TLS 1.3 and authenticated key-exchange protocols on the Internet typically provide <u>one-sided</u> authentication (i.e., client learns id of the server, but not vice versa)

<u>Question</u>: how does the client authenticate to the server (<u>without</u> providing a certificate)
↳ e.g., how does client login to a web service?

<u>Typical setting</u>: client and server assumed to have some shared state [e.g., client has a password and server has an HMAC of the password]

(sk) client —— (vk) server

client → server: AKE protocol
server → client

client learns server's identity

client → server: identification protocol
server → client

} <u>cannot</u> replace this with anonymous key exchange
↳ becomes vulnerable to a man-in-the-middle attack

<u>Threat models</u>: Adversary's goal is to authenticate to server
- <u>Direct attack</u>: adversary only sees vk and needs to authenticate
  (e.g., physical analogy: door lock — adversary can observe the lock, does not see the key sk)
- <u>Eavesdropping attack</u>: adversary gets to <u>observe</u> multiple interactions between honest client and the server
  (e.g., physical analogy: wireless car key — adversary observes communication between car key and car)
- <u>Active attack</u>: adversary can impersonate the server and interact with the honest client
  (e.g., physical analogy: fake ATM in the mall — honest clients interact directly with the adversary)

Simple (insecure) password-based protocol:

<u>client</u> [sk: pwd] —— pwd ——→ <u>server</u> [vk: pwd]

↓ accept if vk = pwd

Not secure even against direct attacks! Adversary who learns vk can authenticate as the client [adversary who breaks into server learns user's password!]

NEVER STORE PASSWORDS IN THE CLEAR!

<u>Slightly better solution</u>: hash the passwords before storing

server maintains mappings
Alice ↦ $H(pwd_{Alice})$
Bob ↦ $H(pwd_{Bob})$

where H is a collision-resistant hash function

<u>client</u> [sk: pwd] —— pwd ——→ server [vk: H(pwd)]

↓ accept if $vk = H(pwd)$

If passwords have high entropy, then hard to recover pwd from H(pwd) [by one-wayness of H]

↳ But not true in practice...

Users often choose weak passwords (e.g., 123456, password, 123456789, ...)

↳ With a dictionary of 360 million entries, can cover about 25% of user passwords
(3% choose 123456)
(10% choose among top 25 common passwords)

} Based on password hashes that have been leaked from compromised databases

Simple hashing vulnerable to "offline dictionary attack":

adversary computes table (pwd, H(pwd)) for common passwords — completely offline

given H(pwd), can now invert with a single lookup if pwd is contained in the database

for LinkedIn breach in 2012, attacker stole password file with ~6 million passwords

(all passwords hashed using single iteration of unsalted SHA-1) ⟶ 90% of passwords recovered in ~6 days!

Problem: One-time precomputation (computing the lookup table) can be reused to compromise many passwords

Overall cost of attack: $O(m+n)$ where m is the dictionary size and n is the number of passwords to attack

Defense #1: Salt passwords before hashing: namely when storing password pwd, sample salt $\xleftarrow{R} \{0,1\}^n$ and store (salt, H(salt ‖ pwd)) on the server

↑ typically, $n \geq 64$

Note: Salt is a public value (needed for verification)

Offline dictionary attack no longer effective since every salt value induces different set of hash values

Overall cost of dictionary attack: $O(mn)$ — need to re-hash dictionary for every salt

Defense #2: Use a slow hash function [SHA-1 is very fast — enables fast brute-force search]

- PBKDF2 (password-based key-derivation function): iterate a cryptographic hash function many times:
(or bcrypt)

PBKDF2(pwd, salt): H(H(⋯ H(salt ‖ pwd) ⋯))

can use 100,000 or 1,000,000 iterations of SHA-256

honest user only needs to evaluate hash function once per authentication; adversary evaluates many times

Drawback: custom hardware can evaluate SHA-256 very fast

- scrypt (more recent: Argon2i): slow hash function that needs lots of memory (space) to evaluate
  ↳ custom hardware do not provide substantial savings (limiting factor is space, not compute)

Can also use a keyed hash function (e.g., HMAC with key stored in HSM)

↳ ensures adversary who does not know key cannot brute force at all!

Best practice: Always salt passwords

Always use a slow hash function (e.g., PBKDF2, scrypt) or keyed hash function or both!

```
$cur = 'password'
$cur = md5($cur)
$salt = randbytes(20)
$cur = hmac_sha1($cur, $salt)
$cur = remote_hmac_sha256($cur, $secret)
$cur = scrypt($cur, $salt)
$cur = hmac_sha256($cur, $salt)
```

md5: raw MD5 hash – not secure!

remote_hmac_sha256: salted, keyed hash function (key on remote service)

scrypt: slow hash function

Facebook password onion (circa 2014)

↓ layers gradually added over time to achieve better security (and probably to avoid password rehashing)

Password-based protocol <u>not</u> secure against eavesdropping adversary
(adversary sees vk and transcript of multiple interactions between honest prover + honest verifier)

One-time passwords (OTP) (SecurID tokens, Google authenticator, Duo)

<u>Construction 1</u>: Consider setting where verification key vk is <u>secret</u> (e.g., server has a secret)

- Client and server have a shared PRF key k and a counter (initialized to 0):

client (k, c) → server (k, c)

client sends $c', y' \leftarrow F(k, c)$; then $c \leftarrow c+1$

concretely: can interpret output as 6-digit number

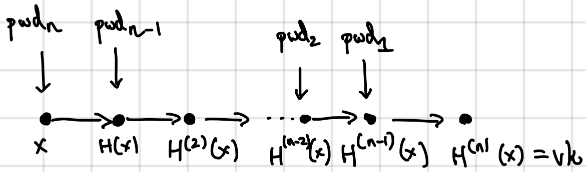
server: check that $y' = F(k, c')$ and $c' > c$ (no replaying); if successful, update $c \leftarrow c'$ } car key authentication

- <u>RSA SecurID</u>: stateful token (counter incremented by pressing button on token)
  - ↳ State is cumbersome — need to maintain consistency between client/server
- <u>Google Authenticator</u>: time-based OTP: counter replaced by current time window (e.g., 30-second window)

If PRF is secure ⇒ above protocol secure against eavesdroppers (but requires <u>server</u> secrets)
↳ can be problematic: RSA breached in 2011 and SecurID tokens compromised and used to compromise defense contractor Lockheed Martin

<u>Construction 2</u>: No server-side secrets (S/Key)

- Relies on a hash function (should be one-way) ← "under composition"
- Secret key is random input x and counter n;
  Verification key is $H^{(n)}(x) = \underbrace{H(H(\cdots H(x)\cdots))}_{n \text{ evaluations of } H}$



to verify y: check $H(y) \stackrel{?}{=} vk$; if successful, update $vk \leftarrow y$ } attacker has to invert H in order to authenticate

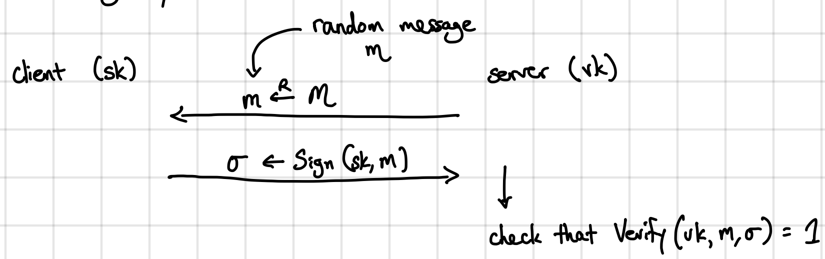
- Verification key can be public (credential is preimage of vk)
  - ↳ Can support <u>bounded</u> number of authentications (at most n) — need to update key after n logins
  - ↳ Output needs to be large (~80 bits or 128 bits) since password is the <u>input/output</u> to the hash function
- Naively, client has to evaluate H many times per authentication (~O(n) times)
  - ↳ Can reduce to O(log n) hash evaluations in an amortized sense by storing O(log n) entries along the hash chain

Thus far, only considered <u>passive</u> adversaries, but in reality, adversaries can be <u>malicious</u>

- Adversary can impersonate server (e.g., phishing) and then try to authenticate as client (but cannot interact with client during auth.) ← no man-in-the-middle protection
- All protocols thus far are vulnerable [all consist of client sending token that server checks, which can be extracted by active adversary]
- For active security, we use <u>challenge-response</u>

Signature-based challenge-response

- Server stores a verification key vk for digital signature scheme
- Client holds signing key sk



Server asks client to sign a random message

↳ Client's signature indicates proof of possession of sk associated with vk

↳ Active adversary that interacts with the client <u>before</u> interacting with the prover cannot forge signatures

Provides active security but signatures are long (~ 384 bits)