Basics of Cryptography

Chapter 1

Vigenère Cipher

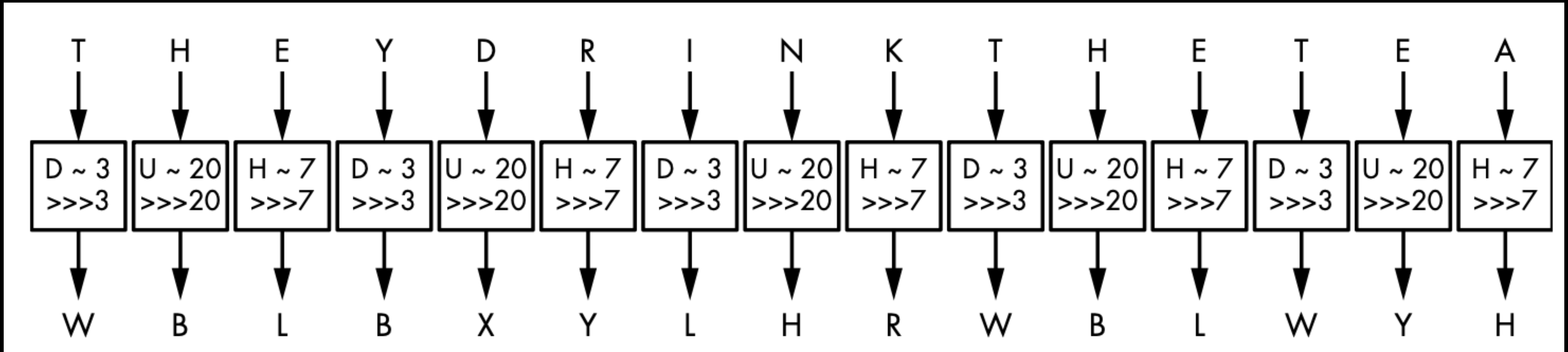
- Similar to the Caesar cipher, except that letters are shifted by values defined by a key.
  - The key is a collection of letters that represent numbers based on their position in the alphabet.

- For example, if the key is DUH, letters in the plaintext are shifted using the values D=3, U=20, H=7.

- The 3, 20, 7 pattern repeats until you’ve encrypted the entire plaintext.

Vigenère Cipher

- Example: encrypting the sentence THEY DRINK THE TEA using the keyword DUH



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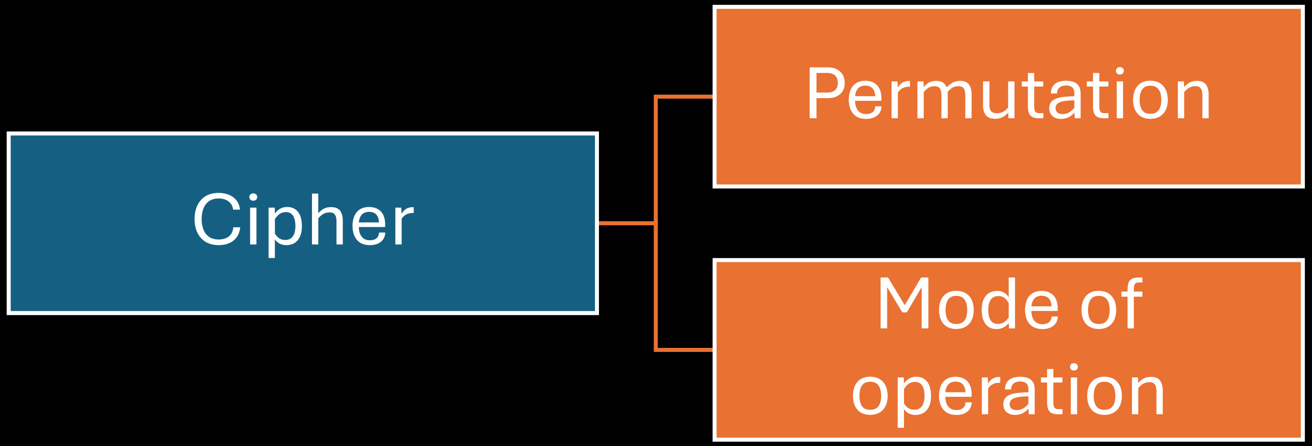
How Ciphers Work?

- Each cipher has two components:

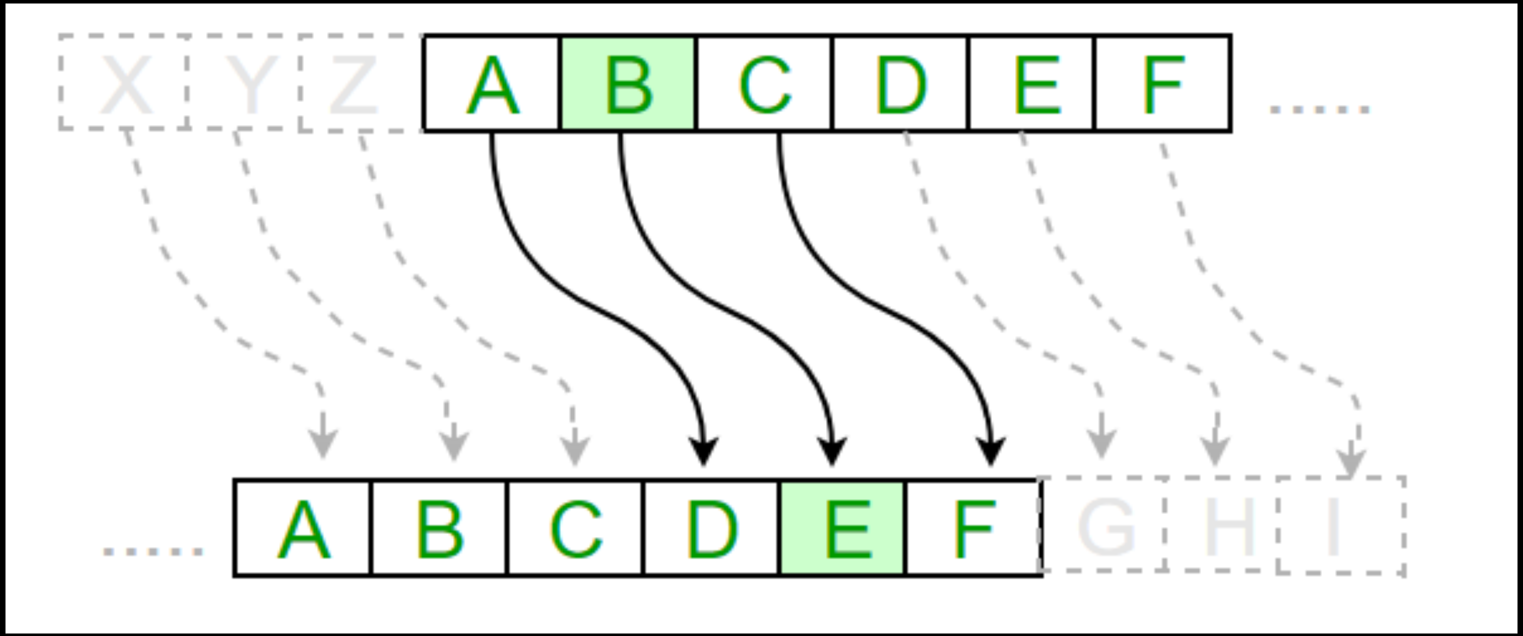


A function that transforms an item (a letter or a group of bits) such that each item has a unique inverse.

An algorithm that uses a permutation to process messages of arbitrary size.

How Ciphers Work?

- In Caeser cipher:
  - **Permutation**: just shifting the letters.
  - **Mode of operation**: repeating the same permutation, shifting, for each letter.



How Ciphers Work?

- Vigenère cipher has a more complex mode:
  - **Permutation**: as Caeser cipher, just shifting each letter.
  - **Mode of operation**: shifting is different for each letter.

Plain Text	P	A	S	S	W	O	R	D
Key	K	E	Y	K	E	Y	K	E
Cipher Text	Z	E	Q	C	A	M	B	H

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The Permutation

- Most of the classical ciphers replace each letter with another letter.
  - They are performing *substitution* – shifting in the alphabet.
- A “substitution” is different from a “permutation”.
- For example:
  - A function that transforms A, B, C, D to G, K, A, Y is a “substitution”
  - A function that transforms A, B, C, D to C, A, D, B is a “permutation”

The Permutation

- Not every permutation is secure.
- A secure permutation satisfies three criteria:

The permutation should be determined by the key.

Different keys should result in different permutations.

The permutation should look random.

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Mode of Operation

- Given a secure permutation that transforms A to X, B to M, and N to L.
- Then, to encrypt BANANA, we get MXLXLX.
- Same permutation → reveals duplicate letters → insecure.
- Analyzing these duplicates → learn something about the message.

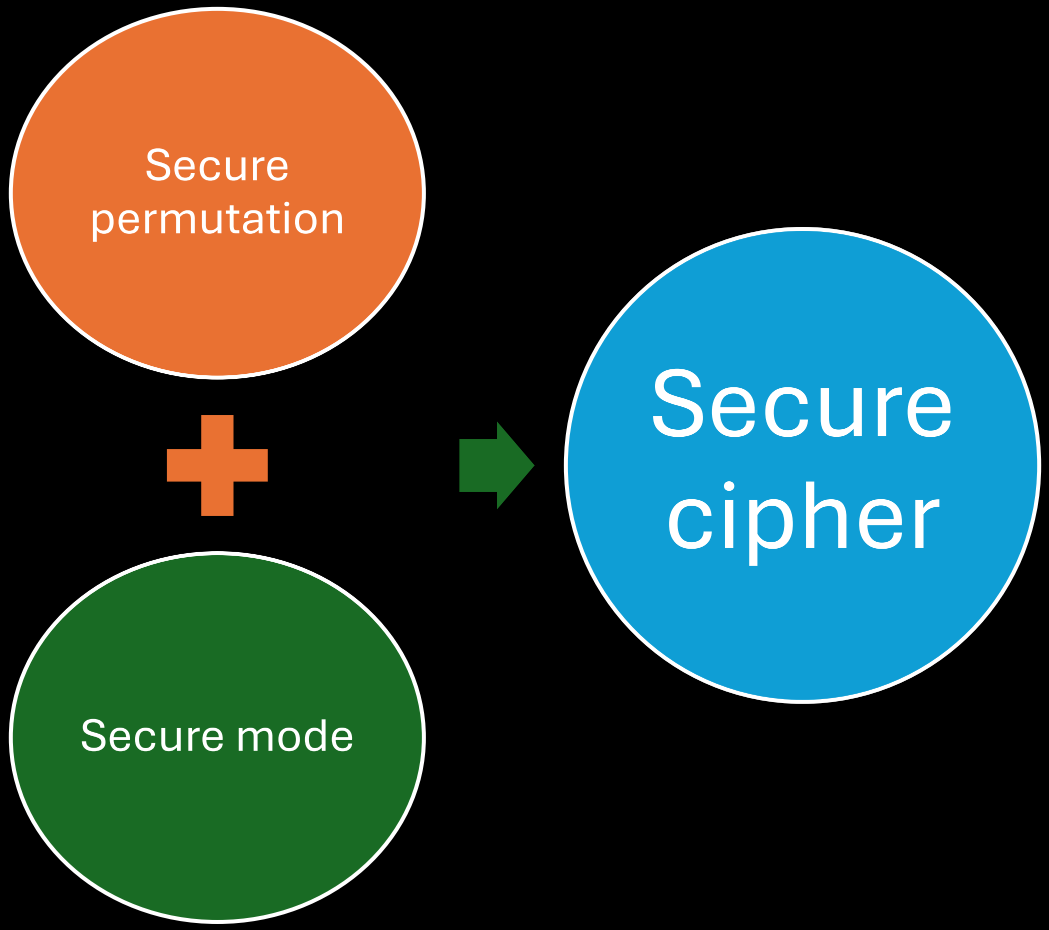
Mode of Operation

- The mode of a cipher mitigates the exposure of duplicate letters in the plaintext by using different permutations for duplicate letters.

- Vigenère cipher: if the key is N letters, then N different permutations will be used for every N consecutive letters.
  - This can still result in patterns in the ciphertext because every Nth letter of the message uses the same permutation.

- Frequency analysis can be used to break Vigenère cipher.

The Mode of Operation



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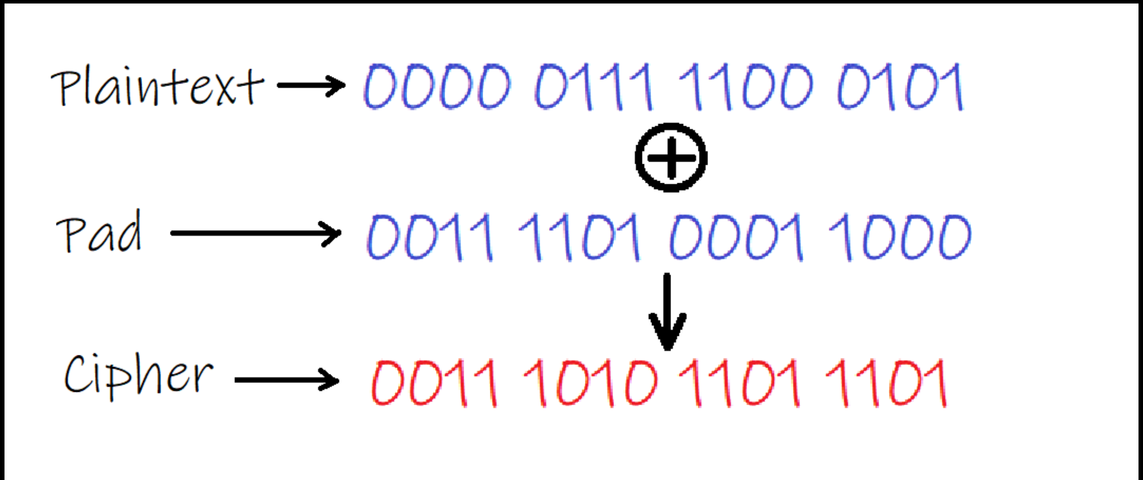
The One-Time Pad

- OTP uses a **single-use** key that is larger ≥ the size of the plaintext.



- **Perfect secrecy**: if an attacker has unlimited computing power, it’s impossible to learn anything about the plaintext, but its length.

The One-Time Pad

Example: P = 01101101 and K = 10110100, then

- To encrypt: $C = P \oplus K = 01101101 \oplus 10110100 = 11011001$
- To decrypt: $P = C \oplus K = 11011001 \oplus 10110100 = 01101101$

	P	0	1	1	0	1	1	0	1
Encrypt: XOR	K	1	0	1	1	0	1	0	0
	C	1	1	0	1	1	0	0	1
Decrypt: XOR	K	1	0	1	1	0	1	0	0
	P	0	1	1	0	1	1	0	1

The One-Time Pad

- Each key K MUST be used only once.
  - If the same K is used to encrypt P_1 and P_2 to C_1 and C_2, then an eavesdropper can compute the following:

$$C_1 \oplus C_2 = (P_1 \oplus K) \oplus (P_2 \oplus K) = P_1 \oplus P_2$$

- Thus, an eavesdropper can learn the XOR difference of P_1 and P_2.
  - If either plaintext message is known, then the other message can be recovered.

- OTP is inconvenient: to encrypt a one-terabyte hard drive, you'd need another one-terabyte drive to store the key!

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Encryption Security

- Two concepts describe the security of a cipher:
  - **Attack models**: assumption about what an attacker can do.
  - **Security goals**: description of what is considered a successful attack.

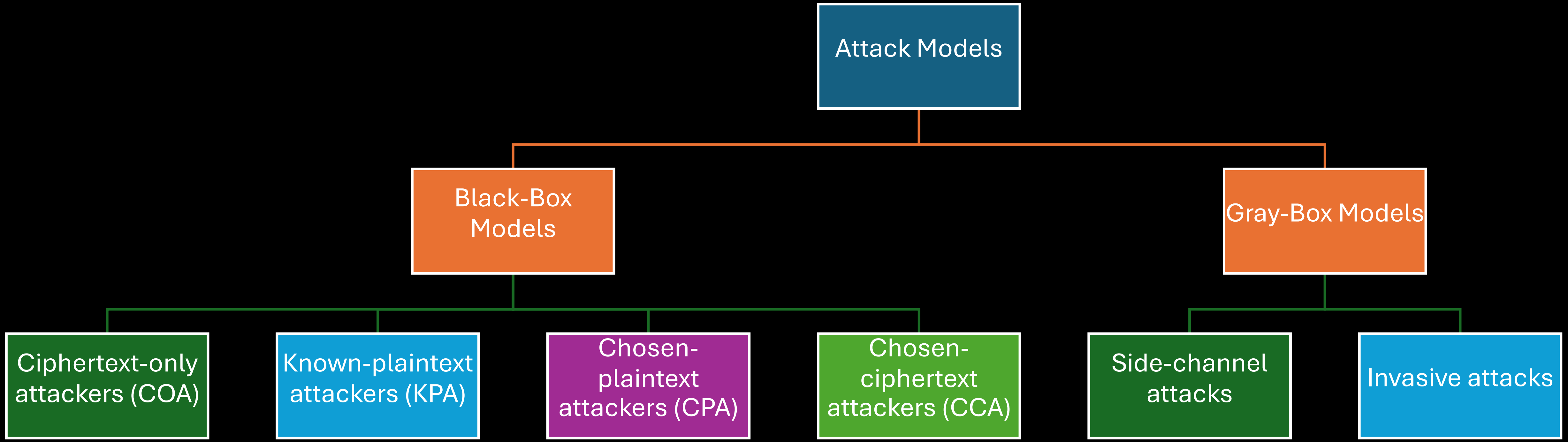
- Security notion = Attack model + Security goal:
  - We say: a cipher achieves <u>a certain security notion</u> if any attacker working in a <u>given model</u> can't achieve the <u>security goal</u>.

Encryption Security: Attack Models

- **Attack model**: a set of assumptions about how attackers interact with a cipher and what they can and can’t do.

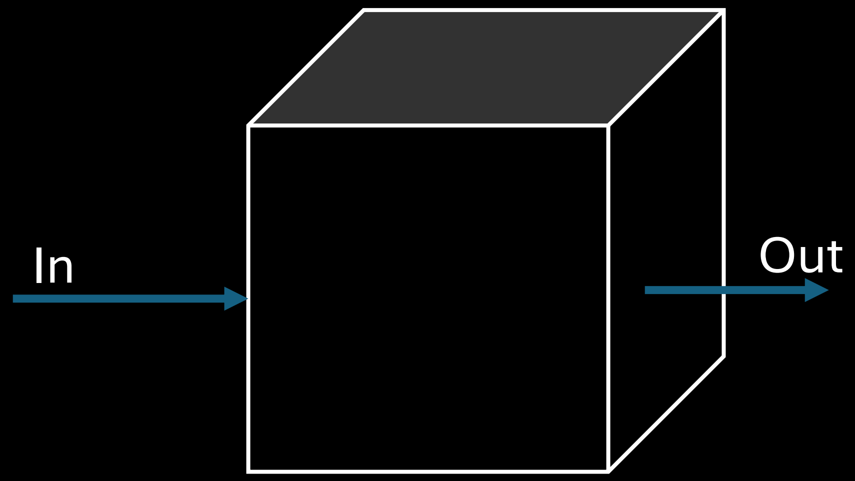
- Kerkhoff's Principle:
  - The encryption algorithm is known.
  - The security of a cipher relies on the <u>**key**</u> and the mechanism of the cipher.

Encryption Security: Attack Models

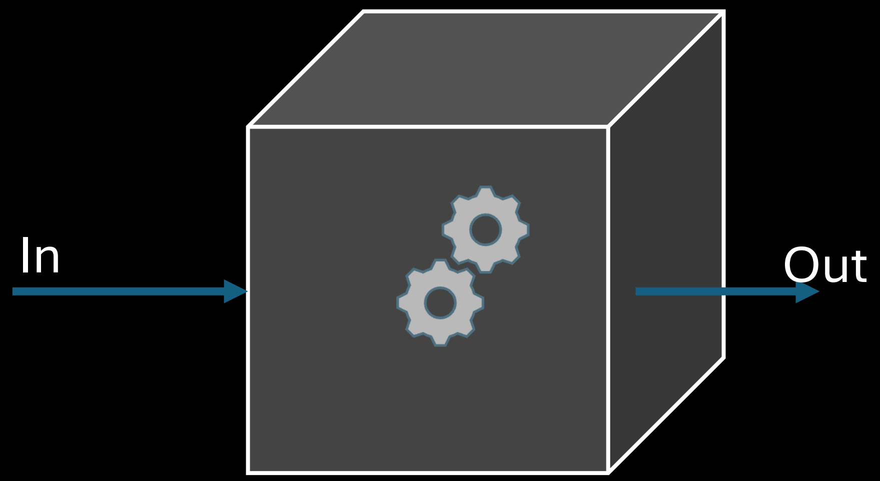


Encryption Security: Attack Models

- Black box models: attackers can see the input/output of a cipher only.
- Gray box models: attackers have access to a cipher’s implementation.



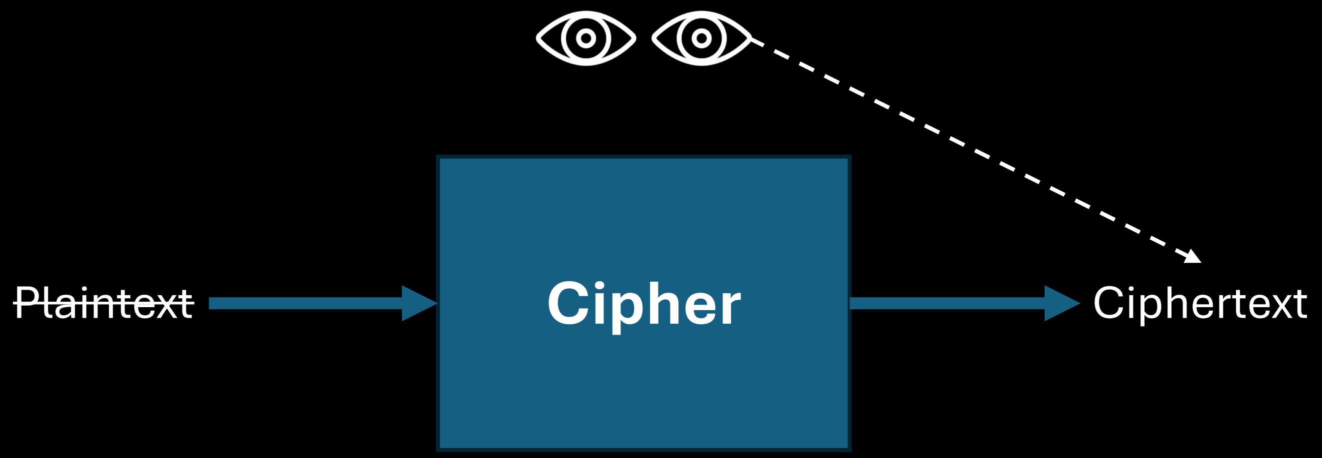
No knowledge



Some knowledge

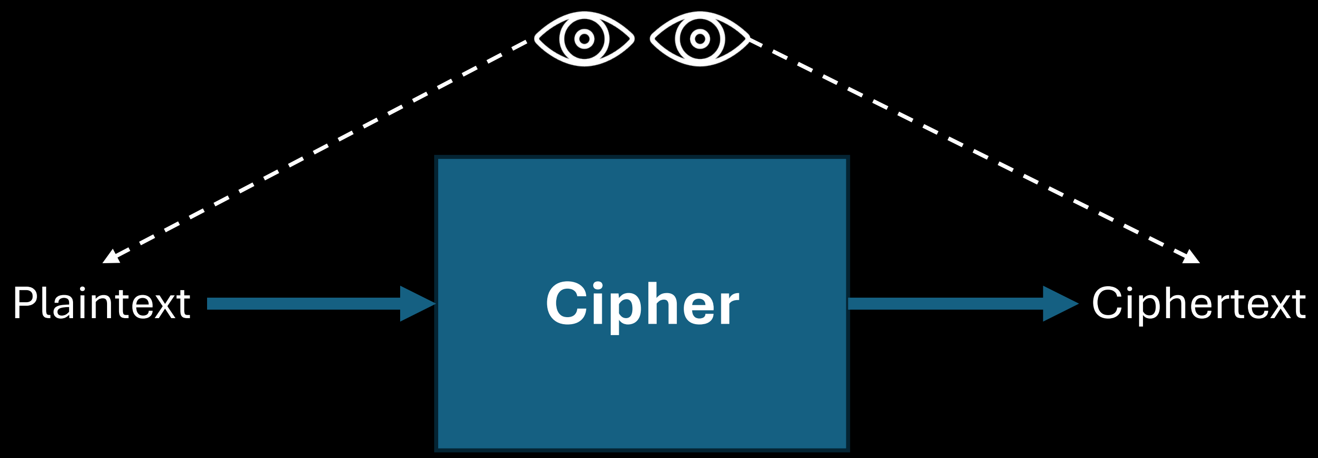
Encryption Security: Attack Models

1. **Ciphertext-only attackers (COA)** observe ciphertexts but don't know the associated plaintexts.
   - Attackers in the COA model are passive and can't perform encryption or decryption queries.



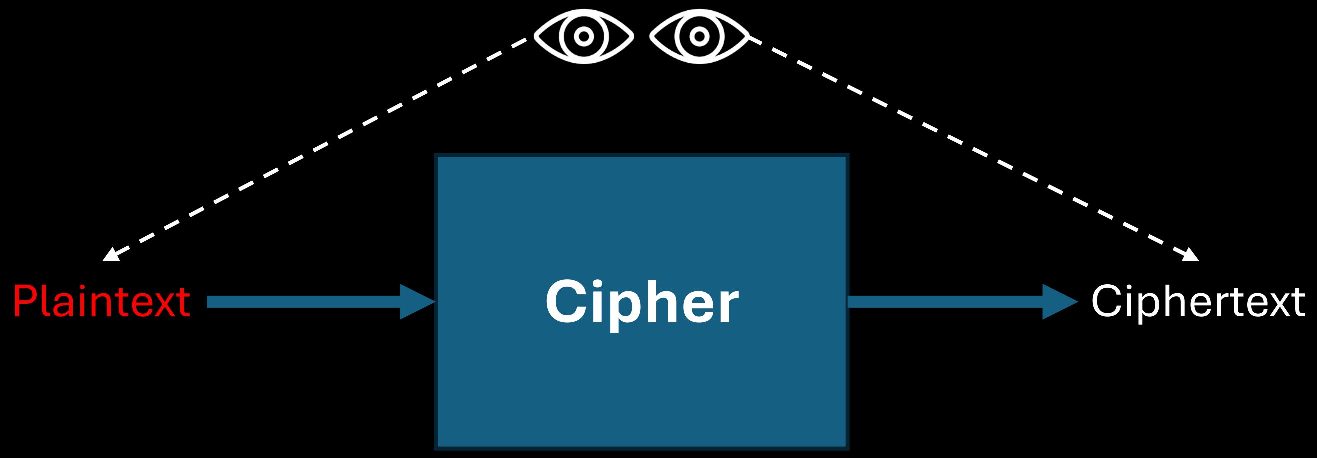
Encryption Security: Attack Models

2. **Known-plaintext attackers (KPA)** observe ciphertexts and know the associated plaintexts.
    - Attackers in the KPA model thus get a list of plaintext–ciphertext pairs,
    - KPA is a passive attacker model.



Encryption Security: Attack Models

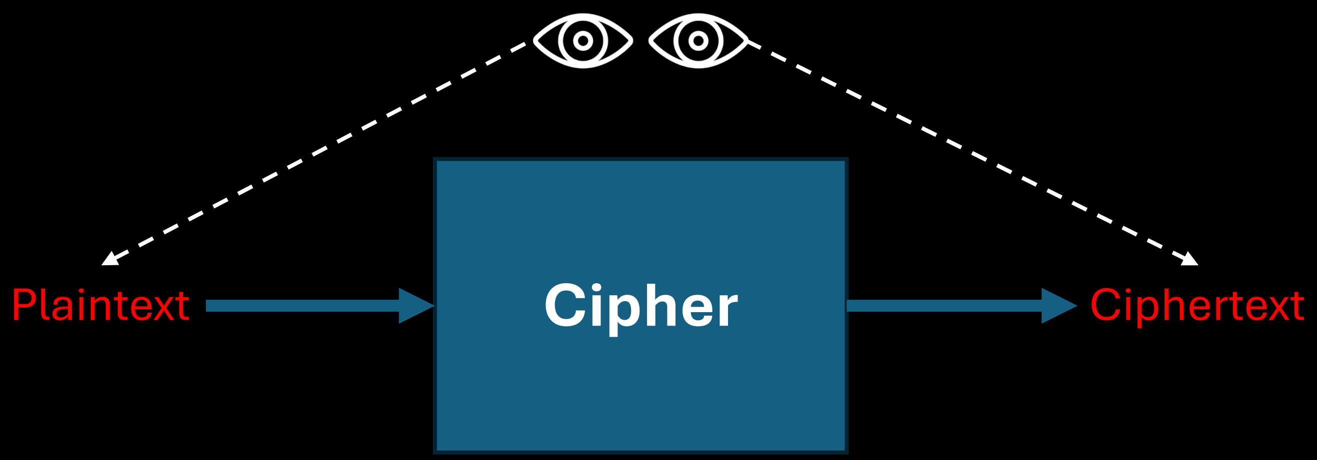
3. **Chosen-plaintext attackers (CPA)** can perform encryption queries for plaintexts of their choice and observe the resulting ciphertexts.
   - Attackers choose all or part of the plaintexts and then observe the ciphertexts.
   - CPA are active attackers, because they influence the encryption processes rather than passively eavesdropping.



Encryption Security: Attack Models

4. **Chosen-ciphertext attackers (CCA)** can both encrypt and decrypt; perform encryption queries and decryption queries.

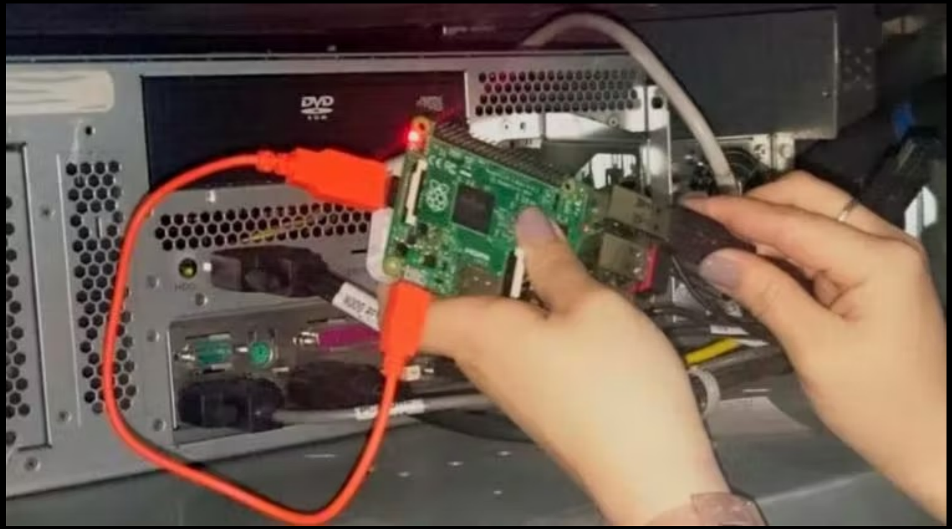
- CCA are active attackers



Encryption Security: Attack Models

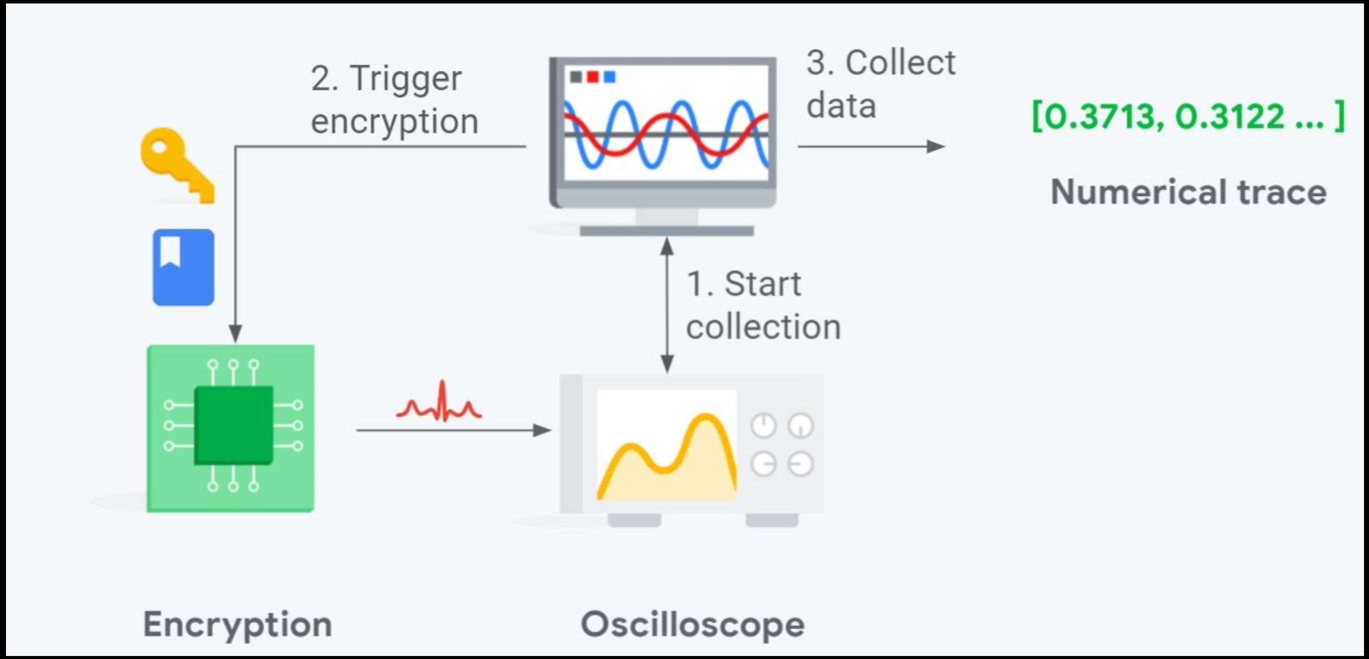
- Gray box models: attackers have access to a cipher’s implementation.
  - More realistic for applications such as smart cards, embedded systems.
  - Attackers have physical access and can tamper with the algorithms’ internals.

Check CSAW-ESC



Encryption Security: Attack Models

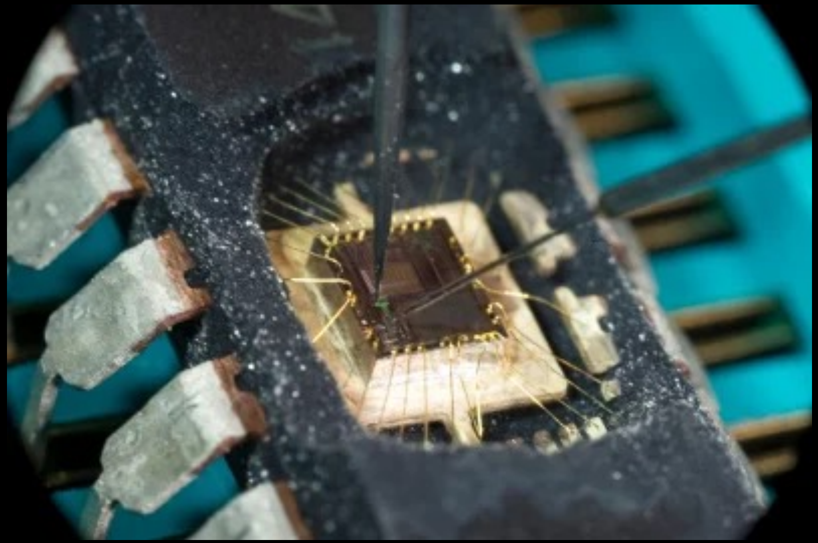
- Gray box models:
  1. **Side-channel attacks**: an attacker exploits the leakage of physical information from a system during the execution of an application.
     - They are noninvasive.

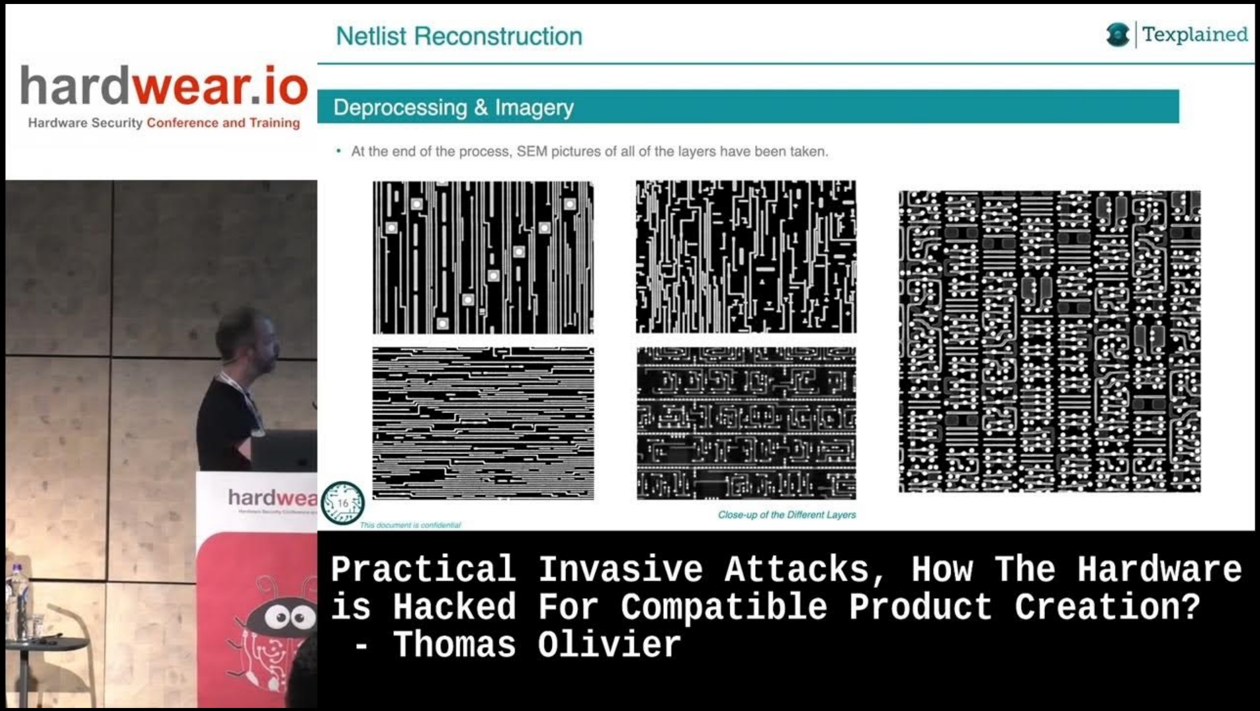


Encryption Security: Attack Models

- Gray box models:

  2. **Invasive attacks**: require direct access to the internal components of the device, which requires a well-equipped and knowledgeable attacker to succeed.
     - Require tools such as a high-resolution microscopes and a chemical lab.





Encryption Security: Security Goal

- Security goal: nothing can be learned about the cipher's behavior.
- Two main security goals:
  1. **Indistinguishability (IND).** Ciphertexts should be indistinguishable from random strings.

  2. **Non-malleability (NM).** Given a ciphertext $C_1 = E(K, P_1)$, it's impossible to create another ciphertext, C_2, whose corresponding plaintext, P_2, is related to P_1 in a meaningful way.
     - The OTP is malleable: given a ciphertext $C_1 = P_1 \oplus K$, you can define $C_2 = C_1 \oplus 1$, which is a valid ciphertext of $P_2 = P_1 \oplus 1$ under the same key K.

Encryption Security: Security Notion

- Security goals are only useful when combined with an attack model.

- The convention is to write a security notion as GOAL-MODEL.
    - IND-CPA
    - IND-CCA
    - NM-CPA
    - NM-CCA

Encryption Security: Security Notion

- The most important one: semantic security – IND-CPA.
- IND-CPA = ciphertexts don't leak any information about plaintexts as long as the key is secret.
- To achieve IND-CPA security, encryption must return different ciphertexts if called twice on the same plaintext.
  - This is can be achieved using **randomized encryption**.

Encryption Security: Security Notion

- In IND-CPA, encryption is expressed as $C = E(K, R, P)$
  - C is the result ciphertext
  - E is the encryption function
  - R is fresh random bits
  - K is the secret key
  - P is the plaintext

- Decryption is expressed as $P = D(K, R, C)$

Encryption Security: Security Notion

- To construct a semantically secure cipher, use a deterministic random bit generator (DRBG).

- **DRBG**: an algorithm that returns random looking bits given some secret value.
- Encryption becomes:

$$E(K, R, P) = (DRBG(K||R) \oplus P, R)$$

  - $K||R$ means concatenating the key with random bits.

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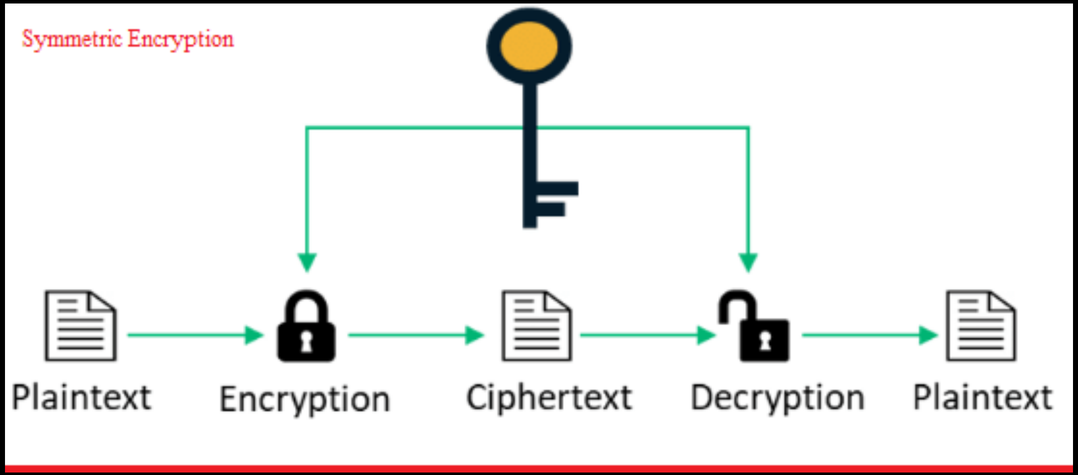
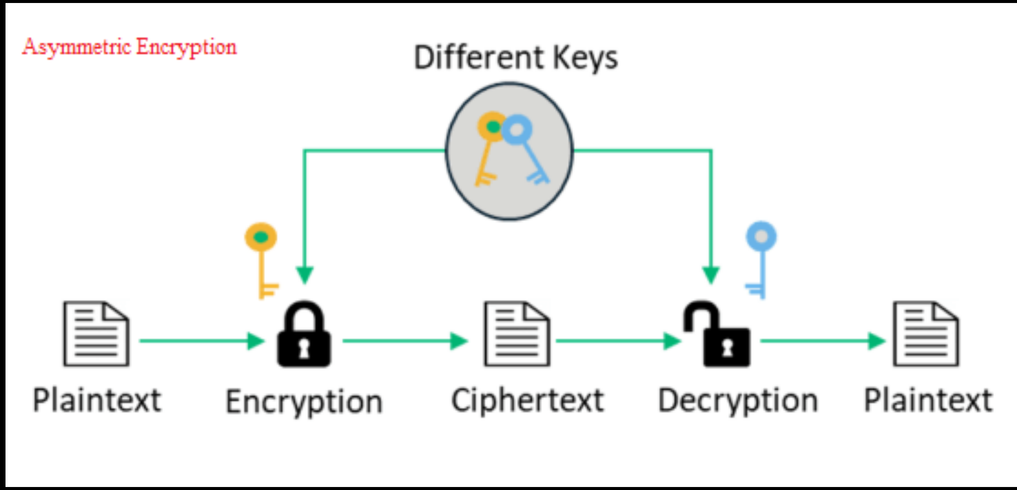
Asymmetric Encryption

- Symmetric encryption: use one key for encryption and decryption.
- In asymmetric encryption, there are two keys:
  - The **encryption** key (**public key**),publicly available to anyone who wants to send you encrypted messages.
  - The **decryption** key must remain secret and is called a **private** key.





Asymmetric Encryption

- The public key can be computed from the private key.
- The private key can’t be computed from the public key.

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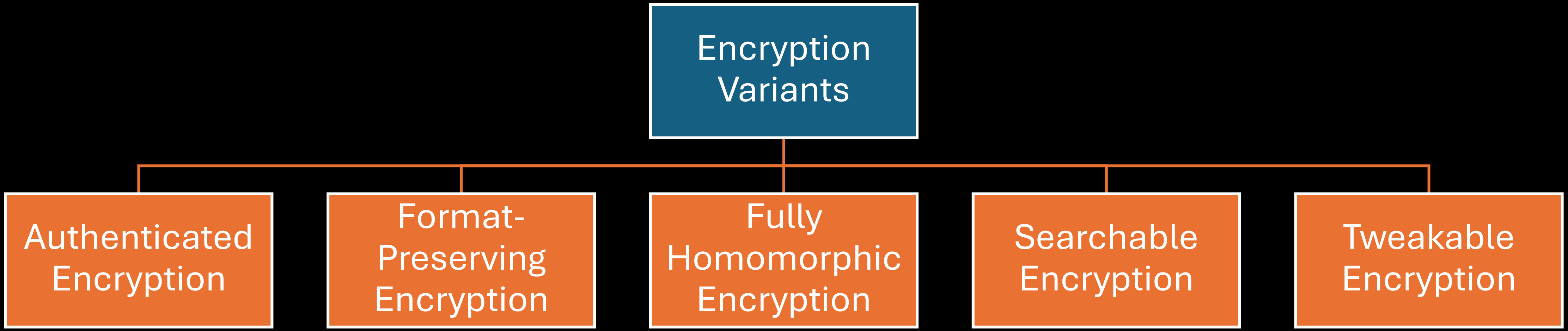


When Ciphers Do More Than Encryption

Authenticated Encryption:

- A symmetric encryption that returns an authentication tag and a ciphertext.
- $AE(K, P) = (C, T)$
  - The tag T is a short string that's impossible to guess without the key.
- The tag ensures the integrity of the message.
  - Evidence that the ciphertext received is identical to the one sent in the first
- Decryption takes K, C, and T and returns P only if it verifies that T is valid otherwise, it aborts and returns some error.

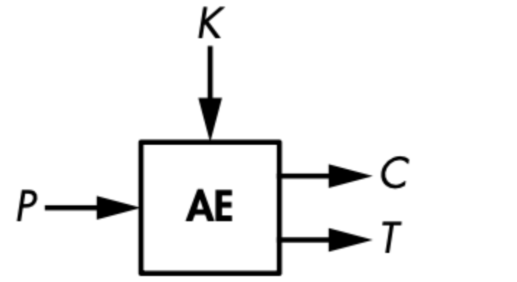


Figure 1-4: Authenticated encryption

When Ciphers Do More Than Encryption

Authenticated encryption with associated data (AEAD):

- An extension of authenticated encryption that takes some cleartext and unencrypted data and uses it to generate the authentication tag.

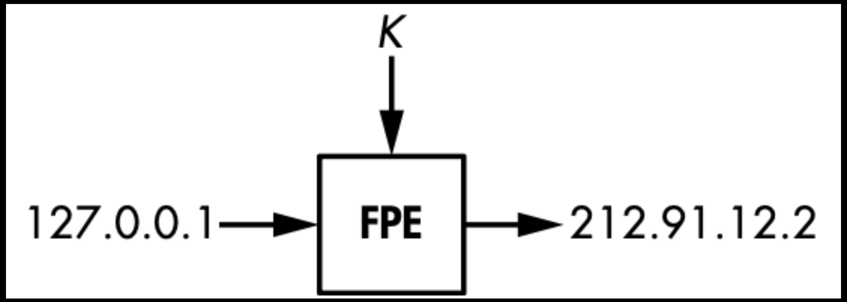
- AEAD(K, P, A) = (C, T).

- Can be used to protect protocols' datagrams with a cleartext header and an encrypted payload.
  - Destination addresses need to be clear in order to route network packets.

When Ciphers Do More Than Encryption

Format-Preserving Encryption:

- It can create ciphertexts that have the same format as the plaintext.
- For example, FPE can encrypt
  - IP addresses to IP addresses
  - ZIP codes to ZIP codes,
  - credit card numbers to credit card numbers



When Ciphers Do More Than Encryption

Fully Homomorphic Encryption:

- Enables computing a function on a ciphertext without the need to decrypting it.
- In FHE:
  - If we need to compute a function F on a plaintext P to get a result.
  - FHE encrypts P to C and transforms F to F`.
  - Then compute F`(C) to C`.
  - When decrypting C`, we get F(P).
- Downside: very slow.

When Ciphers Do More Than Encryption

Searchable Encryption:

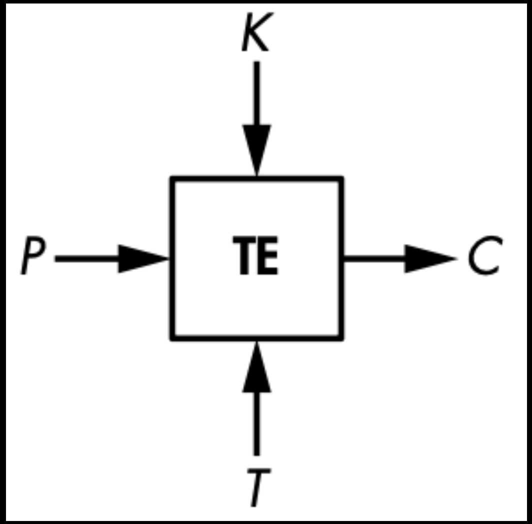
- Enables searching over an encrypted database without leaking the searched terms by encrypting the search query itself.

- FHE and searchable encryption enhance the privacy of cloud-based applications by hiding your searches from your cloud provider.

When Ciphers Do More Than Encryption

Tweakable Encryption:

- Similar to basic encryption, except it has a parameter called a *tweak*.
  - aims to simulate different versions of a cipher.



- The main application is disk encryption.
  - It uses a tweak value that depends on the position of the data encrypted, which is usually a sector number or a block index.

TASK

- Implement the Vigenère cipher. Encrypt the message “I LOVE CRYPTO” using the key “BAD”
- Implement the OTP cipher. Use $secret$ module in Python to generate a secure random key.