Introduction to Computer Security

CE Bootcamp

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What is computer security?

- A set of *policies* for maintaining three properties:
  - Confidentiality
  - Integrity
  - Availability

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Security vs. Privacy vs. Safety

- Security is often about protecting data from unauthorized access.
- Privacy is about making sure that the data is either not collected in the first place or, if collected, not misused.
- Safety (also called resiliency or robustness) is about making sure that systems still work as expected...
    - But the "adversary" is mother nature rather than deliberate human action.

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Why it matters?

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Why it matters?

- Our lives are increasingly dependent on computers
  - Protecting our assets
  - Controlling critical tasks
  - Productibility
  - Safety
    - Flights, cars, medical devices, etc.
  - …

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Why it matters?

- Our lives are increasingly dependent on computers
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  - Productibility
  - Safety
    - Flights, cars, medical devices, etc.
  - …

- *Even beyond individual users – government scale*

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$6

Trillion

Cybercrime Cost
by 2021

11

Seconds

average time
for an attack
by 2021

$1 Trillion

Cybersecurity Spending
by 2021

NotPetya

- Attacking critical businesses in Ukraine.
  - ranging from media outlets to railway firms
- The attackers released a malicious "worm"
  - A program which self-propagates: spreads from computer to computer in an institution.
- And then disabled all the infected computers with a fake "ransomware" payload.
  - Ransomware is a program that "encrypts" the computer's hard-drive.

THE UNTOLD STORY OF NOTPETYA, THE MOST DEVASTATING CYBERATTACK IN HISTORY

Crippled ports. Paralyzed corporations. Frozen government agencies. How a single piece of code crashed the world.

BY ANDY GREENBERG

IT WAS A perfect sunny summer afternoon in Copenhagen when the world's largest shipping conglomerate began to lose its mind.

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NotPetya

- Attackers asked for Ransom to "decrypt" each drive.

- According to the White House estimates, this attack has $10B in damage globally (mainly to Ukraine).

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What is in danger?

- Everything is hackable – especially if they are connected to the internet.

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Security: Status Quo

- For a long time we (mostly) didn't care…
  - We didn't "design for security."
  - Not much "knowledge" about security.
  - Security was a secondary objective.
  - *(What were the main objectives?)*

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Security: Status Quo

- For a long time we (mostly) didn't care…
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  - Security was a secondary objective.
  - *(What were the main objectives?)*

-- We have recently realized that wasn't good enough!

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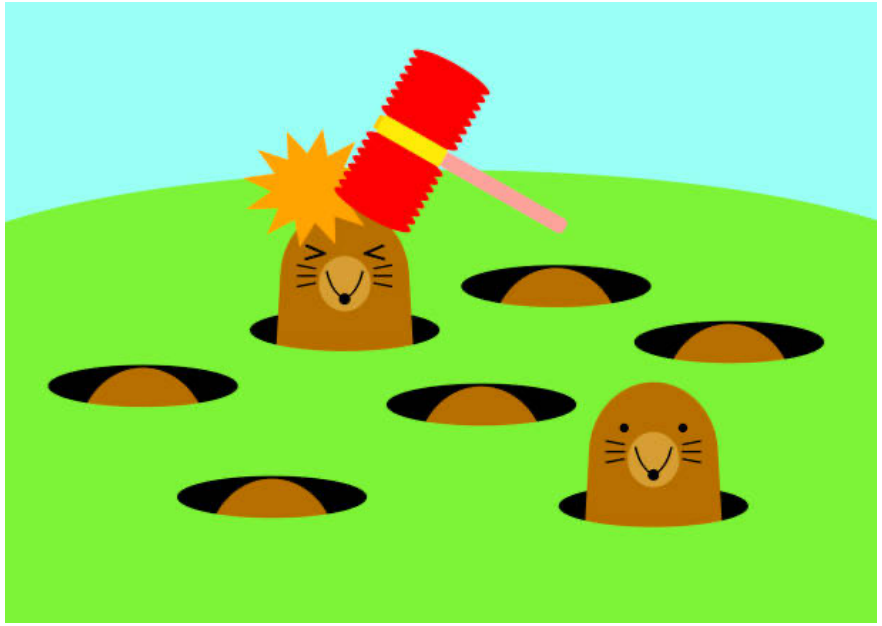
Current Strategy



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Why security is critical in the next decade?

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Why security is critical in the next decade?

1. More Devices (CPS and industry 4.0)

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Video

200

BILLION

BY 2020

$11.1

TRILLION

BY 2025

Video

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Why security is critical in the next decade?

1. More Devices (CPS and industry 4.0)

2. More Security Critical Applications

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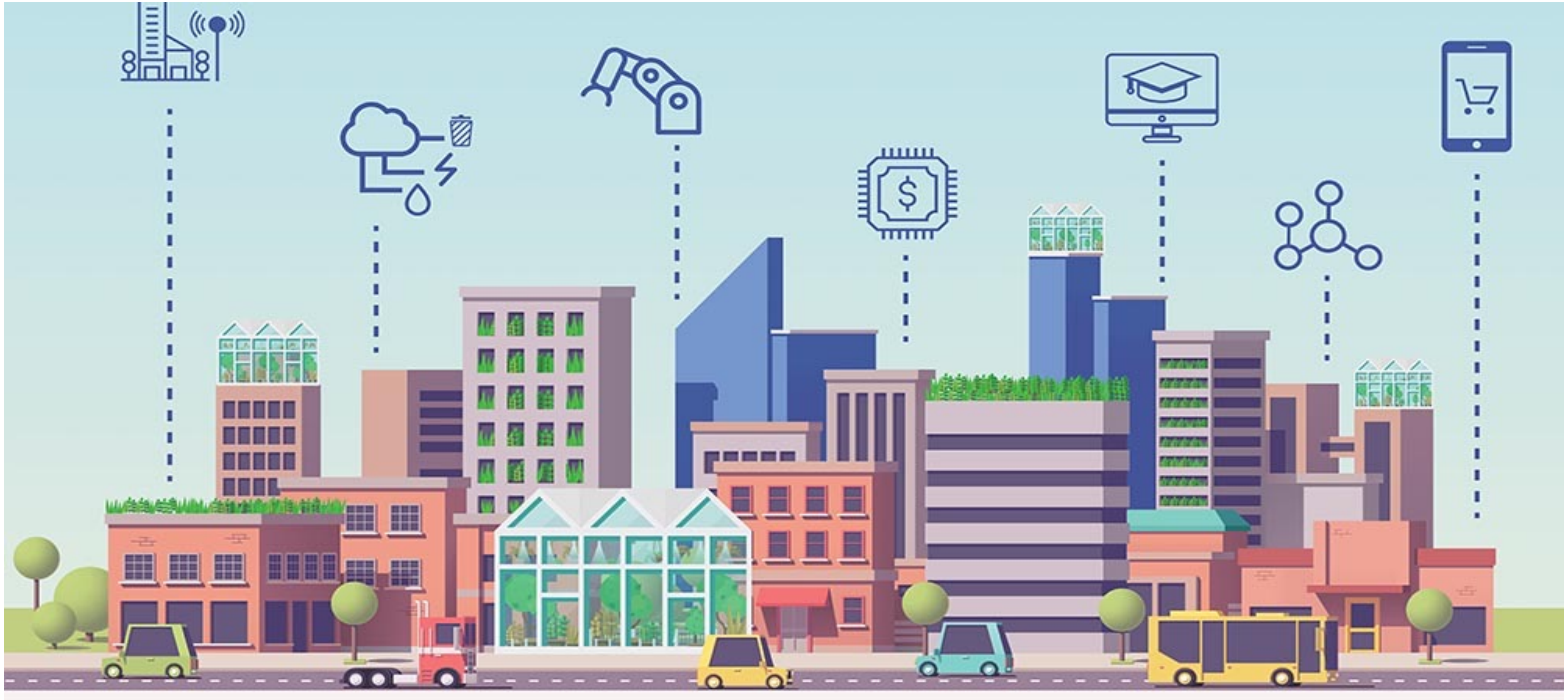

Computers control many *critical* tasks!

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Different Areas in Security

- Hardware Security
- Memory safety
- Operating System Security
- Network Security
- Web/Internet Security
- Software Security
- Cryptography
- Privacy
- …

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How do we enforce security in computers today?

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How do we enforce security in computers today?

1- "Principle of Least Privilege"

Users/Process should only have access to the data and resources needed to perform routine, authorized tasks.

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How do we enforce security in computers today?

1- "Principle of Least Privilege"

Users/Process should only have access to the data and resources needed to perform routine, authorized tasks.

-- This leads to "privilege separation". Typically "user" and "root" level access.

Modern systems have multiple privilege levels.

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How do we enforce security in computers today?

2- Isolation

A process can not access (read or write) the memory content of any other process.

Isolation is typically enforced by OS through address translation.

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How do we enforce security in computers today?

3- Trusted Computing Base (TCB)

Trust something (e.g., hardware), build everything on top/around that.

- *Only need to verify the TCB.*
- *Keep it simple and small so it can be easily(!) verified.*

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Does it work?

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Why?

- Because of design bugs mainly
  - A computer system is very complex with so many components.
  - Hard to verify everything *(known unknown)*

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Why?

- Because of design bugs mainly
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  - Hard to verify everything *(known unknown)*

  - Further, information can be leaked through additional channels called side-channel *(unknown unknown)*

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How do computers work?

Video

How do computers work?

- Theoretical and Historical Points of View

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How do computers work?

- Theoretical and Historical Points of View
    - Turing machines and history of electronics and computers

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Video

How do computers work?

- Theoretical and Historical Points of View
  - Turing machines and history of electronics and computers

Watch This:

- Theory of Computation: https://www.youtube.com/watch?v=PLVCscCY4xI
- History of Computers: https://www.youtube.com/watch?v=pBiVyEfZVUU

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How do computers work?

- We can see a computer as a *box* that runs our programs and shows us the results (display, print, etc.)

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How do ~~computers work~~ we see computers?

- We can see a computer as a *box* [with multiple layers] that runs our programs and shows us the results (display, print, etc.).

Video

How do ~~computers work~~ we see computers?

- We can see a computer as a *box* [with multiple layers] that runs our programs and shows us the results (display, print, etc.).

We define these layers as ***abstraction*** layers.

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Using Abstraction

- We see/define a computer as a *box* with multiple layers of **abstraction.**
  - Depending on which layer we want to work on, we *abstract away* the irrelevant layers.

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Using Abstraction

- We see/define a computer as a *box* with multiple layers of **abstraction.**

  - Depending on which layer we want to work on, we *abstract away* the irrelevant layers.

  - The ***main benefit*** is that we don't need to know the unnecessary details of the other layers in order to be able to work on our layer.

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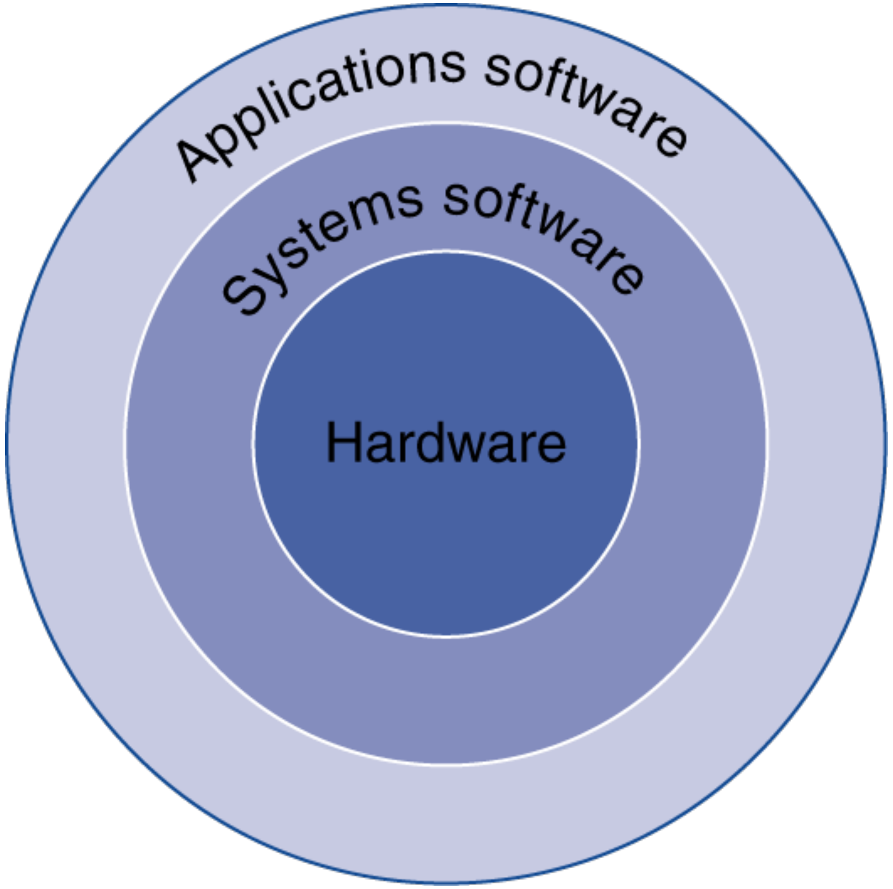
Computer Abstractions



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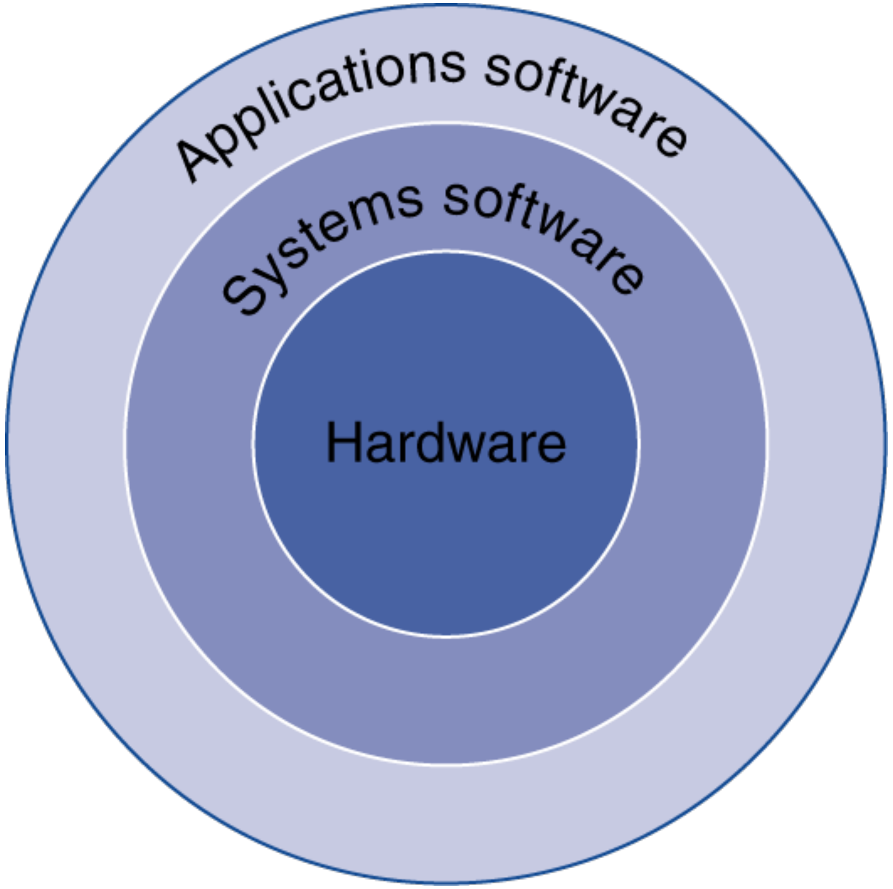
Computer Abstractions



- Application software
  - Translation from *algorithm* to code
  - Written in high-level language (e.g., C, JAVA)
- System software
  - ***Compiler***: translates HLL code to machine code
  - ***Operating System***: service code
    - Handling input/output
    - Managing memory and storage
    - Scheduling tasks & sharing resources
- Hardware
  - Processor, memory, I/O controllers

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Computer Abstractions

Watch This:
https://www.youtube.com/watch?v=_y-5nZAbgt4

- Application software
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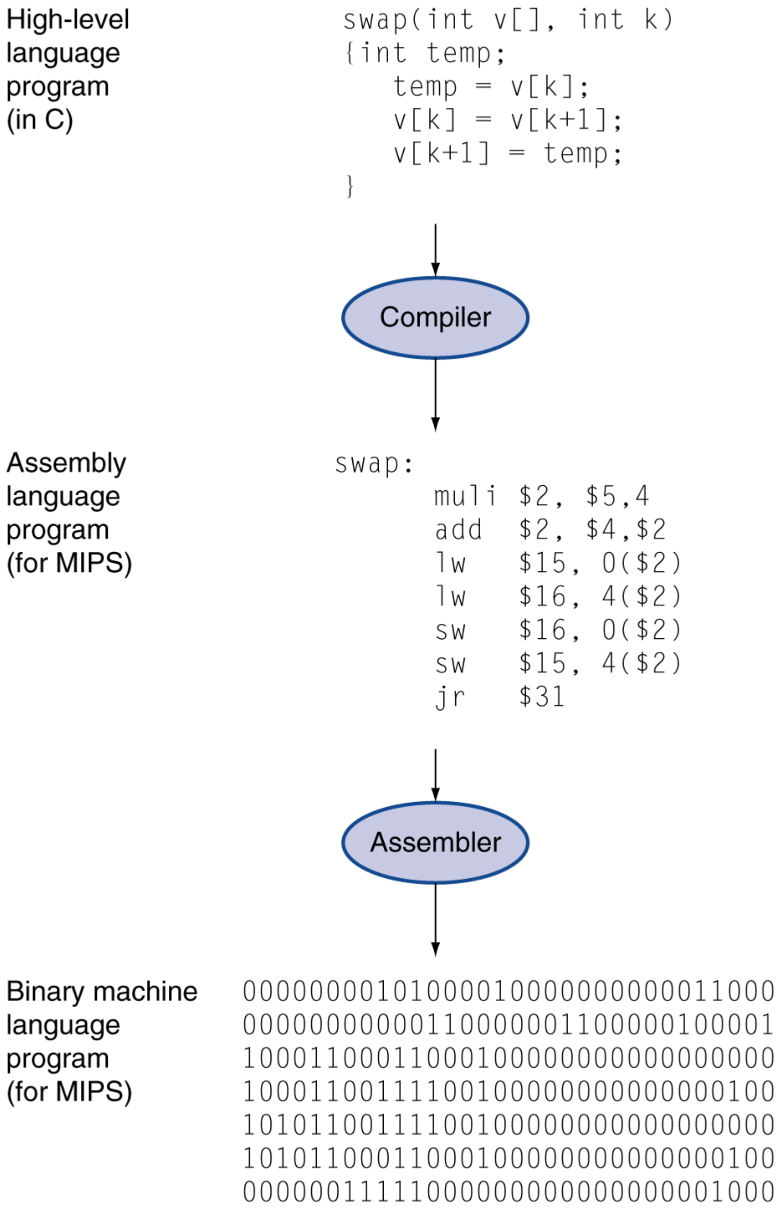
Level of Program Code

- High-level language
  - Level of abstraction closer to problem domain
  - Provides for productivity and portability
- Assembly language
  - Textual representation of instructions
- Hardware representation
  - Binary digits (bits)
  - Encoded instructions and data



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High-level language program (in C)

```
swap(int v[], int k)
{int temp;
   temp = v[k];
   v[k] = v[k+1];
   v[k+1] = temp;
}
```

Compiler

Assembly language program (for MIPS)

```
swap:
      muli $2, $5,4
      add  $2, $4,$2
      lw   $15, 0($2)
      lw   $16, 4($2)
      sw   $16, 0($2)
      sw   $15, 4($2)
      jr   $31
```

Assembler

Binary machine language program (for MIPS)

```
00000000101000010000000000011000
00000000000110000001100000100001
10001100011000100000000000000000
10001100111100100000000000000100
10101100111100100000000000000000
10101100011000100000000000000100
00000011111000000000000000001000
```

Compiler is a piece of software that translates HHL into a set of instructions based on a given hardware.

We will talk about this more!

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Level of Program Code

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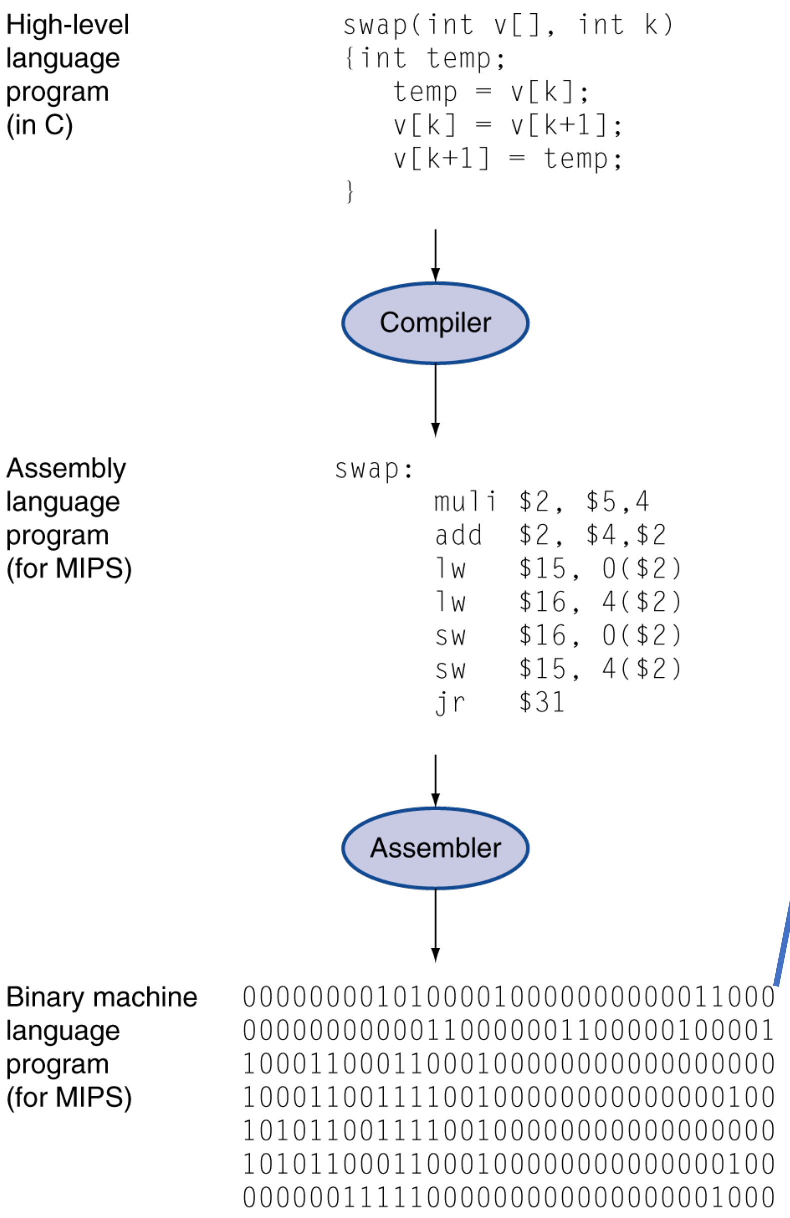

Think about the processor as a *machine* that reads these bits and executes the instructions.

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Computer Abstraction and Security

- For each layer set of rules can be enforced to ensure security
  - Hardware, operating systems, software

- Finding the interaction between layers is hard to quantify (hence new vulnerabilities).

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Why?

- Because of design bugs mainly
  - A computer system is very complex with so many components.
  - Hard to verify everything *(known unknown)*

  - Further, information can be leaked through additional channels called side-channel *(unknown unknown)*

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So, what is “side-channels”?

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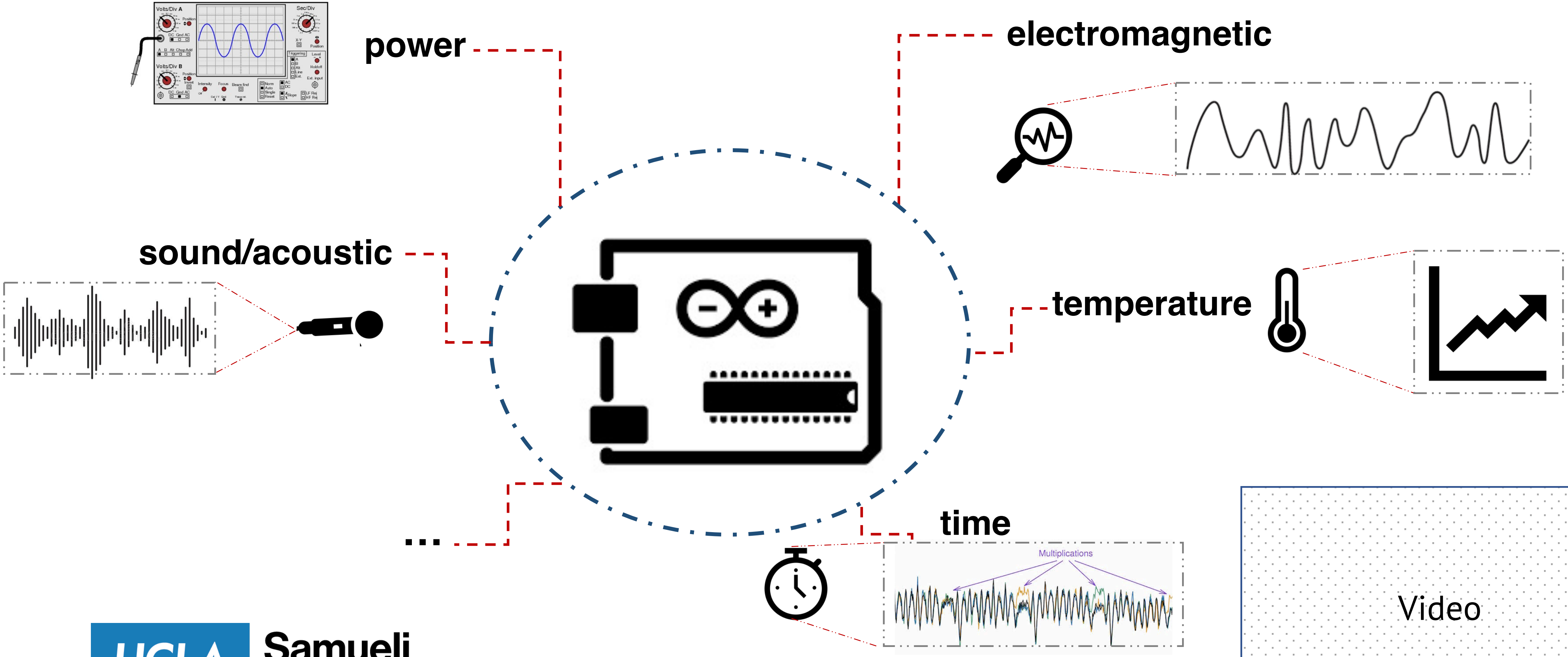
Side-Channels



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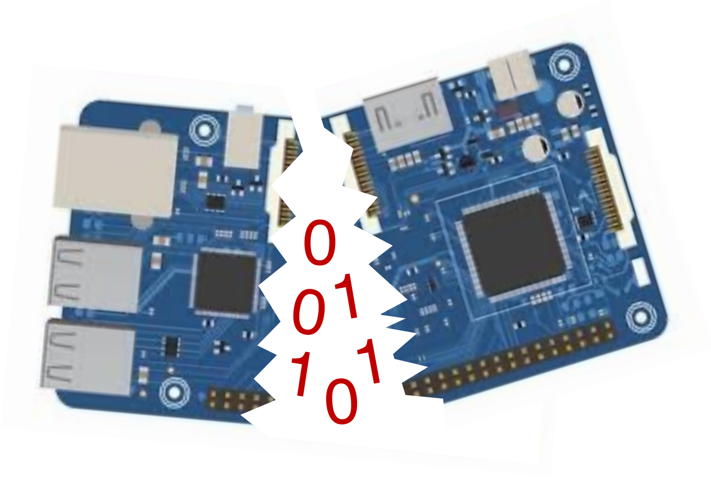
Side-Channels can *leak* secrets!

An adversary can leverage the existing ***correlation*** between the side-channel signals and critical information in the application to discover the secrets.



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Types of Side-Channels

Digital/Microarchitectural

Analog/Physical

- cache
- memory
- u-arch
- TLB

…

- electromagnetic
- power
- temperature
- sound

…

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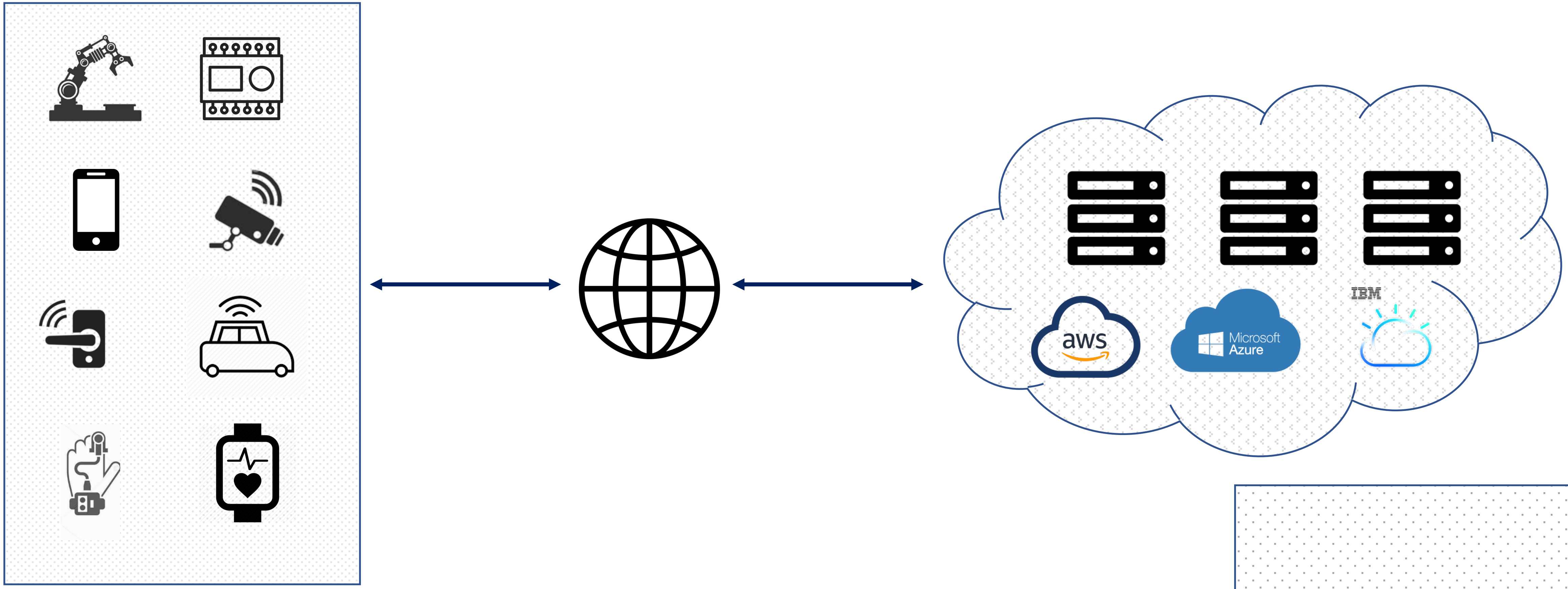
Main issues



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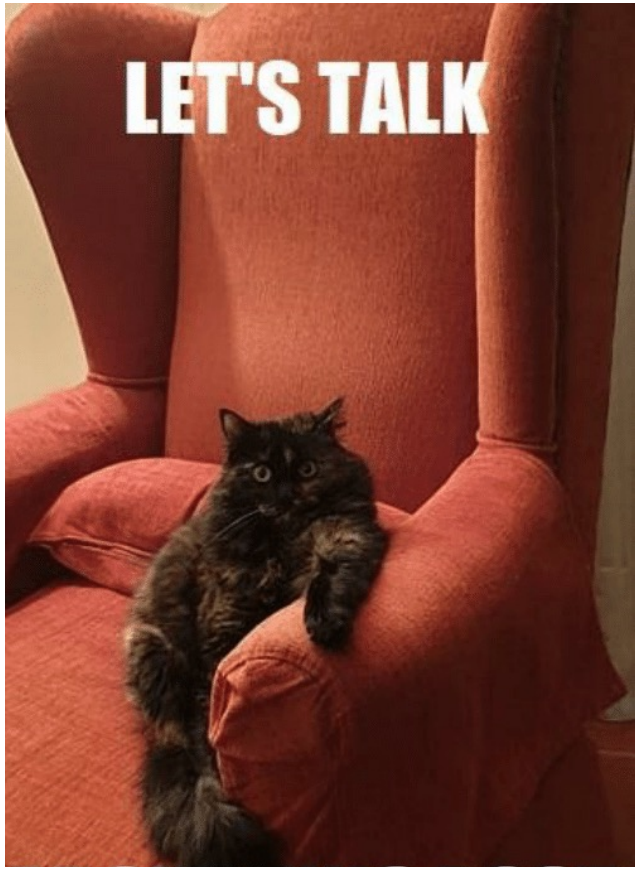
Now let's talk a little bit about cryptography…



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Why do we need cryptographic primitives?

-- *How to ensure communication are secured?*

-- *How to trust a user?*

-- *How to make sure a file is not modified?*

…

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Foundations of Computer Security

- We make some *fundamental assumptions and definitions* (e.g., usually based on some hard problems).

- Using these basic assumptions/definitions, we should be able to ***mathematically*** prove the statement in question.

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Foundations of Computer Security

- We make some *fundamental assumptions and definitions* (e.g., usually based on some hard problems).

- Using these basic assumptions/definitions, we should be able to ***mathematically*** prove the statement in question.

(if assumptions are correct → statement is correct)

- Assumptions may be proven incorrect!
- Assumptions may not be always correct!
- *Hardware implementation can change things!*
- ***Side-Channels!***
- Security can not be ad-hoc!

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Why do we need cryptographic primitives?

- Confidentiality/Privacy
  - Only the communicating parties should know the message.

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  - Guaranteeing that the message is not comprised/modified.

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Why do we need cryptographic primitives?

- Confidentiality/Privacy
  - Only the communicating parties should know the message.
- Integrity
  - Guaranteeing that the message is not comprised/modified.
- Authentication and Trust
  - proving or showing something (e.g., identity, computation) to be true, genuine, or valid.

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A (very) High-Level View of a *Cryptosystem*

- For any cryptosystem we have:
  - A secret value (called key)
  - A cryptographic algorithm (e.g., encryption, MAC, Hash, etc.)
  - An input: usually called a message (code, data, etc.)
  - An output: ciphertext, hash, …

Video

A (very) High-Level View of a *Cryptosystem*

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-- Kerckhoffs's principle / Shannon : A cryptosystem should be secure even if everything about the system, except the key, is public knowledge.*

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Main Cryptographic Modes

- Symmetric Key

- Asymmetric Key

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Main Cryptographic Modes

- Symmetric Key
  - *A value (called secret key) that is secretly shared among trusted parties.*
- Asymmetric Key

Video

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Main Cryptographic Modes

- Symmetric Key
  - *A value (called secret key) that is secretly shared among trusted parties.*

- Asymmetric Key
  - A pair of values: *(public key, private key)*.
  - *Public key* is unique to each user but shared to everyone publicly.
  - *Private key* is unique to every user and should be held secret.

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Encryption/Decryption

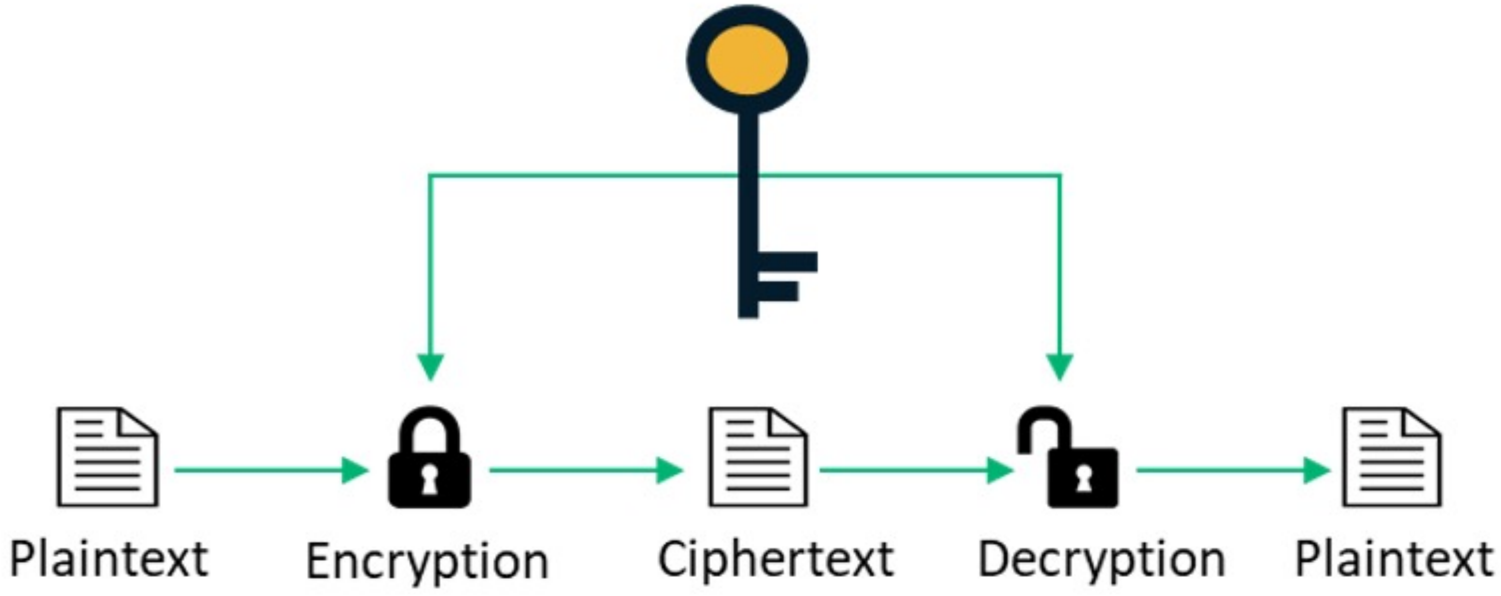

*Image was taken from: https://sectigostore.com/blog/5-differences-between-symmetric-vs-asymmetric-encryption

Correctness:

- M = Dec(Enc(M))

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What is a secure encryption algorithm?

$$c = E(m, k)$$

$$m = D(c, k)$$

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What is a secure encryption algorithm?

- *It should be hard to completely determine m from c, without knowledge of k.*

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What is a secure encryption algorithm?

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-- Is this enough?

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  - Say we have only two messages. Seeing C, if there is not equal chance between: $C = E(m_1,k_1)$ and $C = E(m_2,k_2)$, *then the adversary can guess the correct answer with more than 50%.*

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What is a secure encryption algorithm?

- *It should be hard to completely determine m from c, without knowledge of k.*

-- Is this enough?

- Say we have only two messages. Seeing C, if there is not equal chance between: $C = E(m_1,k_1)$ and $C = E(m_2,k_2)$, *then the adversary can guess the correct answer with more than 50%.*

--- We need perfect secrecy!

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Perfect Secrecy

- If for all $m_0, m_1 \in M$, and all $c \in C$, and random variable k is *uniformly* distributed over K:

$$\Pr[E(k, m_0) = c] = \Pr[E(k, m_1) = c];$$

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Can we achieve perfect secrecy?

- Yes!

-- One-Time Pad:

$$m \oplus k = c$$

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Issue with One-Time-Pad?

- For perfect secrecy we need:

$$|m| = |k|$$

(key should be as large as the message!)

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Semantic Security

- Given two messages and their encryptions, the chance that the attacker finds out which encryption belongs to which message should be *negligible*.

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Message Recovery Attack

- User/challenger encrypts $\hat{m}$ and sends c to the adversary. The chance that the adversary can guess the message better than $1/|M|$ should be *negligible*.

(Semantic Security guarantees this.)

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One time vs. many time encryption

- Add this ….

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PRF and PRP

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Semantically Secure Symmetric Encryption

- Two Options:

  1 - Stream Ciphers

  2 - Block Ciphers

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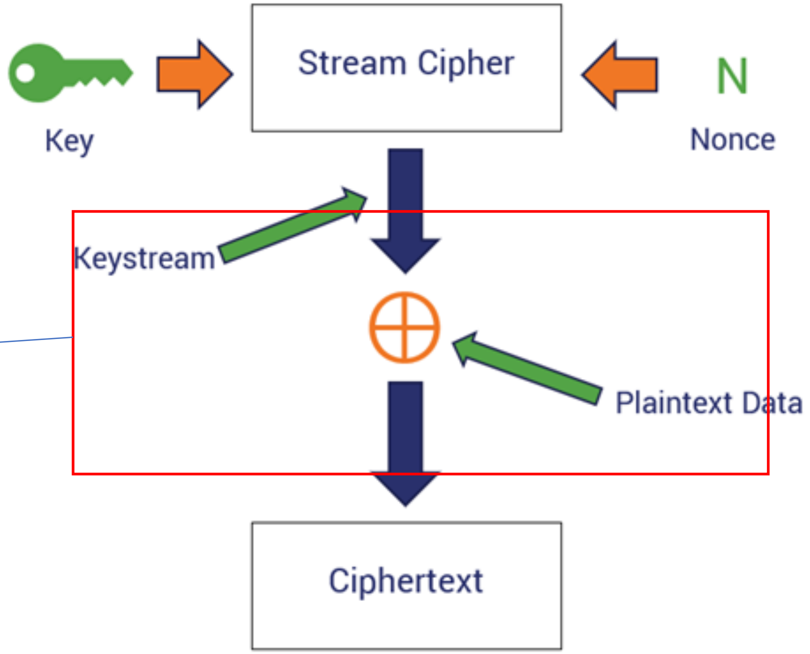
Stream Cipher



One-time pad

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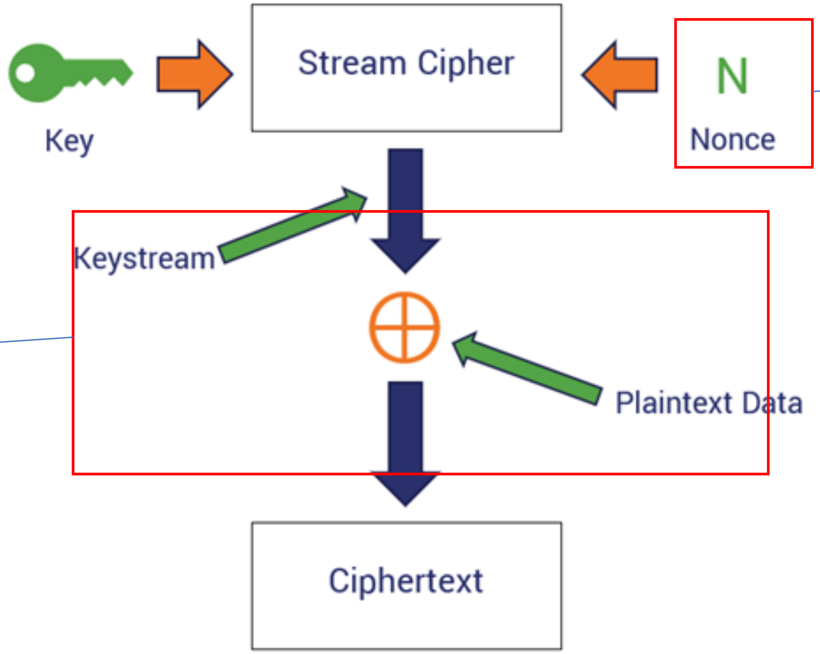
Stream Cipher



Adding randomness

One-time pad

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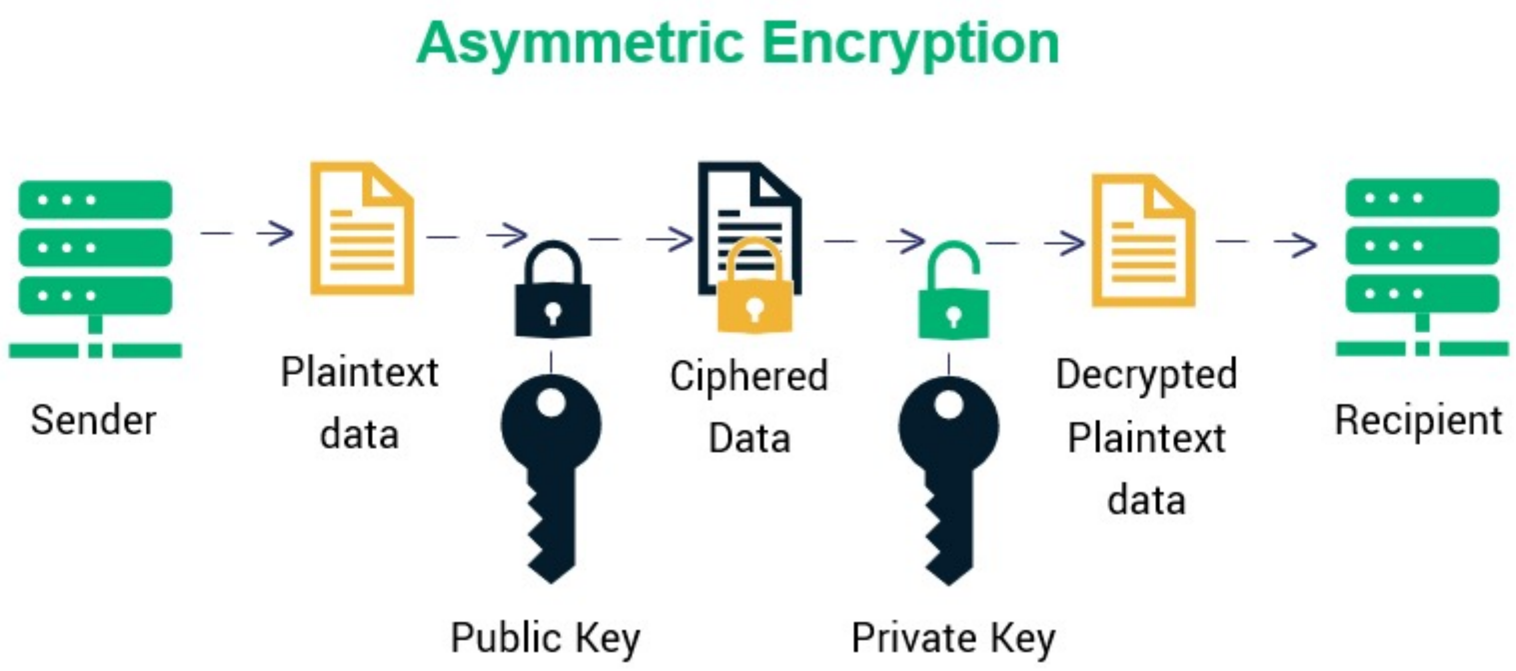
Asymmetric Encryption



different

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*Image was taken from: https://sectigostore.com/blog/5-differences-between-symmetric-vs-asymmetric-encryption

Differences with Symmetric Encryption

- No need to agree on the same key.
- No need to secure others' keys.

- Correctness:

$$D(sk, E(pk, m)) = m$$

- Same security guarantees.

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Differences with Symmetric Encryption

- *Chosen Cyphertext Attack:*
  - In symmetric key cryptography, the adversary cannot send chosen messages (doesn't have access to the key to encrypt).
  - In public-key cryptography, the attacker can actively choose a desired cyphertext (the public key is known).

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Symmetric and Asymmetric Cryptosystems

- AES
- RSA
- …

(how and why secure?)

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Other Applications

- Message Integrity

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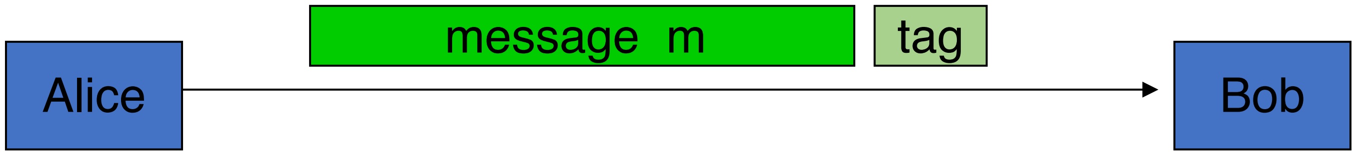
Message Integrity

-- Goal:

Provide proof that the message/data is not modified.



Generate/Sign tag

G(m) = tag

Verify tag:

if (V(m) == tag)

accept …

*Image was taken from: https://crypto.stanford.edu/~dabo/courses/OnlineCrypto/

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Other Applications

- Message Integrity

- Hash Functions

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Hash Function

- A hash function is any function that can be used to map data of arbitrary size to fixed-size values.

- The values returned by a hash function are called *digests*, or simply hashes.

-- Saves space, time, computation, etc.

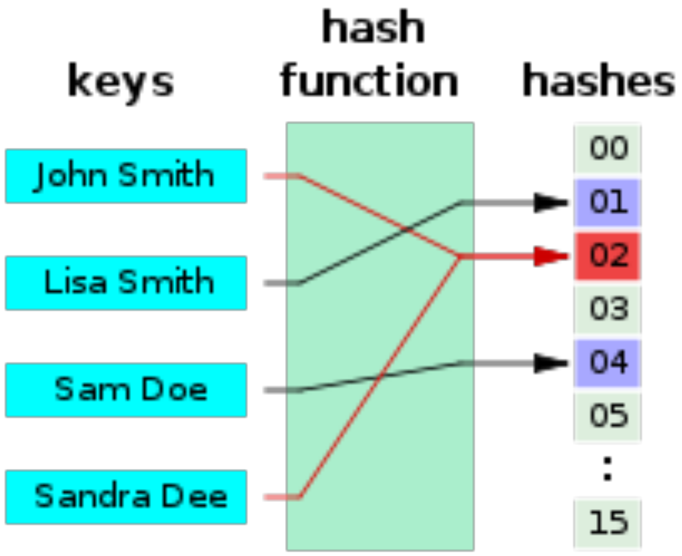

*Image was taken from Wikipedia.

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Secure Hash Function

-- Collision Resistance:

Let $H: M \rightarrow T$ be a hash function ($|M| >> |T|$)

A *collision* for H is a pair $m_0, m_1 \in M$ such that:

$$H(m_0) = H(m_1) \quad \text{and} \quad m_0 \neq m_1$$

A function H is *collision resistant* if for all (explicit) "eff" algs. A:

Pr[A outputs collision for H] is "neg".

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Secure Hash Function

-- *Collision Resistance*

-- *Pre-Image Resistance:*

Given a hash value h, it should be difficult to find any message m such that h = hash(m).

-- *Second pre-image Resistance:*

Given an input m_1, it should be difficult to find a different input m_2 such that hash(m_1) = hash(m_2)

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Other Applications

- Message Integrity
- Hash Functions
- Digital Signature

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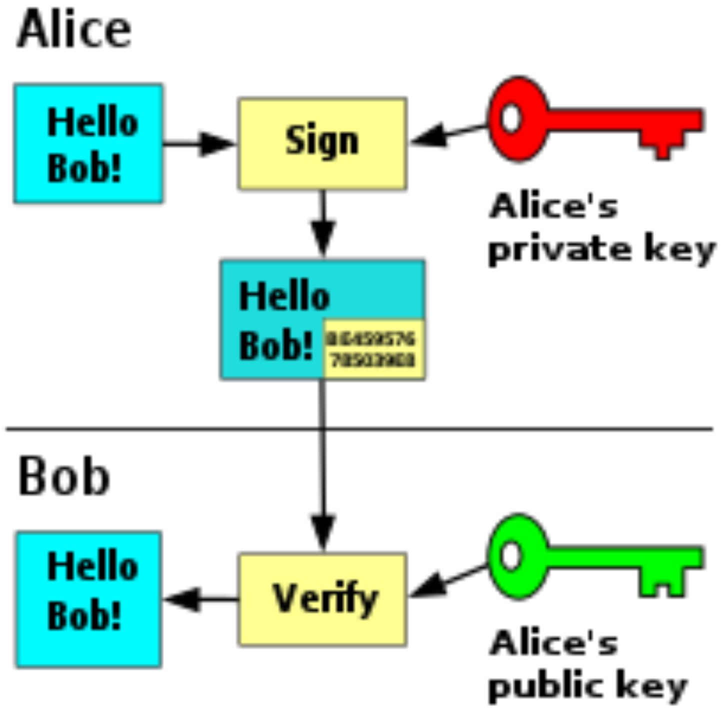
Digital Signature

- A valid digital signature, gives a recipient ensures:
  - The message was created by a known sender (authentication),
  - The message was not altered in transit (integrity).



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Recap

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Summary

- Computer security is a very important topic in our modern era which is receiving a growing attention.

- It crosscuts various disciplines in computer science and engineering.

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Summary

- Security is not just about systems but also about the users.
  - Good practices
  - Following the protocols
  - Being cautions
  - …

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What’s next?

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End of Presentation

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