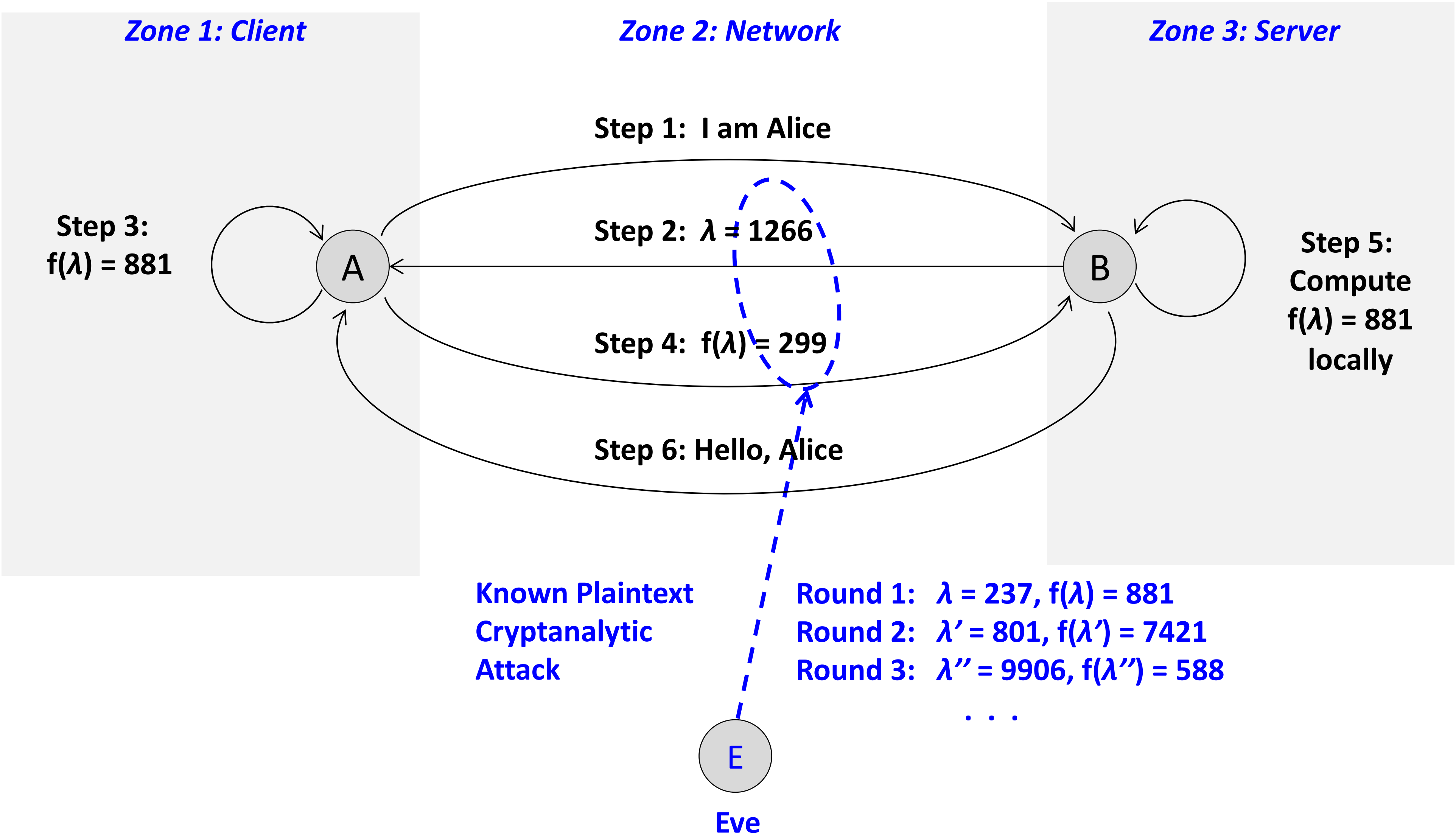
Week 5

# Handheld Authentication Device Protocol



Week 5

# Handheld Authentication Device Protocol



Known Plaintext Cryptanalytic Attack

Round 1: $\lambda$ = 237, f($\lambda$) = 881
Round 2: $\lambda'$ = 801, f($\lambda'$) = 7421
Round 3: $\lambda''$ = 9906, f($\lambda''$) = 588
. . .

# How Does RSA SecureID OTP Work?

# RSA SecurID One-Time Password (OTP) Algorithm

f: integer -> integer

λ: integer seed

$t_0$: initial time

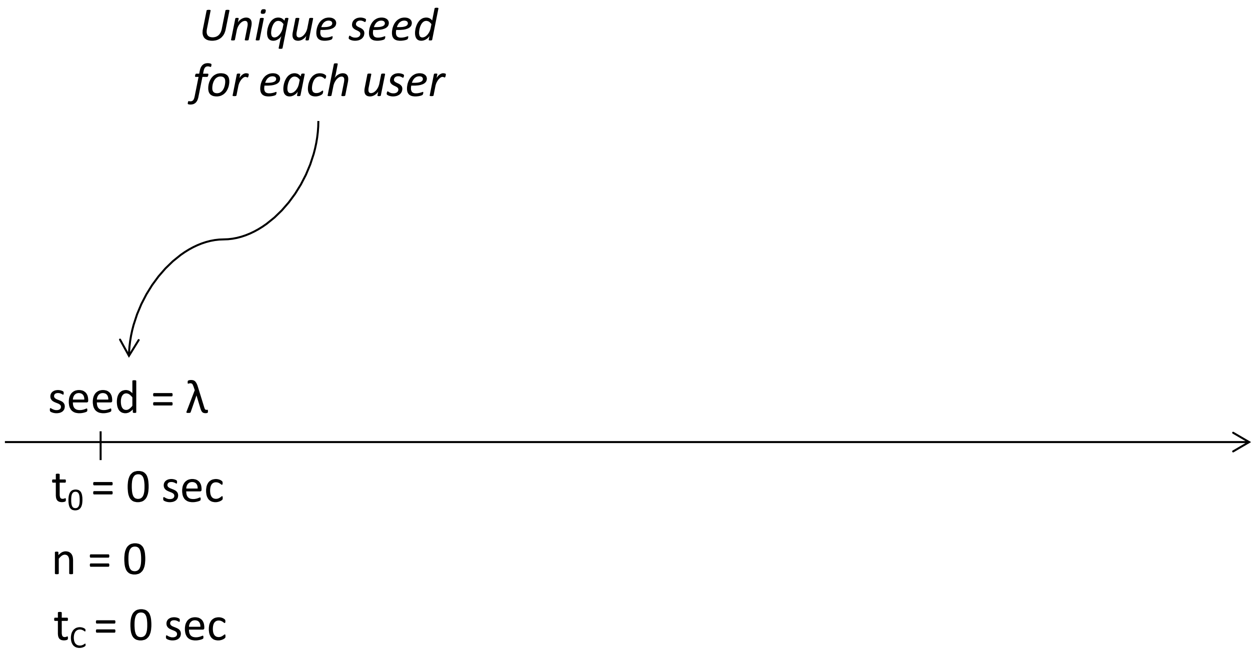
$t_C$: current time

Δt: time interval

$n = (t_C – t_0) / \Delta t$

# RSA SecurID One-Time Password (OTP) Algorithm

f: integer -> integer
λ: integer seed
$t_0$: initial time
$t_C$: current time
Δt: time interval
n = $(t_C - t_0)$ / Δt


*Unique seed for each user*

seed = λ

$t_0$ = 0 sec

n = 0

$t_C$ = 0 sec

# RSA SecurID One-Time Password (OTP) Algorithm

f: integer -> integer

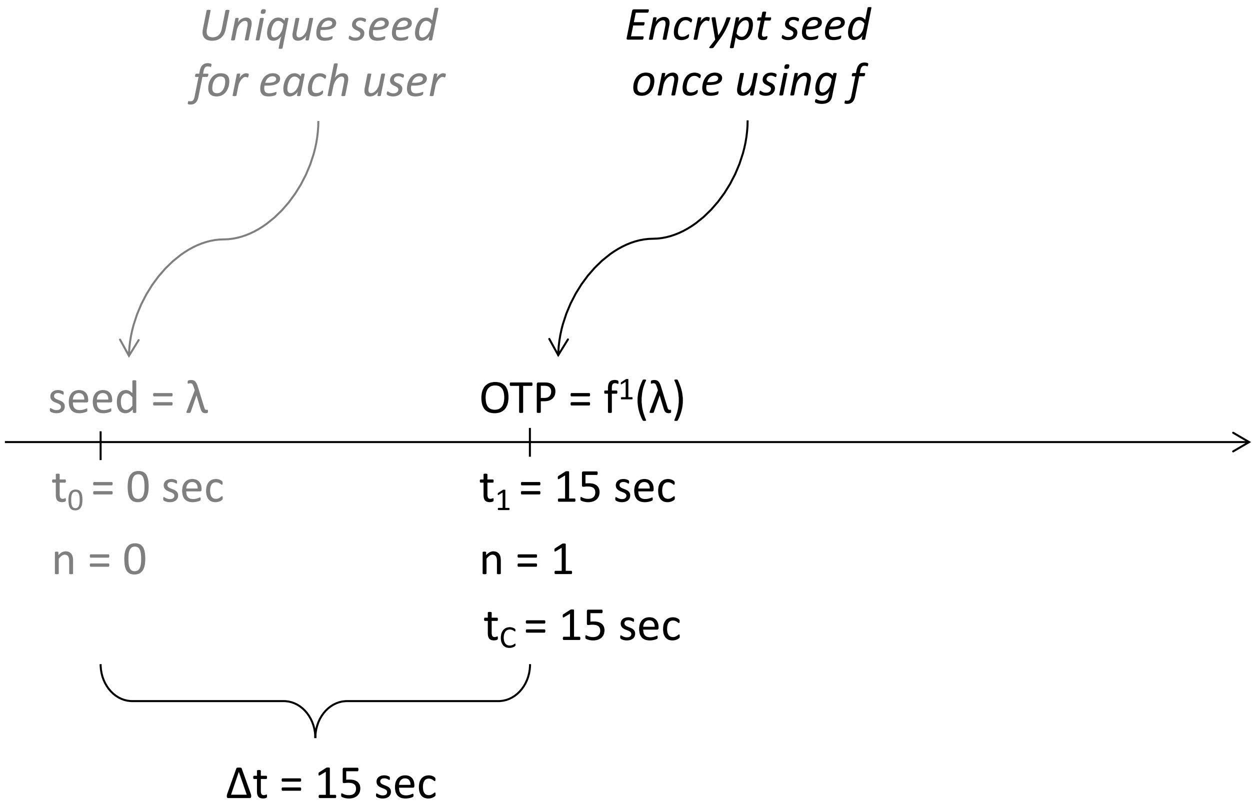
$\lambda$: integer seed

$t_0$: initial time

$t_C$: current time

$\Delta t$: time interval

$n = (t_C - t_0) / \Delta t$



*Unique seed for each user*

*Encrypt seed once using f*

seed = $\lambda$

OTP = $f^1(\lambda)$

$t_0$ = 0 sec

n = 0

$t_1$ = 15 sec

n = 1

$t_C$ = 15 sec

$\Delta t$ = 15 sec

# RSA SecurID One-Time Password (OTP) Algorithm

f: integer -> integer

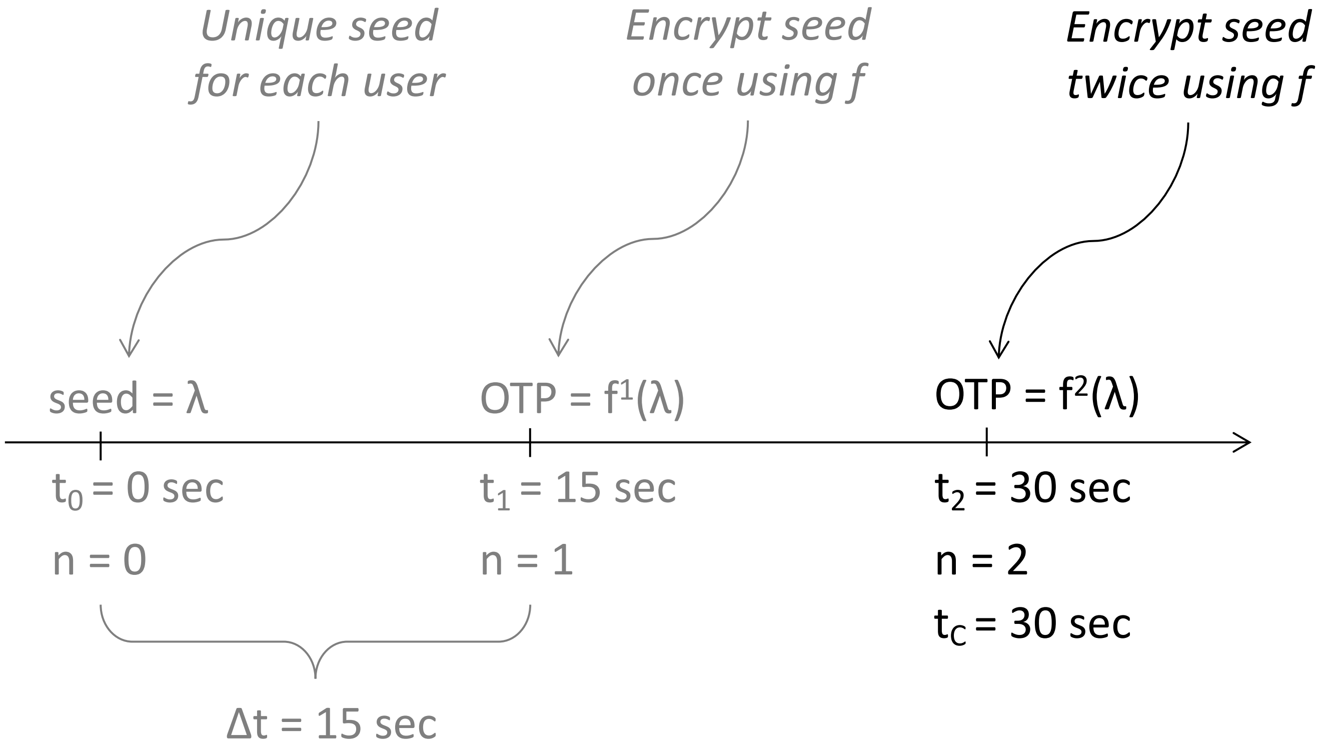
λ: integer seed

$t_0$: initial time

$t_C$: current time

Δt: time interval

$n = (t_C – t_0) / Δt$



*Unique seed for each user*

*Encrypt seed once using f*

*Encrypt seed twice using f*

seed = λ

$OTP = f^1(λ)$

$OTP = f^2(λ)$

$t_0 = 0$ sec

n = 0

$t_1 = 15$ sec

n = 1

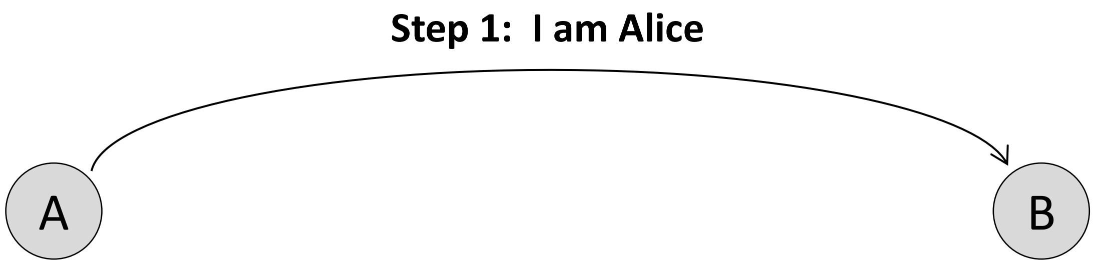
$t_2 = 30$ sec

n = 2

$t_C = 30$ sec

Δt = 15 sec

# RSA SecurID Protocol



f: integer -> integer

λ: integer seed

$t_0$: initial time

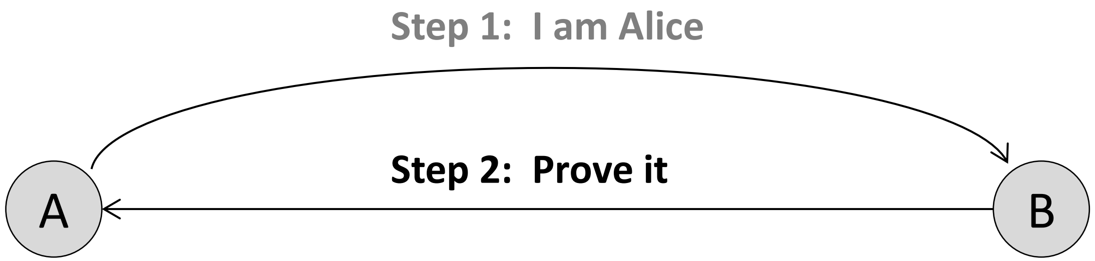
$t_C$: current time

Δt: time interval

$n = (t_C – t_0) / Δt$

| *User* | *Information* |
|---|---|
| **A** | f: integer -> integer |
| | λ: integer seed |
| | $t_0$: initial time |
| | $t_C$: current time |
| | Δt: time interval |
| | $n = (t_C – t_0) / Δt$ |

# RSA SecurID Protocol



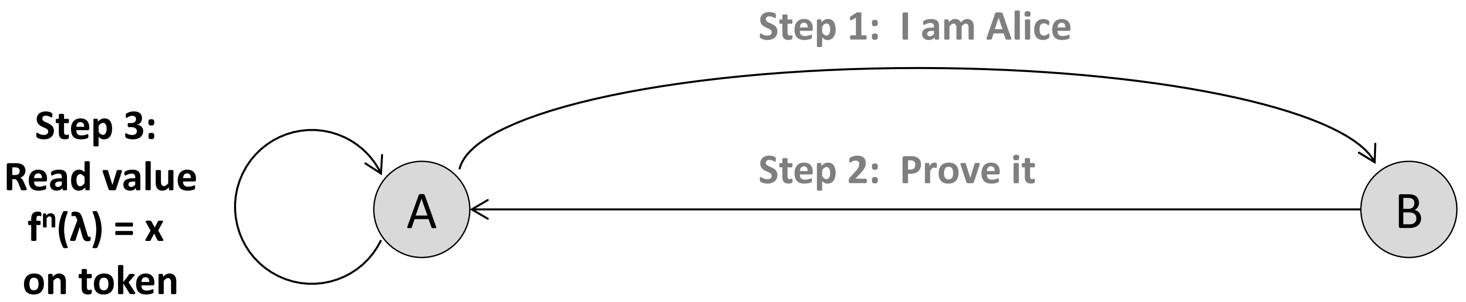
Step 1: I am Alice

Step 2: Prove it

f: integer -> integer
λ: integer seed
$t_0$: initial time
$t_C$: current time
Δt: time interval
$n = (t_C – t_0) / Δt$

| *User* | *Information* |
|---|---|
| **A** | f: integer -> integer<br>λ: integer seed<br>$t_0$: initial time<br>$t_C$: current time<br>Δt: time interval<br>$n = (t_C – t_0) / Δt$ |

# RSA SecurID Protocol



Step 1: I am Alice

Step 2: Prove it

**Step 3: Read value $f^n(\lambda) = x$ on token**

f: integer -> integer

λ: integer seed

$t_0$: initial time

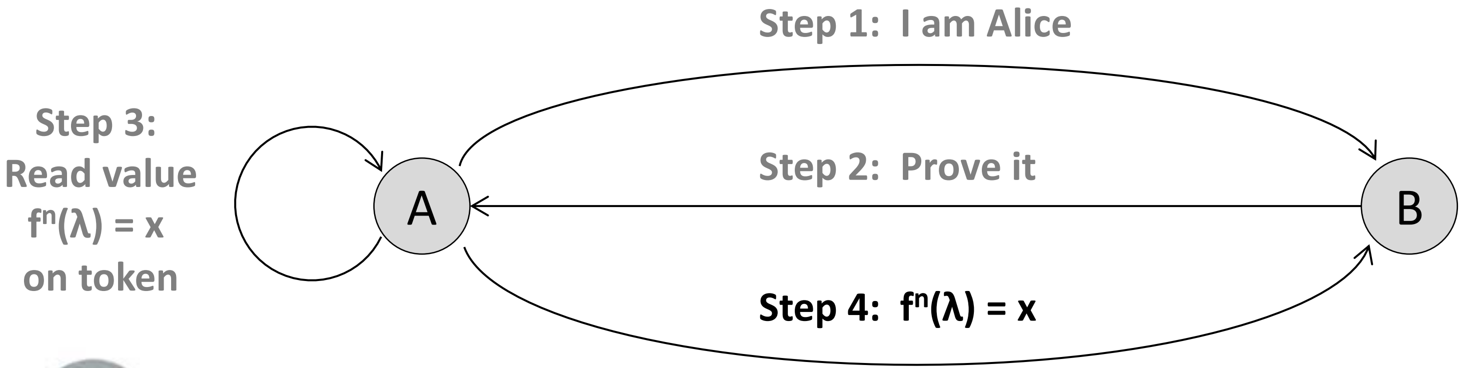
$t_C$: current time

Δt: time interval

$n = (t_C - t_0) / \Delta t$

| *User* | *Information* |
|---|---|
| **A** | f: integer -> integer<br>λ: integer seed<br>$t_0$: initial time<br>$t_C$: current time<br>Δt: time interval<br>$n = (t_C - t_0) / \Delta t$ |

# RSA SecurID Protocol



Step 1: I am Alice

Step 2: Prove it

Step 3: Read value $f^n(\lambda) = x$ on token

**Step 4: $f^n(\lambda) = x$**

f: integer -> integer

λ: integer seed

$t_0$: initial time

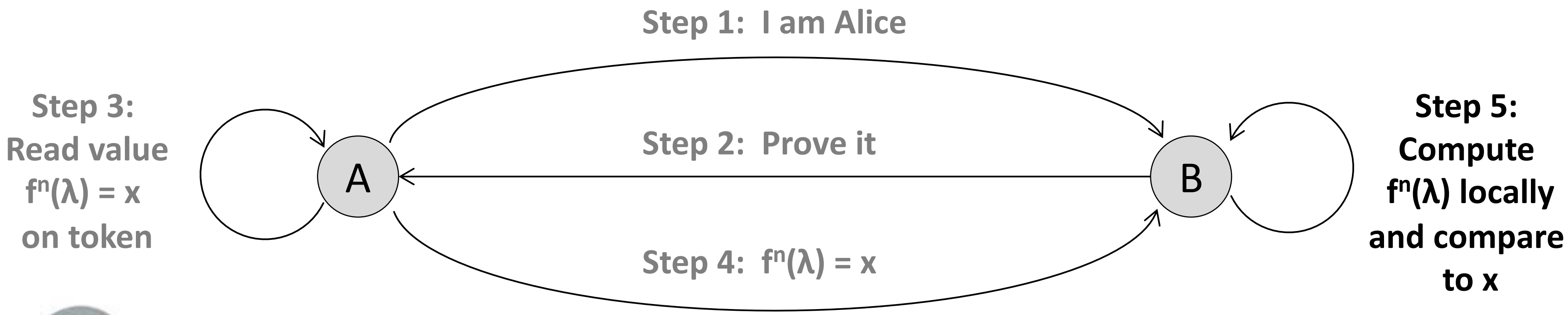
$t_C$: current time

$\Delta t$: time interval

$n = (t_C - t_0) / \Delta t$

| ***User*** | ***Information*** |
|---|---|
| **A** | f: integer -> integer |
| | λ: integer seed |
| | $t_0$: initial time |
| | $t_C$: current time |
| | $\Delta t$: time interval |
| | $n = (t_C - t_0) / \Delta t$ |

# RSA SecurID Protocol



Step 1: I am Alice

Step 2: Prove it

Step 3: Read value $f^n(\lambda) = x$ on token

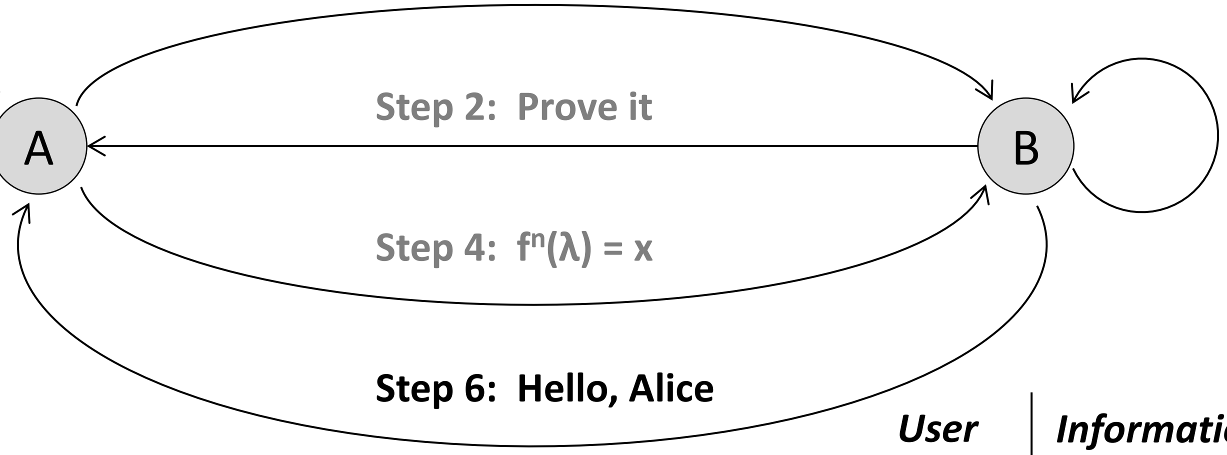
Step 4: $f^n(\lambda) = x$

**Step 5: Compute $f^n(\lambda)$ locally and compare to x**

f: integer -> integer
λ: integer seed
$t_0$: initial time
$t_C$: current time
Δt: time interval
$n = (t_C – t_0) / \Delta t$

| *User* | *Information* |
|---|---|
| **A** | f: integer -> integer<br>λ: integer seed<br>$t_0$: initial time<br>$t_C$: current time<br>Δt: time interval<br>$n = (t_C – t_0) / \Delta t$ |

# RSA SecurID Protocol



Step 1: I am Alice

Step 2: Prove it

Step 3: Read value $f^n(\lambda) = x$ on token

Step 4: $f^n(\lambda) = x$

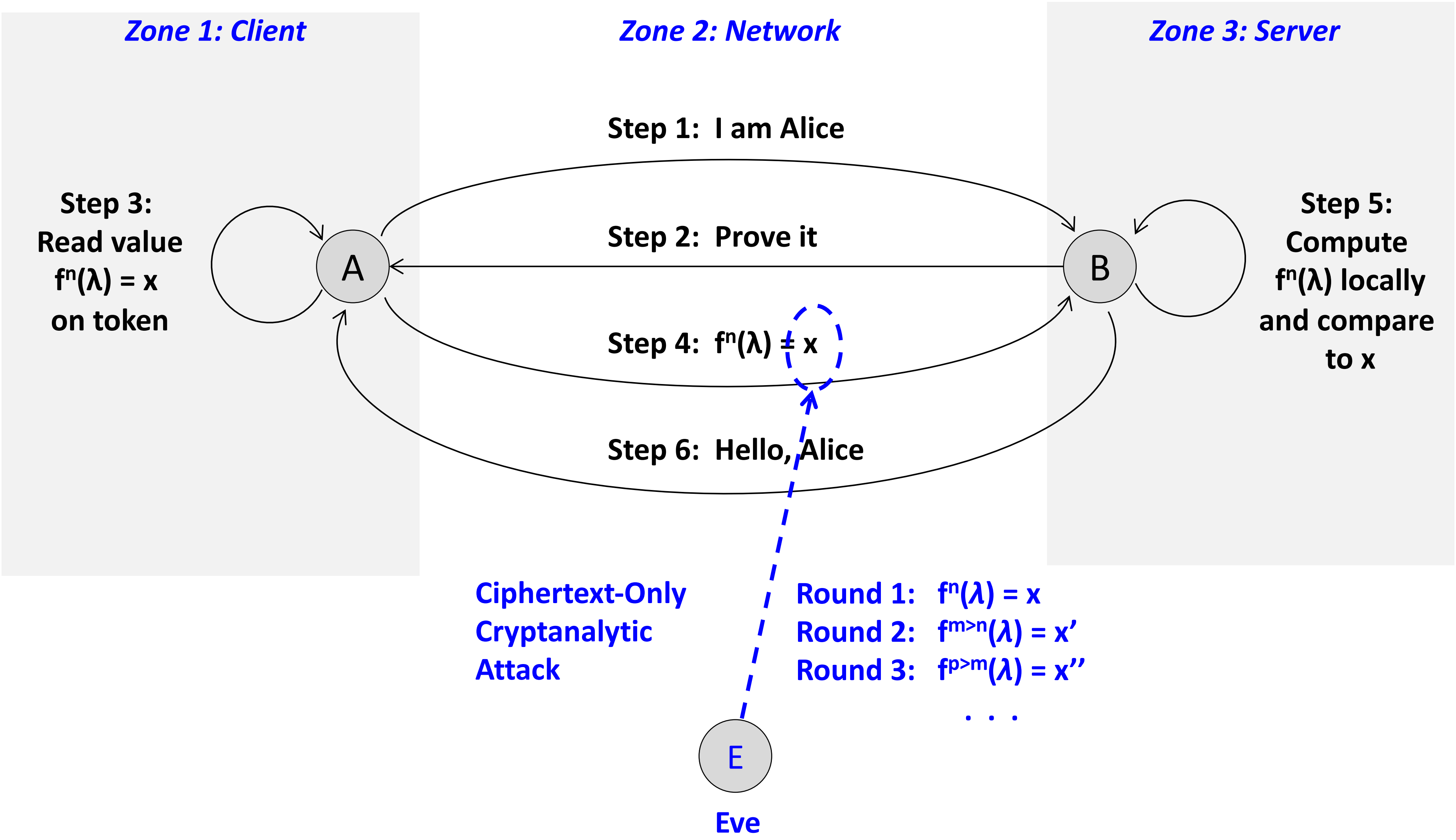
Step 5: Compute $f^n(\lambda)$ locally and compare to x

**Step 6: Hello, Alice**

f: integer -> integer
λ: integer seed
$t_0$: initial time
$t_C$: current time
Δt: time interval
$n = (t_C - t_0) / \Delta t$

| ***User*** | ***Information*** |
|---|---|
| **A** | f: integer -> integer<br>λ: integer seed<br>$t_0$: initial time<br>$t_C$: current time<br>Δt: time interval<br>$n = (t_C - t_0) / \Delta t$ |

# RSA SecurID Protocol



*Zone 1: Client*

*Zone 2: Network*

*Zone 3: Server*

Step 1: I am Alice

Step 2: Prove it

Step 3: Read value $f^{n}(\lambda) = x$ on token

Step 4: $f^{n}(\lambda) = x$

Step 5: Compute $f^{n}(\lambda)$ locally and compare to x

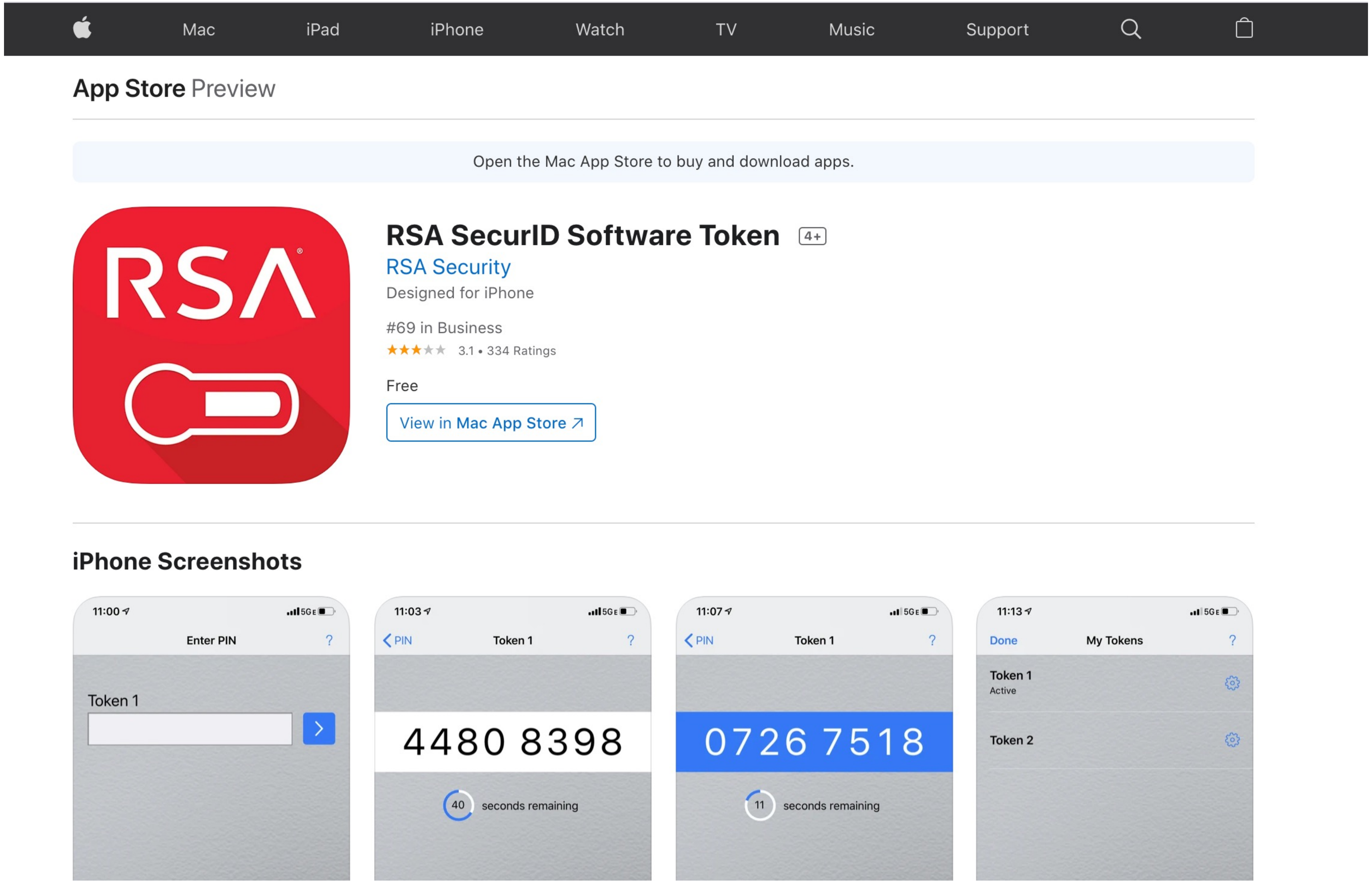
Step 6: Hello, Alice

Ciphertext-Only Cryptanalytic Attack

Round 1: $f^{n}(\lambda) = x$
Round 2: $f^{m>n}(\lambda) = x'$
Round 3: $f^{p>m}(\lambda) = x''$
. . .

Week 5

# RSA SecurID App



App Store Preview

Open the Mac App Store to buy and download apps.

**RSA SecurID Software Token** 4+

RSA Security

Designed for iPhone

#69 in Business

★★★☆☆ 3.1 • 334 Ratings

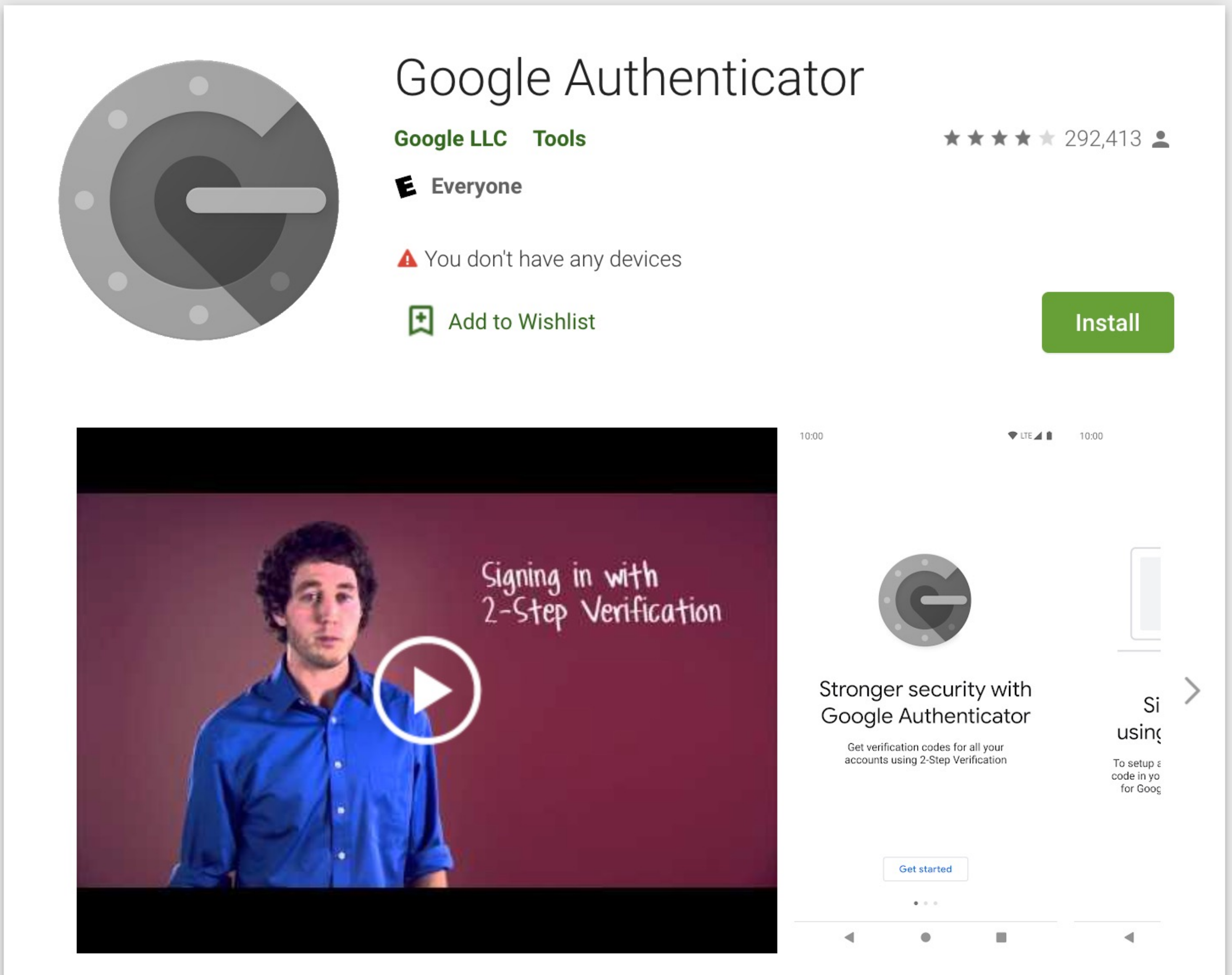
Free

View in Mac App Store ↗

**iPhone Screenshots**

Week 5

# Google Authenticator App



Google Authenticator

Google LLC Tools

★★★★☆ 292,413

Everyone

You don't have any devices

Add to Wishlist

Install

Signing in with
2-Step Verification
10:00
Stronger security with Google Authenticator
Get verification codes for all your accounts using 2-Step Verification
Get started
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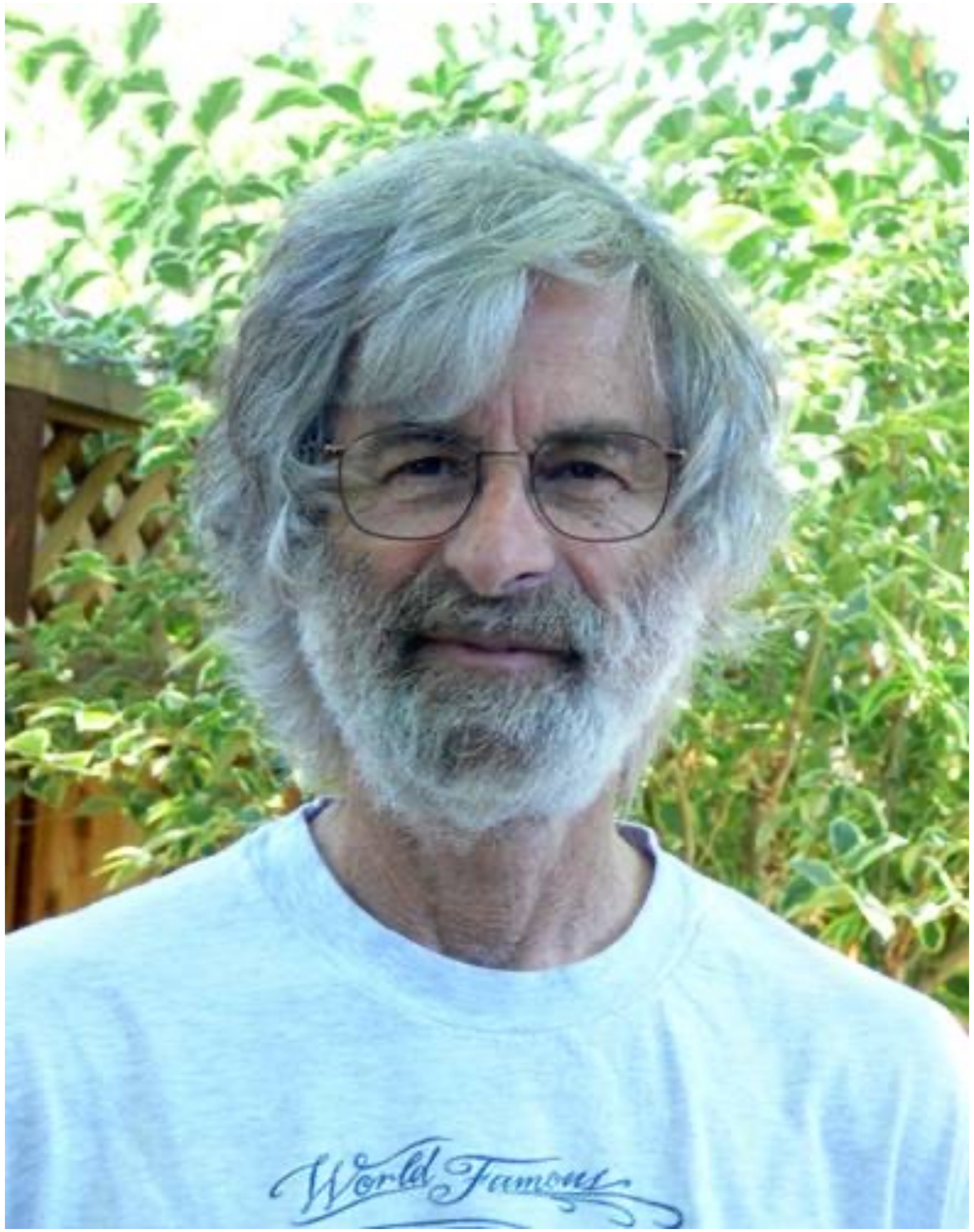
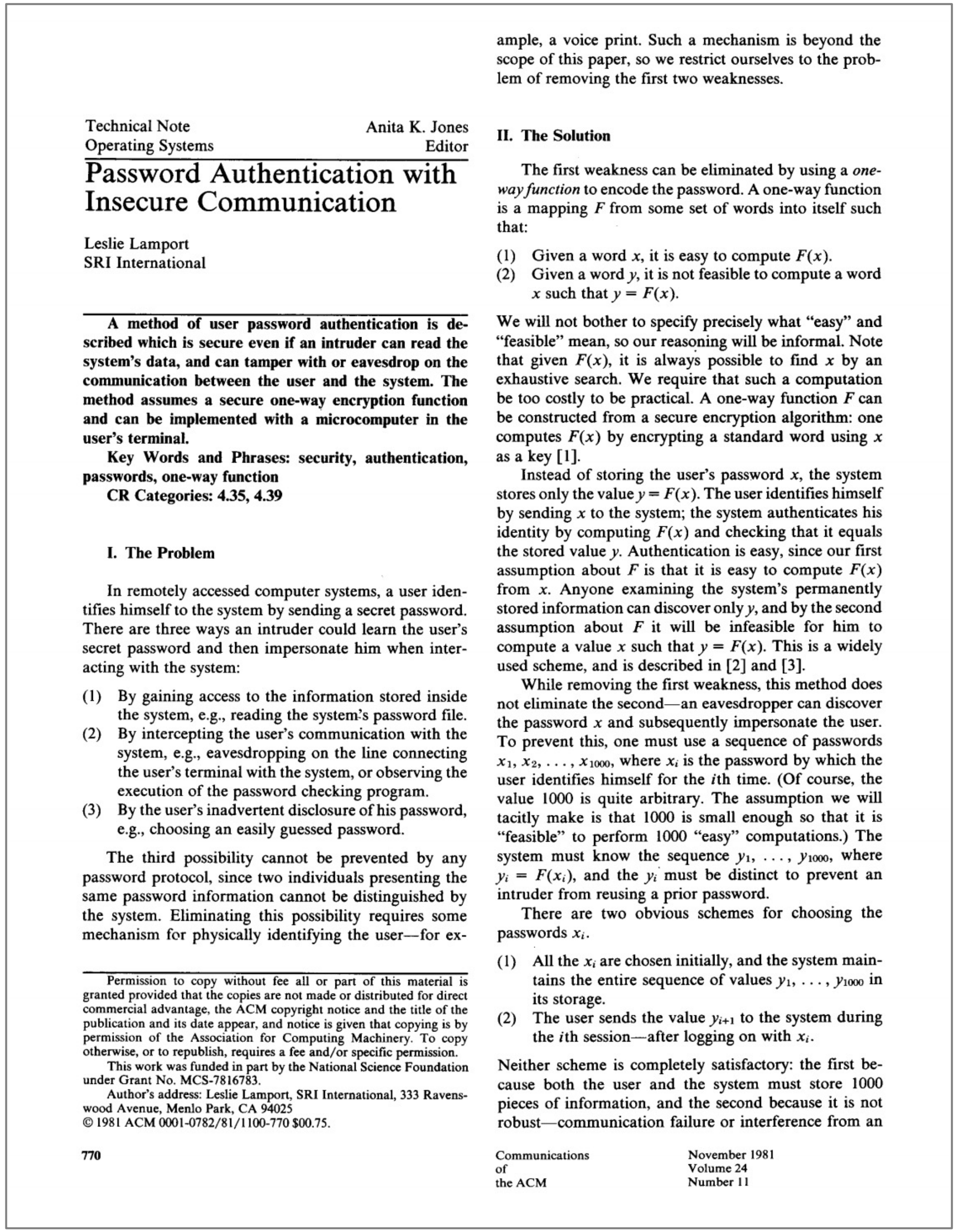
# Are Authentication Protocols with No Challenge Values Always Ciphertext-Only?

Week 5





Technical Note
Operating Systems

Anita K. Jones
Editor

# Password Authentication with Insecure Communication

Leslie Lamport
SRI International

**A method of user password authentication is described which is secure even if an intruder can read the system's data, and can tamper with or eavesdrop on the communication between the user and the system. The method assumes a secure one-way encryption function and can be implemented with a microcomputer in the user's terminal.**

**Key Words and Phrases: security, authentication, passwords, one-way function**

**CR Categories: 4.35, 4.39**

## I. The Problem

In remotely accessed computer systems, a user identifies himself to the system by sending a secret password. There are three ways an intruder could learn the user's secret password and then impersonate him when interacting with the system:

(1) By gaining access to the information stored inside the system, e.g., reading the system's password file.
(2) By intercepting the user's communication with the system, e.g., eavesdropping on the line connecting the user's terminal with the system, or observing the execution of the password checking program.
(3) By the user's inadvertent disclosure of his password, e.g., choosing an easily guessed password.

The third possibility cannot be prevented by any password protocol, since two individuals presenting the same password information cannot be distinguished by the system. Eliminating this possibility requires some mechanism for physically identifying the user—for example, a voice print. Such a mechanism is beyond the scope of this paper, so we restrict ourselves to the problem of removing the first two weaknesses.

## II. The Solution

The first weakness can be eliminated by using a *one-way function* to encode the password. A one-way function is a mapping $F$ from some set of words into itself such that:

(1) Given a word $x$, it is easy to compute $F(x)$.
(2) Given a word $y$, it is not feasible to compute a word $x$ such that $y = F(x)$.

We will not bother to specify precisely what "easy" and "feasible" mean, so our reasoning will be informal. Note that given $F(x)$, it is always possible to find $x$ by an exhaustive search. We require that such a computation be too costly to be practical. A one-way function $F$ can be constructed from a secure encryption algorithm: one computes $F(x)$ by encrypting a standard word using $x$ as a key [1].

Instead of storing the user's password $x$, the system stores only the value $y = F(x)$. The user identifies himself by sending $x$ to the system; the system authenticates his identity by computing $F(x)$ and checking that it equals the stored value $y$. Authentication is easy, since our first assumption about $F$ is that it is easy to compute $F(x)$ from $x$. Anyone examining the system's permanently stored information can discover only $y$, and by the second assumption about $F$ it will be infeasible for him to compute a value $x$ such that $y = F(x)$. This is a widely used scheme, and is described in [2] and [3].

While removing the first weakness, this method does not eliminate the second—an eavesdropper can discover the password $x$ and subsequently impersonate the user. To prevent this, one must use a sequence of passwords $x_1, x_2, \ldots, x_{1000}$, where $x_i$ is the password by which the user identifies himself for the $i$th time. (Of course, the value 1000 is quite arbitrary. The assumption we will tacitly make is that 1000 is small enough so that it is "feasible" to perform 1000 "easy" computations.) The system must know the sequence $y_1, \ldots, y_{1000}$, where $y_i = F(x_i)$, and the $y_i$ must be distinct to prevent an intruder from reusing a prior password.

There are two obvious schemes for choosing the passwords $x_i$.

(1) All the $x_i$ are chosen initially, and the system maintains the entire sequence of values $y_1, \ldots, y_{1000}$ in its storage.
(2) The user sends the value $y_{i+1}$ to the system during the $i$th session—after logging on with $x_i$.

Neither scheme is completely satisfactory: the first because both the user and the system must store 1000 pieces of information, and the second because it is not robust—communication failure or interference from an

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# Lamport S/Key Protocol – Purpose

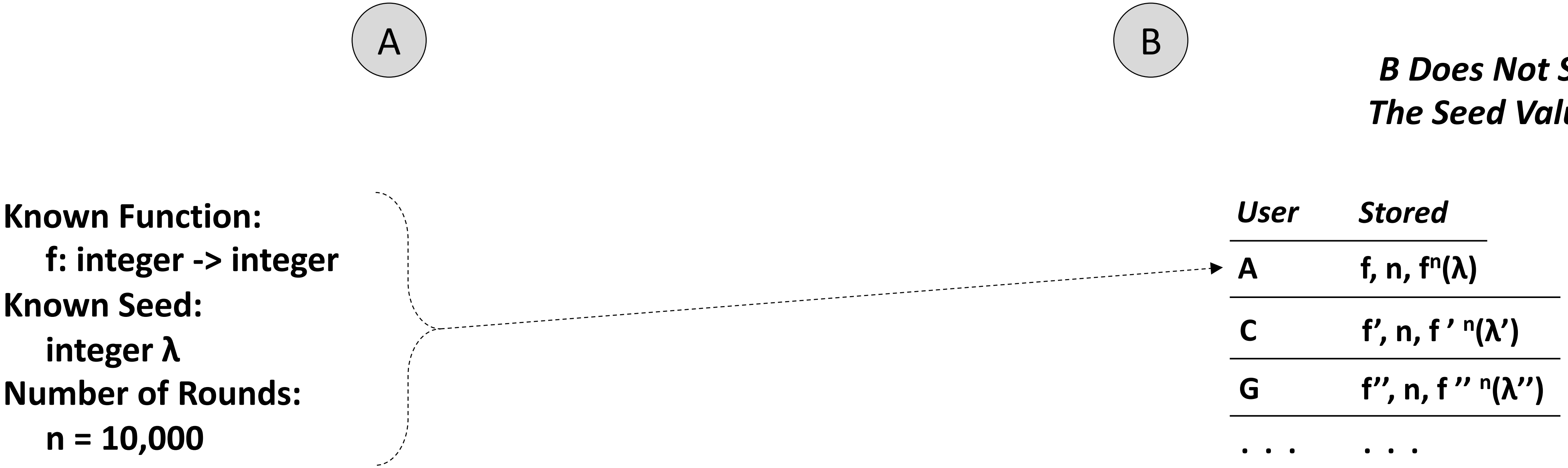
A

B

*A is reporting its identity to B*

*B is attempting to validate A’s reported identity (i.e., authenticating A)*

# Lamport S/Key Protocol – Set-Up

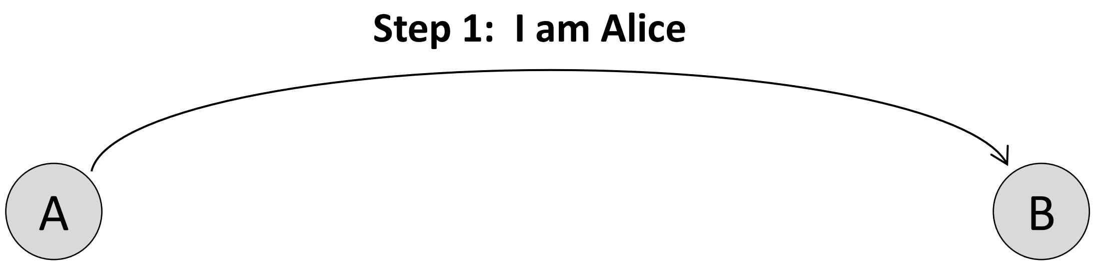


***B Does Not Store The Seed Value (λ)***

**Known Function:**
**f: integer -> integer**
**Known Seed:**
**integer λ**
**Number of Rounds:**
**n = 10,000**

| *User* | *Stored* |
|---|---|
| A | f, n, $f^n(\lambda)$ |
| C | f’, n, $f'^{n}(\lambda')$ |
| G | f’’, n, $f''^{n}(\lambda'')$ |
| . . . | . . . |

# Lamport S/Key Protocol



Step 1: I am Alice

**Known Function:**

**f: integer -> integer**

**Known Seed:**

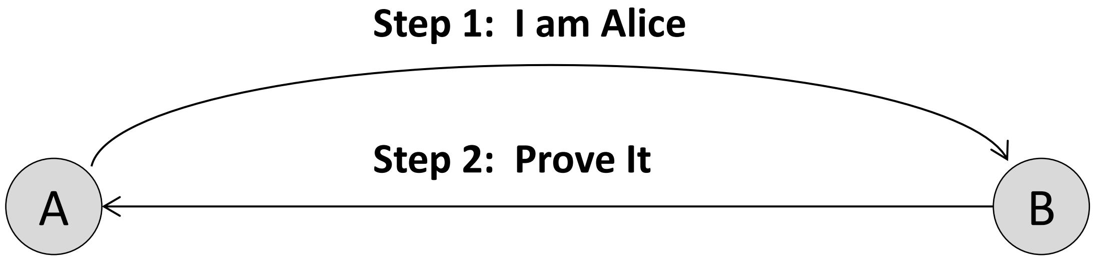
**integer λ**

**Number of Rounds:**

**n = 10,000**

| *User* | *Stored* |
|---|---|
| **A** | **f, n, $f^n(\lambda)$** |

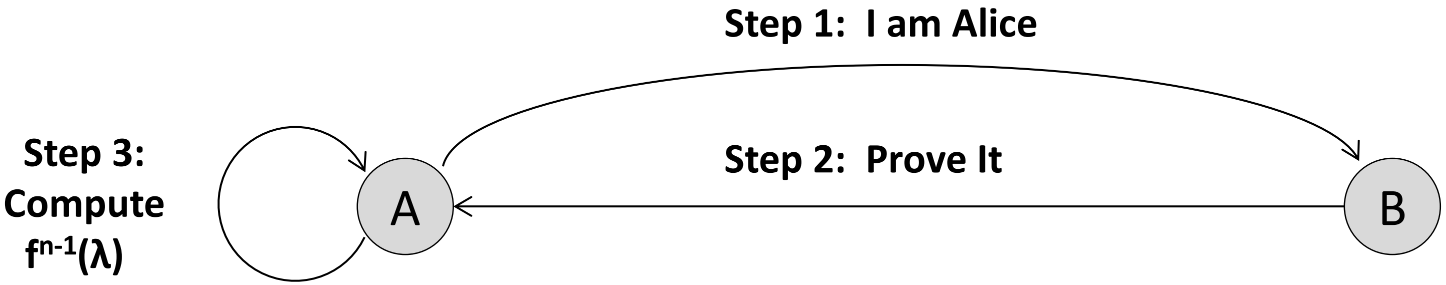
# Lamport S/Key Protocol



**Known Function:**
  **f: integer -> integer**
**Known Seed:**
  **integer λ**
**Number of Rounds:**
  **n = 10,000**

| ***User*** | ***Stored*** |
|---|---|
| **A** | **f, n, $f^n(\lambda)$** |

# Lamport S/Key Protocol



**Known Function:**

**f: integer -> integer**

**Known Seed:**

**integer λ**

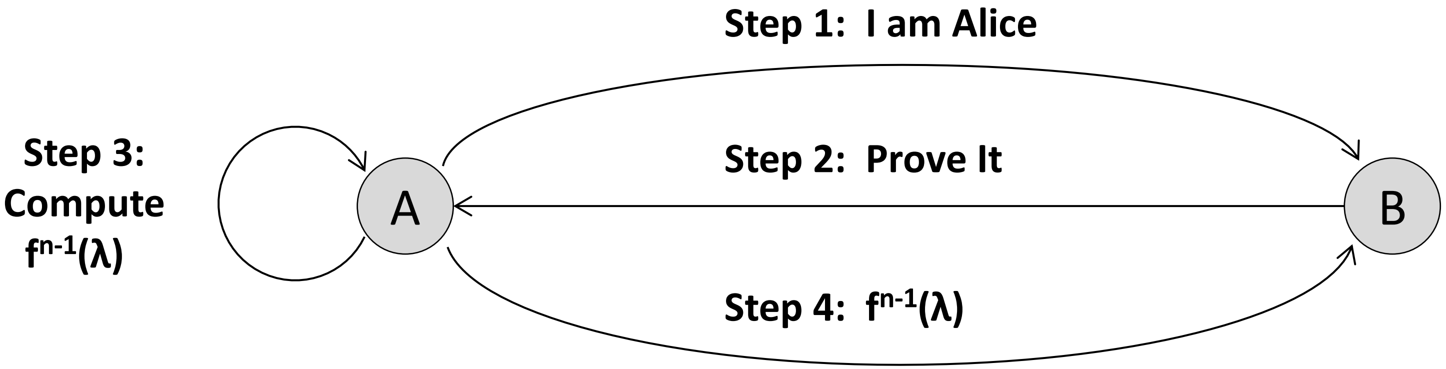
**Number of Rounds:**

**n = 10,000**

| *User* | *Stored* |
|---|---|
| A | f, n, $f^{n}(\lambda)$ |

Week 5

# Lamport S/Key Protocol



Step 1: I am Alice

Step 2: Prove It

Step 3: Compute $f^{n-1}(\lambda)$

Step 4: $f^{n-1}(\lambda)$

**Known Function:**

**f: integer -> integer**

**Known Seed:**

**integer λ**

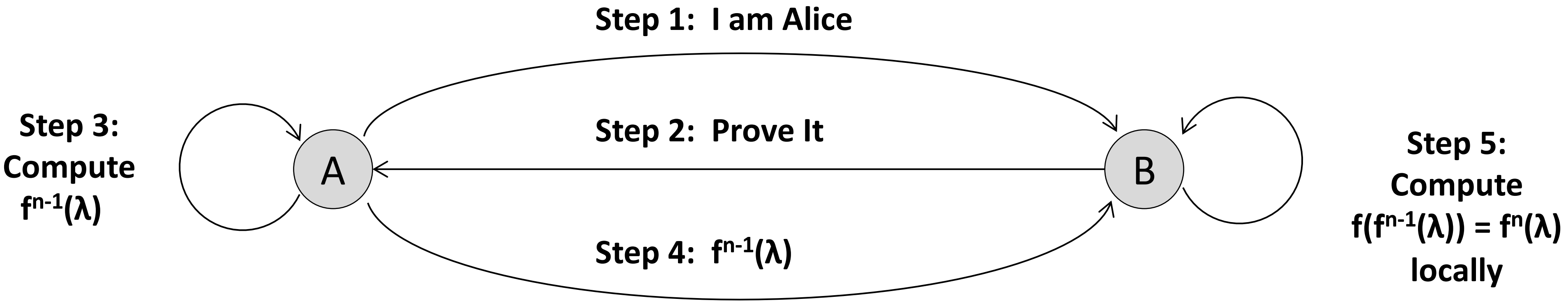
**Number of Rounds:**

**n = 10,000**

| *User* | *Stored* |
|---|---|
| A | f, n, $f^{n}(\lambda)$ |

Week 5

# Lamport S/Key Protocol


Step 1: I am Alice
Step 2: Prove It
Step 3: Compute $f^{n-1}(\lambda)$
A
B
Step 4: $f^{n-1}(\lambda)$
Step 5: Compute $f(f^{n-1}(\lambda)) = f^{n}(\lambda)$ locally

**Known Function:**

**f: integer -> integer**

**Known Seed:**

**integer λ**

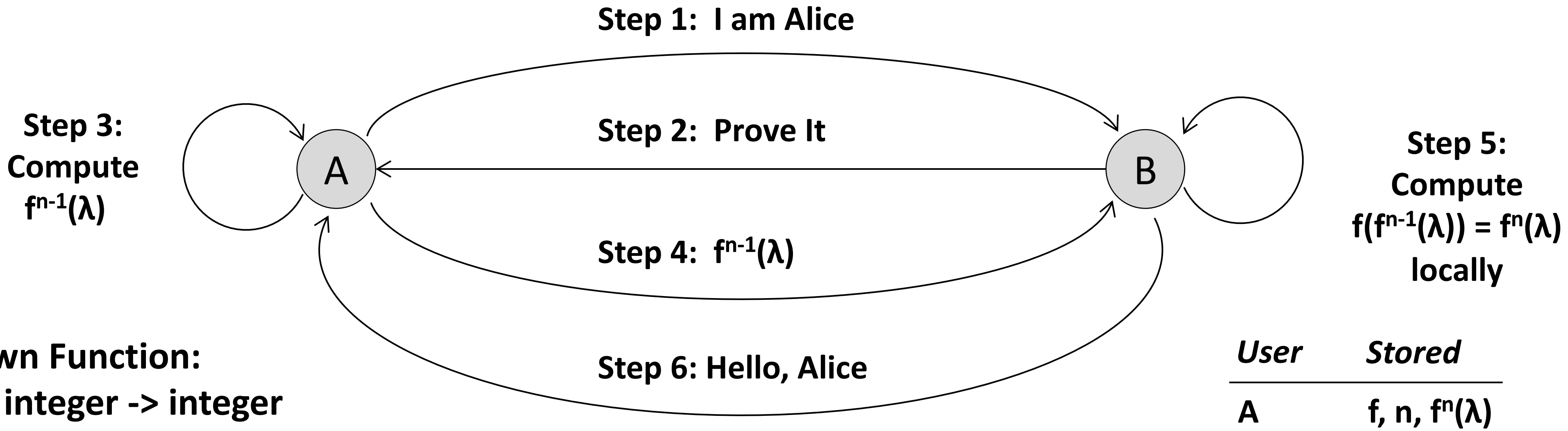
**Number of Rounds:**

**n = 10,000**

| *User* | *Stored* |
|---|---|
| **A** | **f, n, $f^{n}(\lambda)$** |

Week 5

# Lamport S/Key Protocol



Step 1: I am Alice

Step 2: Prove It

Step 3: Compute $f^{n-1}(\lambda)$

Step 4: $f^{n-1}(\lambda)$

Step 5: Compute $f(f^{n-1}(\lambda)) = f^{n}(\lambda)$ locally

Step 6: Hello, Alice

| *User* | *Stored* |
|---|---|
| **A** | **f, n, $f^{n}(\lambda)$** |

**Known Function:**

**f: integer -> integer**

**Known Seed:**

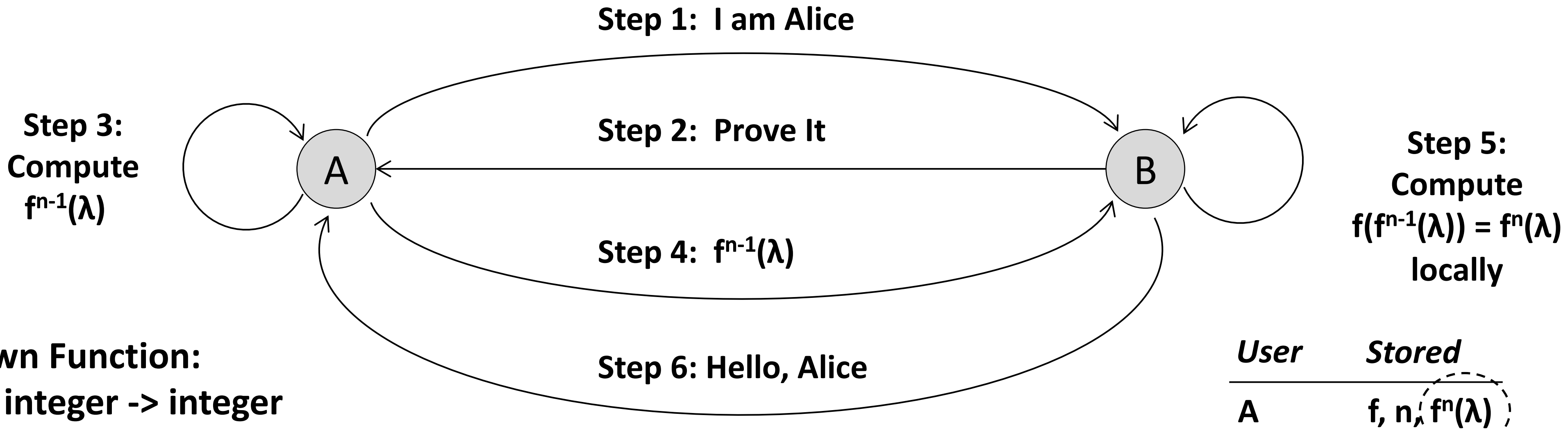
**integer λ**

**Number of Rounds:**

**n = 10,000**

Week 5

# Lamport S/Key Protocol



Step 1: I am Alice

Step 2: Prove It

Step 3: Compute $f^{n-1}(\lambda)$

Step 4: $f^{n-1}(\lambda)$

Step 5: Compute $f(f^{n-1}(\lambda)) = f^n(\lambda)$ locally

Step 6: Hello, Alice

**Known Function:**

**f: integer -> integer**

**Known Seed:**

**integer λ**

**Number of Rounds:**

**n = 10,000**

| *User* | *Stored* |
|---|---|
| A | f, n, $f^n(\lambda)$ |

$f^n(\lambda)$ stored

# Lamport S/Key Protocol

A

B

**Known Function:**

**f: integer -> integer**

**Known Seed:**

**integer λ**

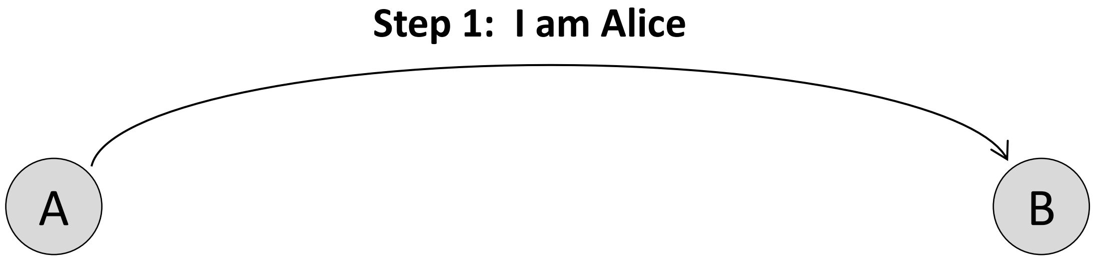
**Number of Rounds:**

**n-1 = 9,999**

**$f^{n-1}(\lambda)$**
**now stored**

| *User* | *Stored* |
|---|---|
| **A** | **f, n, $f^{n-1}(\lambda)$** |

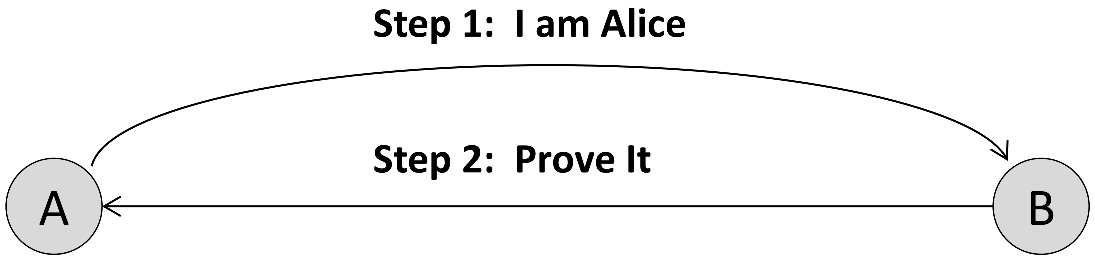
# Lamport S/Key Protocol



**Known Function:**
**f: integer -> integer**
**Known Seed:**
**integer λ**
**Number of Rounds:**
**n-1 = 9,999**

| *User* | *Stored* |
|---|---|
| **A** | **f, n, $f^{n-1}(\lambda)$** |

# Lamport S/Key Protocol



**Known Function:**

**f: integer -> integer**

**Known Seed:**

**integer λ**

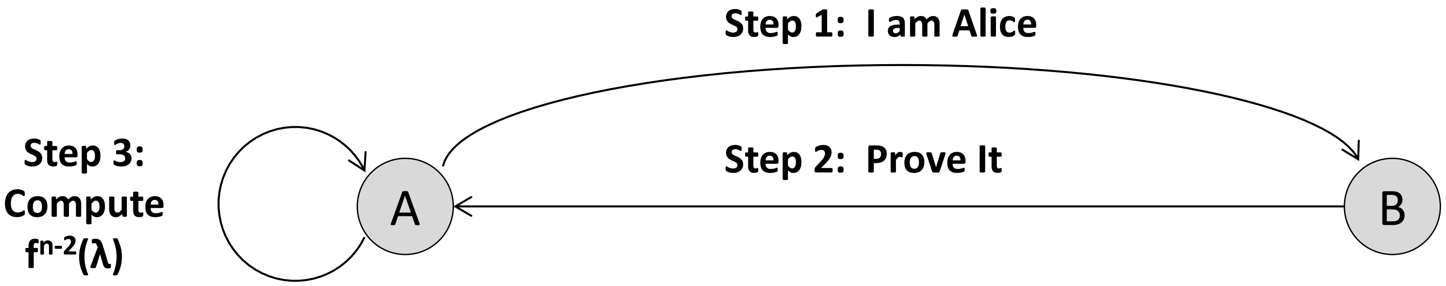
**Number of Rounds:**

**n-1 = 9,999**

| *User* | *Stored* |
|---|---|
| **A** | **f, n, $f^{n-1}(\lambda)$** |

Week 5

# Lamport S/Key Protocol



**Known Function:**

**f: integer -> integer**

**Known Seed:**

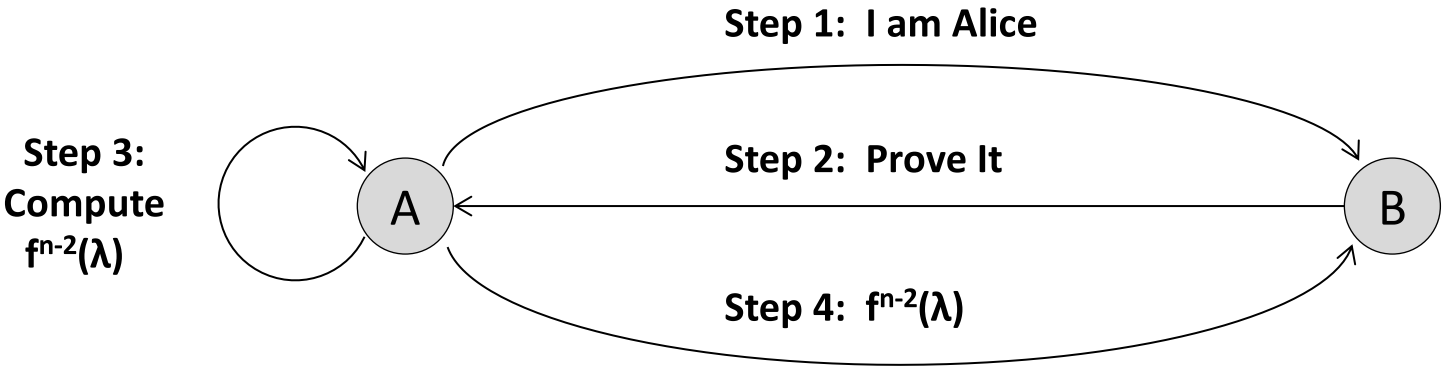
**integer λ**

**Number of Rounds:**

**n-1 = 9,999**

| *User* | *Stored* |
|---|---|
| **A** | **f, n, $f^{n-1}(\lambda)$** |

# Lamport S/Key Protocol



**Step 1: I am Alice**

**Step 2: Prove It**

**Step 3: Compute $f^{n-2}(\lambda)$**

**Step 4: $f^{n-2}(\lambda)$**

**Known Function:**

**f: integer -> integer**

**Known Seed:**

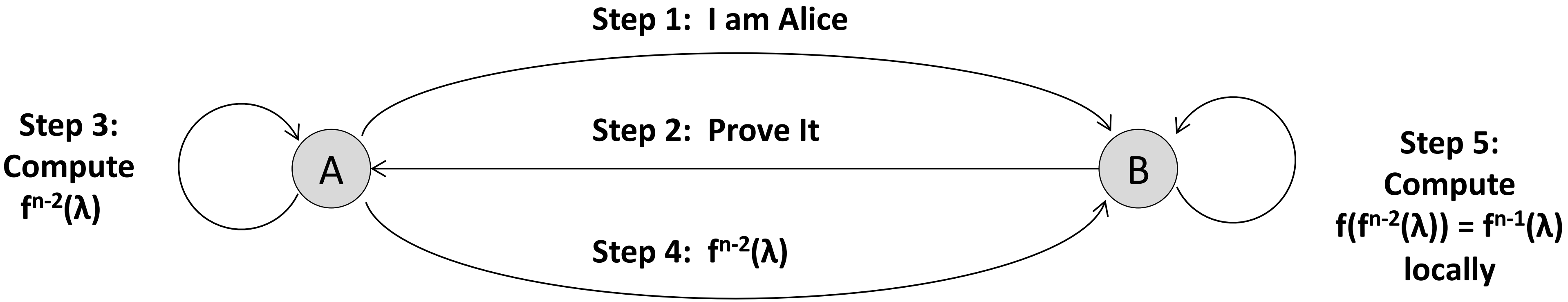
**integer λ**

**Number of Rounds:**

**n-1 = 9,999**

| *User* | *Stored* |
|---|---|
| **A** | **f, n, $f^{n-1}(\lambda)$** |

# Lamport S/Key Protocol



Step 1: I am Alice

Step 2: Prove It

Step 3: Compute $f^{n-2}(\lambda)$

Step 4: $f^{n-2}(\lambda)$

Step 5: Compute $f(f^{n-2}(\lambda)) = f^{n-1}(\lambda)$ locally

**Known Function:**

**f: integer -> integer**

**Known Seed:**

**integer λ**

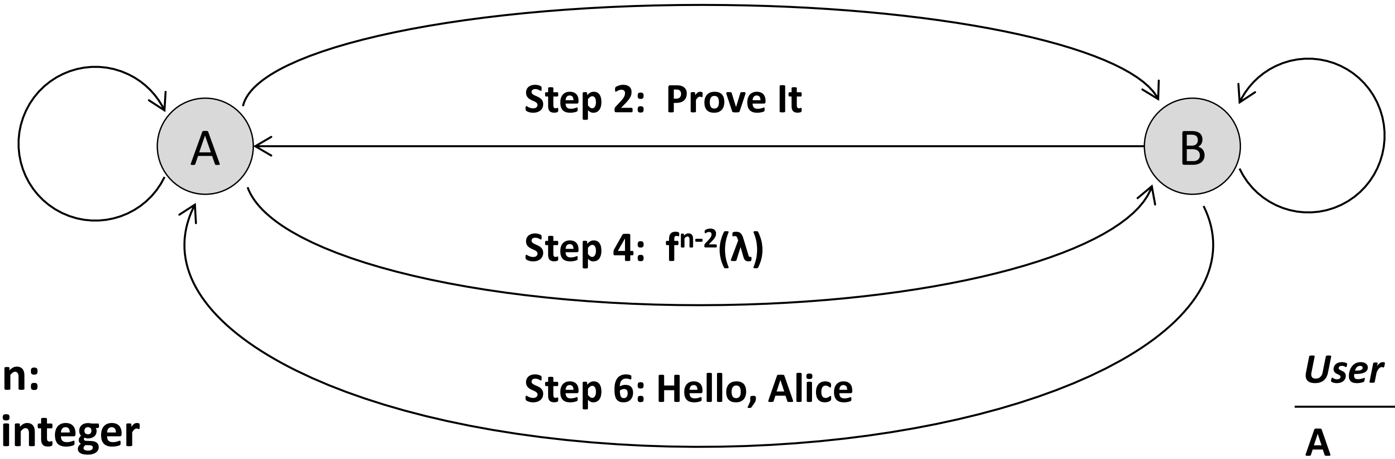
**Number of Rounds:**

**n-1 = 9,999**

| *User* | *Stored* |
|---|---|
| **A** | **f, n, $f^{n-1}(\lambda)$** |

Week 5

# Lamport S/Key Protocol



Step 1: I am Alice

Step 2: Prove It

Step 3: Compute $f^{n-2}(\lambda)$

Step 4: $f^{n-2}(\lambda)$

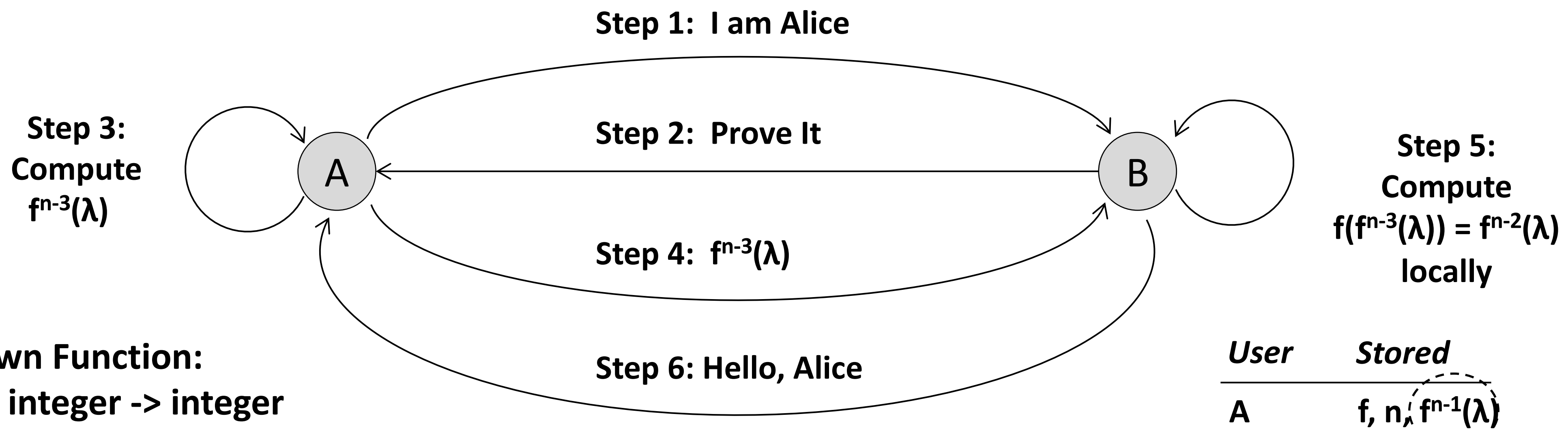
Step 5: Compute $f(f^{n-2}(\lambda)) = f^{n-1}(\lambda)$ locally

Step 6: Hello, Alice

**Known Function:**
**f: integer -> integer**
**Known Seed:**
**integer λ**
**Number of Rounds:**
**n-1 = 9,999**

| *User* | *Stored* |
|---|---|
| A | f, n, $f^{n-1}(\lambda)$ |

# Lamport S/Key Protocol



Step 1: I am Alice

Step 2: Prove It

Step 3: Compute $f^{n-3}(\lambda)$

Step 4: $f^{n-3}(\lambda)$

Step 5: Compute $f(f^{n-3}(\lambda)) = f^{n-2}(\lambda)$ locally

Step 6: Hello, Alice

**Known Function:**

f: integer -> integer

**Known Seed:**

integer λ

**Number of Rounds:**

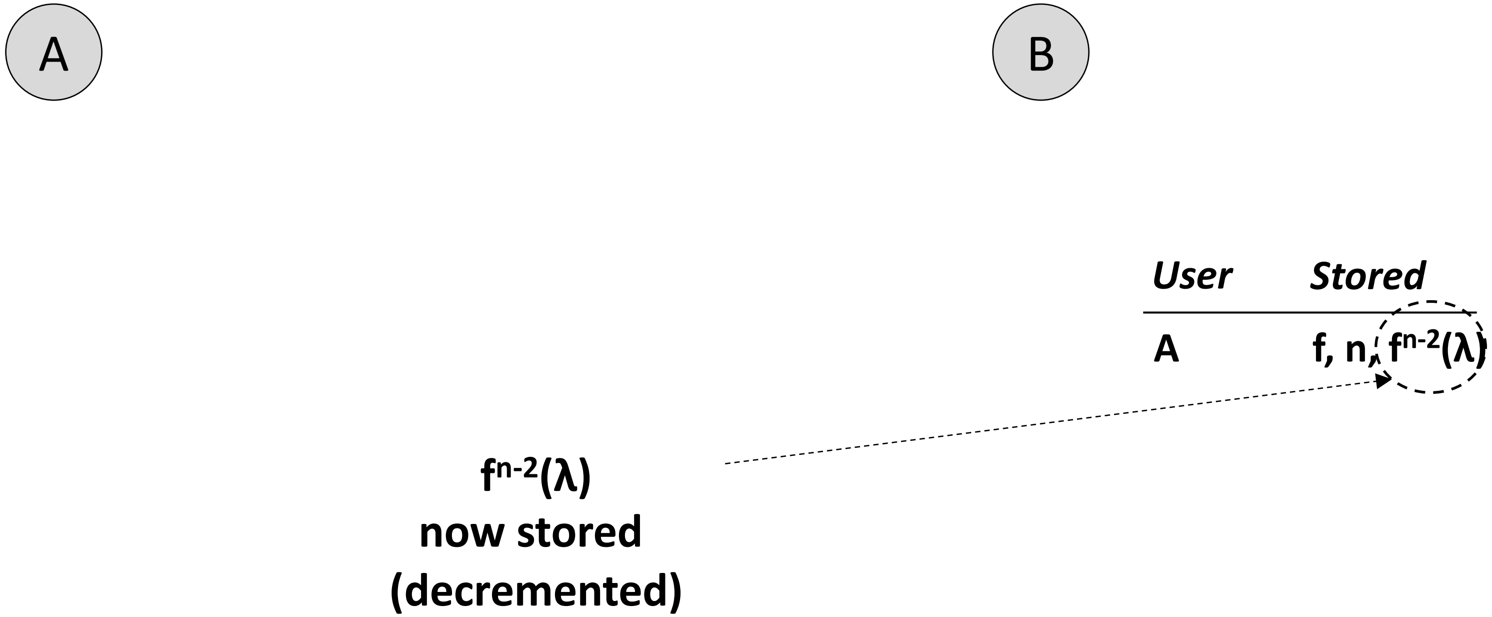
n-1 = 9,998

| *User* | *Stored* |
|---|---|
| A | f, n, $f^{n-1}(\lambda)$ |

$f^{n-1}(\lambda)$ stored

# Lamport S/Key Protocol

**Known Function:**
**f: integer -> integer**
**Known Seed:**
**integer λ**
**Number of Rounds:**
**n-2 = 9,998**



| *User* | *Stored* |
|---|---|
| **A** | **f, n, $f^{n-2}(\lambda)$** |

**$f^{n-2}(\lambda)$**
**now stored**
**(decremented)**

# Lamport S/Key Protocol – Analysis

| | Input | Output |
|---|---|---|
| Round 1 | - | $f^n(\lambda)$ |

Week 5

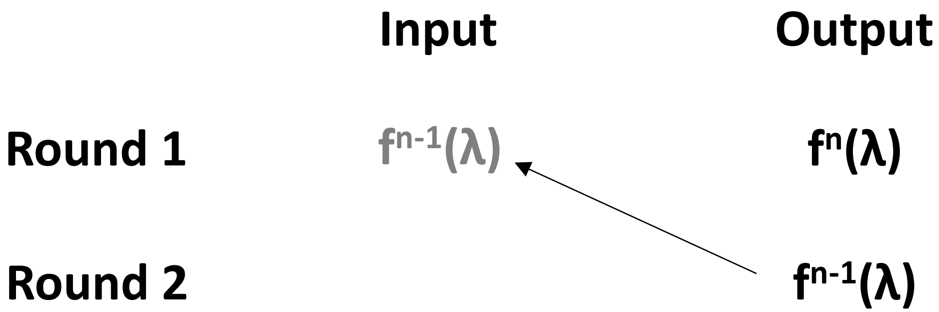
# Lamport S/Key Protocol – Analysis

| | Input | Output |
|---|---|---|
| Round 1 | - | $f^n(\lambda)$ |
| Round 2 | | $f^{n-1}(\lambda)$ |

Note:
$f(f^{n-1}(\lambda)) = f^n(\lambda)$

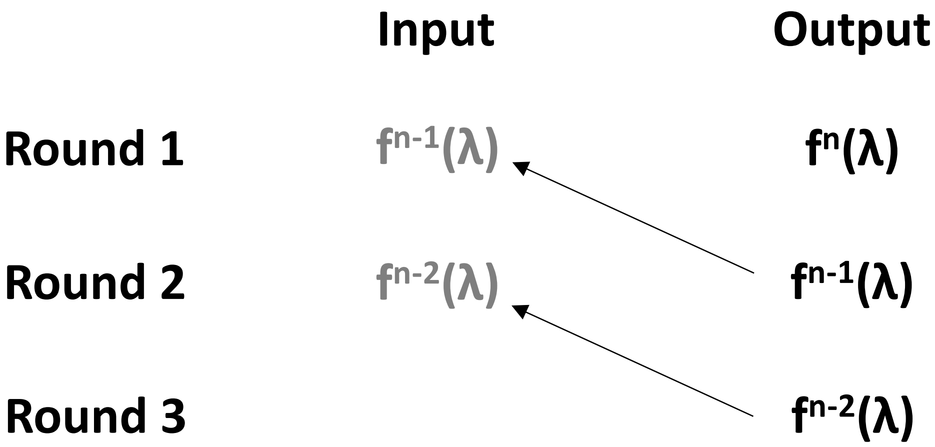
Week 5

# Lamport S/Key Protocol – Analysis



|  | Input | Output |
|---|---|---|
| Round 1 | $f^{n-1}(\lambda)$ | $f^{n}(\lambda)$ |
| Round 2 |  | $f^{n-1}(\lambda)$ |

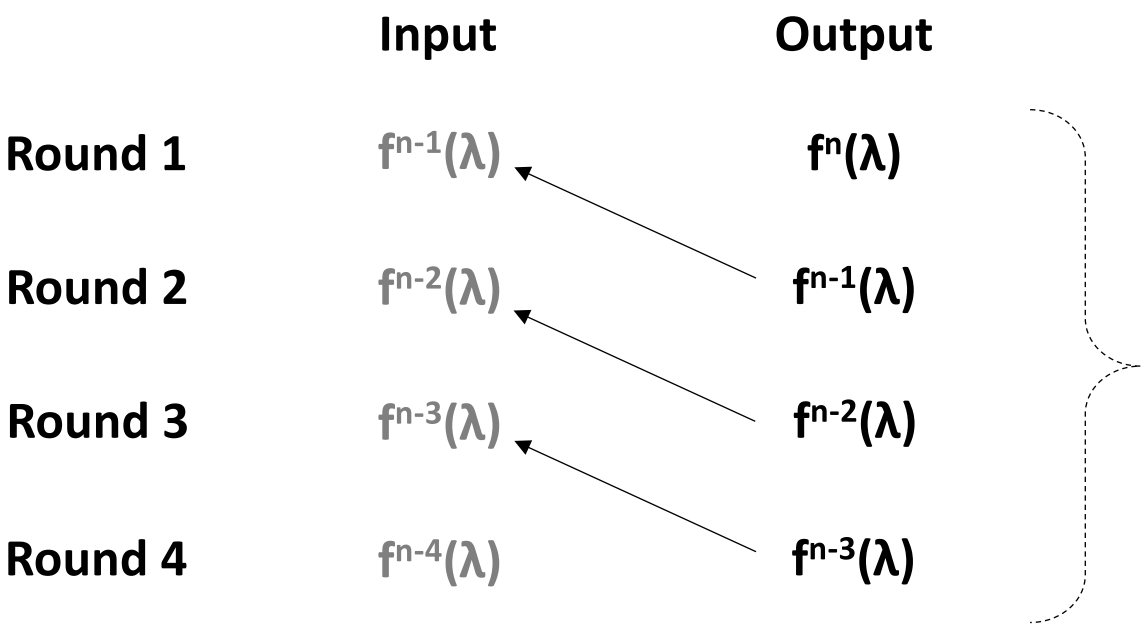
# Lamport S/Key Protocol – Analysis



| | Input | Output |
|---|---|---|
| Round 1 | $f^{n-1}(\lambda)$ | $f^{n}(\lambda)$ |
| Round 2 | $f^{n-2}(\lambda)$ | $f^{n-1}(\lambda)$ |
| Round 3 | | $f^{n-2}(\lambda)$ |

Week 5

# Lamport S/Key Protocol – Analysis

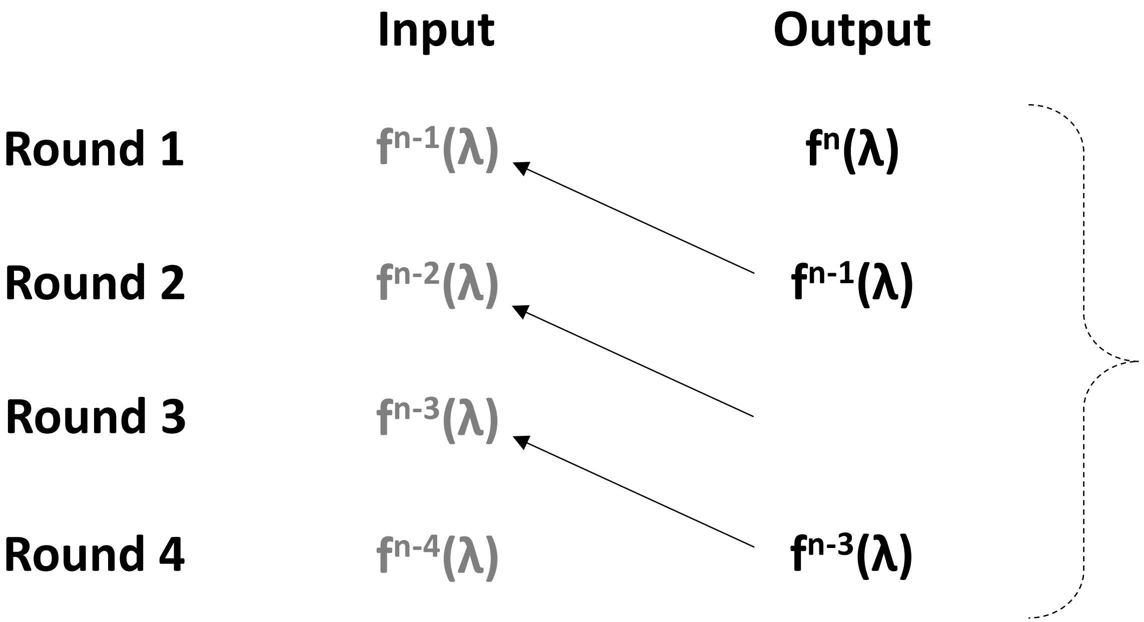


|  | Input | Output |
|---|---|---|
| Round 1 | $f^{n-1}(\lambda)$ | $f^{n}(\lambda)$ |
| Round 2 | $f^{n-2}(\lambda)$ | $f^{n-1}(\lambda)$ |
| Round 3 | $f^{n-3}(\lambda)$ | $f^{n-2}(\lambda)$ |
| Round 4 | $f^{n-4}(\lambda)$ | $f^{n-3}(\lambda)$ |

By waiting for successive rounds, observer Eve can see the plaintext for the previous round

# Lamport S/Key Protocol – Analysis

$f^{n-2}(\lambda)$



| | Input | Output |
|---|---|---|
| Round 1 | $f^{n-1}(\lambda)$ | $f^{n}(\lambda)$ |
| Round 2 | $f^{n-2}(\lambda)$ | $f^{n-1}(\lambda)$ |
| Round 3 | $f^{n-3}(\lambda)$ | |
| Round 4 | $f^{n-4}(\lambda)$ | $f^{n-3}(\lambda)$ |

By waiting for successive rounds, observer Eve can see the plaintext for the previous round

**Implies *Known Plaintext* Cryptanalysis**