Secure Software Design and Engineering
(CY-321)

Authentication Protocols

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Challenge-Response

Alice → Bob : "Hi, I' m Alice."

Bob → Alice : "Hi Alice, please encrypt 0x67f810a762df5e."

Alice → Bob : $\{0x67f810a762df5e\}_k$

Or, more formally,

Alice → Bob : Alice

Bob → Alice : R where R is a random challenge.

Alice → Bob : $\{R\}_k$

Problems with C-R

Its one-sided: Bob knows about Alice, but not vice versa.

Somehow Bob needs to maintain a database of secrets and keep it secure. In practice, thats **bloody** difficult.

Trudy could hijack the connection after the initial exchange.

If K is derived from a password (that only Alice needs to know), then Eve could mount an offline password-guessing attack.

Variation 1

Alice → Bob : Alice

Alice identifies herself.
Bob now knows who she claims to be.

Bob → Alice : $\{R\}_k$

Bob encrypts a random value **R** using the **shared secret key K** associated with Alice.
He sends the **ciphertext** $\{R\}_k$ to Alice.

This requires **reversible encryption** (i.e., symmetric encryption like AES), because Alice will need to decrypt it.

Alice → Bob : R,

Alice decrypts $\{R\}_k$ using K to get R.
She sends R back to Bob in **plaintext** to prove she knows the key.

where R is a random challenge.

Variation 1

$$\text{Alice} \longrightarrow \text{Bob} : \text{Alice}$$
$$\text{Bob} \longrightarrow \text{Alice} : \{R\}_k$$
$$\text{Alice} \longrightarrow \text{Bob} : \text{R},$$

where R is a random challenge.

- Requires reversible cryptography.

- If K is derived from password, and if R is distinguishable from random bits, Eve can mount a password-guessing attack without snooping, by initiating the protocol as Alice

- Authentication is mutual if R is a recognizable quantity with a limited lifetime.

Variation 1

$$\text{Alice} \longrightarrow \text{Bob} : \text{Alice}, \{t\}_k$$

where t is a timestamp.

Where:

- t is the **current timestamp**
- $\{t\}_k$ is the timestamp **encrypted** with a shared secret key K (symmetric encryption)
- Bob knows K (pre-shared secret) and decrypts $\{t\}_k$ to check if the timestamp is valid and recent

Variation 1

$$\text{Alice} \longrightarrow \text{Bob} : \text{Alice}, \{t\}_k$$

where t is a timestamp.

Alice claims her identity and proves knowledge of the shared key K by encrypting a fresh timestamp.

Bob decrypts the message using the shared K and verifies:

1. The decryption worked (so Alice must know K)
2. The timestamp t is **within an acceptable time window**

Variation 1

$$\text{Alice} \longrightarrow \text{Bob} : \text{Alice}, \{t\}_k$$

where t is a timestamp.

- One-sided (Bob authenticates Alice, not vice versa).

- Requires clocks to be reasonably synchronized.

- When using the same secret K for multiple servers, Eve can impersonate Alice at the other servers (if she's fast enough).

- Replay possible if Eve can cause Bob's clock to be turned back.

- Time setting and login are now coupled.

Mutual Authentication

$$\text{Alice} \rightarrow \text{Bob} : \text{Alice}$$

Alice claims her identity.

$$\text{Bob} \rightarrow \text{Alice} : R1$$

Bob sends a **random challenge** R1 to Alice.
Bos
Goal: make Alice prove she knows the shared secret key K

$$\text{Alice} \rightarrow \text{Bob} : \{R1\}_k, R2$$

Alice **encrypts R1** using K to prove her identity.
She also generates her own challenge R2 and sends it in plaintext.
Purpose of R2: now **Bob has to prove he knows K** by correctly handling Alice' s challenge.

$$\text{Bob} \rightarrow \text{Alice} : \{R2\}_k$$

Bob **encrypts Alice challenge R2** using the shared key K.
Alice decrypts it to verify that Bob indeed knows K.

Mutual Authentication "Optimized"

We attempt to optimize this protocol:

$$\text{Alice} \rightarrow \text{Bob} : \text{Alice}, \text{R2}$$

$$\text{Bob} \rightarrow \text{Alice} : \{\text{R1}\}_k, R1$$

$$\text{Alice} \rightarrow \text{Bob} : \{\text{R1}\}_k$$

We eliminated 25% of all messages. Not bad!

Whats wrong with this protocol?

Reflection Attack

Trudy → Bob : Alice, R2

Trudy pretends to be Alice and sends a fake challenge R2R2R2 to Bob.
Bob thinks he's talking to the real Alice

Bob → Trudy : $\{R2\}_k, R1$

Bob responds as usual:

- He proves he knows K by encrypting R2
- He issues his own challenge R1R1R1 for "Alice" (really Trudy) to answer.

Trudy → Bob : Alice, R1

Now here's the trick: Trudy opens **a second session** with Bob!
This time, she replays Bob earlier challenge R1 as if *she* generated it, pretending again to be Alice.

Reflection Attack

$$\text{Bob} \rightarrow \text{Trudy}: \ \{R1\}_k, R3$$

$$\text{Trudy} \rightarrow \text{Bob}: \ \{R1\}_k$$

Bob again responds:

- Encrypts R1 using K — this is what Trudy wanted!
- Sends a new challenge R3R3R3 (not relevant here).

Result: Bob is fooled!

Bob:
Sent Trudy a challenge R1 in step 2

Received {R1}K in step 5

Believes this must be **Alice**, since only someone who knows K could produce {R1}K
But it was Bob himself who generated {R1}K — **Trudy just reflected it back** to him!

Rules

- Dont use the same key K for Alice and Bob. Instead, use K + 1, $K \oplus 0x0F0F0F0F$, $\neg K$, or something like this

- Different challenges. Either remember past challenges and decline to encrypt known challenges, or insist that the challenges must be different for Alice and Bob (see exercises).

- Let the initiator of a protocol be the first to prove his identity.

Authentication With Public Key

$\text{Alice} \rightarrow \text{Bob} : \text{Alice}$

Alice initiates contact and says, "Hi, I’ m Alice."

$\text{Bob} \rightarrow \text{Alice} : R$

Bob responds with a **random nonce** RRR, which acts as a challenge.
His goal: ensure the responder is really Alice (not someone pretending to be her).

$\text{Alice} \rightarrow \text{Bob} : \{R\}_{Alice}$

Alice signs the random challenge RRR with her **key**.
She sends the **digital signature** [R]Alice back to Bob.

Authentication With Public Key

$Alice \rightarrow Bob : Alice$

$Bob \rightarrow Alice : R$

$Alice \rightarrow Bob : \{R\}_{Alice}$

What happens on Bob end?

Bob knows Alice **public key**. He:

- Uses it to verify the signature [R]Alice.
- If the signature is valid, he knows:
  - The responder is **in possession of Alice private key**
  - So this must be **Alice**.

Authentication achieved!

Authentication With Public Key

$$\text{Alice} \rightarrow \text{Bob} : \text{Alice}$$

$$\text{Bob} \rightarrow \text{Alice} : R$$

$$\text{Alice} \rightarrow \text{Bob} : \{R\}_{Alice}$$

Why this works

Digital signatures are like handwritten signatures but cryptographically secure:

- Only Alice can create [R]Alice because only she knows her **private key**.
- But **anyone** (including Bob) can verify the signature using Alice’ s **public key**.

So if Bob verifies the signature on R, he knows Alice must have signed it.

Authentication With Public Key

$$\text{Alice} \longrightarrow \text{Bob} : \text{Alice}$$

$$\text{Bob} \longrightarrow \text{Alice} : \text{R}$$

$$\text{Alice} \longrightarrow \text{Bob} : \{\text{R}\}_{Alice}$$

- Bobs database doesnt contain secrets anymore ⇒ need not be protected against theft

. • Database must still be protected against modification

Variation and Criticism

$$\text{Alice} \rightarrow \text{Bob} : \text{Alice}$$

$$\text{Bob} \rightarrow \text{Alice} : \text{R}$$

$$\text{Alice} \rightarrow \text{Bob} : \{\text{R}\}_{Alice}$$

- Needs encryption in addition to signature.
- Both protocols have the flaw that if Eve can impersonate Bob, she can get arbitrary values signed (or encrypted).
- This is a serious flaw if the Alice key pair is used for things other than authentication (e.g., for signing bank transfers).

Criticism

This problem can be solved if we stipulate that

- keys are never reused for different applications; or

- the system is coordinated that it’ s not possible to use one protocol to break another (for example by formatting the R values differently for different applications).

Also note what this means:

By combining two protocols that are secure in themselves, you get a system that is not secure at all; and you can design protocols whose deployment threatens the security of a system that is already in place!

For people who like to sound clever, we can also say that security isnt closed under composition.

Mediated Authentication

Mediated authentication happened when Alice first asks a trusted intermediary, Trent, to introduce her to Bob.

Because Trent is trusted by both Alice and Bob, authentication is mutual.

Does not need public key!

$$\text{Alice} \rightarrow \text{Trent : Alice wants Bob}$$

$$\text{Trent : Invents } \{K\}_{AB}$$

$$\text{Trent} \rightarrow \text{Alice : } \{\text{Use } \{K\}_{AB} \text{ for Bob}\}_{Alice}$$

$$\text{Trent} \rightarrow \text{Bob : } \{\text{Use } \{K\}_{AB} \text{ for Alice}\}_{Bob}$$

Needham-Schroeder

- Its a classic mediated authentication protocol with mutual authentication.

- Its been a model for many other protocols.

- Its used in Kerberos and Kerberos is used in Active Directory ⇒ huge installed base.

- We ll analyze this protocol in some detail in order to understand its strengths and weaknesses.

Needham-Schroeder

Alice $\rightarrow$ Trent : N_1, Alice wants Bob

Trent : Invents K_{AB}

Trent $\rightarrow$ Alice : $\{N_1$, Bob, K_{AB} , $\{K_{AB}$, Alice$\}_{\text{Bob}}$ $\}_{\text{Alice}}$

Alice : Verifies N_1, extracts K_{AB} and ticket

Alice $\rightarrow$ Bob : $\{K_{AB}$, Alice$\}_{\text{Bob}}$, $\{N_2\}AB$

Bob : Extracts K_{AB} from ticket

Bob $\rightarrow$ Alice : $\{N_2 - 1$, $N_3\}$AB

Alice $\rightarrow$ Bob : $\{N_3 - 1\}$AB

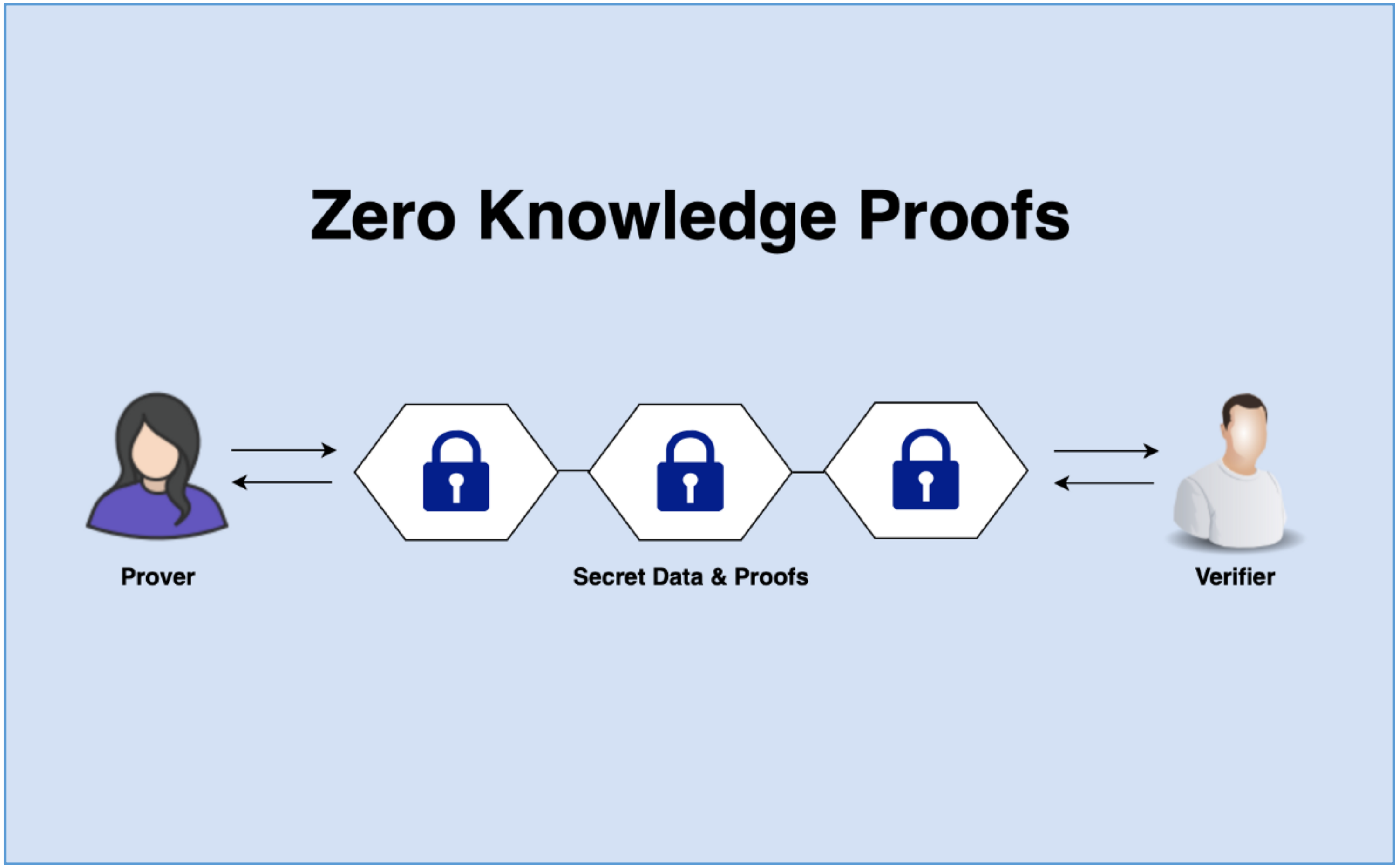
where $\{K_{AB}$, Alice$\}_{\text{Bob}}$ is Trent ticket for Alice conversation with Bob and the Ni are nonces, i.e., quantities used only once.

Zero-Knowledge Proofs (ZKPs)

Think of a magic door that opens only with the correct password. You want to prove you know the password without telling anyone the password.

Zero-Knowledge Proofs (ZKPs) are cryptographic protocols that allow one party (the **prover**) to prove to another party (the **verifier**) that they know a value (or that a statement is true), **without revealing any information** about the value itself.

Zero-Knowledge Proofs (ZKPs)



Zero-Knowledge Proofs (ZKPs)

```
from random import randint
from sympy import isprime, mod_inverse

# Setup
p = 23                  # a small prime number
g = 5                   # a generator of the group
x = 6                   # secret known only to prover
h = pow(g, x, p)        # public key
```

Zero-Knowledge Proofs (ZKPs)

```
# === Prover Step 1: Commit ===
r = randint(1, p-2)            # random nonce
t = pow(g, r, p)               # commitment
print(f"Prover sends t={t} to verifier")
```

Zero-Knowledge Proofs (ZKPs)

```
# === Verifier Step 2: Challenge ===
c = randint(1, p-2)          # random challenge
print(f"Verifier sends challenge c={c}")
```

Zero-Knowledge Proofs (ZKPs)

```
# === Prover Step 3: Response ===
s = (r + c * x) % (p - 1)
print(f"Prover sends response s={s}")
```

Zero-Knowledge Proofs (ZKPs)

```
# === Verifier Step 4: Verify ===
left = pow(g, s, p)
right = (t * pow(h, c, p)) % p
print(f"Verifier checks: g^s mod p =? t * h^c mod p")
print(f"{left} =? {right}")

if left == right:
    print("Verifier accepts the proof.")
else:
    print(" Verifier rejects the proof.")
```

Questions??

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