Introduction to Information Security

5. Message Integrity

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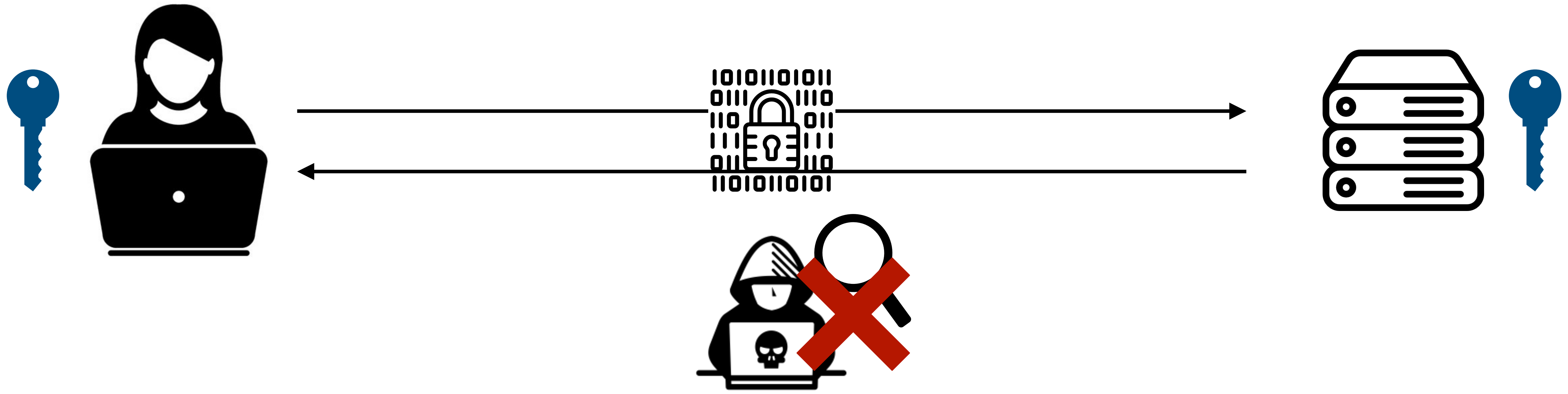
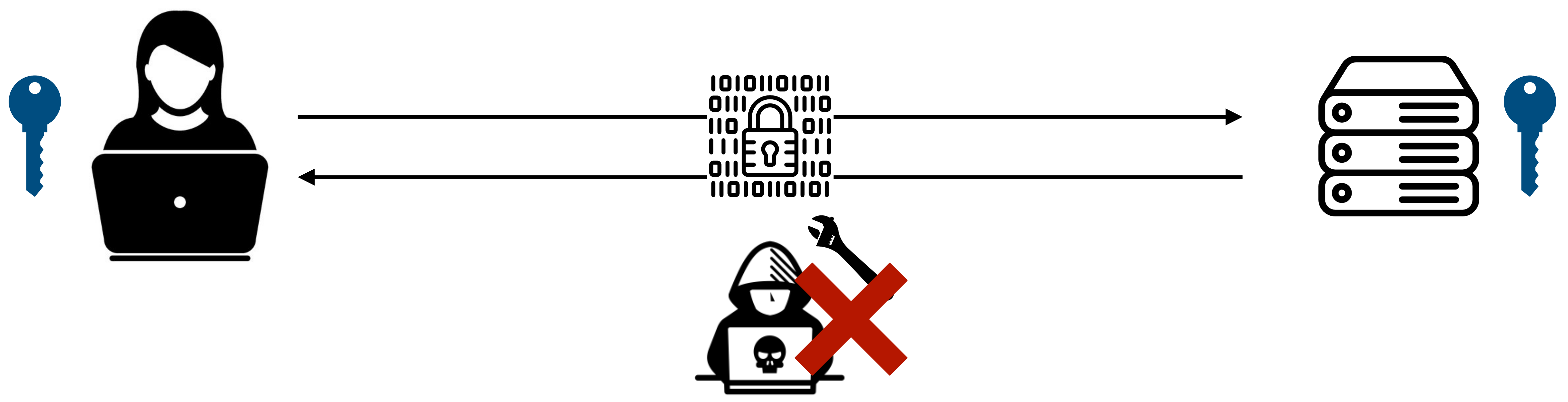
Confidentiality

- Goal: Attackers cannot learn anything about the plaintext w/o the key



Integrity

- Goal: Attackers cannot generate a valid message

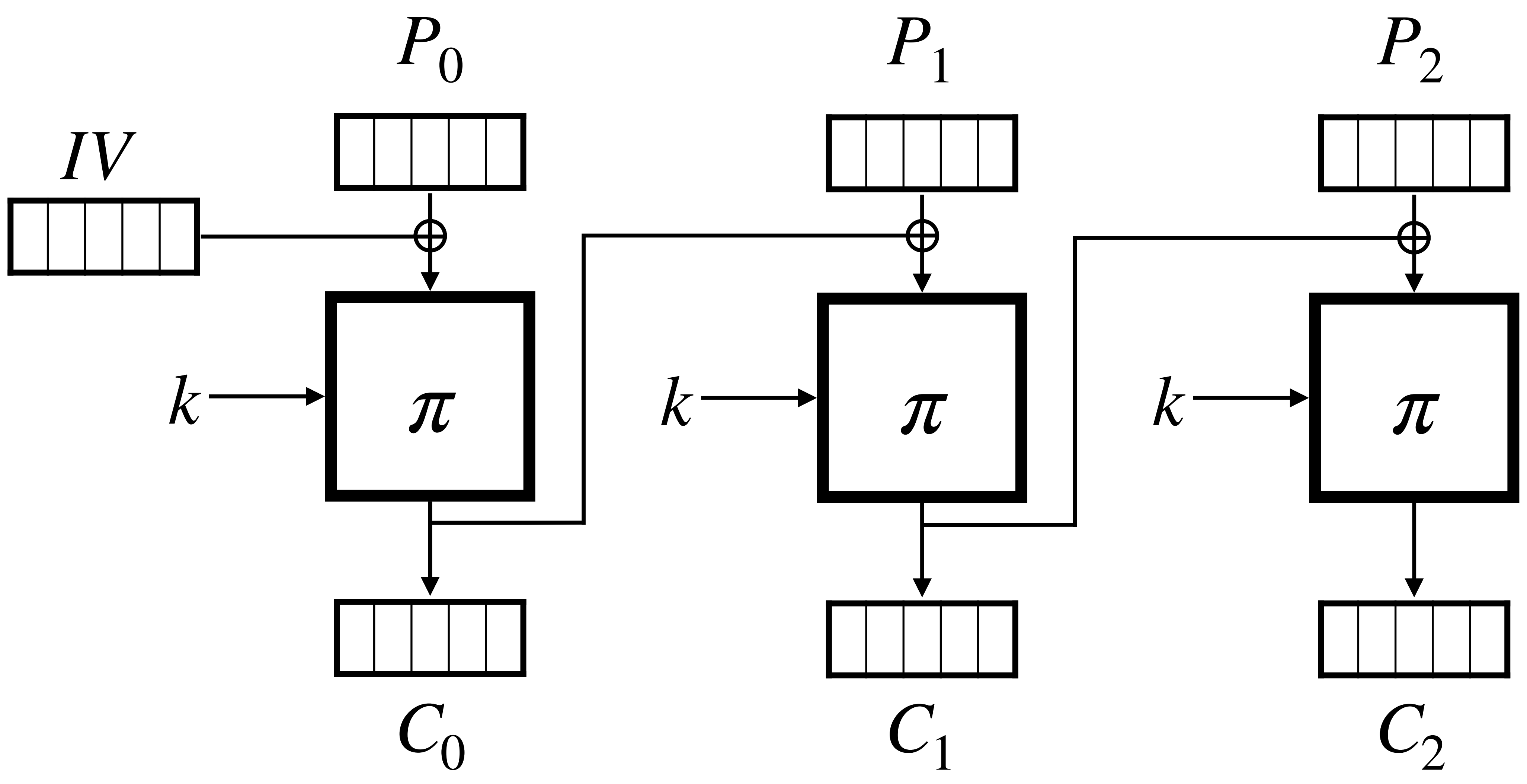


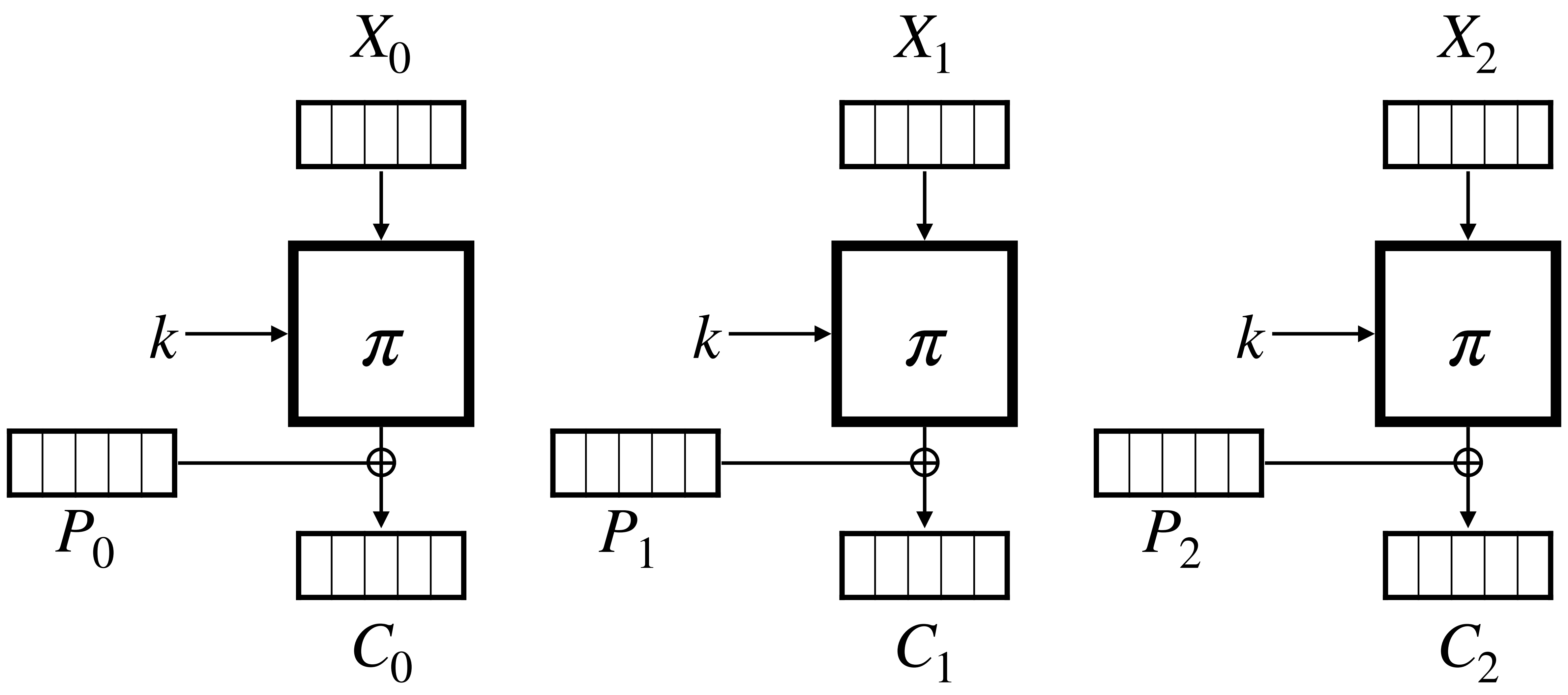
Confidentiality vs Integrity

- What does “secure communication” entail?
- Confidentiality: secret communication
  - Ensured by **encryption** schemes
- Integrity: authenticated communication
  - Ensured by **authentication** schemes
- In many cases, message integrity is equally (or more) important
  - Any examples?

Encryption vs Authentication

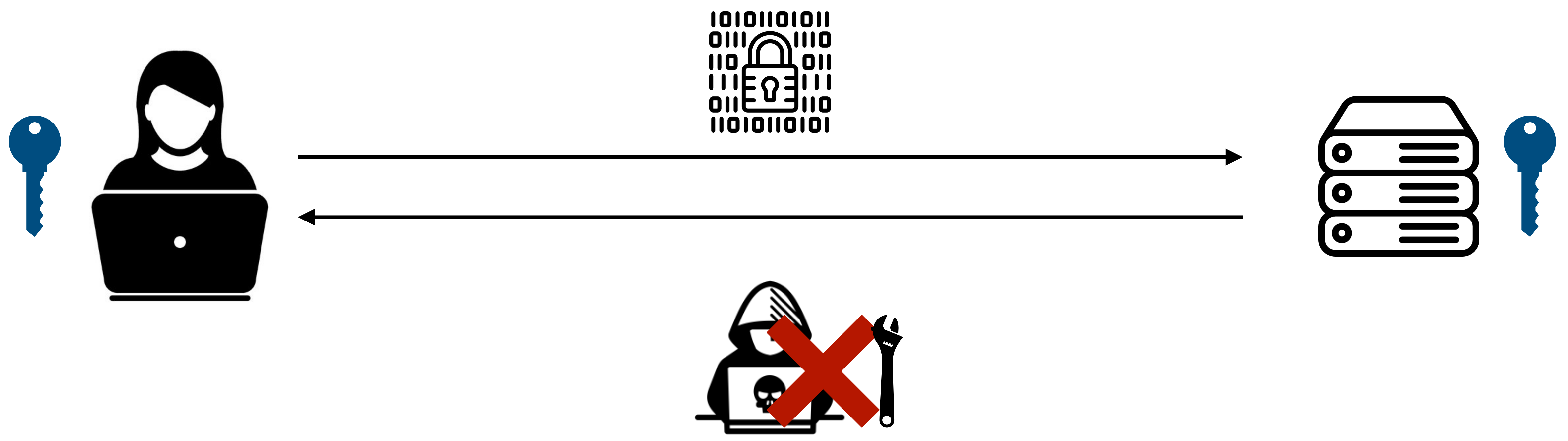
- "Encryption hides message contents and thus adversary cannot modify the encrypted message in any meaningful way" [T / F]?
- Example:
  - CBC-mode encryption
  - CTR-mode encryption





Message Authentication Codes (MAC)

- "Cryptographic checksum" to prevent an adversary from modifying a message
- Assume k is the shared symmetric key
- Sender: send (m, t) where m is a message and $t = Mac_k(m)$
- Receiver: receive (m, t) and check whether $t = Mac_k(m)$
- Example: HMAC (hash-based MAC), CBC-MAC



How to achieve both confidentially and integrity?

Authenticated Encryption Scheme

- Goal: Attackers cannot learn anything about m and cannot modify m
- Secure encryption scheme: (Enc, Dec)
- Message authentication code: Mac
- IMPORTANT: each cryptographic primitive should always use **independent keys**
  - $k_E \neq k_M$
- How to achieve a secure authenticated encryption scheme?

Secure Authenticated Encryption Scheme

- Encrypt-and-authenticate: $c = Enc_{k_E}(m)$, $t = Mac_{k_M}(m)$
  - Not secure: t is deterministic because Mac is deterministic
- Authenticate-then-encrypt: $t = Mac_{k_M}(m)$, $c = Enc_{k_E}(m \,||\, t)$
  - May or may not be secure (e.g., CBC-mode-with-padding)
- Encrypt-then-authenticate: $c = Enc_{k_E}(m)$, $t = Mac_{k_M}(c)$
  - Secure regardless of the choice of Enc and Mac
  - Common practice (e.g., TLS)

Cryptographic Hash Function

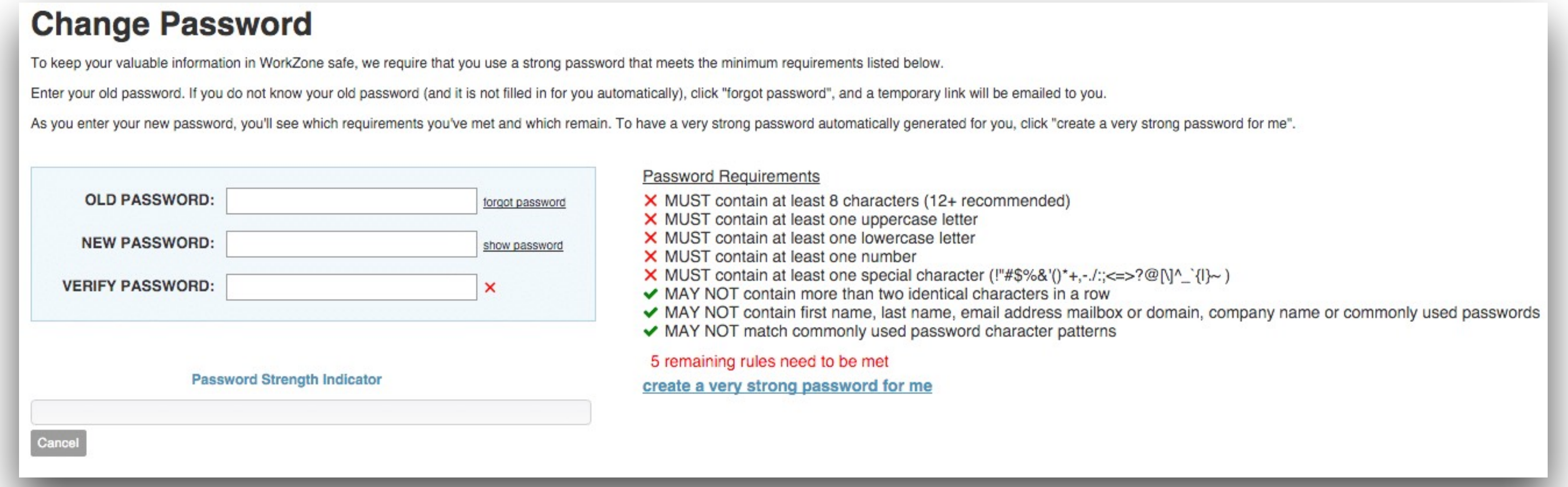
- The most common implementation scheme for MAC
- Hash functions $H : \{0,1\}^* \rightarrow \{0,1\}^l$
    - Take inputs of arbitrary length
    - Compress them into short fixed-length (l) outputs
    - Efficient evaluation and public implementation
- Cryptographic hash function: varying properties required across applications
    - Preimage resistance, second preimage resistance, collision resistance
    - Example: MD5, SHA-1, etc

1. Preimage Resistance

- Given y, computationally infeasible to find x such that $H(x) = y$.
    - So-called one-way property
- How much work is needed to break this resistance?
- Example: storing passwords

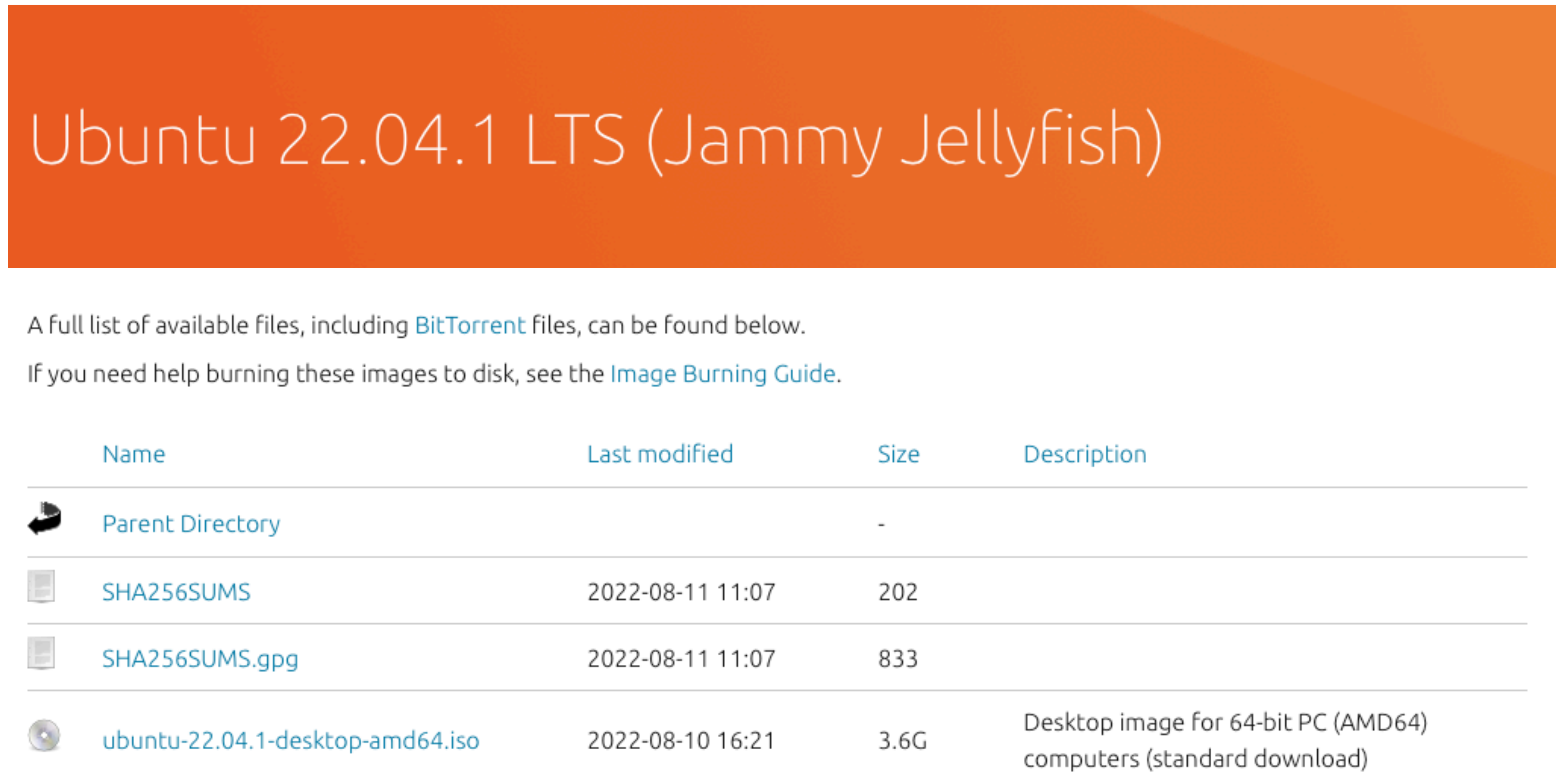
Application: Password Hasing

- Passwords must not be stored in plaintext but hashed and stored
- BTW, why do we need strong password requirements?
- Pre-computation attack: password space is often limited (e.g., dictionary)
- Mitigations
  - Slow hash functions (e.g., bcrypt)
  - Salt: store (h, s) when $h = H(pw \,||\, s)$ and s is a short random string



2. Second-preimage Resistance

- Given x, computationally infeasible to find x' such that $x \neq x'$ and $H(x) = H(x')$
- Example: integrity of software distribution, fingerprinting (e.g., virus, deduplication)
- How much work is needed to break this resistance?


Ubuntu 22.04.1 LTS (Jammy Jellyfish)

A full list of available files, including BitTorrent files, can be found below.

If you need help burning these images to disk, see the Image Burning Guide.

Name	Last modified	Size	Description
Parent Directory		-	
SHA256SUMS	2022-08-11 11:07	202	
SHA256SUMS.gpg	2022-08-11 11:07	833	
ubuntu-22.04.1-desktop-amd64.iso	2022-08-10 16:21	3.6G	Desktop image for 64-bit PC (AMD64) computers (standard download)

3. Collision Resistance

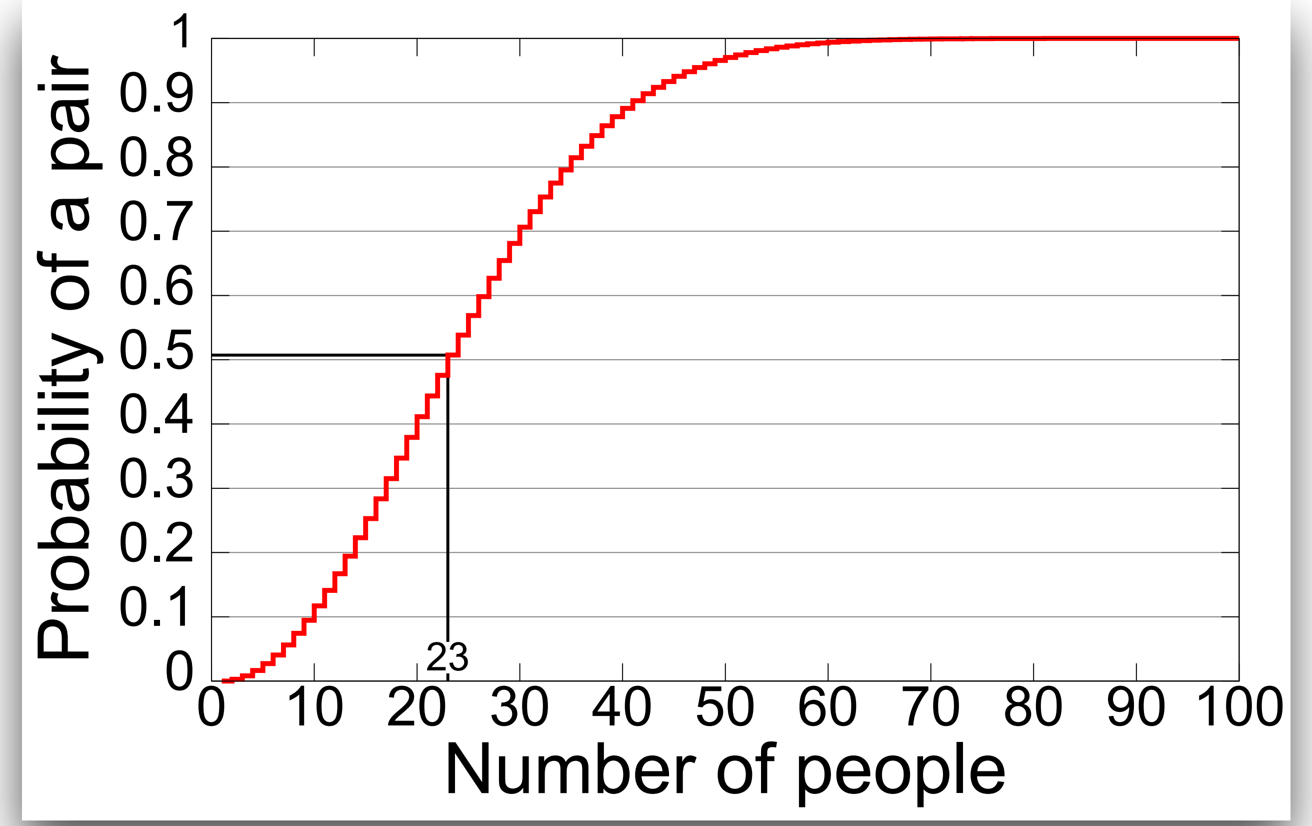
- Computationally infeasible to find x, x' such that $x \neq x'$ and $H(x) = H(x')$
- Example: auction bidding
  - Alice wants to bid B and sends $H(B)$
  - Rival bidders should not recover B (one-wayness)
  - Alice should not be able to change her mind to bid B' such that $H(B) = H(B')$
- How much work is needed to break this resistance?
  - $2^{n/2}$ (not 2^n, birthday paradox)
  - Example (MD5): $2^{128} \approx 3 \times 10^{38}$ vs $2^{64} \approx 2 \times 10^{19}$

Birthday Paradox

- What is the prob. that in a set of n random people, at least two will share a birthday?
  - If $n = 1$, then 0%
  - If $n = 366$, then 100%
  - What is $n = 23, 50$ or 60?
- Let $p(n)$ be the prob. and $\bar{p}(n)$ be that all n birthdays are different, i.e., $p(n) = 1 - \bar{p}(n)$

$$\bar{p}(n) = 1 \times \left(1 - \frac{1}{365}\right) \times \left(1 - \frac{2}{365}\right) \times \cdots \times \times \left(1 - \frac{n-1}{365}\right)$$

$$= \frac{365 \times 364 \times \cdots \times (365 - n + 1)}{365^n}$$



Application: Fingerprinting

- Instead of storing the original data, simply store a shot hash digest
- Examples:
  - Virus fingerprinting
  - Deduplication
  - File sharing
- What happens if there exist a lot of collisions?

Informal Analysis of Cryptographic Hash

- Collision resistance $\rightarrow$ second-preimage resistance
  - If an adversary can find $x' \neq x$ s.t. $H(x') = H(x)$, then it can clearly find a collision
- Second-preimage resistance $\rightarrow$ preimage resistance
  - Assume H is second preimage resistant but not preimage resistant, then contradiction
  - For given x and $y = H(x)$, one can find x' that satisfies $y = H(x')$ (by assumption)
  - When the domain is infinitely large, one can find $x' \neq x$ with high probability

Practical Cryptographic Hash Functions

- MD5 (1991): 128-bit output length
  - Collisions found in 2004. Insecure.
- SHA-1 (1995): 160-bit output length
  - Very commonly used. Yet, collisions found in 2017.
  - Current trend to migrate to SHA-2
- SHA-2 (2001): 256 or 512-bit output lengths
  - Often called SHA256 or SHA512
  - No known significant weaknesses
- SHA-3 (2012): 224, 256, 384, or 512-bit output lengths

SHA-1 Broken?

- SHA-1: 160-bit output length
- SHAttered attack by CWI and Google (2017)
  - Two different PDF files f_1 and f_2 such that $H(f_1) = H(f_2)$
  - $2^{63.4}$ operations (<< 2^{80})
  - 6,500 years of single-CPU, 110 years of single-GPU
- DO NOT USE SHA-1 for any security-critical systems!

Common Mistakes

- MAC vs checksum?
- MAC vs cryptographic hash function?

Summary

- Integrity: attackers cannot generate a valid message
  - As important as confidentiality
- MAC (message authentication code): prevent an adversary from modifying a message
- Cryptographic hash function: a common method to implement MAC