Security and Cryptography

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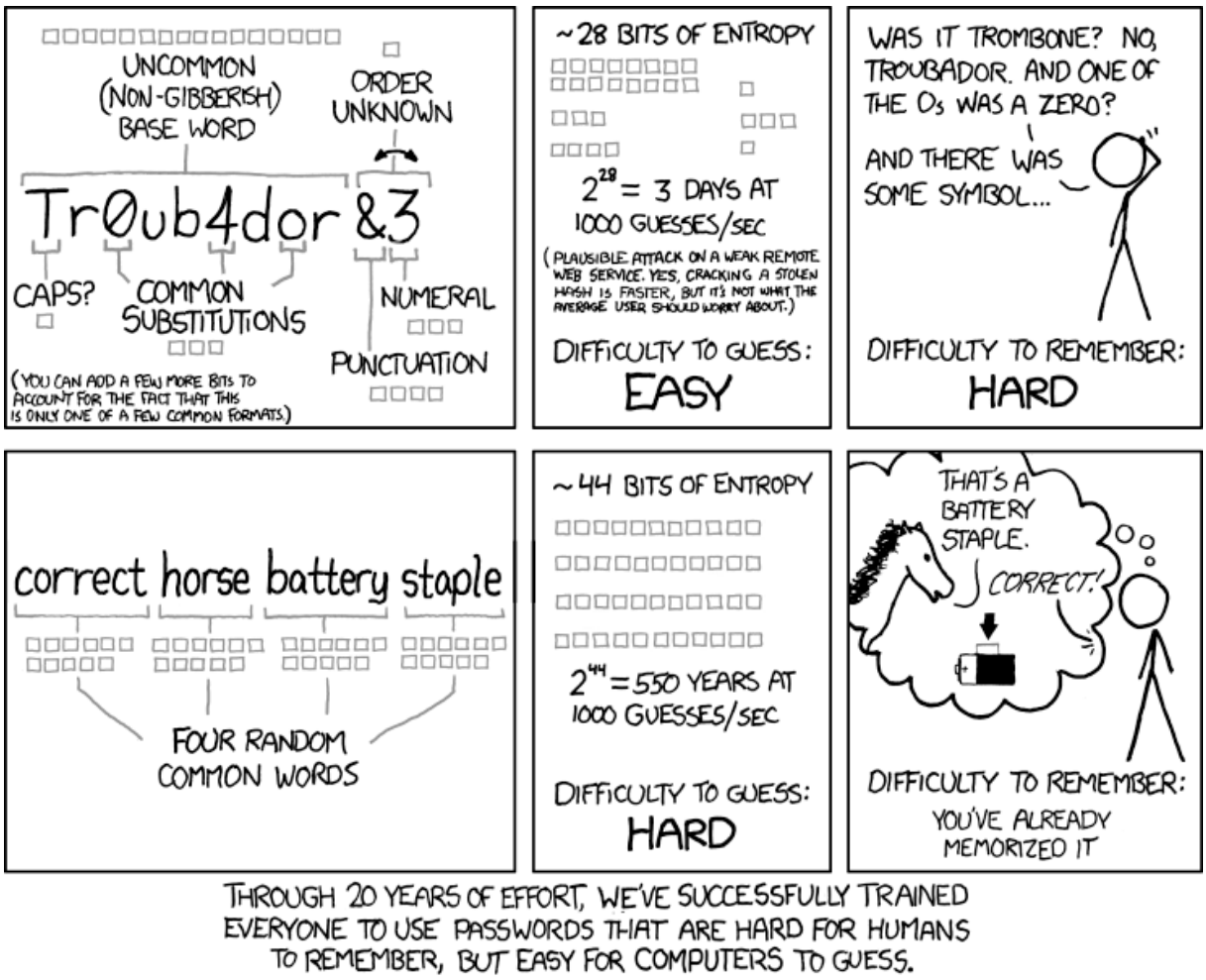
Entropy

- entropy: measure of randomness
- useful for measuring strength of password
- relevant xkcd



- entropy measured in bits: selecting uniformly at random from a set of `n` possible outcomes, entropy is `log_2(n)` - coin toss: 1 bit of entropy - dice roll: 2.58 bits of entropy - consider attacker knows *model* of password, but not the randomness used to select a password - how many bits of entropy suffice? depends on threat model - online guessing: ~40 bits is pretty good - offline guessing: 80 bits+

Hash functions

- cryptographic hash function: maps data of arbitrary size to fixed size

```
hash(value: array<byte>) -> vector<byte, N>  (for some fixed N)
```

- SHA1 is a cryptographic hash function used by Git.
  - maps arbitrary-size inputs to 160-bit output (represented as 40 hex chars)
  - `sha1sum` command performs SHA1 hash

```
$ printf 'hello' | sha1sum
aaf4c61ddcc5e8a2dabede0f3b482cd9aea9434d
$ printf 'hello' | sha1sum
aaf4c61ddcc5e8a2dabede0f3b482cd9aea9434d
$ printf 'Hello' | sha1sum
f7ff9e8b7bb2e09b70935a5d785e0cc5d9d0abf0
```

- hash function: hard-to-invert, random-looking, deterministic function
  - random oracle: a theoretical black box that responds to every unique query with a truly random response chosen uniformly from the output domain
- properties:
  - *deterministic*: same input always generates same output
  - *non-invertible*: hard to find input `m` such that `hash(m) = h` for some desired `h`
  - *target collision resistant*: given input `m_1` it's hard to find `m_2` such that `hash(m_1) = hash(m_2)`
  - *collision resistant*: it's hard to find two inputs `m_1` and `m_2` such that `hash(m_1) = hash(m_2)` - stronger than target collision resistance
- SHA-1 is no longer considered a strong cryptographic hash function
- lifetimes of cryptographic hash functions

Applications

- Git: uses SHA-1 for content-addressed storage (to be updated to SHA-256 eventually. Hash functions needn't be cryptographic: so why does Git use a cryptographic hash function?
  - consistency check to trust data, not intended for security; best hash function available
  - helps to ensure for a Distributed VCS that two different pieces of data will never have the same digest: this is extremely unlikely with good cryptographic hash functions.
- short summary of file contents e.g. for verification of files from 3rd party mirrors match value specified by trusted source
- *(Commitment scheme)[https://en.wikipedia.org/wiki/Hash_function]*: Suppose you want to commit to a particular value, but reveal the value itself later. For example, I want to do a fair coin toss "in my head", without a trusted shared coin that two parties can see. I could choose a value r = random(), and then share h = sha256(r). Then, you could call heads or tails (we'll agree that even r means heads, and odd r means tails). After you call, I can reveal my value r, and you can confirm that I haven't cheated by checking sha256(r) matches the hash I shared earlier.

Key derivation functions

- Key derivation functions (KDFS):
  - similar to cryptographic hashes; produce fixed-length output for use as keys in other cryptographic algorithms
  - usually deliberately slow in order to slow down offline brute-force attacks

Applications

- *symmetric cryptography*; producing keys from passwords for use in other algorithms
- *storing login credentials*:
  - generate and store a random salt for each user `salt = random()`
  - store `KDF(password + salt)`
  - verify login by matching KDF of entered password + salt to stored value

Symmetric Cryptography

Hiding message contents with symmetric cryptography

```
keygen() -> key  (this function is randomized)

encrypt(plaintext: array<byte>, key) -> array<byte>  (the ciphertext)
decrypt(ciphertext: array<byte>, key) -> array<byte>  (the plaintext)
```

- encrypt function: given ciphertext, it's hard to determine plaintext without key
- decrypt function has correctness: `decrypt(encrypt(m, k), k)= m`
- e.g. Advanced Encryption Standard: AES

Applications

- encrypting files for storage in untrusted cloud service

Asymmetric cryptography

Public-key cryptography

Two keys with two roles 1. Private key is kept private 2. Public key is publicly shared without compromising security

Functionality for encrypt, decrypt, sign, verify: - randomised key generation function

```
keygen() -> (public key, private key)
```

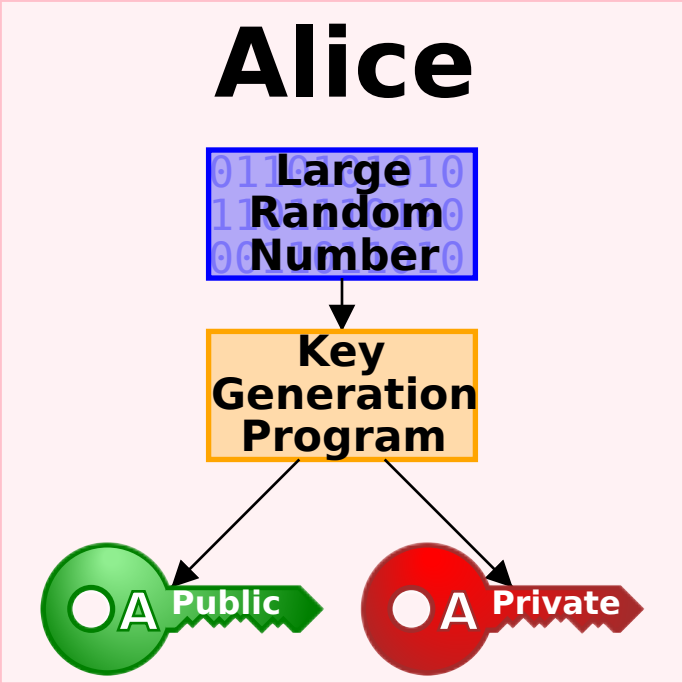
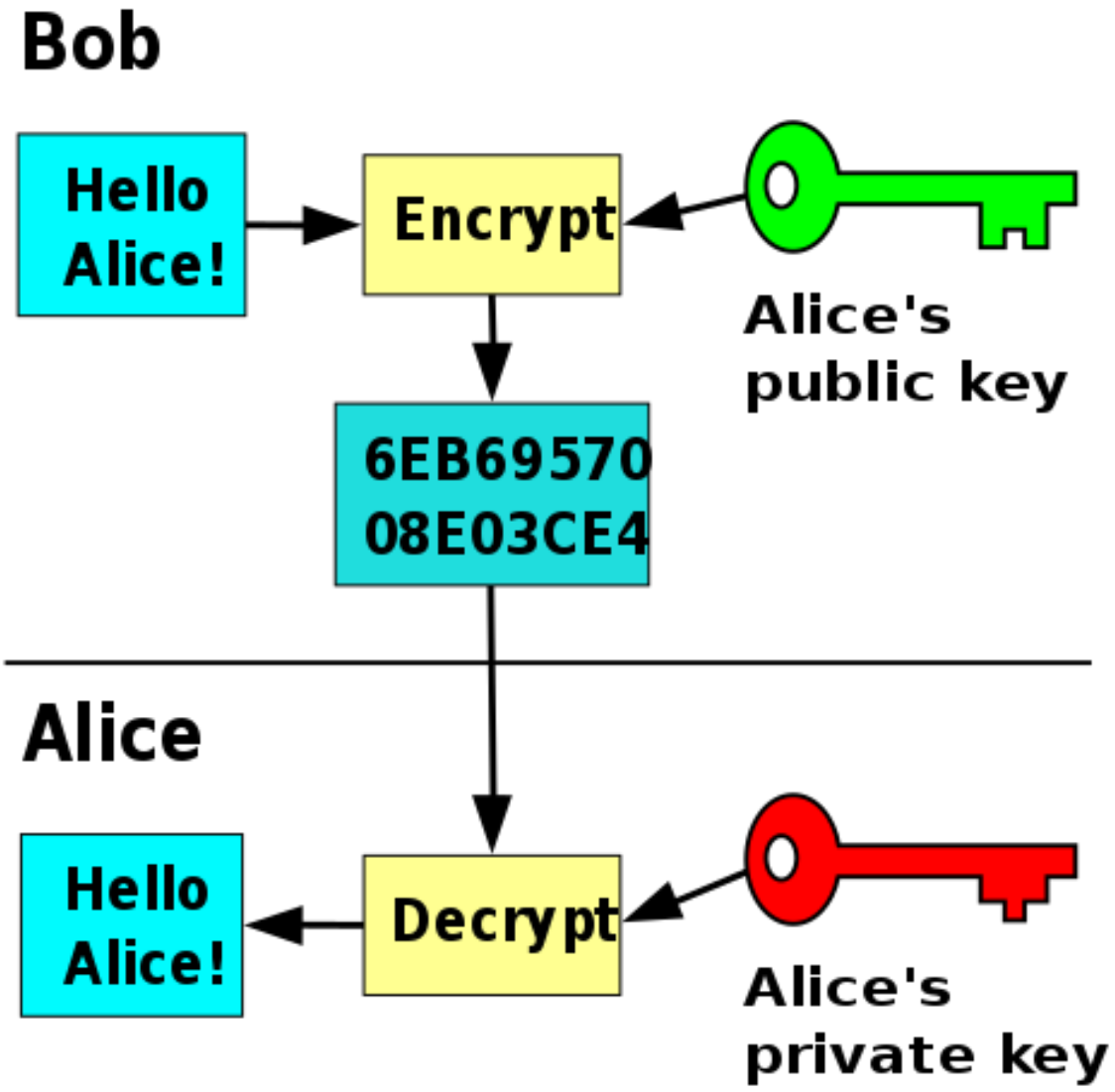


Figure 1: Key generation

```
encrypt(plaintext: array<byte>, public key) -> array<byte>  (ciphertext)
decrypt(ciphertext: array<byte>, private key) -> array<byte>  (plaintext)
```



You can also use a key-pair for authentication: sign and verify an unencrypted message:

```
sign(message: array<byte>, private key) -> array<byte>  (signature)
verify(message: array<byte>, signature: array<byte>, public key) ->
   bool  (whether or not the signature is valid)
```

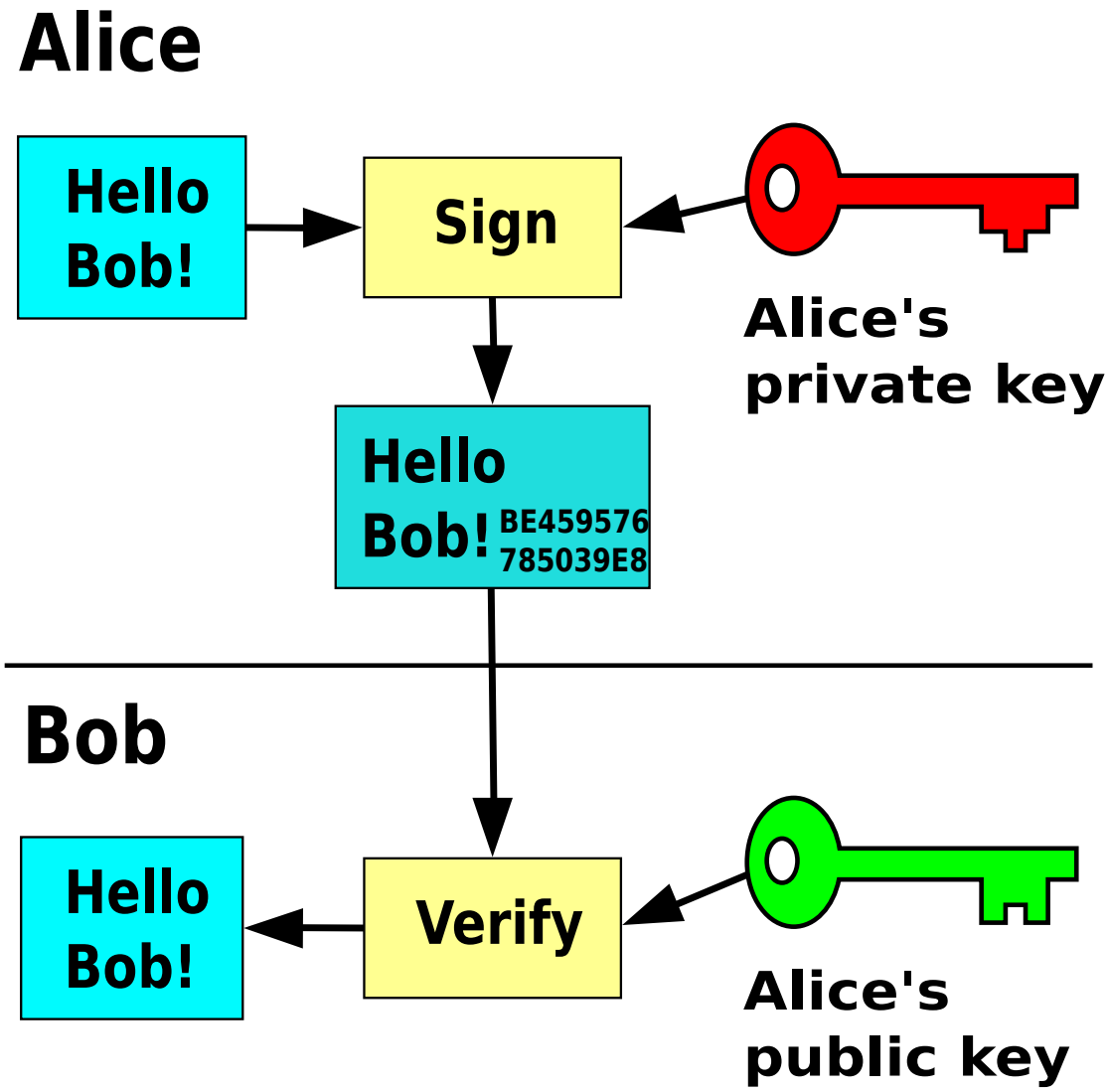


Figure 2: signing and verification, without encryption

- Messages encrypted with *public key*
- Given *ciphertext* its hard to determine *plaintext* without *private key*
- decrypt function has correctness property
- sign/verify functions are such that it's hard to forge a signature
- sign: without the *private key* it's hard to produce a signature such that `verify(message, signature, public key)= true`
- verify: correctness property `verify(message, sign(message, private key), public_key)= true`

Lock analogy

- symmetric cryptosystem: like a door lock; anyone with a key can lock and unlock
- asymmetric encryption: like a padlock with a key; you could give the unlocked lock to someone (public key); they could lock a message in a box; but only you can open it because you have the key to the lock (private key)

Applications

- PGP email encryption: post public keys online, and then anyone can send you encrypted email
- private messaging e.g. signal, keybase use asymmetric keys to establish private communication channels
- signing software: Git can have GPG-signed commits. Publicly posted keys allow verification of authenticity

Key distribution

- distribution of public keys/mapping public keys to real world identities are big challenges
- signal: relies on trust on first use; with out-of-band verification in person
- PGP: uses a web of trust
- Keybase: uses social proof

Case Studies

- *2FA* Helps protect against stolen passwords and phishing attacks
  - TOTP: time-based one-time password e.g. google authenticator doesn't protect against phishing
  - ideally use a FIDO/U2F dongle e.g. YubiKey
  - SMS is useless except for strangers picking up password in transit
- *disk encryption*: protect your files if your device is lost or stolen
  - encrypt entire disk with symmetric cipher, with key protected by passphrase
  - Bitlocker, Windows
  - cryptsetup + LUKS, Linux
  - *private messaging*: Signal, Keybase
    * end-to-end security bootstrapped from asymmetric-key encryption
    * critical step: obtaining contacts' public keys

        * for good security you need to authenticate out-of-band, or trust social proofs
        * Electron based desktop apps: huge trust stack so avoid where possible

- *SSH*:
    - `ssh-keygen`: generates asymmetric keypair `public_key`, `private_key`
        * randomly generated using OS entropy (hardware events, …)
        * public key stored as is
        * at rest, private key should be stored encrypted: when you supply a passphrase, key derivation function is used to produce a key which then encrypts the private key with a symmetric cipher
    - `.ssh/authorized_keys` stores public keys
    - connecting clients prove identity through asymmetric signatures, challenge-response.
        * server picks random number and sends to client
        * client signs the message and sends signature to server, which verifies signature against public key on record
        * proves that client possesses private key corresponding to public key stored by server, authenticating connection

- *Tor*:
    - not resistant to powerful global attackers
    - weak against traffic analyis attacks
    - useful for small scale traffic hiding, but not particularly useful for privacy
    - better to use more secure services (Signal, TLS, …)

Resources

- 2019 security lecture