POLITECNICO DI TORINO

Master degree in Cybersecurity

Information Systems Security

Notes from the course 01TYMUV of Prof. Antonio Lioy
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IMPORTANT NOTICE: these notes are not in any way promoted or checked by the professor or any person of the course teaching staff, so they are provided "AS-IS" and without any guarantee. However, we put a great effort to make them and verify their correctness, we hope they will be useful for you.

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Preliminary notes

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Chapter 1

Introduction to the security of ICT systems

1.1 Why is security an important issue?

Cybersecurity has become very important in today's world. Since every system relies on computer systems, any kind of damage can result in significant economic losses. Even indirect attacks that do not aim to steal money have economic costs. Cybersecurity is essential because attacks can be performed without the need to physically access the target location.

The reasons why cybersecurity is important are as follows:

- Big damage on successful attacks
- Easy accessibility of systems

We must consider all the possible consequences of a successful attack. First, there can be **financial loss** (direct loss, for example, if someone gains access to bank account credentials, and indirect loss if the revelation that the company has been attacked negatively affects the stock exchange). There can be **recovery costs** because every successful attack results in damage, and there will be expenses required to return the system to normal operations and to enhance it to prevent new attacks. There can also be **productivity losses** if the attacks halt or delay processes. A successful attack may lead to **business disruption** because customers may seek alternative suppliers if a company is vulnerable to attacks.

For all these reasons we should protect systems. Most of the innovation is based on two main pillars:

- The ability to communicate from any part of the world (communication networks)
- The increasing use of personal and mobile devices

These two foundations are no longer sufficient for innovative products; every new product now requires a security system.

1.2 Complexity of the ICT scenario

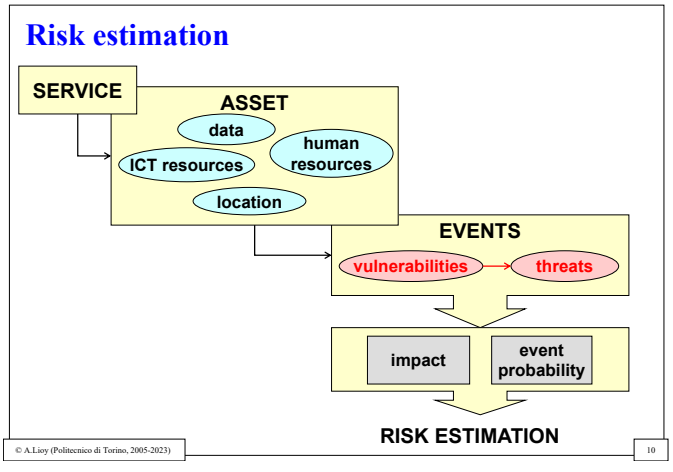
The ICT scenario is complex for various reasons. One key factor is the sheer number of different mobile and connected **devices**, including desktops, laptops, tablets, smartphones, smart TVs, fridges, and cars. All these devices can now connect to the internet, making security a critical concern. **Communication networks** have shifted to data-only networks, meaning there are no more analog phone networks. This change implies that almost everything is vulnerable to potential attacks. It's not just wireless networks that can be targeted; even wired networks are susceptible to security threats. **Distributed services** are on the rise, requiring constant technical solutions to keep them running. This often involves outsourcing parts of server management, hosting, and adopting cloud services. This means that computers are no longer confined within a company, which necessitates trust in the service providers. Additionally, software development is getting more complicated due to various factors like software layering, framework integration, and the use of multiple programming languages. This complexity increases the chances of errors and vulnerabilities. In terms of security, the challenges can be summarized by the first engineering axiom:

"The more complex a system is, the harder it is to ensure its correctness."

Therefore, it's essential to keep systems as simple as possible. For instance, the number of bugs in a program tends to increase more than proportionally with the number of lines of code. The current complexity of information systems favors attackers, who can discover increasingly ingenious and unforeseen attack paths.
To express this idea clearly, we follow the **KISS rule**: *"Keep it Simple, Stupid."*

1.3 Risk estimation

Before setting up a defense, we must understand what the risks are. To make a risk estimation, it is good to start from the **service**. Once we know the service we need to protect, we must identify the assets used to provide that service, and there are four categories of assets: **ICT resources** (computers, disks, networks), **data** (not the disks but something intangible that could be deleted or modified), **location** (assets must be inside a protected room), and **human resources** (which means the group of people who possess the knowledge that must not be shared).



After considering the assets, the next step is to identify the events that could

affect their normal operation. The first point is that each asset has some **vulnerabilities** (for example, disks that are vulnerable to physical damage like a hammer hitting the disk), and some vulnerabilities can pose a real **threat** depending on the environment. For example, if a disk is left in an open place, someone might use a hammer to damage the disk. However, if the disk is locked in a room where nobody can access it, the vulnerability still exists but is not a real threat.

So, the process of analyzing a service searching for risks take place as follows:

- Find the **assets** of the service to be protected;
- Finding the **vulnerabilities** of each asset;
- Finding the **threats**, giving the way in which the assets are used;

Once we identify the threats we must:

- decide for each threat which **impact** it could have (what happens if disk is destroyed? If there's only one copy it could be a disaster, but if there are many that's not a problem)
- the **event probability** of the threat. This is the last point to get the **risk estimation**.

Recap of terminology:

Asset: the set of goods

Vulnerability: weakness of an asset;

Threat: deliberate action/accidental event that can procure the loss of a security property exploiting a vulnerability;

Attack: threat occurrence (deliberate action);

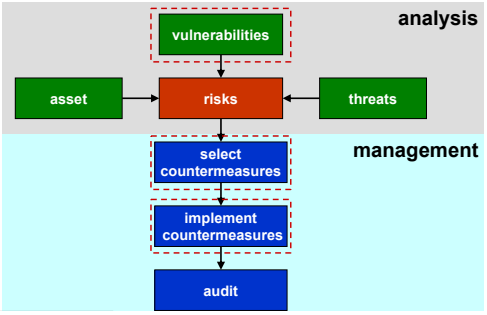
(negative) Event: threat occurrence (accidental event)

1.4 Risk management

To prioritize the risks, we can build a **risk assessment matrix** (or risk heat map):

catastrophic (5)	5	10	15	20	25
significant (4)	4	8	12	16	20
moderate (3)	3	6	9	12	15
low (2)	2	4	6	8	10
negligible (1)	1	2	3	4	5
	improbable (1)	remote (2)	occasional (3)	probable (4)	frequent (5)

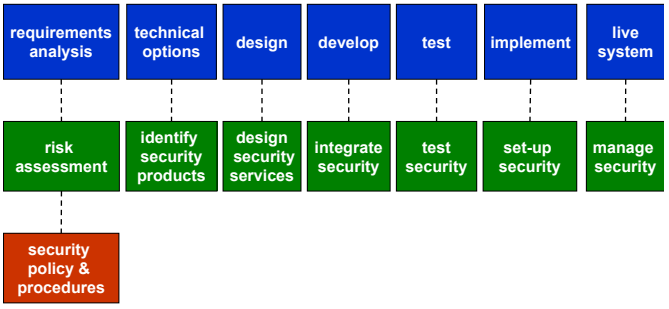
1.5 Analysis and management of security



Risk estimation is only a piece for analysis and management of security. We can see that **assets**, **vulnerabilities**, **threats** give us the **risks** and then we start the **management** of the security. This means that for those risks that are not acceptable, either because they have high impact or high probability to end up in an attack, we need to select countermeasures and implement them. The last step is **audit**, that means that some independent person comes to check our work (if we correctly identified risks, selected the correct countermeasures, implemented them correctly).

In this course we will consider three of these blocks: vulnerabilities, the available countermeasures, and how to implement countermeasures.

What is the correct step in the lifecycle of a system to implement security?
In brief, there is no single correct point for implementing security because it must be addressed at each stage of the design process.



In more detail, when we perform the **analysis of requirements** for our system, we must conduct a risk assessment; based on these risks, we can define security policies and procedures that we will apply throughout the rest of the system design.
When evaluating **technical options**, we also need to identify security products. For example, when choosing a database, we must consider security alongside other factors such as speed and cost. If we opt for a database that automatically encrypts data, we have already addressed a security concern. Conversely, if we choose a faster database that lacks an encryption system, we will need to design that separately, incurring additional costs and efforts.
When **designing** the services that the system will offer, we must also include the security services component. Security should be integrated at each stage of the design process, not added as an afterthought. If we create a prototype website or app without any security measures, it will be challenging to retrofit security later on.

1.6 Relation in the security field

During the development of our system, we must integrate security at each step and ensure that the design is correctly implemented. We must test the system, including its security aspects. An example of this is testing against unexpected inputs to ensure that the system does not accept

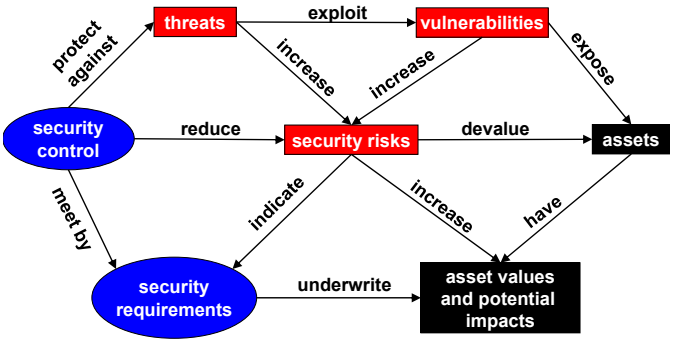
and process incorrect inputs.

While implementing our system, it is important to establish security mechanisms. Some systems include security functions, but they are often deactivated due to associated costs (generally, activating security may slow down the system). For instance, the default password of a home router may be shared among different units, so it is necessary to change that password.

When the system is operational, security must be managed on a daily basis, as the security landscape changes constantly.

1.7 Relation in the security field

The black box is the system itself. Assets are exposed to vulnerabilities, and those vulnerabilities increase security risks. Additionally, threats exploit vulnerabilities, and the existence of vulnerabilities creates the opportunity for a threat.



On the left, there are the security requirements that we want to implement. Security requirements are indicated by security risks, and security requirements are met by security controls.

The **security control** is the most important piece of the picture nowadays. It is an element placed in the system to **protect against a specific threat** and **reduce the risks to which the system is exposed**. Examples of security controls include firewalls, VPNs, and disk encryption.

Some terminology:

Incident: A security event that compromises the integrity, confidentiality, or availability of an information asset (generic definition).

(Data) breach: An incident that results in the disclosure or potential exposure of data.

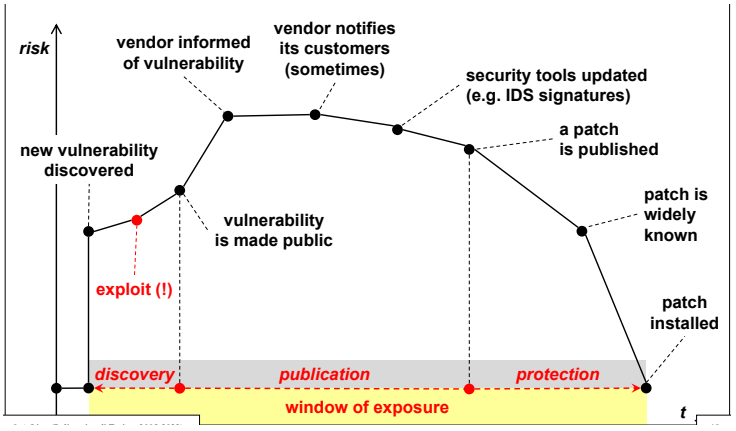
- Disclosure: Occurs when data is intentionally given to someone.
- Exposure: Data becomes available to anyone who knows where to find it.

(Data) disclosure: A breach for which it is confirmed that data was actually disclosed (not just exposed) to an unauthorized party.

The difference between the last two is that the last one is a breach involving data that were not just exposed but also confirmed to be disclosed to an unauthorized party.

1.8 Window of exposure

The **window of exposure** is *the time between the discovery of a new vulnerability and the installation of a patch.*



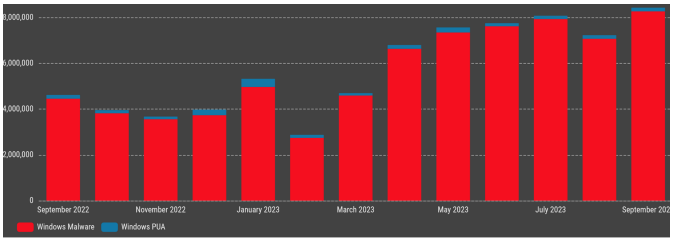
Analyzing the graph from the left, we notice a consistently low level of risk, which, although it can never be reduced to 0, remains close to it. However, at a certain juncture, a new vulnerability is discovered, causing the risk to surge due to its uncontrollable nature. At a specific point (marked as the red point), an individual exploits this vulnerability to execute an attack. This action leads to the vulnerability becoming public, thereby making it accessible to everyone. This initial stage is commonly referred to as **discovery**.

After an attack is carried out, two distinct groups of individuals become aware of it: the *bad guys* who aim to compromise the system and the *good guys* who strive to safeguard the system. Within these two categories, there is also the product vendor, who must be informed of the vulnerability. The vendor should, in turn, promptly notify its customers of the newly discovered vulnerability. While the vendor is working on fixing the vulnerability, users of that product should refrain from attempting to fix it, which is typically impossible. Instead, they should focus on updating their security tools, at the very least, to detect if the vulnerability is actively being exploited in attacks. This is the **publication** phase during which the vulnerability becomes public knowledge, and everyone is awaiting a fix while also making efforts to detect potential attacks.

Finally, at some point in time, the vendor creates a patch to fix the vulnerability. However, the patch must be distributed, and the risk only decreases when the patch becomes widely known and is eventually installed, rendering the system **protected**. The window of exposure can persist for days or even months, which is why security is an ongoing effort.

1.9 Some statistics

The graphic shows that there are about 10 million attacks per month using malware. That is why we should always keep our anti-virus/anti-malware updated. If we consider web servers across all sectors, 44% of servers were consistently vulnerable to attacks every day of the year.



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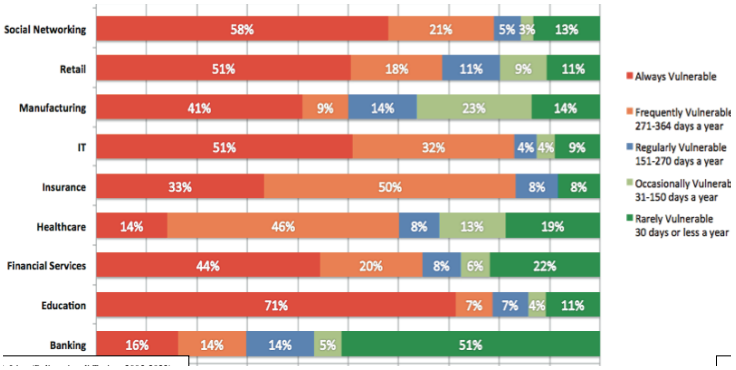
The term **0 day** refers to the first day



when a vulnerability is reported to the public and has not yet been fixed.

The banking sector boasts the best security track record, with the lowest vulnerability rate (rarely vulnerable for 30 days or less each year).

In general, achieving strong security is challenging. Vulnerabilities can be discovered by both well-intentioned individuals (good guys) and malicious actors (bad guys). Some people investigate software to uncover vulnerabilities and inform the vendor to patch them before they are exploited by malicious actors. This proactive approach is taken to ensure patches are in place before vulnerabilities are discovered by the bad guys.

The "**0-day initiative**" (**ZDI**) discovers vulnerabilities and notifies the relevant organizations *before* making them public. ZDI typically provides a 120-day grace period from the discovery of a new vulnerability to allow the vendor to fix it before disclosing it to the public. Longer deadlines can be risky, as bad guys may discover the vulnerability during the extended time frame.

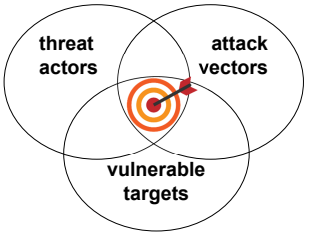
Example:

- 8 May 18: ZDI reports the vulnerability to the vendor, and the vendor acknowledges the report.
- 14 May 18: The vendor replies that they have successfully reproduced the issue reported by ZDI.
- 9 Sep 18: The vendor reports an issue with the fix and states that the fix might not be included in the September release.
- 10 Sep 18: ZDI issues a caution about a potential 0-day (which means that the vulnerability, for which a fix is not available, is going to be published).
- 11 Sep 18: The vendor confirms that the fix did not make it into the build.
- 12 Sep 18: ZDI confirms its intention to 0-day on 20 Sep 18.

1.10 Cyber threats

1.10.1 Components

There are **three main components** in cyber threats:



- threats actors (and their motivation)
- attack vectors (vulnerabilities and context)
- vulnerable targets (value for owner and attacker)

1.10.2 Motivations: *MICE*

What are the motivations behind this?

- **M is for Money:** direct transfer, blackmail, ... or indirect (e.g. data reselling);
- **Is is for Ideology:** political, religious, hacktivism;
- **C is for Compromise:** individuals with no choice due to blackmail or threat against their families or themselves;
- **E is for Ego:** bragging around and positive reputation, "we do it because we can".

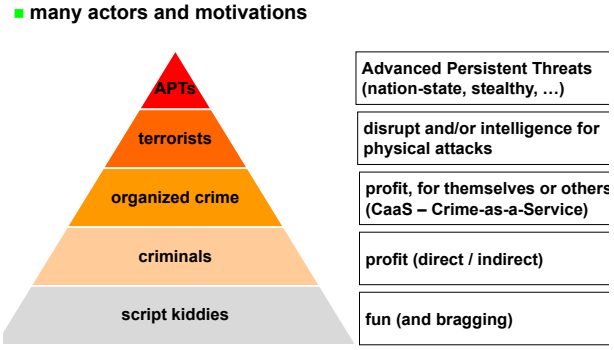


Figure 1.1: Threat actors

1.10.3 Standardization bodies

Standardization bodies in cybersecurity are organizations that develop and publish standards and guidelines to enhance security and interoperability in computer systems and networks.

(Cybersecurity) Standardization bodies (I)

- **ISO (International Organization for Standardization)**
- **ITU-T (International Telecommunication Union, Telecommunication standardization sector)**
- **ISOC (Internet Society)**
  - IETF (Internet Engineering Task Force)
  - IRTF (Internet Research Task Force)
- **NIST (National Institute of Standards & Technology)**
- **ANSI (American National Standards Institute)**

(Cybersecurity) Standardization bodies (II)

- **ETSI (European Telecommunications Standards Institute)**
- **CEN (European Committee for Standardization)**
- **CENELEC (European Committee for Electrotechnical Standardization)**
- **BSI (British Standards Institution)**
- **UNI = Italian national body for standards (unification)**
  - UNINFO = UNI body for information technologies and their applications
- **generically named SDO (Standards Developing Organization), or SSO (Standards Setting Organization)**

1.11 What is Security?

"Security is a process, not a product".

(Bruce Schneier, Crypto-Gram, May 2005)

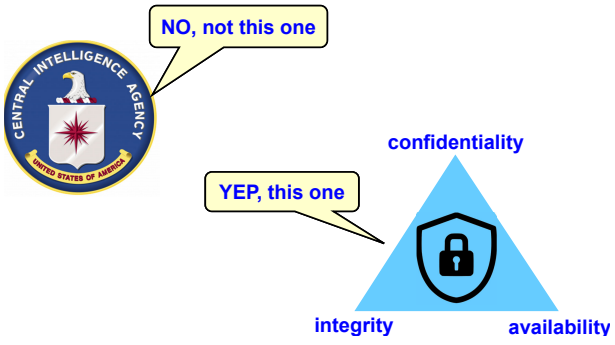
If we have learned anything from the past couple of years, it is that **computer security flaws are inevitable**. Systems break, vulnerabilities are reported in the press, and still many people put their faith in the next product, or the next upgrade, or the next patch. "This time it's secure", they say. So far, it has not been.
Security is a process, not a product. Products provide some protection, but the only way to effectively do business in an insecure world is to put processes in place that recognize the inherent insecurity in the products. **The trick is to reduce your risk of exposure regardless of the products or patches**.

Security Principles

To make it possible, it is necessary to follow some security principles:

- **Security in depth**: if the enemy can defeat the first line of defense, there must be a second line to stop the attacker. Do not rely on just one defense, as that defense may have a bug or problem. It is better to have multiple levels of defense, so as the attacker breaks through the defenses, it will become increasingly difficult to keep penetrating.
- **Security by design**: this means that the security design is integrated into the system from the beginning and not added as an afterthought.
- **Security by default**: users should not have the choice to activate or deactivate security. Security should be enabled by default, and it should require significant effort to disable security features.
- **Least privilege**: this principle dictates that any element operating within the system should be assigned the minimum amount of privileges necessary to perform its task. Imagine a scenario where a system has excessive privileges, and it is being attacked by a virus. The virus could gain access to everything because of the excessive privileges.
- **Need-to-know**: this principle emphasizes that access to any component of the system should be granted only for the data required to execute a specific task. For example, in the case of Amazon, several people work within the system. When a customer places an order on Amazon, the first person handling the order can only see the details of what was ordered. They do not have access to information about who placed the order or the destination of the goods.

1.12 Security and C.I.A.



The **C.I.A. triad**, standing for **Confidentiality**, **Integrity**, and **Availability**, is a foundational concept in information security. These three concepts have the following meaning:

- **Confidentiality** covers two related concepts:

Data confidentiality: assures that private or confidential information is not made available or disclosed to unauthorized individuals.

Privacy: assures that individuals control or influence what information related to them may be collected and stored and by whom and to whom that information may be disclosed.

In terms of requirements and the definition of a loss of security, it means preserving authorized restrictions on information access and disclosure, including means for protecting personal privacy and proprietary information. A loss of confidentiality is the unauthorized disclosure of information.

- **Integrity covers** two related concepts:

  Data integrity: assures that information (both stored and in transmitted packets) and programs are changed only in a specified and authorized manner.

  System integrity: assures that a system performs its intended function in an unimpaired manner, free from deliberate or inadvertent unauthorized manipulation of the system.

  In terms of requirements and the definition of a loss of security, it means guarding against improper information modification or destruction, including ensuring information nonrepudiation and authenticity. A loss of integrity is the unauthorized modification or destruction of information.

- **Availability:** assures that systems work promptly, and service is not denied to authorized users. In terms of requirements and the definition of a loss of security, it means ensuring timely and reliable access to and use of information. A loss of availability is the disruption of access to or use of information or an information system.

This definition is a good starting point for cybersecurity, but more than the C.I.A. triad is required; two of the most mentioned are as follows:

- **Authenticity:** the property of being genuine and being able to be verified and trusted; confidence in the validity of a transmission, a message, or message originator. This means verifying that users are who they say they are and that each input arriving at the system came from a trusted source.

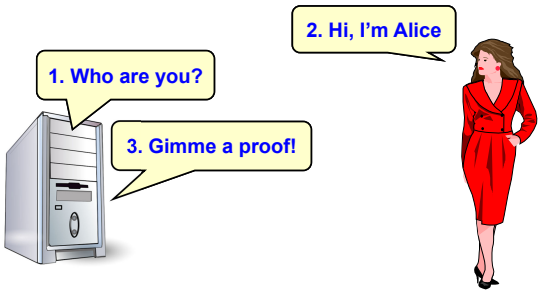
- **Accountability:** the security goal that generates the requirement for actions of an entity to be traced uniquely to that entity. This supports non-repudiation, deterrence, fault isolation, intrusion detection and prevention, and after-action recovery and legal action.

1.13 Security properties

Authentication (simple/mutual)	autenticazione (semplice/mutua)
Peer authentication	autenticazione (della controparte)
Data/origin authentication	autenticazione (dei dati)
Authorization, access control	autorizzazione, controllo accessi
Integrity	**integrità**
Confidentiality, privacy, secrecy	**riservatezza, confindenzialità**
Non-repudiation	non ripudio
Availability	**disponibilità**
Traceability, accountability	tracciabilità

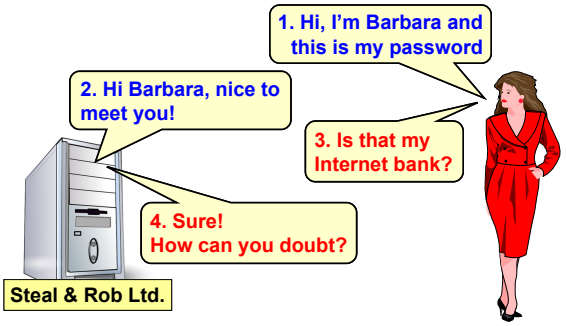
1.13.1 Authentication

Simple peer authentication



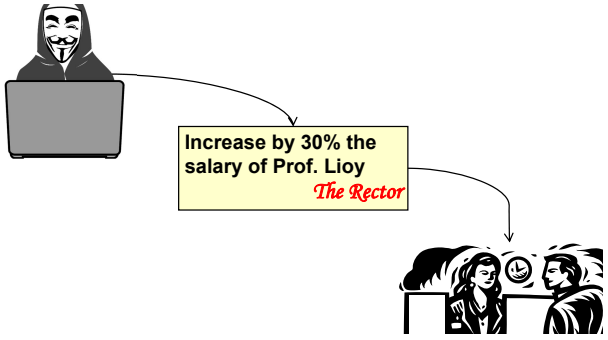
When there is communication between two peers that take part in the communication, they must authenticate. Two entities are considered peers if they implement the same protocol on different systems; for example, two TCP modules in two communicating systems. Computer systems usually ask some questions like the ones in the picture. Typically, for a proof, we provide a password. This is simple authentication: only one party authenticates. It attempts to provide confidence that an entity is not engaging in either masquerade or an unauthorized replay of a previous connection.

Mutual peer authentication



In mutual peer authentication, we also require a formal proof that we are connected to the real server. A fake server could display the same page as the ordinary bank just to obtain credentials from the user. When we connect to a server, we typically trust the server, but we need proof. Both parties authenticate each other.

Data origin authentication



Someone could write an email to request an increase in someone's salary, signed by the director, but there is no proof that the email came from the director. An electronic email typically lacks proper authentication. The same issue applies to files. Data are usually not authenticated, so there is a need for an authentication system for data as well.

1.13.2 Non-repudiation

Non-repudiation is a **formal proof** that is admissible in a court of law, providing **undeniable evidence of the data's creator**. Non-repudiation prevents either the sender or receiver from denying a transmitted message. This has several implications because we not only need **authentication** but also **integrity**. If someone alters data in a document, it should be detectable because it is no longer the original authenticated document.

There is a difference between authentication and identification. Authentication involves using electronic means to verify identity, such as a username and password. However, if the password is stolen, it raises doubts about whether it is the legitimate user or someone else. On the other hand, identification is much stronger, as seen in technologies like the Touch ID on smartphones, where the user is the only one capable of performing that operation.

Beware! The concept of "non-repudiation" is typically associated with not only technical aspects but also with specific procedures carried out voluntarily. We rarely achieve non-repudiation with protocols or procedures that automatically perform actions on behalf of the user.

Example of non-repudiation

Let's consider non-repudiation of an electronic signature:

- Syntax (is that your signature?)
- Semantics (did you understand what you were signing?) - what you don't understand has no legal value (for example the small lines in a document that are not understandable).
- Will (have you signed voluntarily?)
- Identification (was really YOU the signer?)
- Time (when did you sign?)
- Place (where did you sign?)

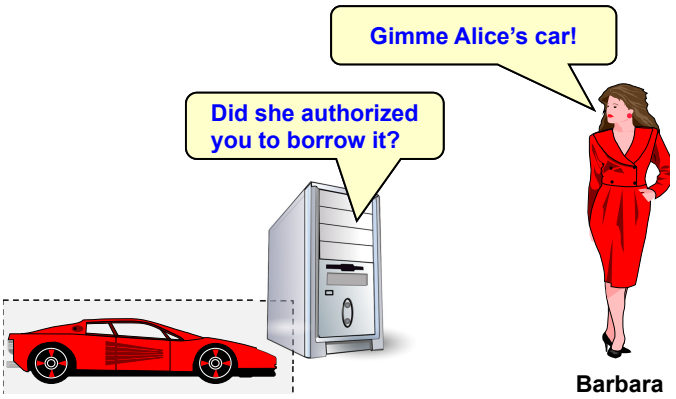
The electronic signature is a set of bits that represent the signature of a person. If we do not know where these bits must be placed to represent the signature, we cannot know which person the signature belongs to. For these reasons, there are specifications for electronic signatures.

1.13.3 Availability

An availability service is one that protects a system to ensure its availability. This service addresses the security concerns raised by denial-of-service attacks. It depends on proper management and control of system resources and thus depends on access control service and other security services.

1.13.4 Authorization (access control)

Authentication means identifying the actors in the system. After authentication, we can make decisions. For example, in the figure, Barbara has correctly identified herself and then asks the computer to "open the box of Alice's car" and the computer performs an **authorization decision (or access control)**. This is because the car in the box does not belong to Barbara. Therefore, a system must also determine if someone is authorized to perform an operation or not.



Important difference!

- **Authorization** is the process of verifying whether you, who have already been authenticated, are permitted to perform a particular operation.
- **Authentication** is the process of identifying the users of a system.

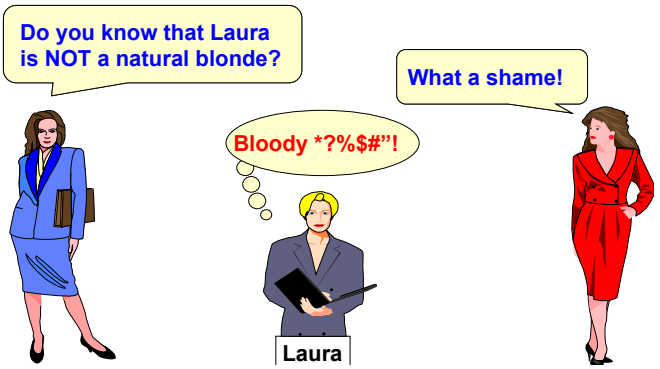
1.13.5 Privacy

Privacy (communication)

Privacy has several meanings. Communication privacy, for example, ensures that when two peers are communicating, it should not be possible for a third party to understand the communication. Even if someone can intercept the data passing through the network, no one (except the two end users) should be able to comprehend the contents of the communication.

Privacy (data, actions, position)

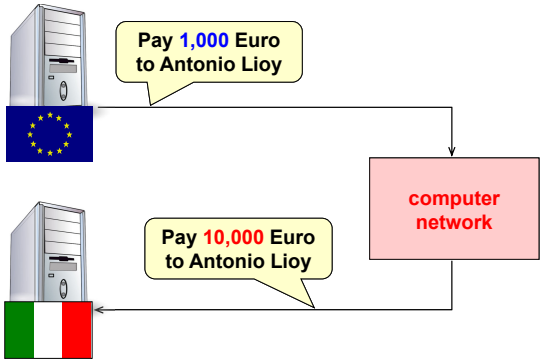
- **Data privacy:** Even if we have access to the physical location where data is stored, we might not be able to access the data.
- **Privacy of actions:** Companies have the right to monitor the websites visited by users, as do law enforcement agencies, especially in cases related to anti-terrorism laws. In Italy, all data sent over the network are stored for 7 years in case of future investigations.



- **Privacy of location:** Information about the location of users is available to those who manage the network. When defining the security properties of an application, we must consider concerns related to data, actions performed over the network, and potentially the location from which the communication originates.

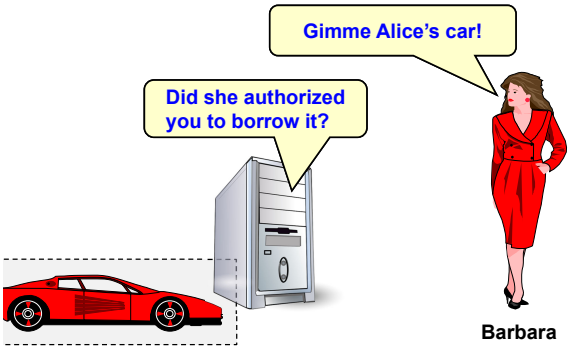
1.13.6 Integrity

Integrity (data modification)



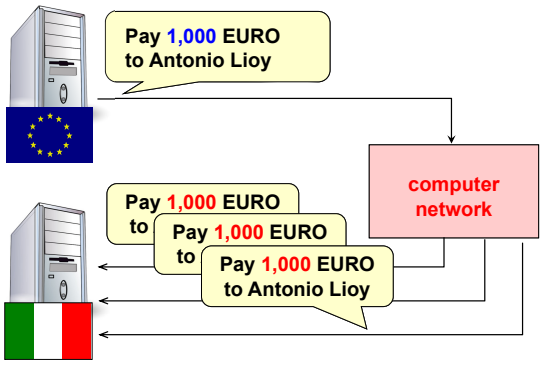
It means that if data have been modified, we are able to detect it. It doesn't mean that nobody can change the data; that's impossible. Network managers can always read and potentially modify data. That's why integrity refers to the detection of modified data.

Integrity (data cancellation/filtering)



Data can also be deleted, so we must ensure that if data deletion occurs, we are able to detect it. This is more challenging to detect because the receiver does not receive any notification (and does not have any hint that the payment shown in the picture should have been received).

Replay attack



Data sent over the network can be encrypted and thus made non-modifiable by the network manager. However, it is still possible to record the message sent over the network and replay it multiple times. Authentication will pass because the message is not modified, and it may not be easily understood by developers.

1.14 Data Protection

During the explanation of security properties, we always talked about protecting data. There are three types of data protection:

- **Data in transit:** when data are transmitted over a communication channel.
- **Data at rest:** when data are stored in a memory device.
- **Data in use:** when data are in RAM for use by a process.

Where is the enemy?

To defend something, we must know where the enemy is. There are a few possibilities:

- **Outside our organization:** In this case, perimeter defense using a firewall is required.
- **Outside our organization, except for our partners:** In this scenario, the firewall needs to be supplemented with protected paths or routes that allow communication between trusted users. This requires extranet protection, often in the form of a VPN (Virtual Private Network), which extends the intranet to include trusted partners.
- **Inside our organization:** In this case, we should focus on protecting the Local Area Network (LAN) and intranet applications, which can be challenging as we need to facilitate information sharing among users on the same network.
- **Everywhere:** Since attackers can be both inside and outside the organization, security measures must be implemented at the application level. Furthermore, since applications handle data, data protection must be independent of the physical location where the data is stored. For example, if a service like Dropbox is used but is not considered secure by the company, it is possible to encrypt the data before uploading it to Dropbox.

An example of this is an article from Corriere in 2009, which reported: "US PCs sold at the Peshàwar market: Computers of the US army with restricted data sold for 650$ along the road where NATO troops are attacked by the Taliban. Still full of classified information, such as names, sites, and weak points.

Threat model: where is the enemy? Which actions can it perform?

- ***MITM* (Main-In-The-Middle):** Sits between two peers A and B;
- ***MATE* (Main-At-The-End):** Resides inside one peer;
- ***MITB* (Main-In-The-Browser):** Resides inside one specific component of one peer (typically the web browser);
- **Passive Attacker:** Can only read the data/traffic;
- **Active Attacker:** Can read, but also modify, delete, or create data/traffic.

Basic problems (technological)

- The networks are insecure:
  - Most communications are made in clear (unless you take some actions);
  - LANs operate in broadcast (sending messages to everybody, and "if it's not for you, don't read");
  - Geographical connections are NOT made through end-to-end dedicated lines but through shared lines or through third-party routers.
- Weak user authentication (normally password-based);
- There is no server authentication;
- The software contains many bugs.

1.15 Some classes of attacks

Passive and attive attacks

A useful means of classifying security attacks is in terms of *passive attacks and active attacks.*

A **passive attack** attempts to learn or make use of information from the system but does not affect system resources. Examples of passive attacks are:

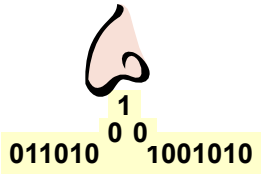
- **Packet sniffing:** The content of network packets (e.g., passwords and/or sensitive data) is read by unauthorized parties.
- **Traffic analysis:** Even if the packet content cannot be understood by a third party, an opponent could extract some information about the nature of the communication taking place.

An **active attack** attempts to alter system resources or affect their operation, involving some modification of the data stream or the creation of a false stream. Examples of active attacks are:

- **IP spoofing / shadow server:** Someone uses the address of another host to take its place as a client (and hide its own actions) or as a server.
- **Connection hijacking / data spoofing:** Data is inserted/modified/cancelled during its transmission.
- **Denial-of-service / distributed DoS:** The functionality of a service is limited or disrupted (e.g., ping bombing).

1.15.1 Packet Sniffing (Eavesdropping)

Packet sniffing refers to reading packets addressed to another network node. It is easy to do in a broadcast network (e.g., LAN) or at switching nodes (e.g., router, switch). This is possible by putting the network card in promiscuous mode, which means that the card will read every packet passing through the device. This kind of attack allows intercepting anything (passwords, data, etc.). Some possible countermeasures are avoid using broadcast networks or encrypt the packet payload (if a non-broadcast network is not possible).



1.15.2 Traffic Analysis

Traffic analysis is more subtle than packet sniffing. Suppose we had a way of masking the contents of messages or other information traffic so that opponents, so that the content of the messages cannot be understood by a third party. Even with encryption in place, the opponent could determine the location and identity of communicating hosts and could observe the frequency and length of messages being exchanged. This information might be useful in guessing the nature of the communication that was taking place.

1.15.3 IP Spoofing (Masquerading)

IP spoofing means forging the source network address. Typically, the level 3 (IP) address is forged, but it is equally easy to forge the level 2 address (e.g., ETH, TR, etc.). A better name would be source address spoofing. This is typically used for attacks where an answer is not needed. If everybody is in the same subnet, due to the broadcast function, it is also possible to read the replies. Attacks of this type go for data forging and unauthorized access to systems. The countermeasure for this type of attack is to never rely on address-based authentication: generally, network addresses should not be trusted.

1.15.4 Denial-of-Service (DoS)

Denial-of-service refers to keep a host busy so that it cannot provide its services. For example, in public administration for a call to a competition, offers can be sent until a date. We can make an offer and stop all the others from sending email. A possible solution is to send tons of email keeping the server busy until the message "Message did not deliver because the destination mailbox is full". We saturated the mail service. Other examples:

- **Mail/log saturation:** As explained before.
- **Ping flooding ("ping bombing"):** The ICMP echo request usually uses a small number of bits (8 bytes) and starts a timer waiting some seconds for a response. We could use the largest amount of bytes possible: 64 Kbytes. We should send a lot of echo requests at maximum speed without starting timers. This will keep the host busy answering all these packets and prevent it from performing other tasks.
- **SYN flood:** It is a form of denial-of-service attack in which an attacker rapidly initiates a connection to a server without finalizing the connection. The server must spend resources waiting for half-opened connections, which can consume enough resources to make the system unresponsive to legitimate traffic (see TCP SYN flooding).

Usually, DoS attacks block the use of a system/device, and there are no countermeasures for it because it is not possible to know if someone connecting to the service is intentionally keeping the service busy or not. In other words, DoS is quite like a high increase in customers using that service. Monitoring and oversizing can mitigate the effects. Every time there is an alert that some threshold is passed, for example, resource saturation, it is time to investigate. It could be a system problem or a security problem. Security and system managers must work together.

1.15.5 Distributed Denial-of-Service (DDoS)

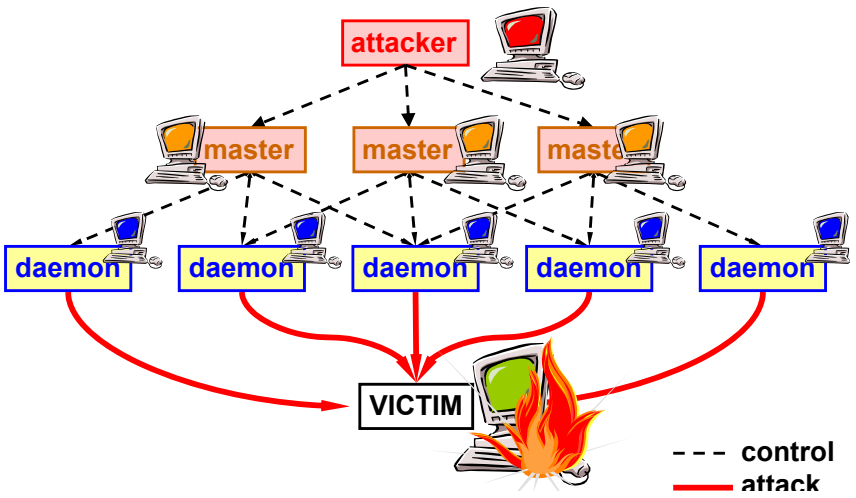
DDoS is essentially the same kind of attack as a DOS attack but magnified by the number of attackers simultaneously targeting a victim. Typically, a small number of individuals gain control of numerous nodes by installing DoS software on them. Each compromised node is often referred to as a **daemon, zombie,** or **malbot**, with the aim of creating a **botnet**.
A botnet is a network of compromised computers (*slaves*) controlled by a *master*. The master typically uses a **command and control (C&C)** infrastructure, which can be either client-server or peer-to-peer. The communication between the zombies (compromised computers) and the master is often encrypted or routed through "covert" channels. Covert channels are intended to mislead investigations; for example, information may be concealed by embedding it in `UDP packets` within `ICMP Request` messages, making it harder to detect since ICMP messages are common in normal network traffic.

These bots are sophisticated, and there have been cases where they can auto-update themselves to execute new attack techniques; by increasing the number of daemons (compromised computers), the impact of the attack can be magnified.

Other techniques to improve the attack include using a **"reflector"**. This involves utilizing a potentially legitimate third-party component to relay the attack traffic to the victim. This approach offers two main advantages:

- **It hides the attackers' identities:** attackers send packets to the reflector servers with a source IP address set to their victim's IP (IP spoofing), indirectly overwhelming the victim with response packets.
- It **multiplies the effect** through an **"amplification factor"** N:1 (typically protocol-dependent), where the reflector server's response size is much larger than the request size. For example, when making a specific query to DNS, the DNS response can be up to 70 times larger than the request.

DDOS attack



There is an attacker and a victim. The attacker somehow creates a network of daemons, then selects some nodes to be masters (usually more than one for redundancy), which are part of the botnet. The attacker sends the IP address to attack and then *disconnects from the network* to avoid being tracked. The other masters will coordinate the work of the daemons, which must perform the attack at the same time. Masters do not directly take part in the attack; they try to remain hidden as much as possible to avoid being detected during an investigation because this would stop the attack. The huge class of amplification factors that daemons can create can overwhelm the victim.

Masters and daemons are not real individuals but part of the botnet. The only human involved is the attacker, who disconnects after initiating the DDOS attack.

Case history: DDoS towards Yahoo Server Farm

The first well-known attack of this kind occurred on Feb 8th, 2000, at 10:30 am (PST) against the Yahoo Server Farm. Administrators wrote a report that stated:

- "The initial flood of packets, which we later realized was in excess of 1 Gbit/sec, took down one of our routers..."
- "... after the router recovered, we lost all routing to our upstream ISP..." This happened because an internet connection requires two routers. Yahoo's people rebooted their own router, but at the other end of the communication link, the router was still down.
- "... it was somewhat difficult to tell what was going on, but at the very least, we noticed lots of ICMP traffic..."
- "... at 1:30 pm, we got basic routing back up and then realized that we were under a DDoS attack."

Later, the attack was traced back to the 15-year-old Canadian boy Michael Calce (aka MafiaBoy). Even if getting to the attacker is not always possible, a U.S. lawyer can easily identify who the daemons are and seek refunds from them, even if the daemon was a victim of the attacker, for example, if the attacker took control of a computer for DDoS purposes.

Case history: DDoS towards "Krebs on Security" Blog

On September 27, 2016, the administrator of the blog received a DDoS attack that generated 665 Gbps, and it was generated by a botnet of IoT devices (or claimed to be such). There was no use of any reflectors or amplifiers, just millions of devices that performed perfectly valid requests. It seemed like millions of users wanted to connect to the website at the same time. This generated a significant amount of traffic, and even though the blog was hosted on Akamai, the traffic was so substantial that the company had to give up and made the blog unreachable by dropping that destination from their routing table on September 29. There was no known reason for the attack; perhaps it is connected to Krebs' analysis of similar attacks against online game servers.

1.15.6 Shadow Server / Fake Server

In **shadow server** attacks, a host manages to impersonate itself as a service provider to victims without having the right to do so. There are two techniques to achieve this:

- If the attacker **can sniff requests and spoof responses faster than the real server**, the latter will not be able to communicate because the second package will be discarded, considering it a duplicate.
- **Routing or DNS manipulation**, mapping the real name to the IP of the shadow server.

The attacks that can be carried out in these scenarios include:

- **Issuing incorrect answers**, providing a "wrong" service to victims instead of the real one.
- **Capturing victim's data** provided to the wrong service.

The countermeasure to this type of attack is to **require server authentication**.

1.15.7 Connection Hijacking / Man In The Middle (MITM)

It is also referred to as **data spoofing**, and this form of attack involves gaining control of a communication channel to insert, delete, or manipulate the traffic. This can be achieved through logical means (by altering the network's routing) or physically (if one can physically access a router or switch).

These attacks can be executed for various reasons, such as eavesdropping, inserting false data, and altering data exchanged between two parties.

Countermeasures include **authentication**, ensuring data **integrity** (verifying whether it has been altered), and packet **serialization** (ensuring that no packets are added or deleted, and that packets are received in the same manner as they were sent) for each individual network packet.

1.15.8 Trojan

A Trojan is a program that hides a malicious payload within a seemingly harmless exterior. Despite the increasing security of network channels, user terminals have become more susceptible to such attacks. This vulnerability extends to devices like smartphones, smart TVs, and various Internet of Things (IoT) devices.

These attacks tend to target less tech-savvy or "ignorant" users. Attack tools can take on various forms, from traditional methods like embedding keyloggers within seemingly innocuous applications to more contemporary approaches, such as malicious browser extensions.

Trojans are frequently used to carry out two distinctive types of attacks: **"Man-At-The-End"**(*MATE*) and **"Man-In-The-Browser"** (*MITB*).

1.15.9 Zeus

The Zeus attack, also known as **Zbot**, is a major malware threat combined with a botnet. It was first discovered in 2007, and law enforcement has been actively seeking the owner of this network. The owner claimed to have sold it in 2010.

Zeus can be used in the following ways:

- Directly: For example, it can be employed for Man-In-The-Browser (MITB) attacks to perform keylogging or form grabbing (software that reads data in a form).
- Indirectly: It can also be used to deliver other malware, such as the CryptoLocker ransomware.

Zeus is challenging to detect and remove because it employs stealth techniques to conceal itself. In the USA alone, there are approximately 3.6 million active copies of Zeus.

1.15.10 Software Bug

Even the best software can have bugs, which can be exploited for various purposes. One common way to exploit a software bug is to create a Denial of Service (DoS) attack.

For instance, there was an attack against the WinNT server (versions 3.51 and 4.0) where attackers discovered that the server hosted a service on an undocumented TCP port 135. They attempted to communicate with this port by sending 10 random characters followed by a carriage return (CR). This caused the server to become unavailable, as it experienced 100% CPU load even though it was not performing any useful work.

The issue stemmed from the fact that at port 135, there was a new Microsoft-only service that was a remote procedure call (RPC) and had a bug. When it received a malformed packet, it went into an infinite loop, continuously asking, "where is a good packet?" Since the ARP server (?) was part of the operating system's kernel, it consumed 100% of the CPU without the possibility of interruption. Microsoft developed a solution with Service Pack 3 (SP3), in which they addressed and corrected this bug.

1.16 Virus & Co. (malware)

- **Virus**: A virus is a malicious program that damages the target and then duplicates itself. It is propagated by humans involuntarily.
- **Worm**: A worm damages the target indirectly by replicating itself to the extent that it achieves resource saturation. Additionally, a worm will attempt to propagate automatically. Worms are usually more challenging to detect because the damage they cause may resemble normal activity unless a careful analysis of the network pattern is conducted.
- **Trojan Horse**: The Trojan horse is a program that carries some malware. It may appear to be a valid program but can also install malware.
- **Backdoor**: A backdoor is a piece of software that provides an unauthorized access point. While illegal, it is common among developers. For example, if a developer is concerned about not being paid, they might create a backdoor to gain access in case of payment problems.
- **Rootkit**: A rootkit is a set of tools that provides privileged access. It is hidden, often disguised as a modified program, library, driver, kernel module, or hypervisor. Due to its stealthy nature, rootkits are challenging to detect and remove.
- **PUA (Potentially Unwanted Applications)**: It's a sort of grayware, not directly dangerous.

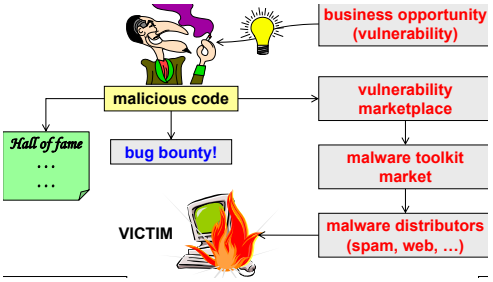
Virus and worm (malware)

Virus and worms require some kind of complicity (may be involuntary) from **the user** (gratis, free, urgent, important), the **system manager** (wrong configuration), **the producer** (automatic execution, trusted).

Some countermeasures are user awareness, correct configuration/secure software, antivirus (installed and updated).

Malware food chain

When someone discovers a vulnerability, it can be exploited for the development of malicious code (for example, this code could be used to gain access to a website and manipulate its data). Such information can be exploited in two ways:

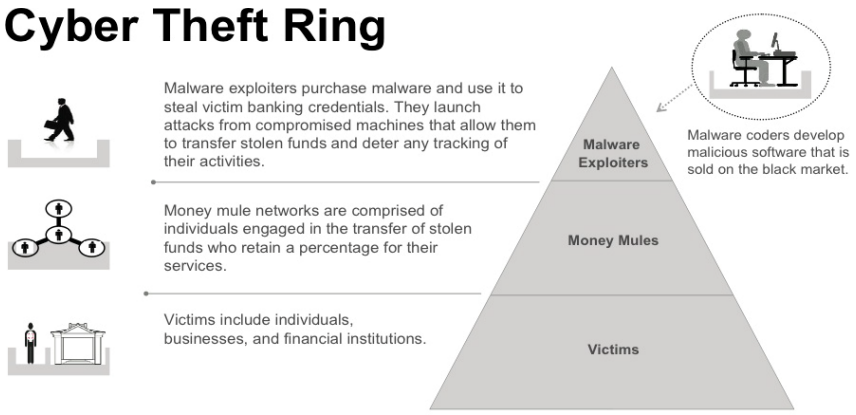


- Especially in the past some individuals may perform the attack primarily for the sake of recognition, like being in a "Hall of Fame".
- More recently, individuals have been motivated by business interests. They sell the information about the vulnerability or a working code that exploits it on the *vulnerability marketplace*, a hidden marketplace and is found exclusively on the internet, on dummy servers that appear for a brief time during the night.

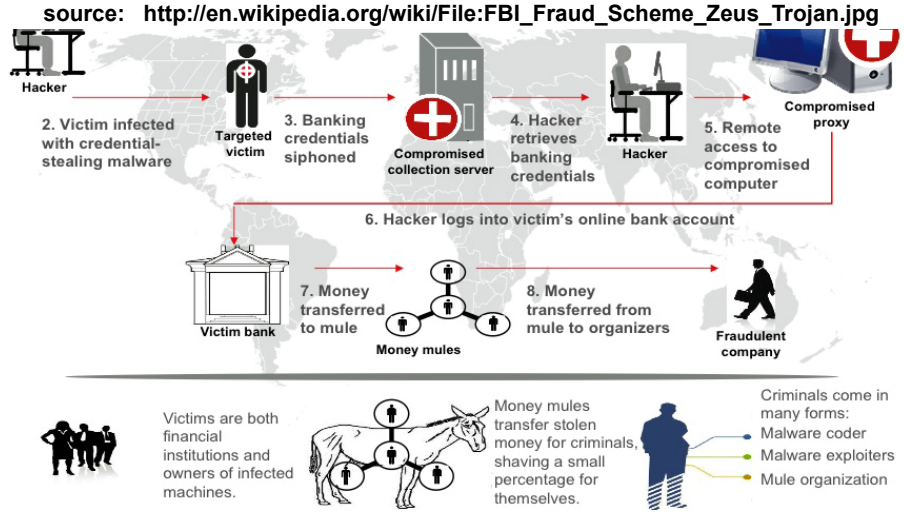
Payment for these vulnerabilities is often made using cryptocurrency. The buyers of these vulnerabilities are typically the **malware toolkit makers**, which are used to develop attack programs that incorporate malware; malware distributors, such as spammers and website owners, then employ this type of software for their illicit activities.

Zeus: Cyber Theft Ring

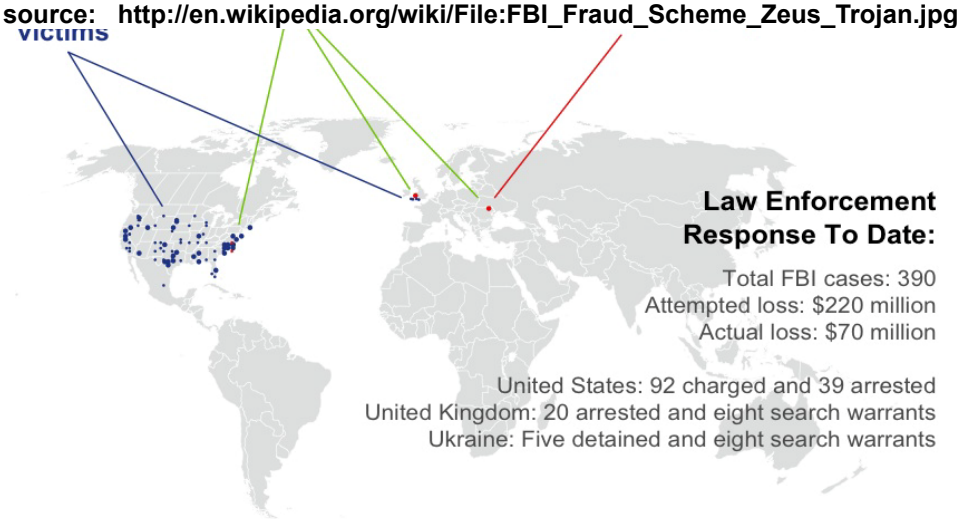
It often happens to receive an email that asks you to send money outside of the country in exchange for a large sum of money. If you accept this request, you will supposedly receive the money. They may begin by testing you, sending a small amount of money, for example, $10,000, and then ask you to send $7,000 to Nigeria, allowing you to keep $3,000 for yourself. However, by agreeing to this, you will be facilitating money laundering, as the funds are stolen from someone's bank account and transferred to you, making you appear responsible. You will then send the money via MoneyGram, while the individuals in Nigeria will disappear, leaving you to face potential legal consequences. This scenario is a typical case of acting as a 'money mule,' which involves accepting funds from a stolen bank account and forwarding them to the intended destination."



source: http://en.wikipedia.org/wiki/File:FBI_Fraud_Scheme_Zeus_Trojan.jpg



source: http://en.wikipedia.org/wiki/File:FBI_Fraud_Scheme_Zeus_Trojan.jpg



source: http://en.wikipedia.org/wiki/File:FBI_Fraud_Scheme_Zeus_Trojan.jpg

Most of the victims are based in US or UK. The mule organization is spread across many countries: US, Europe, British Ireland, but malware coders/exploiters are typically in the East Europe. In the picture there are also numbers about the Law Enforcement Response.

Ransomware

Ransomware is a type of malware that is designed to extort a **ransom**, typically by demanding money in exchange for releasing something. When ransomware infects a computer, it usually encrypts the contents of the disk, rendering them unreadable. This also applies to tablets and smartphones, for example, by changing access passwords to data.

However, paying the requested ransom (usually in bitcoin) does not always guarantee the recovery of your data. This is because the key required to unlock the files is typically stored on a server that could be shut down as a result of a police investigation. As a result, the attacker may no longer have access to the key used for locking the data.

Ransomware-as-a-service

For some time, there was a *ransomware-as-a-service*, in which individuals provided the source code for ransomware; this enabled people to use ransomware even if they had little understanding of how it worked. This service was known as the **TOX malware** and operated on the **TOR anonymous network**. TOX would demand a ransom and handle the payment, charging a 20% service fee. The "customer" has the only task to distribute it to the victims (for example by leaving a USB pen in public places). TOX saw rapid growth, with around 1,000 customers per week and infecting approximately 100 devices per hour.

Even though TOX was eventually stopped by law enforcement, ransomware threats continue to exist. Technology alone is insufficient for protecting against ransomware. While having a robust anti-malware system installed is helpful, it's important to note that this type of attack targets not only end-users but also servers.

Ransomware: Not only technology but also procedures and organization

Ransomware typically **encrypts data** that can only be restored with the proper decryption key. Regular backups can provide a potential solution, but is that enough?

- **How old is the backup?** Consider the age of your backups. Even if you create daily backups, ransomware developers are aware of this practice and have developed a stealthy variant known as silent ransomware. *Silent ransomware* infiltrates your system but instead of encrypting your current data, it targets your backup files. This can continue for several days, rendering your backups unreadable, and it may only be discovered later that the backups are corrupted.
- **Offline or Network Backups?** Backups should be made offline. For instance, consider a case where a dentist's office used a Network-Attached Storage (NAS) system for continuous backup of local data; ransomware found this setup and encrypted the data on the network storage, rendering the backups useless.

To enhance security, an inverted backup technique is recommended. In this approach, the backup disk is not directly connected to the target PC (the one whose data is being backed up). Instead, there should be another node that remotely mounts the target PC's disk, makes a copy, and then disconnects from the target PC. Even if the target PC is infected, this process remains unaffected. Importantly, the backup node should not be connected to the network to prevent potential malware interference.

- **Verified or "Trusted" Backups?** Have you verified the correctness of your backups, or have you merely trusted them? There is a well-known case in Sweden where magnetic tapes used for backups were corrupted during transportation due to heated seats generating currents on wires, creating magnetic fields that damaged the tapes. This issue was only discovered when data corruption occurred, and there was a need to access the backups.
- **When was the attack?** To identify the correct backup, it's essential to know the timestamp of the attack. There have been cases, such as a video archive, where determining the accurate backup was challenging. In this example, a journalist looking for video clips noticed inconsistencies in file names. While backups existed, determining which one was correct depended on when the attack took place. Without knowledge of the attack's timing, selecting the right backup for restoration becomes impossible.

1.17 Basic problems (non-technological)

Figure 1.2: Even the most sophisticated technological tools can be made useless by human error

- **Low Problem Understanding (Awareness):** People often lack awareness of security issues and tend to implement security measures only after experiencing problems. This behavior stems from the belief that such issues will not affect them.
- **Human Mistakes (Especially When Overloaded or Stressed):** Errors are more common when individuals are under stress or overwhelmed with work.

- **Inherent Human Trust:** Humans tend to have a natural inclination to trust others, especially in online interactions where face-to-face contact is absent.
- **Complex Interfaces/Architectures Can Mislead Users and Lead to Errors.**
- **Performance Decrease Due to the Application of Security Measures:** Consider the example of a company that sought Lioy's assistance with antivirus software. Although the company claimed to have the best antivirus, they frequently experienced virus infections that disrupted their system. Lioy visited the company's premises and examined everything, including antivirus installation and updates. While exploring the office to understand the problem, he noticed a desktop with the antivirus icon disabled. Lioy inquired about this, and an employee explained that the antivirus's file scanning process caused delays in accessing files, prompting employees to disable it temporarily for more efficient work. Surprisingly, all employees followed the same practice. Lioy concluded that the company had a non-technological problem.

Social engineering techniques and strategies

In the context of information security, **social engineering** is the psychological manipulation of people to induce them into performing actions or divulging confidential information. Typically, the targets are **naive users**, such as those who may be urged to "immediately change their password due to an alleged PC attack". However, even experienced users can be targeted, for instance, by replicating a genuine email but altering its attachment or URL.

These tactics are employed through various channels, including email, phone, fax, and even physical documents; they often relay on **psychological pressure**. Usually, this is achieved in two ways:

- By exploiting human empathy towards a friend or a co-worker, for example generating a fake message conveying a message like "Help me, otherwise I'll be in trouble...", leading to some action that could be against best practices, creating an opportunity for an attack.
- By pretending to be a boss, also asking for something that could be forbidden, under the threat "do it, or I'll report it to your boss...".

In general, those who run these psychological attacks try to show familiarity with the company's procedures, habits, and personnel to gain trust and make the target lower his **defenses**.

Phishing(pronounced "fishing")

It is an attack technique based on attracting a network service user to a fake server (shadow server), using mail or IM, for acquiring his authentication credentials or other personal information, or persuading him to install a plugin or extension which turns out to be a virus or a Trojan. An example message can look like: "Dear Internet banking user, please fill in the attached module and return it to us ASAP according to the privacy law 675...". There are some variants:

- **Spear phishing**, when the message includes several personal data to disguise the fake message as a legitimate one (e.g., email address, name of Dept/Office, phone number, etc.)
- **Whaling**, when the target user holds a position of responsibility or power, such as a CEO or CIO. This has two main advantages from the attacker's point of view: the damage done by deceiving these types of people can be much greater, as their credentials can give the attacker great power; these people generally occupy a commercial and administrative position, which usually means that they do not have the necessary knowledge to handle security issues.

Pharming

It's a term of controversial use and embodies a set of several techniques to redirect a user towards a shadow server by:

- changing the "hosts" file at the client.
- changing the nameserver pointers at the client.
- changing the nameservers at a DHCP server (e.g., an ADSL/Wireless router).
- poisoning the cache of a nameserver.

This could happen via a **direct attack** if there is a vulnerability or misconfiguration, or via an **indirect attack** with a virus or worm.

Fake Mail / IM

Creating a fake email is relatively easy, but maintaining the right "tone" can be challenging. For instance, questions like "Should I sign the emails as Antonio Lioy, or just Antonio, or A. L.?" need to be addressed, as an incorrect tone can lead to the detection of the fake email. The creation of fake SMS or instant messages (IM) is also possible, allowing for various deceptive scenarios:

- *Fake ATM withdrawal* messages that prompt the recipient to call a specified number, which then solicits their confidential credentials.
- *Fake kidnapping alarms*, often delivered via IM. It is not uncommon for individuals, particularly older men, to approach the police claiming, "Help me because my daughter has been kidnapped, and they demand 200,000 euros for her release." In reality, the person making the request is often a woman met on social media who has established a fake relationship with the victim to elicit empathy and financial support.

Case history: "Mr. Confindustria in Brussels tricked by a hacker: 500,000 Euros lost. Fired." (Repubblica journal on 30th September 2017)

"Transfer immediately half a million to this foreign bank account." However, this email was sent by a hacker, and the money disappeared. The fake order was (seemingly) signed by Director Panucci: "Please execute and don't call me because I'm out of the office with the president."

Final message: all the employees should be trained in the security problems of modern life.

Case history: T.J. Maxx attack (2007)

In 2007, there was an attack against T.J. Maxx, a chain of shops. The attack occurred externally, allowing the attacker to access 45 million credit card numbers from customers. The attack lasted for about 18 months, ending in January 2007. It gained notoriety when a group of 300 banks, affected by the attack as they had to refund customers, initiated a class action lawsuit against T.J. Maxx, seeking a $10 million refund. This was due to the fact that, even though it was known in 2007 that the wireless protocol WEP was insecure, T.J. Maxx continued to use WEP instead of WPA. The attacker didn't need to physically enter the shop; instead, they could sit in a nearby park with a laptop and appropriate software, intercepting all transactions between the cash register and the back-end server. The attack was carried out by 10 people (3 USA, 3 UKR, 2 CHN, 1 BEL, 1 EST + "Delpiero") with the assistance of an ex-hacker who had been hired by the US Secret Service.
This practice is not uncommon; when an attacker is apprehended, they are often given the opportunity to work for the government as a consultant or to help prevent future attacks."

Considering the legislation, in general, the law does not prescribe specific security measures to be taken, but merely advises establishing defenses in accordance with the state of the art. This means that a security manager must always stay up-to-date and apply the most recent solutions against new types of attacks.

Case history: US Air Force phishing test transforms into a problem (04/2010)

In April 2010, during an Operational Readiness Exercise (ORE) at Andersen Air Force Base located on Guam Island, a phishing email was used to test the response of airmen. The email, sent by security testers, claimed that film crews were starting production of 'Transformers 3' on Guam and invited airmen to submit applications on a website if they wished to work on the shoot. The website then requested sensitive information, which the airmen should have been trained not to provide. The outcome of this exercise became widely known because one of the airmen posted the news outside the base, reaching the civilian world. As rumors spread that the highly anticipated film was coming to Guam, local media began contacting the base, leading to efforts to clarify the situation.
Andersen AFB's leadership expressed regret for any confusion caused by this phishing exercise. They emphasized the importance of individuals being cautious about the genuine threat posed by phishing emails, with the hope that others can learn from this exercise.

1.18 Some important recent attacks

The first attack discussed is **Stuxnet**, known for being the first cyber-attack to cause physical damage. Next is **Black Energy**, one of the most well-known attacks used against critical infrastructure, such as the electrical grid distribution. Finally, we have **Mirai**, **BlueBorne**, and **BrickerBot**. These attacks are all targeted at IoT devices, embedded systems, the automotive sector, and home devices.

1.18.1 Against Cyber-Physical Systems

Stuxnet (2010)

It is important because it is the prototype of a new kind of attack, since it caused physical damage (like a virus) and it attempts to propagate itself to other systems (like a worm): the target were **SCADA systems** of a specific manufacturer attached to the infected nodes. SCADA stands for Supervisory Control and Data Acquisition, and they are those computer systems that control process plants or machinery, for example production systems for cars, food, and so on. Since SCADA is the interface between computer and physical reality, an attack against it could damage physical system components. Stuxnet was a very sophisticated attack because this worm contained four attack vectors:

- one was based on an already known vulnerability (for which a patch existed);
- one exploited an already known vulnerability, but for which no patch was available (for those who got the patch for the first one);
- two "zero-day" vulnerabilities (if there were countermeasures for the known vulnerability).

Attack mode It seems that the first infection came through a USB pen inserted in one of the computers that managed the SCADA system. Then it propagated through all the computers connected to the network of the enrichment plant in Iran thanks to shared disks, Microsoft Spooler Subsystem and RPC services bugs. The infection via USB key was possible because inside that network of computer there was no internet connection, and a USB Key was required for updates of SCADA systems. It seems that the technician arrived from another country for the maintenance with the USB pen (and good software in it), got distracted in the hotel from some girls while someone added to the USB pen the malware. This malware was disguised as a driver (pretended to be a driver) with a digital signature validated by Microsoft and used two different certificates. Additionally, the guilty was not only from Microsoft but also of the developers, because the SCADA system had only one shared default password for the back-end database.

Attack motivations Even the timing and the location are peculiar. First, on 17/6/10, the first damage was created, and it became known that Stuxnet existed. For this reason, an investigation started, and one week later, on 24/6/10, the analysts detected the use of the first signature certificate and revoked it on 17/7/10. However, the malware then started using a second signature certificate. Since its discovery, it took one month for security bulletins by CERT (Computer Emergency Response Team) and MS (Microsoft). Then, Microsoft started developing patches that were gradually released through October '10. This malware stopped propagating itself on 24/6/2012 (which was written inside its code). This suggests that the malware was targeted to a specific time window.

Most of the attacks are against the most developed countries, but this malware was found in 52% of cases in Iran. It seems to be targeted at a specific area: *this worm had the target of destroying the uranium enrichment plant in Iran.*

Attack consequences The malware was able to manipulate the speed of the cylinders used for uranium enrichment beyond safe limits, all without triggering any alerts in the monitoring system used by the technicians. As a result, the technicians only managed to halt the system after significant damage had already occurred. This setback delayed the Iran Uranium Program by several years in their efforts to restore the proper functioning of the facilities.

Lessons learnt from this attack:

- Physical system separation (air gap) does not imply security: in fact, without any other standard protections (anti-virus, OS patches, firewall), these systems are not secure. In this specific case, the systems did not use any kind of standard protection, relying too much on the physical barrier;
- Unnecessary active services can be a source of vulnerabilities: MS-RPC, shared network print queues, shared network disks were not necessary but still running. In general, any unnecessary service should be disabled;

- A validation list for software to be installed should be used: it seems that the technician copied all the content of his USB pen, also copying the added malware. He should have copied only the file necessary for the SCADA systems update.

1.18.2 Against critical infrastructure

Fancy Bear / APT 28

This hacking group is believed to have ties to the Russian military intelligence agency, GRU. Over the years, they have been involved in cyber-attacks and espionage activities against various high-profile targets; some of their notable targets include the German and Norwegian parliaments, the French television network TV5Monde, the White House, NATO, the U.S. Democratic National Committee, and the Organization for Security and Co-operation in Europe (OSCE).
Additionally, during the years 2014-2016, they developed Android malware specifically designed to target the Ukrainian Army's Rocket Forces and Artillery.

Against Internet-of-Things, automotive, home

Mirai

Mirai is the most famous IOT **cyberworm** discovered around September-November 2016. This kind of attack does not damage directly but simply saturates the resources (like the DoS). Every system infected by Mirai becomes part of a huge botnet for a large-scale DDoS. It was used for disruptive attacks such as:

- Krebs on Security → up to 620 Gbit/s
- Ars Technica → up to 1Tbit/s
- Dyn DNS provider → requests from tens of millions of IPs

Botnets are deployed into millions of IoT devices such as cameras, residential routers, or baby monitors because these devices have almost no installed protection. In this way, Mirai can easily spread into home networks. The fast networks (such as 4G and 5G) make it even more critical because these devices can send a lot of data per second. Mirai is a very complex malware because it has almost no external dependencies (this means that the malware is compiled with static libraries) and it is cross-compiled to be executed on several platforms. Mirai is released as an open-source worm: this means that not only it is possible to study it, but also that new variants can be easily developed by other attackers. Mirai contains a propagation scan phase to compromise additional targets (starts contacting other nodes if it can infect them). It also observes the victim system before contacting the C&C: when Mirai is installed on a device, it doesn't know if it is a true or fake device (maybe used to study Mirai's behavior) and for this reason, when it starts, it connects to a fake C&C. `IF` the communication works, it means that there is a problem (because the connection should not work, which means that someone is giving Mirai full access), and it shuts down automatically. Only after performing this check, it `THEN` contacts the real C&C.

The kind of attacks, since it is a DoS network-based, is driven by C&C that can decide which attack to make and can open many `TCP` connections, send tons of `UDP` packets, or use `GRE` or simple `SYN flooding`.

BrickerBot

In October 2017, a message appeared on blogs and chat platforms (as shown on the left side). In this particular case, Wind, a telecommunications company, was faced with an issue where they had to physically replace all the modems. They were unable to resolve the problem remotely. The modems had malfunctioned and needed replacement. The individual responsible for this attack claimed to have done it for the greater good, possibly to prevent the formation of a botnet. This incident bore some similarities to the Deutsche Telekom case in 2016, albeit with more severe consequences.

Lesons learnt:

- **Use strong passwords**;
- **change default password** upon installation;
- **Permit external administrative access only from specific "trusted" networks** (and not from any address on internet): using IP addresses as "filter" to allow access is anyway weak, but at least is better than allowing it from all;
- **Apply timely all security patches to minimise the WOE**: in the Wind-Infostrada case, the bug was well-known, so the company should have installed the patches.

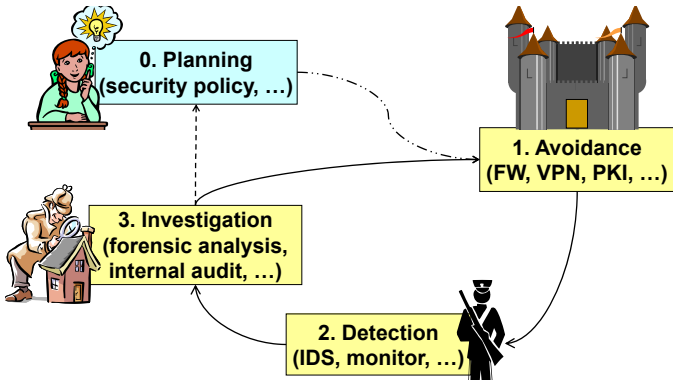
1.19 Attack maps: sample data sources

There are many websites that can show how many attacks are being performed. It is possible because many of these sites are providers of security solutions. They get the information from their own software which is installed on millions of devices and detects possibly attacks. The websites have many labels which tell exactly what attack is:

- **OAS** = *On-Access Scan*: Anti-malware that performs a scan to detect malware before accessing a file.
- **ODS** = *On-Demand Scan*: Scans inserted USB pens before files are copied.
- **MAV** = *Mail Anti-Virus*: Antivirus for emails that checks attachments.

- **WAV** = *Web Anti-Virus*: Before downloading something from the internet, the item is temporarily stored in a central facility, checked for possible malware, and only transmitted to the destination if nothing is found.
- **IDS** = *Intrusion Detection System*: Monitors networks and hosts for possible attacks.
- **VUL** = *Vulnerability Scan*: More pro-active; some machines periodically try to contact others on the network and check for vulnerabilities. If something is found, a warning is sent.
- **KAS** = *Kaspersky Anti-Spam*: Specifically for Kaspersky.
- **BAD** = *Botnet Activity Detection*: Detects botnets performing activity.

1.20 The three (four) pillars of security

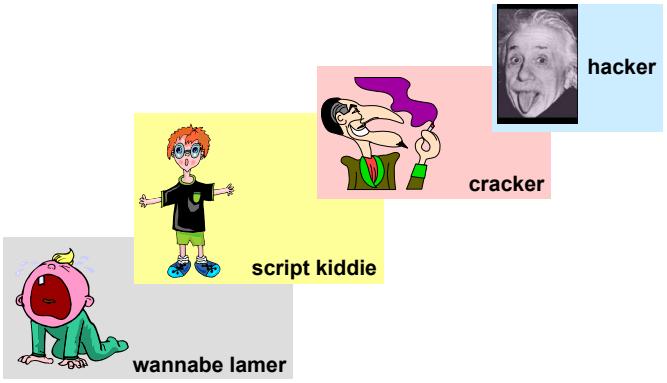


1. **Planning** (security, policy, ...);
2. **Avoidance** (FW, VPN, PKI, ...);
3. **Detection** (IDS, monitor, ...);
4. **Investigation** (forensic analysis, internal audit, ...);

1.21 The NIST cybersecurity framework

Figure 1.3: https://www.nist.gov/cyberframework/online-learning/five-functions

1.22 Final slides

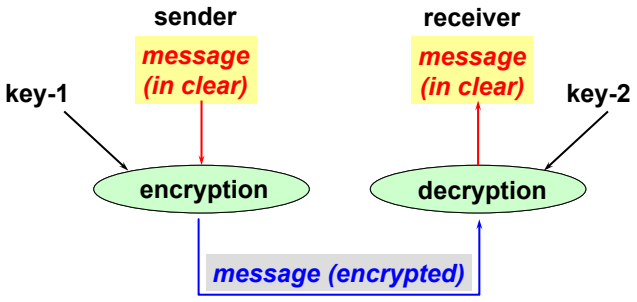


Kevin Siers, NC, USA (cartoon from the Charlotte Observer)

Chapter 2

Cryptographic techniques for cybersecurity

2.1 Cryptography



The most used technique to achieve protection for many centuries is **cryptography**; a mathematical technique that involves algorithms for encryption and decryption:

- the encryption algorithm takes a message (in clear) and transforms it in such a way that it becomes unintelligible;
- to recover the original text, the decryption algorithms make it readable again.

Next to the algorithms, **key-1** is needed for encryption and **key-2** for decryption, both of which are streams of bits. Cryptography is used in communication and for data storage (for example, to store data on disks without permission to read them except for authorized users). The common terminology used in cryptography includes two other keywords:

- **Plaintext** or **cleartext**: the unencrypted message, typically referred to as **P**;
- **Ciphertext**: the encrypted message, typically referred to as **C**. Note that in some countries, the term "encrypted" may sound offensive for religious reasons (related to the cult of the dead); in such cases, "*enciphered*" is preferred.

2.1.1 Cryptography's strength (Kerchoffs' principle)

Kerckhoffs' Principle (1883) states that the security of a cryptosystem must lie in the choice of its keys only; everything else (including the algorithm itself) should be considered of public knowledge. However, this principle relies on the fact that the keys have the following properties.

- Are kept **secret**;
- Are managed only by **trusted systems**;
- Are of **adequate length**

If these properties are met, not only it has no importance that the encryption and decryption algorithms are kept secret, but it is better to make the algorithms public so that they can be widely analysed, and their possible flaws and vulnerabilities identified.

Security through obscurity (STO)

The Kerckhoffs' Principle is related to the concept of **Security through obscurity**: it means that a system is protected, but the details on how it has been protected are not disclosed.
Generally, this alone is not considered a valid security mechanism because if someone discovers how the system has been protected (and we have seen that there are also non-technical ways by which this can be achieved), it is no longer secure.

For this reason, we say that *"Security through obscurity is as bad with computer systems as it is with women"*.

> "Men try to hide things from women, but when they discover the truth, it is worse than if they had known it from the beginning"
>
> (Antonio Lioy)

Editor's note: don't hide things from your partner, regardless of gender.

However, there is a category of people (such as military men) which tend to apply STO, but as an additional layer. It is possible to use STO as a layer only if a really strong algorithm is used (but not a secret one).

2.2 Symmetric cryptography

Depending on which relation exists between key-1 and key-2 there are different kinds of cryptography.

Secret key / symmetric cryptography

It is so named because **only a single key** is shared by the sender and receiver. In the diagram, there is a plaintext used as input for the encryption (E) block, along with the key. The result is a comprehensible text that is transmitted to the receiver. To retrieve the original text, the

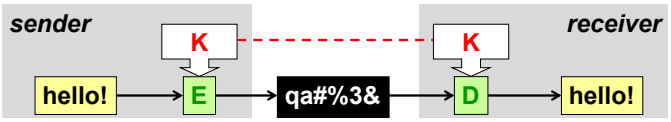


Figure 2.1: Symmetric cryptography

decryption (D) block algorithm is used with the same key that was used for encrypting the initial text. If a different key is used, an output is generated, but it will be incorrect (and typically understandable).

The formulas used are as follows.

$$K_1 = K_2 = K$$
$$C = enc(K, P) \quad \text{or} \quad C = \{P\}K$$
$$P = dec(K, C) = enc^{-1}(K, C)$$

Note that $C = \{P\}K$ means "encrypt the plaintext P using the key K".

The issue in the diagram (Figure 2.1) is represented by the dashed line: how can the key be securely shared between the sender and receiver? We'll see it in *Key distribution for symmetric cryptography*.

2.2.1 Block algorithms

name	*key (bit)*	*block (bit)*	*notes*
DES	56	64	obsolete
3-DES	112	64	56…112-bit strength
3-DES	168	64	112-bit strength
IDEA	128	64	famous for PGP
RC2	8-1024	64	usually 64-bit key
Blowfish	32-448	64	usually 128-bit key
CAST-128	40-128	64	usually 128-bit key
RC5	0-2048	1-256	optimal when B=2W
AES	128-192-256	128	state-of-the-art

Figure 2.2: Some famous symmetric encryption algorithms (block)

There are many algorithms, and the table on the left represents just a small selection. The first column provides the name, the second indicates the key length, and the third specifies the basic unit each algorithm can encrypt. These algorithms are referred to as "**block algorithms**" because they operate on a fixed number of bits.

The **DES** algorithm, once a standard for many years, is now considered obsolete and should never be used.

The most commonly used algorithm of this kind is **AES**, currently recognized as the state of the art (the strongest).

RC5 performs optimally when the block size is double the word size of the CPU architecture (e.g., 64-bit architecture -> 128-bit block) on which the algorithm is implemented.

Why are there so many algorithms? Because there are various types of computers, and many algorithms are not suitable for low CPU power.

The EX-OR (XOR) function It is the ideal "confusion" operator, available on all CPU.
The peculiarity of this truth table is that it has 50% of 0 and 50% of 1: if XOR is performed with 2 random inputs (probability 0:1 = 50% : 50%), then the output will also be equally random; while, for example, AND is more likely to produce 0. That means that XOR does not change the probability distribution of the input, even though it generates different outputs. Some properties:

⊕	0	1
0	0	1
1	1	0

Figure 2.3: XOR function

- if $A \oplus B = Z$
  then $Z \oplus B = A$ or $Z \oplus A = B$
- $A \oplus 0 = A$
  $A \oplus 1 = \overline{A}$
  $A \oplus A = 0$
  $A \oplus \overline{A} = 1$

DES

DES stands for "**Data Encryption Standard**" and it is a standard defined by *FIPS 46/2* (Federal Information Processing Standard, the body responsible for setting standards for the American government). The modes for applying DES to data that is not equally divided into blocks are mentioned in the FIPS 81 standard.

DES is a unique algorithm because it has a 64-bit key, but its effective strength is equivalent to that of a **56-bit key**, as 8 bits are used for parity. This means that when a key is generated for the DES algorithm, only 56 bits are truly random, and every 7 bits, the algorithm inserts a bit that serves as the parity of the preceding 7 bits. When an attacker attempts to crack DES, they only need to discover these 56 truly random bits. DES is the only algorithm that distinguishes between actual (bits used to create the key) and effective (total number of bits) bits.

Developed in the 1960s, DES uses a **64-bit data block**, a size chosen when computers were less powerful. To perform all the necessary mathematical computations, a special-purpose unit called an **encryption processor** was created because DES relies on it to perform:

- **XOR**: which is not a problem → elementary operation;
- **Shift**: not a problem → elementary operation;
- **Permutation**: expensive operation. The permutation is not random, there are several ones, but still implementing that was much more efficient if done directly in hardware.

Triple DES (3DES, TDES)

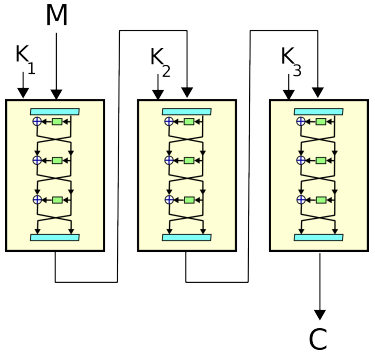
Triple DES is the repeated application of DES (three times). It is possible to use two or three different 56bit keys. Typically, the process involves taking the input, encrypting it, and then repeating this operation two more times, using the output of the previous encryption as the input for the next encryption (resulting in three consecutive encryptions).

Normally, it is implemented in **EDE** mode, which, in its standard form, requires two keys: the plaintext is first encrypted with key-1, then the decryption algorithm is applied to the output using key-2 (which does not actually decrypt but applies another transformation), and finally, this last output is encrypted again using key-1. This mode was chosen because setting $K_1 = K_2 = K_3$ allows for the implementation of the simple DES in EDE mode. Thus, both EEE and EDE work equally well. It has been shown that 3DES with two keys can have lower security guarantees than expected.

In particular, denoting K_{eq} as the equivalent key obtained by applying the discussed transformations:

- **3DES with 2 keys**, $K_{\text{eq}} = 56$ bits if $2^{59}B$ of memory is available, otherwise $K_{\text{eq}} = 112$ bits:
$$C' = \text{enc}(K_1, P) \quad C'' = \text{dec}(K_2, C') \quad C = \text{enc}(K_1, C'')$$
- **3DES with 3 keys**, $K_{\text{eq}} = 112$ bits:
$$C' = \text{enc}(K_1, P) \quad C'' = \text{dec}(K_2, C') \quad C = \text{enc}(K_3, C'')$$

The 3DES is a standard FIPS 46/3 and ANSI X9.52 (family X9 is standard for security in banking and financial applications).



Why not Double DES? The double application of any encryption algorithm is susceptible to a **known-plaintext** attack known as *meet-in-the-middle* see below), which allows for the decryption of data with at most 2^{N+1} attempts (if the keys are N bits long), instead of the 2^{2n} steps one would expect from an ideally secure algorithm with $2n$ bits of key. If the attacker knows one plaintext, they can execute the attack. For this reason, **the double version of encryption algorithms is never used** because the computation time doubles, but the effective key length increases by just one bit.

Furthermore, it has been proven that if the base symmetric algorithm is a group , then there exists an equivalent key K_3 such that:

$$\text{enc}(K_2, \text{enc}(K_1, P)) = \text{enc}(K_3, P)$$

This implies that in this case, the time needed for normal encryption/decryption doubles, but not a single bit is gained in terms of K_{eq}.

Meet-in-the-middle attack By hypothesis, N-bit keys are used, and we have known plaintext (P) and ciphertext (C) such that

$$C = \text{enc}(K_2, \text{enc}(K_1, P))$$

Note that $\exists M$ such that

$$M = \text{enc}(K_1, P)$$
$$C = \text{enc}(K_2, M)$$

The attacker computes 2^N values $X_i = \text{enc}(K_i, P)$ and then computes 2^N values $Y_j = \text{dec}(K_j, C)$. The search then involves finding those values K_i and K_j such that $X_i = Y_j$. There can be "false positives" but these can be easily discarded if more than one (P, C) pair is available.

hypothesis:
- N bit keys
- known P and C such that C = enc (K_2, enc (K_1, P))

note:
- ∃ M such that M = enc(K_1,P) and C = enc(K_2,M)

actions:
- compute 2^N values X_i = enc (K_i, P)
- compute 2^N values Y_j = dec (K_j, C)
- search those values K_i and K_j such that $X_i = Y_j$
- “false positives” can be easily discarded if more than one (P,C) couple is available

Let’s consider a company protecting its communication between Turin and Milan using double DES. If the attacker sniffs the network (and reads the encrypted data), they can send a message over that line (meaning they control the plaintext), and then observe the ciphertext (of the sent plaintext) automatically generated by the security system. This is a way to obtain a pair of (P, C) without knowing the keys.

2.2.2 Application of block algorithm

How is a block algorithm applied to a data quantity different from the algorithm's block size? There are two cases[1]:

1. `Data size to encrypt` > `algorithm's block size`
   - **ECB (Electronic Code Book):** Nowadays considered not secure and must never be used.
   - **CBC (Cipher Block Chaining):** Currently the best way to apply an encryption algorithm to data that is bigger than the size of the algorithm's block size.
2. `Data size to encrypt` < `algorithm's block size`
   - **Padding:** Used only when the data size is not exactly a multiple of one block size (e.g., when data is 2.6 blocks long). Note that this technique is not used to pad data that is just shorter than one block size.
     - **CTS (CipherText Stealing):** Permits the use of block algorithms without padding, avoiding an increase in the size of the ciphertext compared to the plaintext.
   - **CFB (Cipher FeedBack), OFB (Output Feedback), CTR (Counter mode)**.

ATTENTION! These are NOT algorithms; they are application modes for an algorithm.

It is necessary to specify: the algorithm, the size of key, and if it is a block algorithm, also the mode of the application (e.g., AES-128-CBC, that which "using EAS in CBC mode").

ECB

Encryption This mode splits the plaintext into blocks, and each block is encrypted separately with the key; that means that, for each block $i = 0, \ldots, N$,

$$C_i = \text{enc}(K, P_i)$$

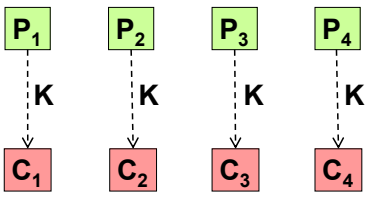


Figure 2.4: Encryption with ECB

It must **NOT** be used! [*Lioy said that the exam will not be passed if ECB is used somehow*]. In particular, it must not be used on long messages (any message longer than 1 block) because:

[1]The distinction should be: is the `data size` **multiple** of the *algorithm's block size*?

- If the attacker is intercepting the ciphertext and exchanges the position of 2 blocks, it is not detected (**block swapping**). This permits to exchange data inside an encrypted message;
- Identical blocks generate identical ciphertexts, hence it is vulnerable to **known-plaintext attacks**. Plaintext attacks require the precomputation of all possible encryptions of a known plaintext: comparing the encrypted block with all the precomputed possible encryptions, it is possible to figure out what the key is.

Known-plaintext attack example Let us suppose that we want to intercept a message sent by the rector of the Politecnico di Torino. It is possible to assume that his messages will contain the word "Torino", so we start encrypting this word with all possible keys. Next, we can go sniffing the blocks sent by the rector: if any of these blocks is equal to the encryption of "Torino", then we can use the key used to obtain that encryption of "Torino" to decrypt the rest of the message. Some arguments against this method could be: in which way is "Torino" written (e.g., "TORINO", "Torino")? What if "Torino", since it is shorter than one machine word, is split into different blocks (e.g., $P_i =$ "...To", $P_{i+1} =$ "rino..")? The known-plaintext attack is made possible by the fact that usually people exchange data in a structured format, so that there are metadata that are usually known (e.g., fixed header).

If a Word file is created with just a word, it is big KBs of memory (and not just bytes). This happens because Word applies a header on the document which is always the same (and always at the beginning of a file). If the first block of a Word file is encrypted, it can serve as a dictionary for Word files. This means that we do not even have to guess some plaintext, but just the file format.

Decryption Decryption is a straightforward process as it involves taking the ciphertext block and decrypting it with the corresponding key. In the case of an error in transmission, it only affects the decryption of that specific block, and **there is no propagation of the error to other blocks**.

- For each block, $P_i = \text{enc}^{-1}(K, C_i)$

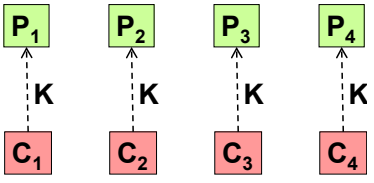


Figure 2.5: Decryption with ECB

CBC (Cipher Block Chaining)

Encryption This mode resolves all of ECB's problems. It divides the plaintext into blocks, but before each block is encrypted, it is **XORed with the ciphertext of the previous block**.

This introduces unpredictability in the encryption process. However, there is an issue with the first block (which serves as the header of the mentioned file); to apply CBC, an additional element called the **Initialization Vector (IV)** must be introduced, considered as C_0, with the sole purpose of altering the first plaintext block.

CBC also provides protection against block swapping because if blocks are swapped, the output will be different due to being altered with the incorrect XOR element.

- For each block, $C_i = \text{enc}(K, P_i \oplus C_{i-1})$
- Requires **IV**

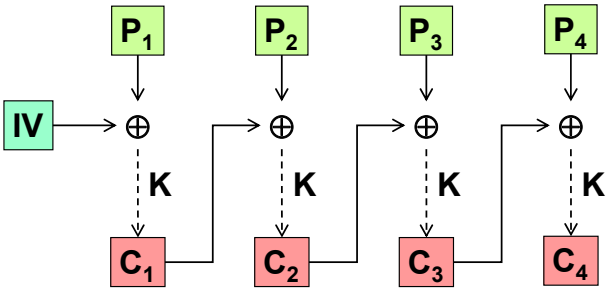


Figure 2.6: CBC encryption

Decryption The IV vector needs to be known at the receiver as well because, when the ciphertext is received, the IV must be known to decrypt the first block (since XOR is the inverse operator of itself). The IV must also be different every time (hopefully random) to avoid being guessed, as its purpose is to make it impossible to precompute the possible encryptions of the first block. It must also be a **NONCE** (Number used once), meaning that the IV should be generated and never reused in the future.

In some cases, the IV is sent in clear because even if the attacker knows it, they could start the computation only at that moment, and this is a time-consuming task. Moreover, it will permit the attacker to attack only the sent message, as the next one will have another IV. The IV can also be sent encrypted using ECB since it is just a block.

Opposed to ECB, **one error in transmission** generates an error at the decryption of **two blocks**. For example, if there's an error in C1, it affects the decryption, causing incorrect P1 and P2. However, P3 remains unaffected because C2 and C3 are needed for its decryption, and they are error-free in this case.

- $P_i = \text{enc}^{-1}(K, C_i) \oplus C_{i-1}$
- Requires **IV** to be known by the receiver

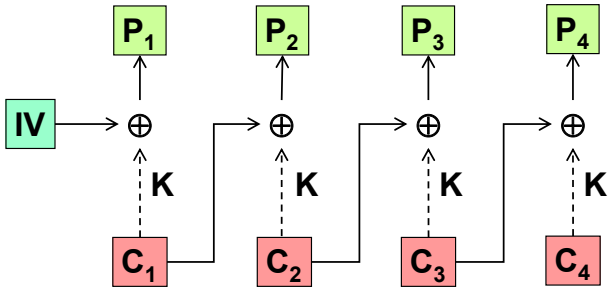
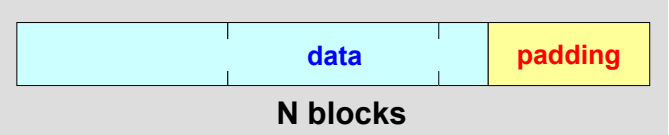


Figure 2.7: CBC decryption

Padding (aligning, filling)



It is not always possible to have the plaintext split into blocks that are all the same size. In the picture, the data consists of two complete blocks and a partial block at the end. To encrypt this small part, a technique called padding is used. Bits are added at the end of the original data until it reaches a multiple of a block. However, it has some problems since:

- The ciphertext gets longer than the plaintext: adding useless data means transmitting / storing more data than needed;
- Which should be the value of padding bits? How can we distinguish the padding from the original plaintext at the receiver? The are numerous **padding techniques**:
  - If the length is known or it can be obtained as in the case of a C string, it is possible to add null bytes at the end: `0x00 0x00 0x00`;
  - The original DES specified to add one "1" bit followed by as many "0" as needed: `1000000`;
  - One byte with value 128 followed by null bytes: `0x80 0x00 0x00`;
  - Last byte's value equal to the length of padding: `0x??  0x??  0x03` (3 bytes of padding. The last one has value 3, and the previous has a value to be specified). There are numerous padding techniques available, and the choice of a specific padding method plays a crucial role in preventing or mitigating various types of attacks. Consider the value of other bits (`0x??`)[2]:
    - (Schneier) null bytes, e.g., `0x00 0x00 0x03`
    - (SSL/TLS) bytes with value L, e.g., `0x03 0x03 0x03`

[2] do not remember all the techniques, just remember there are many and the proper one must be selected

- (SSH2) random bytes, e.g., `0x05 0xF2 0x03`
- (IPsec/ESP) progressive number, e.g., `0x01 0x02 0x03`
- Byte with value $L - 1$, e.g., `0x02 0x02 0x02`

Some notes

- B stands for the size of the algorithm's block
- D stands for the size of data to process

Some of these techniques offer (minimal) integrity control: if the key is wrong or data is manipulated, then the padding bytes are incoherent (e.g., length of something bigger than one block or wrong padding values).
Typically, this is applied to large data, on the last fragment resulting from the division into blocks (e.g., for ECB or CBC). If $|D| < |B|$, an ad-hoc technique is preferred (CFB, OFB, CTR, ...). If there is just a byte, it is not good to add 65 bytes of padding.
Even if the plaintext is an exact multiple of the block, padding must be added anyhow to avoid errors in the interpretation of the last block. The biggest padding is required when there is no padding to add.
With SSH2, padding equal to data gives different ciphertexts (even when encrypted with the same key).
The padding type for a certain algorithm determines the type of (some) possible attacks, but it also depends upon the algorithm used.

Ciphertext stealing (CTS)

When using padding, the size of the ciphertext is bigger than the plaintext. This may not be acceptable in several cases (for example, data encrypted on a hard disk that may not fit on the same disk). It is possible to use CTS instead of padding. The last (partial) block is filled with bytes taken from the second-to-last block (encrypted), then these bytes are removed from the second-to-last block (which becomes a partial one). After encryption, the positions of the last and second-to-last blocks are exchanged. It is useful when it is not possible to increase the size of data after encryption, but the computation time slightly increases.

In order to encrypt or decrypt data, use the standard block cipher mode of operation on all but the last two blocks of data. The following steps describe how to handle the last two blocks of the plaintext, called P_{n-1} and P_n, where the length of P_{n-1} equals the block size of the cipher in bits, B; the length of the last block, P_n, is M bits; and K is the key that is in use. M can range from 1 to B, inclusive, so P_n could possibly be a complete block. The CBC mode description also makes use of the ciphertext block just previous to the blocks concerned, C_{n-2}, which may, in fact, be the IV if the plaintext fits within two blocks.

For this description[3] the following functions and operators are used:

- Head(*data*, a): returns the first a bits of the 'data' string.

[3] `https://en.wikipedia.org/wiki/Ciphertext_stealing#CBC_ciphertext_stealing`

- Tail($data$, a): returns the last a bits of the 'data' string.
- enc(K, $data$): use the underlying block cipher in encrypt mode on the 'data' string using the key K.
- dec(K, $data$): use the underlying block cipher in decrypt mode on the 'data' string using the key K.
- XOR: Bitwise Exclusive-OR. Equivalent to bitwise addition without the use of a carry bit.
- $\|$: Concatenation operator. Combine the strings on either side of the operator.
- 0^a: a string of a 0 bits.

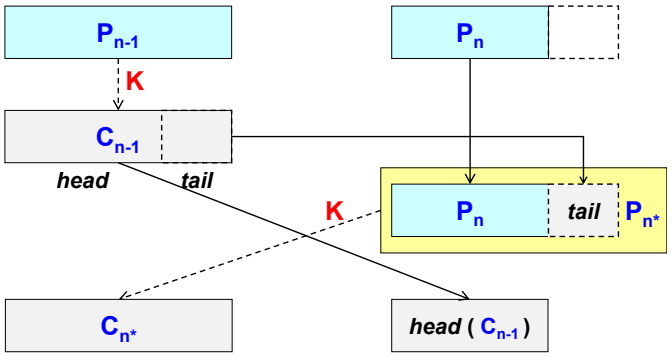


Figure 2.8: CTS with ECB (encryption)

CTS Example with *ECB* (encryption)

1. $E_{n-1} = \text{enc}(K, P_{n-1})$.
   Encrypt P_{n-1} to create E_{n-1}. This is equivalent to the behavior of standard ECB mode.
2. $C_n = \text{Head}(E_{n-1}, M)$.
   Select the first M bits of E_{n-1} to create C_n. The final ciphertext block, C_n, is composed of the leading M bits of the second-to-last ciphertext block. In all cases, the last two blocks are sent in a different order than the corresponding plaintext blocks.
3. $D_n = P_n \text{ Tail } (E_{n-1}, B - M)$.
   Pad P_n with the low-order bits from E_{n-1}.
4. $C_{n-1} = \text{enc}(K, D_n)$.
   Encrypt D_n to create C_{n-1}. For the first M bits, this is equivalent to what would happen in ECB mode (other than the ciphertext ordering). For the last $B - M$ bits, this is the second time that these data have been encrypted under this key (It was already encrypted in the production of E_{n-1} in step 2).

Shorter description

1. The plaintext is split into blocks;
2. The second-to-last block is full, so it is possible to encrypt it with the key;
3. The last one is not full and creates a problem;
4. The encrypted block C_{N-1} is split into two parts: *head* and *tail*. The tail has the same size as the part that is missing in the last block;
5. The tail is added to the partial block, creating a full block;
6. The fully created block is transmitted, and then the head is transmitted.

The receiver must reverse the procedure. Bits corresponding to the tail are encrypted twice. Exchanging the blocks is necessary because if we send the head without the tail, then the beginning of the next block is interpreted as part of the previous one.

Please note that **ECB must never be used**; the example is intended to make it easier to understand.

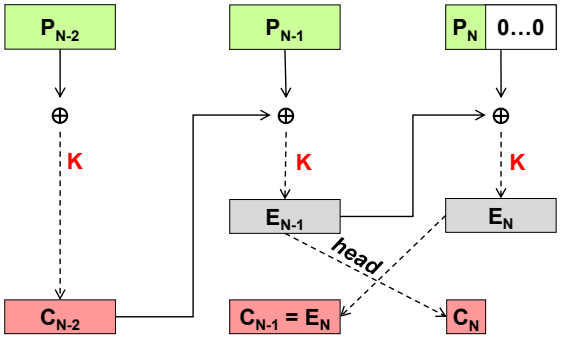


Figure 2.9: CTS with CBC (encryption)

CTS Example with *CBC* (encryption)

1. $X_{N-1} = P_{N-1} \oplus C_{N-2}$.
   XOR P_{N-1} with the previous ciphertext block, C_{N-2}, to create X_{N-1}. This is equivalent to the behavior of standard CBC mode.
2. $E_{N-1} = \text{enc}(K, X_{N-1})$.
   Encrypt X_{N-1} to create E_{N-1}. This is equivalent to the behavior of standard CBC mode.
3. $C_n = \text{Head}(E_{N-1}, M)$.
   Select the first M bits of E_{N-1} to create C_n. The final ciphertext block, C_n, is composed of the leading M bits of the second-to-last ciphertext block. In all cases, the last two blocks are sent in a different order than the corresponding plaintext blocks.

4. $P = P_N \| 0^{B-M}$.
   Pad P_n with zeros at the end to create P of length B. The zero padding in this step is important for step 5.

5. $D_n = E_{N-1} \oplus P$.
   XOR E_{N-1} with P to create D_n. For the first M bits of the block, this is equivalent to CBC mode; the first M bits of the previous block's ciphertext, E_{N-1}, are XORed with the M bits of plaintext of the last plaintext block. The zero padding of P in step 4 was important because it makes the XOR operation's effect on the last $B - M$ bits equivalent to copying the last $B - M$ bits of E_{N-1} to the end of D_n. These are the same bits that were stripped off of E_{N-1} in step 3 when C_n was created.

6. $C_{N-1} = \text{enc}(K, D_n)$.
   Encrypt D_n to create C_{N-1}. For the first M bits, this is equivalent to what would happen in CBC mode (other than the ciphertext ordering). For the last $B - M$ bits, this is the second time that these data have been encrypted under this key (It was already encrypted in the production of E_{N-1} in step 2).

Shorter description The various blocks are encrypted with a key and XOR operation, particularly C_{N-2}, which is utilized in the P_{N-1} XOR encryption. In the last step, P_N is padded with all zeros and XORed with the encrypted block E_{N-1} (encryption of P_{N-1}), thus encrypting the last block. E_N is then positioned in the $N-1$ position. On the contrary, the E_{N-1} encryption is not transmitted completely, only the head is sent. It may seem that part of E_{N-1} is missing, but since the tail is XORed with all zeros, it will be recovered by C_{N-1}.

Since XOR with zero does not alter data, the tail is embedded into E_N as the $N-1$ block. This ensures that the ciphertext has the same dimensions as the plaintext. With this mode, if the blocks are fully filled from the plaintext, there is no need for additional padding. This mode is widely used today, especially for encrypting storage on embedded devices such as smartphones.

CTR (Counter mode)

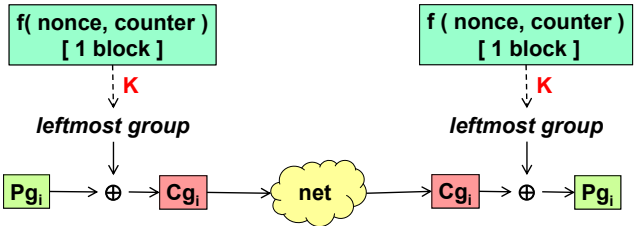


Figure 2.10: CTR (counter mode)

This is useful for plaintext smaller than one block, as it does not make sense to encrypt it using padding. **CTR** is the most used technique that **uses a block algorithm to cipher N bits at a time** (a "group", often a byte). It has nice properties that permit random direct access to any ciphertext group, and it doesn't require padding.

Take CBC, for instance; it's not possible to encrypt or decrypt individual blocks due to the need for concatenation. In contrast, with CTR, decrypting a single block is possible, however it **requires a nonce** (also known as IV) **and a counter** that are combined in various ways — such as concatenation, summation, XOR, etc.

In this example (Figure 2.10), there is a group (e.g., 1 byte) smaller than one block, denoted as P_{g_i}, situated above a register exactly the size of one block. The register is filled with a nonce and a counter, combined in the predetermined manner. As it is one block in size, we can directly encrypt it with the key. Subsequently, the leftmost group is selected. For instance, if P_{g_i} is 1 byte, only the last byte from the encryption of the register is considered. Following this, we apply an XOR operation, generating the corresponding ciphertext C_{g_i}, which can be transmitted over the network.

On the receiving end, another register must be present, initialized in the same manner as the sender, and undergo the same inverse operation. Naturally, the sender and receiver must share the same nonce and maintain identical counter values to stay synchronized. This type of transmission is vulnerable to **cancellation attacks**; if a message is removed, synchronization is lost. However, this risk can be mitigated using integrity techniques, which will be discussed later.

Example of CTR A long data stream must be enciphered in CTR mode, byte- oriented, with key K, nonce N, and $f(...)$ is just concatenation. For the sender:

```
for (i=0; i<data_size; i++)
        ctext[i] = ptext[i] xor MSB( enc(K, nonce || i) )
```

For the receiver, if he needs to decipher only bytes no. 30 and 31:

```
ptext[30] = ctext[30] xor MSB( enc(K, nonce || 30) )
ptext[31] = ctext[31] xor MSB( enc(K, nonce || 31) )
```

Note: the byte-oriented CTR mode of a block algorithm may be considered a stream algorithm (see chapter 2.2.3).

2.2.3 Symmetric stream encryption algorithms

Stream algorithms operate on *one bit* or *one byte* at a time, eliminating the need for block division.
Within this category, the **one-time pad** is the only *ideal algorithm*, requiring a key as long as the message, making it impractical for most use cases.
Real algorithms use pseudo-random key generators, necessitating synchronization between the sender and receiver. Examples of modern algorithms include Salsa20 and Chacha20, while older ones include RC4 and SEAL.

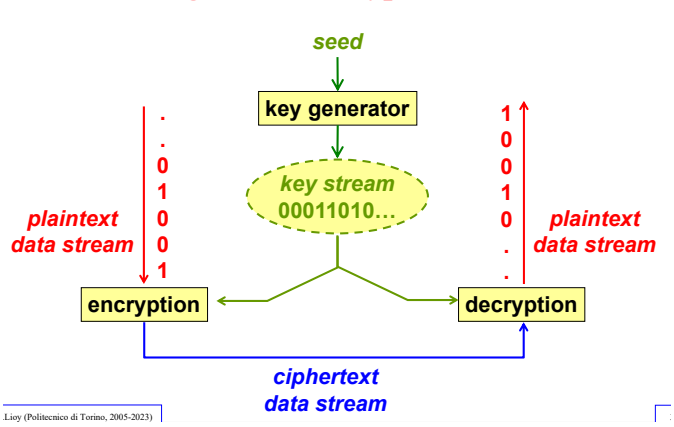


Figure 2.11: Algorithms of type stream

The plaintext data stream on the left is encrypted one bit at a time. As the data stream can be lengthy, the key stream must also be long. The key stream is generated from a key generator, which is initialized with a **seed** (the seed is essentially the key, as it must be identical for both the receiver and sender). The encryption function essentially employs an XOR operator (no more complex function is required), as this ensures the operations are unpredictable.

At the receiver, decryption is performed using the same key stream, meaning the same seed and algorithm are used for generating the key.

If an attacker manages to delete a portion of the ciphertext data stream, decryption will produce incorrect results since the wrong part of the key stream will be used. On the other hand, these algorithms are known for their speed.

Salsa20 and ChaCha20

These are symmetric stream algorithms invented by D. J. Bernstein, featuring *128* or *256-bit keys*. ChaCha20 is an improvement of Salsa20, where there is more "diffusion" of bits, meaning that changing 1 bit of the input results in more bits of the output being changed. ChaCha20 is also faster on some architectures.

The base operation is a 32-bit ARX (add-rotate-XOR), while the base function is expressed as:

$$f(\text{Key256}, \text{Nonce64}, \text{Counter64}) = 512 \text{ bit keystream block}$$

This permits $O(1)$ decryption of any block at random. Salsa20 performs 20 mixing rounds of the input, while Salsa20/12 and Salsa20/8 have a reduced number of mixing rounds: 12 and 8 respectively, which is faster but less secure. ChaCha20 has been standardized and is widely adopted, with documentation in RFC-8439 (Chacha20 and Poly1305 for IETF protocols). The IETF has slightly modified the original specification: a bigger nonce and a smaller block counter. In particular,

- 96-bit nonce;
- 32-bit block counter, note that counter may start from 1 (rather than 0) if the first block is used as an authentication tag (as in AEAD);
- Hence a limit of 256 GB (2^{32} 64-byte blocks)
- To overcome this limit, use the original definition by Bernstein.

This has become famous because it is used by Google (for Chrome on Android), OpenSSH, and various CSPRNGs (e.g., `/dev/urandom` since Linux kernel 4.8).

Length of secret keys If Kerchoff's conditions are met, that is:

- the encryption algorithm was well designed
- the keys (N-bit in length) are kept secret
- the algorithm is executed by a trusted party (e.g. no malware)

Then the only possible attack is the **brute force** (exhaustive) **attack** which requires a number of trials proportional to 2^{Nbit}:

$$T \propto 2^{Nbit}$$

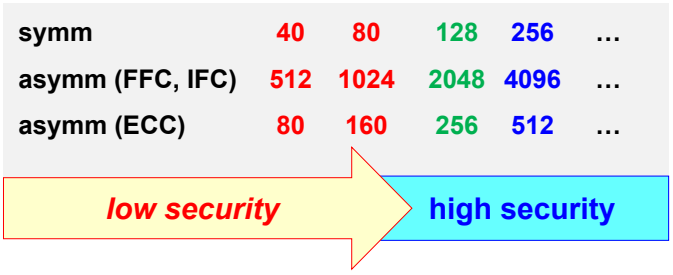


Figure 2.12: Length of cryptographic keys

The table (Figure 2.12) what is currently considered secure or insecure.
Currently, any key less than 128 bits is considered insecure. This is due to the current speed of CPUs and the possibility of parallelizing key search (e.g., using several computers to work on a

specific set of keys).
The second row refers to asymmetric keys with FFC and IFC, where any key under 2048 bits is considered insecure. There are no borders in the column, but an arrow that is always expanding to the right.
The third row refers to asymmetric keys using ECC, where the minimum key size is 256 bits. The area of low security increases each year because computers become more powerful.

Another challenge is determining **how long data will remain secret**. If secrets must remain secure, it is essential to avoid the low-security arrow and always stay in the right part of the table. However, as the key size increases, the algorithms become slower, and it's not a simple doubling. For symmetric algorithms, doubling the key cuts performance in half, but for asymmetric algorithms, doubling the key means a factor from 4 to 10 of lower performance.

AES (Advanced Encryption Standard)

The US government initiated a competition to select a new symmetric algorithm to replace DES: **AES** (Advanced Encryption Standard). There were 15 candidates, but only 5 finalists[4]. The winner was announced on 2nd Oct 2000, called **RIJNDAEL**, and the algorithm was published in November 2001 as FIPS-197.
This algorithm uses a **key length** of **128 / 192 / 256 bits** and a **block size** of **128 bits**.

Even though the algorithm was published in 2001, it has been gradually adopted after 2010. It takes so long because crypto algorithms are like wine: the best ones are those aged for several years.

2.2.4 Key distribution for symmetric cryptography

Symmetric encryption uses a single and secret key. It is needed one key for each couple (or group) of users. In the example (Figure 2.13) X has a shared key with Y. If X wants to talk with Z, they will need a different key. But it is also possible to decide to have a common key (group key) which is common to X,Y and Z but other people that are part of the group, but are not the destination of a message, would be able to read it.

A complete pairwise private communication between N parties requires $\frac{N\times(N-1)}{2}$ keys, which is equal to the diagonals of a polygon with N vertices. If N gets bigger, the number of keys also increases significantly. The problem is how to securely distribute the keys to the communicating parties. Those solutions are:

- **OOB** (Out-Of-Band): the key is shared among the parties without utilizing the same electronic channel used for transmitting the message. Direct communication, such as whispering the key to someone, would be an ideal solution for key sharing.
- **By means of key exchange algorithms**. See Chapter 2.3.3

[4] `www.nist.gov/aes`

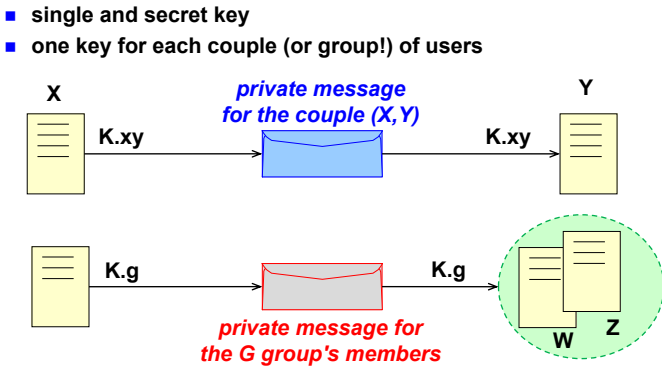


Figure 2.13: Symmetric encryption

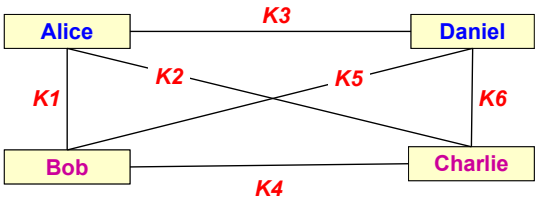


Figure 2.14: Key distribution for symmetric encryption

2.3 Public key / asymmetric cryptography

Nowadays, there is a second type of cryptography invented in the 1970s, known as **public cryptography**. In this type of cryptography,

$$key_1 \neq key_2$$

If one key is used for encryption, the other must be used for decryption, but their roles can be exchanged. It is also referred to as an **asymmetric algorithm**, and the keys are used **in pairs**. Since there is not only one key, they are named according to the way they are stored: one is public (**public key**, PK), while the one is kept private (**private key**, SK).
These keys have **inverse functionality**, meaning data encrypted with one key can be decrypted only by the other key.

This type of cryptography has a **high computational load**, so it is usually used to distribute secret keys and to create electronic signatures (with hashing), not for storing data.
The main algorithms include Diffie-Hellman, RSA, DSA, ElGamal, and others.

Keys In Figure 2.15, a message is encrypted with a private key and sent to the receiver, who will use the corresponding public key to decrypt the message. Typically, the sender uses its private key to encrypt something, and all other individuals will know the public key and be able to decrypt the message.

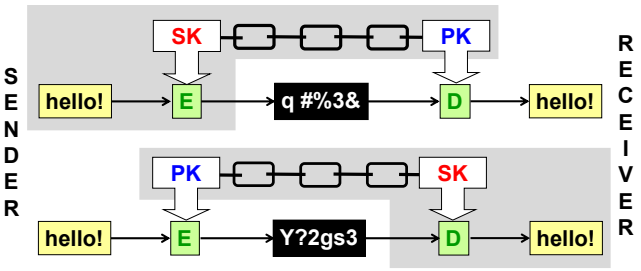


Figure 2.15: How a key pair can be used in asymmetric encryption in a communication

On the bottom, there is the case where someone uses the public key of the destination, as only the destination will have the corresponding private key.

These two ways of using a pair of keys are employed to achieve two different functionalities: **digital signature** and **confidentiality without shared secrets**, described below.

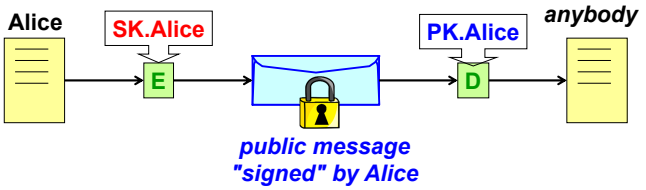


Figure 2.16: Digital signature

Digital signature The following outlines the *basic idea* of a digital signature.
A digital signature follows the scenario depicted in the upper case of the previous image (Figure 2.15), involving the encryption of data with the private key of the author.

Suppose X wants to sign a document. X encrypts the document using his private key. Since it was encrypted with the private key, anyone can use X's public key to decrypt it. Therefore, the content is not a secret message, but it is "signed" by the sender. If someone attempts to use a different public key, it will not be possible to decrypt the message. This serves as proof and is legally valid evidence that the bits were created by a specific person.

If the message is too large, encrypting the entire message would be time-consuming. For this reason, only a summary (digest) of the data is encrypted. This process provides both **data authentication** and **integrity**.

However, this is NOT the real implementation of the digital signature, that is completely explained next.

Confidentiality without shared secrets It is possible to generate a **secret message** for a receiver using only its public key. The message is encrypted with the public key, and only the intended recipient possesses the corresponding private key necessary for decryption. This

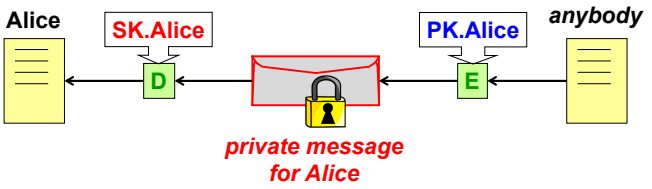


Figure 2.17: Confidentiality without shared secrets

approach eliminates the need for key sharing between the sender and receiver. However, for large messages, the encryption and decryption processes can become time-consuming.

2.3.1 Public key algorithms

There are two mains algorithm used nowadays: **RSA** (Rivest - Shamir - Adleman) and **DSA** (Digital Signature Algorithm).

RSA RSA consists in the computation of the product of **two prime numbers**. If you are the attacker, you observe the result, and if you want to compromise the system, you must discover what the two factors are. Therefore, very long keys are needed because if the result is for example 21, it will be easy to attack: 3 and 7 will be the prime numbers. The point is that there are no formulas to compute all prime numbers; for this reason, the larger the number you are considering, the harder it is to find the prime numbers, making the problem more complex for the attacker.

RSA can be used to implement both functionalities: **digital signature** and **confidentiality without shared secrets**.

It is patented only in the USA by RSA, but the patent expired on 20/09/2000 (no problems of royalties).

DSA DSA is the primary contender for digital signatures/ This algorithm exploits a similar mathematical problem: **given a base and an exponent, perform the power**. If you are the attacker, you see the result, but it is not easily known which is the base and the exponent of that number. This is like taking the logarithm of a number without knowing the base.

The limitation of DSA is that it can only be used to create a digital signature because, within the algorithm, there is a one-way lossy compression function. By losing information, the original plaintext cannot be recovered. This intentional design choice was made by the US government when creating DSA, aiming to prevent citizens from hiding information.

To achieve **confidentiality without shared secrets**, you must use the **El-Gamal algorithm** (following the same principle as DSA).

DSA is a standard defined by NIST for DSS (FIPS-186).

Hardware and example

Twinkle Every year, there is a conference named Eurocrypt, focusing on cryptography in Europe. A scientist from RSA Laboratories attended the Ramp Session, where interesting and promising ideas are presented. Professor Adi Shamir (who contributed the "S" in RSA) showcased an unusual piece of hardware called *TWINKLE* (The Weizmann Institute Key Locating Engine). It is an electro-optical computer that implements the sieving algorithm to find prime numbers. The Twinkle machine is expected to find the factors of an RSA key two to three orders of magnitude faster than a conventional fast PC. It operates at a very high clock rate (10 GHz), must trigger LEDs at precise intervals of time, and uses wafer-scale technology. According to estimates by Professor Shamir, the device can be fabricated for about $5,000. Unfortunately, Shamir never returned to the next conference to showcase the device.

Twirl (The Weizmann Institute Relation Locator) This is an electronic device designed for factoring large integers. It implements the sieving step of the Number Field Sieve integer factorization algorithm, which is, in practice, the most expensive step in factorization. TWIRL is more efficient than previous designs by several orders of magnitude, thanks to high algorithmic parallelization combined with adaptation to technological hardware constraints. Although the design is fairly detailed, it remains hypothetical since the device has not been actually built. TWIRL is constructed using current VLSI technology, and it would be possible to factor 1024-bit integers, thus breaking 1024-bit RSA keys in one year at the cost of a few dozen million US dollars.

Firmware Signature for TI Calculators These facts demonstrate that RSA is not totally secure: there is evidence that sooner or later, the factors will be found, and the mathematical problem will be solved. An example is the TI83+ graphing calculator, which has firmware protected by a 512-bit RSA signature. The signature key was factored in July 2009 after 73 days of computation on a 1.9 GHz dual-core Athlon64 PC. In 1999, the same computation would have required 8000 MIPS-years + Cray C916. Now, all users may autonomously modify the firmware themselves. A signed firmware means that a software is signed with a digital signature (which is a piece of software). If anybody alters the software, then the digital signature will fail, and there is a hardware control that will not operate if the software is modified.

2.3.2 Key distribution for asymmetric cryptography

Private keys must never be disclosed and must be protected. The other key does not need protection, since it is a public key that must be distributed as widely as possible. However, the problem is: who guarantees the binding (correspondence) between the public key and the identity of the person?

There are two solutions to this problem:

1. Exchange of keys **Out-Of-Band** (OOB) (e.g., key party!)
2. Distribution of the public key by means of a specific data structure named **public-key certificate** (=digital certificate). But what is the format of the certificate? Do you trust

the certificate issuer?

2.3.3 Secret key exchange by asymmetric algorithms

In principle, asymmetric cryptography can guarantee confidentiality without a shared secret by itself, but, as previously mentioned, it is slow. This makes it applicable only to a small quantity of data. For this reason, a common practice is **to use it to send the secret key chosen for a symmetric algorithm**, solving at the same time the issue of symmetric key distribution for symmetric algorithms and the slowness of asymmetric ones for big data.

In the example (Figure 2.18), X is willing to send an encrypted message to Y: to do so, it produces a key K (usually 128-256 bits long) and encrypts it using the public key of Y (PK.Y), resulting in ε. Note that, given the small size of K, performing its asymmetric encryption is fast enough. At this point, Y uses its private key (SK.Y) to decrypt ε, obtaining the original symmetric key K, which will be used for the rest of the communication between X and Y, in the example to send "hello." Typically, the key K can be changed for each message or for each network session; however, it is not meant to be long-term (e.g., years). This type of encryption is applied every time a server connection is created.

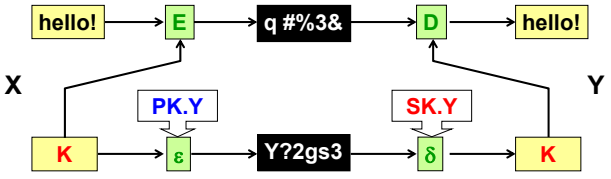


Figure 2.18: Secret key exchange by asymmetric algorithms

Is this schema issue-safe? In some environments, the fact that X decides what key will be used for the actual communication is not acceptable. Y could argue that X's key is not safe, maybe it has been disclosed, and someone could be able to decrypt the message in the communication without violating the asymmetric encryption used to exchange the key. The same reasoning could apply to the opposite case, in which Y decides the key to be used. In such cases, the key can be produced jointly using the *Diffie-Hellman algorithm*.

Diffie-Hellman algorithm

The two parties (called Alice and Bob in this example[5]) involved in the communication agree on two public integers (p, g) , p (a large prime number), and g (called the "generator"), given the constraint $1 < g < p$. The length of a Diffie-Hellman key is defined as the number of bits in the binary representation of p. Both numbers p and g are public values, and typically, $g = 2, 3,$ or 5.

Both parties decide autonomously on a (random) number, called x for peer Alice and y for peer Bob. Alice computes the number $X = g^x \bmod p$, and Bob computes $Y = g^y \bmod p$. They then exchange these values in clear. It is easy to see that $K_A = K_B = g^{xy} \bmod p$, so the parties

[5]In this example, "Alice and Bob" were used; the figures uses A and B

have decided together on a value for the symmetric key to be used because it depends on both x and y.

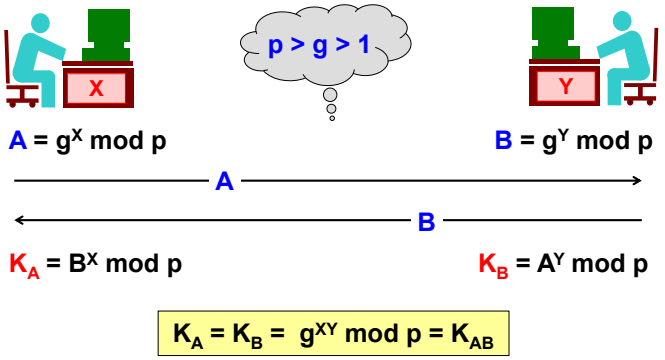


Figure 2.19: Diffie-Hellman (DH)

Recap:

- Alice and Bob choose p (prime, large) and g (generator, a primitive root module p) such that $1 < g < p$, typically $g = 2, 3, 5$. The length of DH key will be equal to the number of bits of p.
- Alice arbitrarily chooses an integer $x > 0$ and computes $A = g^x \mod p$
  Bob chooses an integer $y > 0$ and computes $B = g^y \mod p$
- Alice and Bob exchange these values in clear.
- Alice computes $K_A = B^x \mod p$
  Bob computes $K_B = A^y \mod p$
- It is easy to see that $K_A = K_B = g^{xy} \mod p$

Vulnerabilities From an attacker's perspective, even if they know the values for p and g, as well as the values A and B being exchanged (e.g., attempting a passive man-in-the-middle attack), it is not possible to compute K_{AB}. This is because the attacker would need to also know x or y. Therefore, the Diffie-Hellman algorithm is **resistant to sniffing attacks**. However, it is vulnerable to man-in-the-middle attacks if the attacker can manipulate the data. This manipulation can be detected if the exchanged values are authenticated. In such cases, certificates for Diffie-Hellman keys are required, or there is a variant of the algorithm called **Authenticated Diffie-Hellman** (or **MQV**, named after the scientists who invented it, Menezes-Qu-Vanstone).

As it uses only public information, it is referred to as the first public key algorithm ever invented. It is commonly used to agree on a secret key, earning it the title of a key-agreement algorithm, as opposed to the key-distribution algorithm discussed earlier. While it was patented in the USA, it has been royalty-free since April 29, 1997.

DH: man-in-the-middle attack As stated, the only way to attack Diffie-Hellman after performing sniffing is to execute a brute-force attack to find $x = \log_g A \bmod p$. However, solving this is infeasible since it involves a discrete logarithmic problem. In the case of an attacker performing an active man-in-the-middle attack, the outcome is different.

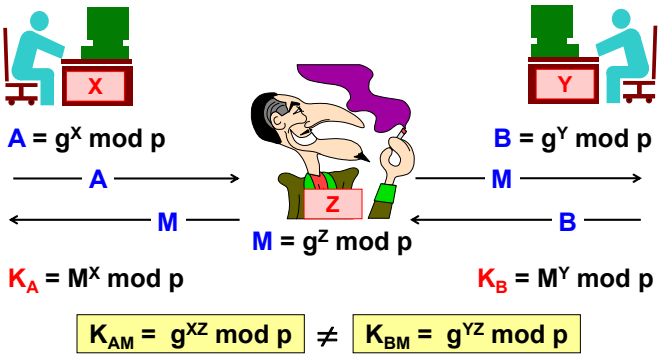


Figure 2.20: DH: man-in-the-middle attack

Let us suppose that a man-in-the-middle entity, Z, is participating in the communication. Similar to X and Y, Z computes $M = g^z \bmod p$. When peer X sends its value A, Z intercepts it and sends the value M in exchange. Similarly, when peer Y sends its value B, Z intercepts it and sends the same value M. By doing so, peer X will compute $K_A = M^x \bmod p$, while Y will compute $K_B = M^y \bmod p$.

This time, the two values are not equal. In fact, $K_{AM} = g^{xz} \bmod p$, while $K_{BM} = g^{yz} \bmod p$. They are effectively computing a shared key with the man-in-the-middle, and any data they encrypt can be decrypted by the man-in-the-middle, who can inspect, modify, and then re-encrypt the data for the destination using the other shared key.

This attack is made possible because when a peer receives a value, it has no proof of who sent it. This is the reason why one possible solution is to use **certificates**. One application of Diffie-Hellman (DH) could be in HTTPS: the browser could produce a key and send it encrypted with the public key of the server, or the server could publish its DH value signed with its private key and distribute it. DH is widely used nowadays to agree on a key, and there is also the possibility to have authentication (because otherwise, such a Man-in-the-Middle attack is possible).

Elliptic curve cryptography A new kind of cryptography of this type is ECC (Elliptic Curve Cryptosystem). The concept is the following: instead of using modular arithmetic, the operations are executed on the surface of a 2D (elliptic) curve. Not all the points in the Cartesian space are valid points, but only those that satisfy the 2D curve equation. The problem of the discrete logarithm on such a curve is that since the point representation is more complex, the problem, in general, is more complex than the one in normal modular arithmetic. This gives the opportunity to use keys shorter by a factor of approximately 1/10.

Most algorithms have been revisited to adapt them to the elliptic curve (RSA cannot be adapted):

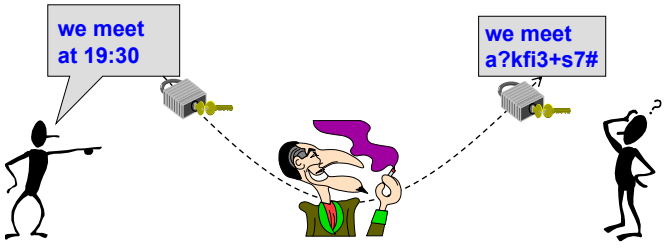
- ECDSA for digital signature:
  - Message digest computed with a normal hash function (e.g., SHA-256);
  - Signature = pair of scalars derived from the digest plus some operations on the curve (see below about operations on the curve).
- ECDH for key agreement;
- ECMQV for authenticated key agreement;
- ECIES (EC Integrated Encryption Scheme) for key distribution:
  - Generates a symmetric encryption key (e.g., an AES-128 one) with operations on the curve;
  - Provides the receiver with the information (based on their public key) needed to recomputed the encryption key.

Case history: Sony PS3 hacking

The Sony PS3 is a Linux machine on which direct access to the system is blocked by Sony, as well as any modification to it, by digitally signing the firmware with Sony's own signature. The PS3 has embedded Linux with a loader verifying the ECDSA signature of binaries before execution. The generation of an ECDSA signature requires a random nonce; otherwise, the private key can be computed from the signature. The problem arose because Sony decided on a fixed random number (technically not a nonce anymore). As a consequence, the private key was computed and distributed worldwide, allowing anyone to run their own binaries on their PS3.
Sony attempted to take the hackers to court, accusing them of violating their software. However, the judge dismissed the charge because the security measure was not implemented correctly.[a]

[a] More info at `https://fahrplan.events.ccc.de/congress/2010/Fahrplan/events/4087.en.html`

2.4 Message integrity

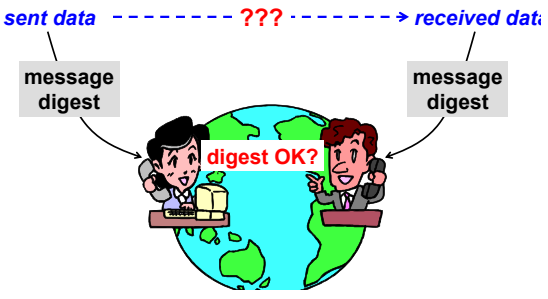


So far, we have seen that there are methods to guarantee that a message from a sender to the receiver cannot be understood by a third party. However, it is still possible for an attacker to intercept the traffic from the two parties and change the encrypted message. Even if this does not give him the possibility to alter the message in a specific way, he can change it in an unpredictable way (for example, flipping some bits in the message). In certain types of communication, this causes the message to become not intelligible anymore when decrypted by the receiver. Consequently, it becomes evident that something went wrong during transmission. In this case, the receiver can ask for retransmission, and a continuous attack like this is, at the very least, a Denial of Service (DoS). In other cases, for example, when the message is a bank account number, there is a high likelihood that the result will be a different number, but still a valid one, so the destination has no way to check if it is wrong. This is particularly dangerous when the communication takes place between automatic systems.

So, along with confidentiality, integrity is a very important matter. Integrity is not about preventing modifications of data; it means that when some data is received, *the receiver can verify if the data has been modified or not.* This is important not only in communications but also for storing data on the disk; it can be important to verify if someone has changed the data on the disk since it has been written. The importance of integrity is shown by a study conducted by the UK army, which estimated that only 10% of their communications needed confidentiality, but 100% of them needed integrity. **Integrity also implies authentication** since a message that has not been modified is also authentic (which means that it is the same as sent by the sender).

To guarantee integrity, the technique used is to compute a **digest**, which is a *fixed-length* summary of the whole message to be protected. A digest is conceptually similar to a checksum (widely used in communication to detect transmission errors); however, the algorithms used to compute a checksum are easy to attack. Therefore, a digest is usually calculated via a **cryptographic hash function**. The digest must be:

- Fast to compute;
- impossible or very difficult to invert;
- it should be difficult to create "collisions" (two different messages should not produce the same digest).



2.4.1 Cryptographic hash functions

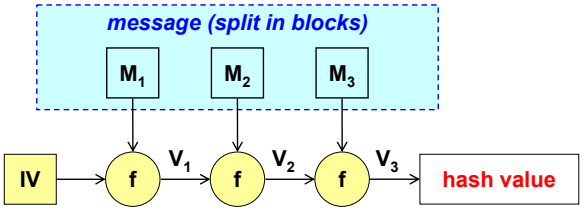


Figure 2.21: Hash functions (dedicated)

The hash function works like this:

- Split the message M into N blocks $M_1, \ldots, M_N$;
- Iteratively apply a base function (f);
- $V_k = f(V_{k-1}, M_k)$ with $V_0 = \text{IV}$ and $h = V_N$.

The IV is an initialization value that does not need to be announced or be random. Typically, it is fixed and specified inside the algorithm itself (source and destination must perform the same computation).

SHA

SHA-2 family

The most widely used algorithms nowadays are those in the **SHA-2 family**: they have the same block size but an increasingly digest size. Because they inherit the structure of SHA-1, which has been broken[6] and should never be used anymore, it is possible that soon they will not be secure enough. SHA-3 has already been developed and should be the choice to adopt once its strength is proven.

The SHA-2 family was a quick fix after the SHA-1 attack, and it was developed by making the digest longer. The main algorithms are SHA-256, which uses a 32-bit word, and SHA-512, which uses a 64-bit word (suitable for 32/64-bit PCs, respectively).

Digest length The digest length is important to avoid **aliasing**, which is the collision of two different messages producing the same digest. Breaking a digest algorithm means finding a second message that will generate the same digest as the first one. If the algorithm is well-designed and generates a digest of N bits, then the probability of aliasing is $P_\text{A} \propto \frac{1}{2^{N\text{bits}}}$. This is the reason why digests with many bits are required, as statistical events are involved.

As a consequence of statistical considerations (see the birthday paradox[7]), an N-bit digest algorithm is insecure when more than $2^{N/2}$ digests are generated because the probability of

[6] https://www.schneier.com/blog/archives/2005/02/sha1_broken.html
[7] https://en.wikipedia.org/wiki/Birthday_problem

name	block	digest	definition	notes
MD2	8 bit	128 bit	RFC-1319	obsolete
MD4	512 bit	128 bit	RFC-1320	obsolete
MD5	512 bit	128 bit	RFC-1321	obsolete
RIPEMD-160	512 bit	160 bit	ISO/IEC 10118-3	old + rare
SHA-1	512 bit	160 bit	FIPS 180-1	sufficient
SHA-224	512 bit	224 bit		
SHA-256	512 bit	256 bit	FIPS 180-2	good
SHA-384	512 bit	384 bit	FIPS 180-3	
SHA-512	512 bit	512 bit		
	SHA-2			
SHA-3	1152-576	224-512	FIPS 202 FIPS 180-4	excellent

Figure 2.22: Cryptographic hash algorithms

having two messages with the same digest is $P_A \sim 50\%$. If an attacker sniffs the network, they can simply store all the messages and their digests passing by. With many messages and digests stored, the probability of having the same digests for two different messages is high. At this point, it is possible to exchange the two messages because they have the same digest.

A cryptosystem is "balanced" when the encryption and digest algorithms have the same resistance. So, SHA-256 and SHA-512 have been designed for use respectively with AES-128 and AES-256, while SHA-1 (i.e., SHA-160) matched Skipjack-80 (an algorithm developed by the UK secret service). Notice that AES has half the bits of SHA (due to $N/2$).

SHA-3 family

Because of the already cited problem with SHA-2 family, SHA-3 was a competition for a new dedicated hash function: the winner was announced on 2 October 2012 and was **Keccak** (pronounced *catch-ack*) (developed by G.Bertoni, J.Daemen, G. Van Assche (STM), M.Peeters (NXP)). The NIST team praised the Keccak algorithm for its many admirable qualities, including its elegant design and its ability to run well on many different computing devices. The clarity of Keccak's construction lends itself to easy analysis (during the competition all submitted algorithms were made available for public examination and criticism), and Keccak has higher performance in hardware implementations than SHA-2 or any of the other finalists.

function	output	block	capacity	definition	strength
SHA3-224(M)	224	1152	448	Keccak[448](M || 01, 224)	112
SHA3-256(M)	256	1088	512	Keccak[512](M || 01, 256)	128
SHA3-384(M)	384	832	768	Keccak[768](M || 01, 384)	192
SHA3-512(M)	512	576	1024	Keccak[1024](M || 01, 512)	256

Figure 2.23: Strength of different hash functions belonging to SHA-3 family as function of digest length and block size

Keccak is used to define various hash functions (FIPS-202): there are three versions of SHA-3, which are intended as the replacement of the corresponding hash functions in the SHA-2 family

because they produce the same output length and have the same strength. Moreover, there are variable-length outputs since it is possible to parametrize the output length. Of course, a shorter digest leads to weaker protection.

Other variations have been defined (NIST SP.800-185):

- cSHAKE (customizable domain parameters);
- KMAC (keyed digest);
- TupleHash (hash of a tuple, where sequence matters);
- ParallelHash (fast hash by exploiting internal CPU parallelism).

KDF (Key Derivation Function)

Cryptographic hash functions are not only for digests, but they can also be used to derive (create) a key. A cryptographic key must be random, meaning that 1 and 0 bits are to be uniformly distributed. However, typically, users insert passwords or passphrases that are guessable and not random. This happens because it is impractical for a user to remember a meaningless sequence of bits. Usually, a key is derived from a password or passphrase inserted by the user, so that $K = \text{KDF}(P, S, I)$, where:

- P is the user's password or passphrase;
- S is a salt, an unpredictable variation to make K difficult to guess even knowing P;
- I is the number of iterations of the base function (to slow down the computation and make life complex for attackers).

When providing information to the destination, the passphrase is transmitted in a secure way, while the salt will be inserted in the message itself. The salt is something like an IV, a large random number used to prevent precomputations. There are two main key derivation functions that are based on cryptographic hash functions:

- **PBKDF2** (RFC-2898) uses SHA-1, with $|S| \geq 64$ and $I \geq 1000$: The function is $DK = PBKDF2(PRF, PWD, \text{Salt}, C, dkLen)$, where:
  - PRF = pseudorandom function of two parameters with output length $hLen$ (e.g., a keyed HMAC);
  - PWD = password from which a derived key is generated;
  - Salt = cryptographic salt;
  - C = number of iterations desired;
  - dkLen = desired length of the derived key;
  - DK = generated derived key $T_1 \| T_2 \| \ldots \| T_{\text{dkLen/hLen}}$, where each T_i has length $hLen$.

An important application of this KDF is in wireless networks, specifically in WPA2 solutions. When the passphrase is entered, there is an implicit use of this function: $DK = PBKDF2(HMAC-SHA1, PWD, ssid, 4096, 256)$, where *ssid* is the name of the wireless connection.

However, PBKDF2 can be attacked because C may be large, but this requires only a lot of computation but not a lot of RAM, hence it can be attacked by ASIC or GPU. A countermeasure is to increase the RAM needed for the attack. A public competition (Password Hashing Competition, *PHC*) about that was launched in 2013, and on July 20, 2015, the winner was **Argon2**.

- **HKDF** (RFC-5869) uses HMAC.

MAC, MIC, MID We have seen that a digest could be used in pair with a message to achieve integrity; typically, the part added to the message for integrity is called **MIC** (Message Integrity Code), because of the code added to the message to protect its integrity. If a message is not being modified, it means that it is also authentic and in this case the code is also named **MAC** (Message Authentication Code). They mean the same thing, but MIC is usually used in the telecommunication and networking environment, while MAC is mostly used in the application field. Usually when talking about MIC or MAC, we are also assuming that the digest is keyed, as we will see next. Since this code is an addition to the original message, usually also a unique identifier for the message is included to avoid replay attacks, and that is called **MID** (Message IDentifier). In this context a replay attack is not an attack to the integrity of a single message but to the integrity of the transmission process.

2.4.2 Protecting the digest

The problem now to be faced is how to protect the digest: in the simple case in which a digest is used to verify that a file on disk has not been changed, a good approach could be to store the digest in a different and secure place, so that it will not be altered. When sending data, the digest cannot be exchanged out of band, so it means that the digest must be intrinsically secure. There are two mostly adopted techniques:

- Authentication by means of **keyed digest** (Chapter 2.4.2);
- Authenticated encryption (Chapter 2.4.3).

Authentication by means of keyed digest

The digest is sent along with the message, but it is calculated not only on the data but also on a secret key that is shared between the sender and receiver. So, these operations are performed:

- **Sender:** $d = \text{digest}(K, M)$;
- **Transmission:** $M \| d$;
- **Receiver:** $d' = \text{digest}(K, M)$;

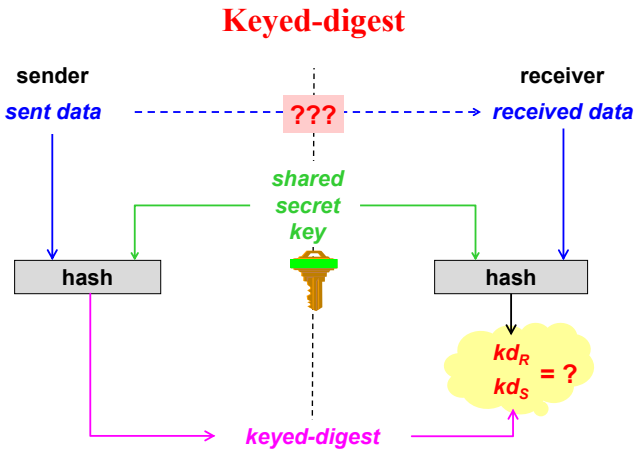


Figure 2.24: A scheme of how a keyed digest works

- **Verification:** if $(d == d')$ then OK else it means that something has been changed during transmission (the data or the digest, it does not matter).

Advantages Advantages of this technique are that there is only one operation (calculation of the digest) and that only few data are added. It is worth noticing that this mechanism guarantees authentication, since only those who know the key can compare the transmitted digest with the digest calculated on the received data. This is the fastest solution to provide integrity and authentication to the data. However, it does not provide non-repudiation: let us suppose that the receiver of a commercial order wants to take the sender of that order to court because he repudiates the order itself; then the receiver would show as proof the message along with the digest that proves integrity and authenticity. In this case, it is not possible to say that the sender originated the order, since the receiver has all the means to create it by himself: he has the data and the key upon which to compute a valid keyed digest.

So, this solution **guarantees authentication** since the receiver can be sure that the data is coming from the sender and has not been modified, but it does not provide non-repudiation by itself since it is impossible for one of the two parties to demonstrate to a third party that the other created the message.

Keyed digest:

HMAC HMAC is defined in RFC-2104 and it uses a base hash function H. So, HMAC is not a hash function but a way to compute a secure MAC starting from a hash function H. The base hash function H must have a block size B, with an output L bytes long, where $B > L$. Then there are some definitions:

- $ipad = 0x36$ repeated B times; it is a padding composed of $0x36$ repeated B times to fill all the block.

- $opad = 0x5C$ repeated B times;
- Deprecated keys such that $|K| < L$; never use a key smaller than the output. For example, if HMAC with SHA-1 is being used, it requires a minimum of a 160-bit key.
- If $|K| > B$, then $K' = H(K)$; else $K' = K$; if the key is bigger than the block, then the size of the key is reduced by computing the hash of the key (otherwise, the original one is used).
- If $|K'| < B$, then K' is 0-padded up to B bytes.

Given that, $hmac = H(K' \oplus opad \| H(K' \oplus ipad \| data))$.
The K' is XORed with *ipad* and it is pre-appended to the data. Then, the hash is computed. After the hashing, the K' is XORed with *opad* and it is pre-appended to the result of the hash, and the hash is again computed. It is easy to see that basically HMAC is a double hash of the data composed in some way with the key. This is much stronger than just pre- or post-appending the key to the data. This is the most widely solution used when it is needed to create a MAC (or MIC, it is the same). HMAC is typically used to protect integrity. If confidentiality must also be protected, there is CBC-MAC.

CBC-MAC Sometimes we do not need only integrity but also confidentiality, so we compute encryption. In that case, rather than using another function (for example, we are using AES for encryption and we also need to have SHA-256 for integrity, which means we need to have more code, which is not always possible, for example, in embedded systems), it is possible to compute a MAC not based on a hash function but based on a symmetric algorithm: this is named CBC-MAC.

It exploits a block-oriented symmetric encryption algorithm in CBC mode with a null IV, taking the last encrypted block as the MAC. The message M is split into N blocks $M_1, \ldots, M_N$. Then, taking $V_0 = 0$, for $k = 1, \ldots, N$, do $V_k = \text{enc}(K, M_k \oplus V_{k-1})$; finally, the CBC-MAC is equal to V_N. So, the size of the CBC-MAC is equal to the size of one block of the underlying symmetric encryption algorithm. If, for example, we are using AES-CBC-MAC, then the digest will be 128 bits long. The best version of DES-based CBC-MAC is the Data Authentication Algorithm (standard FIPS 113, ANSI X9.17).

CBC-MAC is secure only for fixed-length messages because attacks that extend the length of the message can be successful; for variable-length messages, it is better to use **CMAC**.

2.4.3 Integrity and secrecy: how to combine?

We discussed that in most applications, we need both integrity and confidentiality. This can be achieved through two orthogonal operations: symmetric encryption with a key K_1 for secrecy and key digest (MAC) with K_2 for integrity. There are various ways to combine these operations:

1. **Authenticate-and-encrypt (A&E)**: first, the plaintext is encrypted with K_1, then the result is concatenated with the MAC computed on the plaintext with K_2, in formulas,

$$\text{enc}(K_1, p) \| \text{mac}(K_2, p)$$

In this way, nobody can read the plaintext because it is encrypted, and nobody can alter the ciphertext because after decryption, it is possible to compute the MAC again, and any difference will be noticed.

The main drawback is that for verifying integrity, the message must be decrypted first (an operation that takes time), because the MAC is computed on the plaintext, so there is a vulnerability against DoS attacks. Moreover, for the same reason, the MAC may leak some information about the plaintext. It is not the best solution, but it is used by the SSH protocol.

2. **Authenticate-then-encrypt (AtE)**: first, the MAC is computed with K_2 on the plaintext, then it is concatenated with the plaintext, and the result is encrypted with K_1, in formulas,
$$\text{enc}(K_1, p \| \text{mac}(K_2, p))$$
For reasons like the previous case, this solution is still vulnerable to DoS attacks since it is necessary to decrypt the whole message before being able to verify integrity by computing the MAC. However, this solution is better than the previous one because it does not leak information, since the MAC is not sent in clear but is encrypted.

   This solution is used by SSL and TLS up to version 1.2; TLS version 1.3 uses a completely different approach.

3. **Encrypt-then-authenticate (EtA)**: first the plaintext is encrypted with K_1, then the result is concatenated with the MAC computed on the ciphertext obtained in the previous step: in formulas,
$$\text{enc}(K_1, p) \| \text{mac}(K_2, \text{enc}(K_1, p))$$
In this way, it is possible to avoid DoS attacks; in fact, an alteration on the ciphertext will be immediately noticed, that is, without first decrypting the message. This is the solution used by IPsec.

Security of these compositions

Improper combination of secure algorithms may lead to an insecure result!

- **Authenticate-and-encrypt (A&E)**: insecure unless performed in a single step;
- **Authenticate-then-encrypt (AtE)**: secure only with CBC or stream encryption;
- **Encrypt-then-authenticate (EtA)**: the most secure mode but beware of implementation errors: for example, one should always include IV and the name of the algorithms in the computation of the MAC, otherwise some attacks are possible.

Because neither of these three solutions is perfect, current efforts are towards a joint AE algorithm: this is named **authenticated encryption**.

Authenticated encryption

Authenticated Encryption (**AE**) represents a cryptographic approach that integrates both **privacy** and **authentication/integrity** within a single operation. This unified approach ensures that the same dataset serves the dual purpose of maintaining confidentiality while simultaneously verifying the authenticity/integrity of the information.

This methodology is characterized by the use of a single key and algorithm, promoting efficiency and reducing the likelihood of errors in combining these two crucial functions.

One notable advantage of AE is its ability to counter chosen-ciphertext attacks that may occur during online encryption processes. In such attacks, an adversary manipulates a ciphertext and observes the recipient's response to detect potential vulnerabilities, such as through padding or decryption oracle attacks. AE addresses this concern by emphasizing the need to verify the integrity of the ciphertext before decryption. This verification process ensures that the data maintains its confidentiality (through encryption) and authenticity/integrity simultaneously.

IGE (Infinite Garble Extension) IGE[8] is an authenticated encryption algorithm, providing **confidentiality, integrity, and authentication** all in one. Essentially, it is similar to CBC with one addition: in CBC, a modification in one block of the ciphertext affects only the block itself and the next one (and then propagation stops). In contrast, IGE uses a mechanism by which a modification in any block will affect every block after the mangled one.

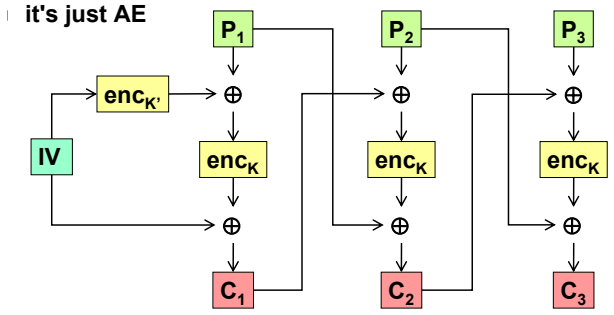


Figure 2.25: How Infinite Garble Extension (IGE) works.

This is important because it means that by putting a last block of plaintext with fixed content (e.g., composed of all zeros or containing the number of blocks of the plaintext), in the decryption phase, it is sufficient to look at the last block and check if it contains the expected value. If not, one can immediately conclude that there has been an attack against integrity. In this context, the last block is what was previously called the tag.

RFC 5116 - Interface and algorithms for authenticated encryption There are various ways to perform authenticated encryption; one of the most important is *Authenticated Encryption with Associated Data* (**AEAD**), documented in RFC 5116.

[8]This algorithm is not recommended, but the professor explained it for teaching purposes.

This is precisely the type of solution needed for emails and network packets. In essence, authenticated encryption is an algorithm that provides both of the aforementioned functionalities on plaintext. Conversely, AEAD distinguishes between the part that requires privacy and the part that needs integrity.

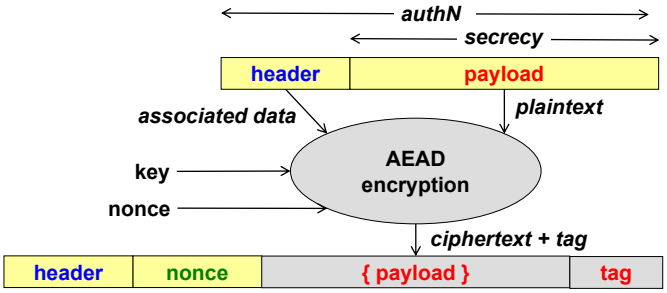


Figure 2.26: AEAD

Referring to Figure 2.26, the header is the portion that needs only integrity and authentication (also called associated data), while the payload is the part for which confidentiality is also required (hence referred to as plaintext).

This algorithm requires a single symmetric key and a nonce to prevent replay attacks. The result is the ciphertext, which is placed inside the packet as encrypted payload. In front of that, in clear, there are the header and the nonce. Inside the encrypted payload, there is one part that provides integrity not only for the payload itself but also for the header and the nonce; this part is typically referred to as the **tag**.

Authenticated encryption: standards

ISO/IEC 19772:2009 defines six standard **modes**. By applying these modes with basic encryption algorithms, it is possible to achieve authenticated encryption with associated data (AEAD):

- OCB 2.0 (Offset Codebook Mode) [single-pass AEAD, patented];
- AESKW (AES Key Wrap);
- CCM (CTR mode with CBC-MAC) [double pass];
- EAX (Encrypt then Authenticate then X(trans)late) = CTR + OMAC [double-pass AEAD, free];
- Encrypt-then-MAC;
- GCM (Galois/Counter Mode).

other modes exist and are/will be recommended by other bodies (e.g. NIST, IETF).

GCM as an example of AEAD An algorithm applied in GCM mode encryption takes these parameters:

- On encryption, $(C, T) = \text{algo\_GCM\_enc}(K, IV, P, A)$, with
  - IV size: $[1 \dots 2^{64}$ bits] (96 bits is most efficient)
  - P size: $[0 \dots 2^{39} - 256$ bits]
  - A (associated authenticated data) size: $[0 \dots 2^{56}$ bits]
  - C has the same size as P
  - T is the authentication tag with size: [0 . . . 128 bits]: Comparing with cryptographic hash functions, this tag is not very large, and we argue that a big integrity code is necessary for strong security. However, beware that since we are not using a hash algorithm here, the security is equal to the number of bits, whereas for cryptographic hash functions, we saw that the protection is half the length of the digest. Therefore, in this case, a tag of 128 bits provides the same protection as a digest that is 256 bits long.
- On decryption, $P = \text{algo\_GCM\_dec}(K, IV, C, A, T)$
  - P is the original plaintext (if authentication is OK)
  - ... or a special value FAIL if the authentication check failed

GCM is defined for only the encryption algorithms with 128-bit block (for example we cannot have DES in GCM, but it is possible to have AES).

CCM as an example of AEAD It is Counter-mode with CBC-MAC: first an authentication tag of (plaintext + associated data) is computed by CBC-MAC, then the plaintext and the tag are (separately) encrypted in CTR mode: so, it is a double pass algorithm. It is defined for encryption algorithms with 128-bit block

Authenticated encryption: applications

- TLS-1.3 uses GCM and CCM;
- 802.11i uses CCM;
- ZigBee (short-range protocol for IoT) uses CCM* (=CCM + auth-only + enc-only);
- ANSI C12.22 (network transmission of electronic measures, e.g., house power meter) uses **EAX'** (a famous case of failure): nowadays, it is common to use the electric wire to send electronic measures of a power meter. Because there is no firewall over an electric wire, by attaching a proper device to the electric network, it could be possible to read measures of other people or create fake transmissions. Therefore, protection is needed for privacy (for example, a house not consuming could signal that nobody is at home and so it can be robbed) and for authenticity (the measures sent must be the real ones).

  - The modification of the base algorithm created a vulnerability, so the algorithm has been proven to be broken (article[9] by Minematsu, Morita, and Iwata);
  - EAX had a formal proof of its security ... but ANSI sacrificed it for 3-5 less encryption steps and 40 bytes less memory usage (was this so important for embedded systems?).

Comparison of AE modes

- **GCM:** the most popular, on-line single-pass AEAD, parallelizable, used by TLS, present in OpenSSL;
  - For encryption, generates ciphertext + authentication tag;
  - For decryption, first computes the authentication tag and only if it matches the one in input then the ciphertext is decrypted;
  - Fast on Intel architecture (4 cycle/byte) using AES-NI for encryption and PCLMULQDQ for the tag.
- **OCB 2.0:** the fastest one, on-line single-pass AEAD, GPL patented so scarcely used, now free but for military uses;
- **EAX:** on-line double-pass AEAD, slow but small (uses just the encryption block), so very good for constrained systems;
- **CCM:** off-line double-pass, the slowest one. Note that double-pass is 2x slower than one-pass (in software).

NIST lightweight crypto (LWC) The NIST Lightweight Cryptography (LWC) initiative, launched in August 2018, aimed to identify efficient Authenticated Encryption with Associated Data (AEAD) lightweight algorithms for embedded system. After two rigorous rounds of evaluation, the winner announced on July 2, 2023, is **ASCON**. ASCON is proven to be highly effective for encryption, AEAD, and hashing applications.

ASCON Ascon is a family of lightweight authenticated ciphers that had been selected by US National Institute of Standards and Technology (NIST) for future standardization of the lightweight cryptography.

It is not designed to replace AES or SHA3 but rather serves as a lightweight solution suitable for resource-constrained environments. For Authenticated Encryption with Associated Data (AEAD) applications, ASCON offers various configurations such as Table 2.1 and Table 2.2

2.4.4 Authentication by Digest and Asymmetric Cryptography: Digital Signature

As mentioned earlier in Chapter 2.4.2, authenticated encryption offers data integrity, authentication, and confidentiality. However, as discussed in the context of keyed digest, it lacks the

[9] `https://eprint.iacr.org/2012/018.pdf`

Configuration	Key	Nonce	Tag	Rate	Capacity	pa	pb
ASCON-128	128	128	128	64	256	12	6
ASCON-128a	128	128	128	128	192	12	8

Table 2.1: ASCON AEAD Configurations

Configuration	Output	Rate	Capacity	Permutation pa	Permutation pb
ASCON-hash	256	64	256	12	12
ASCON-xof	arbitrary	64	256	12	12
ASCON-hasha	256	64	256	12	8
ASCON-xofa	arbitrary	64	256	12	8

Table 2.2: ASCON Hashing Configurations

ability to provide non-repudiation. This limitation arises from the fact that peers share the key used to compute a valid keyed digest. Consequently, it becomes challenging to determine which of the two peers generated it.

Non-repudiation is achieved by using digest and asymmetric cryptography: the digest is encrypted with the private key of the sender, so that the use of his public key will prove the source.

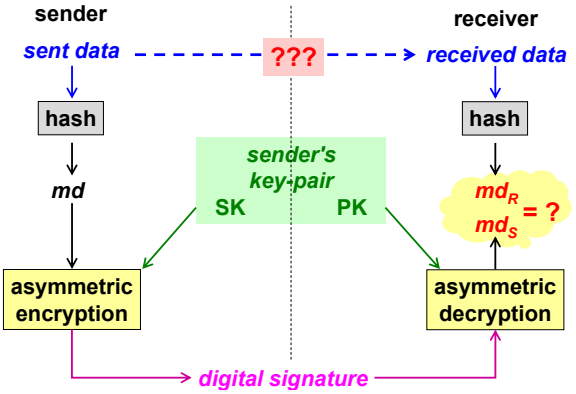


Figure 2.27: Digital signature: computing and verifying a message digest encrypted via asymmetric encryption

Using formulas, such a communication takes place as following:

- Signer: $H = \text{enc}(S.SK, \text{hash}(M))$
- Transmission: $M \| H$
- Verifier: $X = \text{dec}(S.PK, H)$
- Verification phase: if $(X == \text{hash}(M))$ then OK, else it means that something has been changed during transmission.

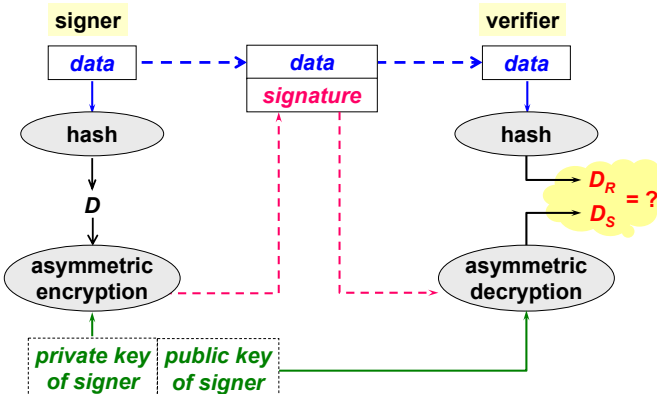


Figure 2.28: Signature creation and verification

This is the mechanism by which **digital signatures** are implemented. The last piece to obtain full non-repudiation is a mechanism by which it must be possible to guarantee that the association between a public key and an identity is true: this is called a **public key certificate** (Chapter 2.4.5).

An attack that is possible to perform against this schema is the *modification of a digital signature*: changing any bit of the encrypted data leads to a failure in the verification phase, but the same happens with any modification to the digital signature. No matter if the data is correct; it is not possible to say whether the modification affected the data or the signature.

Another case worth discussing is taking a digital signature performed by someone else, then taking that person's public key as well (to make sure the public key fits the digital signature), and then attaching it so as to make it appear that the file is attributed to that person. This will still result in a failure in the verification phase since the digital signature contains the encrypted digest of the original data; the digital signature is bound to the data, so it is not possible to attach a signature to other data.

Authentication and integrity: analysis

We have examined two methods to achieve authentication and integrity:

- By means of a **shared secret:**
  - Useful only for the receiver.
  - Cannot be used as proof without disclosing the secret key.
  - Not useful for non-repudiation.
  - Good for two peers who trust each other, serving as protection against a third party.
- By means of **asymmetric encryption:**
  - Being slow, it is applied to the digest only.
  - Can be used as formal proof.

  - Can be used for non-repudiation, provided that it is possible to demonstrate the owner of the public key (public key certificate, Chapter 2.4.5).

Digital vs handwritten signature Digital signatures provide both authentication and integrity, whereas handwritten signatures offer only authentication. Therefore, digital signatures are considered superior due to their tight bound with the data. It's important to note that each user possesses a private key, which can be utilized to generate an infinite number of digital signatures, each unique to a different document.

2.4.5 Public key certificate

As we have seen so far, a digital signature has a great benefit; it can provide non-repudiation. However, non-repudiation is achieved if, in addition to performing a correct digital signature, it is possible to ascribe with certainty the public key to an actor's private key. The attribution of a key to an actor is usually done through a **public key certificate**: it is *"a data structure used to securely bind a public key to some attributes."* Typically, it binds a key to an identity, but other associations are possible too (e.g., IP address). The security in this binding is provided by a digital signature: the entity that created the certificate, named the *certification authority* (**CA**), digitally signs the certificate, so that it is at the same time:

- a proof of authentication: it is a valid certificate because it has been created by a certification authority;
- a proof of integrity: the data are correct, and they have not been modified since the document was issued.

Like a common identity document, a public key certificate also has a **limited lifetime**. It can also **be revoked** on request, both by the user and the issuer.

Formats for public key certificates

- **X.509:**
  - v1, v2 (defined by ISO): not very successful;
  - **v3** (ISO + IETF): has achieved great usage and is nowadays the most common format because it can be applied to the security of several internet protocols;
- **Non-X.509:** Since X.509 was developed by ISO, seen as the standardization body for big corporations, some people who do not trust big corporations have created alternative certification structures such as:
  - PGP: mostly used in the underground movement;
  - SPKI (IETF).

  None of these have achieved great diffusion.
- **PKCS#6:** It is a standard promoted by RSA before X.509 was invented. It is partly compatible with X.509, but RSA declared it obsolete.

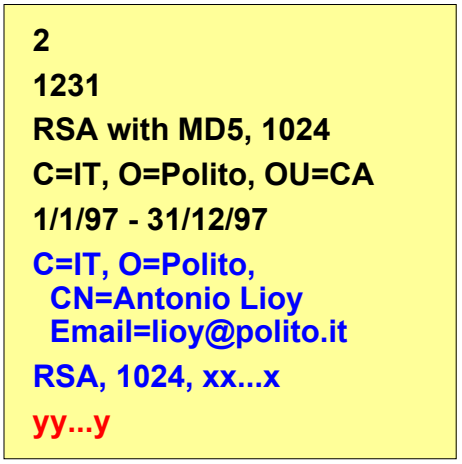


Figure 2.29: Structure of a X.509 certificate

Structure of a X.509 certificate

- **Version:** Since there are multiple versions of the same format, as seen previously.
- **Serial number:** Each certificate is uniquely identified.
- **Signature algorithm:** Since the certificate is protected with a digital signature, its format includes information about the algorithm used for the signature.
- **Issuer:** This is the name of the entity that created the certificate, the certification authority. The syntax used to specify this information is called DN (distinguished name), composed of three different fields:
  - `C`: Country (e.g., Italy).
  - `O`: Organization (e.g., Politecnico di Torino).
  - `OU`: Organizational unit, which means the department that created this certificate (e.g., certification authority).
- **Validity:** Defines the period for which the certificate is considered valid. Outside that period, the CA does not guarantee the correspondence.
- **Subject:** The entity controlling the private key corresponding to the certified public key. Here, the DN is used to identify that entity, with additional fields not mentioned earlier:
  - `CN`: Common name (e.g., Antonio Lioy).
  - `Email`: The email of the entity. Including these fields is important because public key certificates are used to protect internet applications. For example, to send an email to "Antonio Lioy," the mail server needs to understand the certified mail for the entity, making the email field necessary. The same reasoning applies to other applications for which protection is wanted.

- **subjectPublicKeyInfo:** The field containing the public key; it specifies the algorithm, the key length, and all the bits that constitute it.
- **CA digital signature:** The digital signature of the certification authority computed over the certificate. This way, any modification to it can be detected, as seen previously (Chapter 2.4.5).

So, this mechanism finally solves the problem of knowing who the actor controlling the private key corresponding to the public key is.

PKI (Public-Key Infrastructure)

This is an infrastructure which is performing two kind of tasks: technical (create certificates) and administrative (before creating a certificate, checking the identity of the requestor is needed). So, this infrastructure oversees *creating*, *distributing*, and *revoking* the public key certificates.

Certificate revocation Every certificate has a certain validity, but it can be revoked before its expiration date. The revocation can be requested by the owner or by the creator of the certificate:

- The owner can request the revocation in case he has no more control over the private key (e.g., private key stored on a stolen smartcard). This case resembles when a credit card is lost: the owner should go and request to revoke the certificate as soon as possible because if the thief uses that private key, it will appear as if the original owner has performed the signature. This is the most common case in which a certificate is revoked.
- The creator can revoke the certificate in case a certificate has been created for a fake identity. If someone has managed to demonstrate a fake identity to a certification authority, he will receive a valid certificate. Nevertheless, if later the certification authority discovers the deception, it will revoke the certificate automatically.

When a certificate is revoked, the certification authority creates a list stating that the certificate is no longer valid. Since the certification authority does not know when and where the stolen key will be used, the transaction protected by a signature is received by various actors (the receivers). These receivers must check whether the certificate was valid at the time of the signature. The actor responsible for verifying if the signature was valid or not is called the **relying party** (**RP**). This means that before trusting the certificate, it should be checked if it is valid or not.

Revocation mechanism There are two mechanisms to perform a check on the signature:

- **CRL (Certificate Revocation List):** The certification authority creates a list of revoked certificates. The list is digitally signed by the CA to ensure authenticity and integrity. Without the digital signature, someone could manipulate the list by removing or adding certificates. The CRL contains information about all revoked certificates, allowing the

receiver to verify the validity of a certificate at the time it was issued. For instance, if a document signed three months ago is received today, the verification must consider the validity status of the key three months ago. The drawback is that the entire list must be downloaded to check a single certificate, but it provides a comprehensive history of each certificate.

- **OCSP (On-line Certificate Status Protocol):** This mechanism is preferred for real-time checks, such as transactions. OCSP is a client-server protocol where a specific service can be queried to determine the current validity status of a certificate. Unlike CRL, OCSP does not consider previous states of the certificate. The response from the server is signed, preventing anyone from providing a fake response.

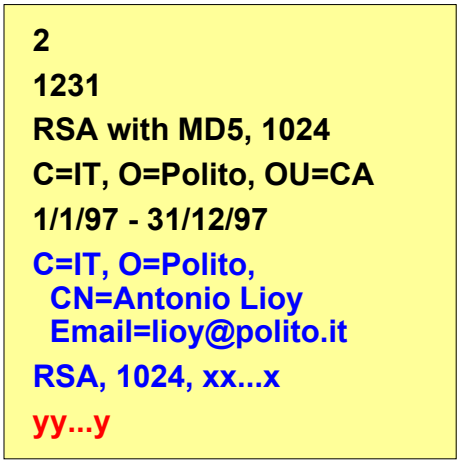


Figure 2.30: Structure of a X.509 CRL

Structure of a X.509 CRL The X.509 CRL shares common parameters with the X.509 certificate, including *version*, *signature algorithm*, and *issuer*. However, the X.509 CRL structure introduces the "**thisUpdate**" parameter, indicating the time when the CRL was created. This timestamp is crucial because if a signature check is conducted on a document signed before this date, the relevant information is found in the CRL. Conversely, if the verification pertains to an event occurring after the "thisUpdate" date, the current CRL may not be suitable, and a more recent CRL needs to be obtained. Following this parameter, there is a list of revoked certificates, each accompanied by the *userCertificate* and *revocationDate*.

Verification of a signature / certificate

Suppose we want to verify a signature. The verification process involves obtaining the public key certificate signed by the entity providing it (e.g., the certificate of "Antonio Lioy" is signed by "Politecnico di Torino"). A crucial question arises: how can we verify that this last signature is valid? To check the validity of the CA's signature, we need the public key certificate of that CA. However, this certificate is created and signed by another CA, and the verification of

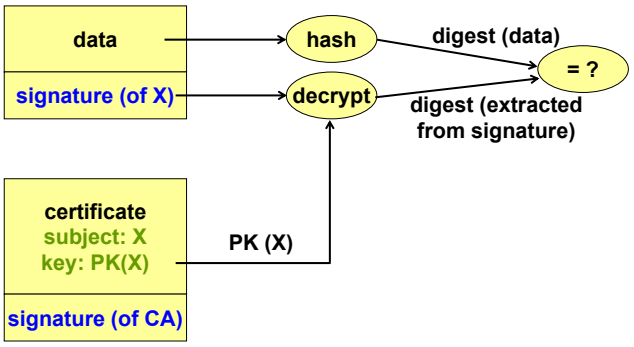


Figure 2.31: Verification of a signature / certificate

this signature requires the public key certificate of the second CA. This chain of dependencies creates a recursive problem[10]. Consequently, a hierarchical infrastructure for the certification and distribution of public-key certificates becomes essential.

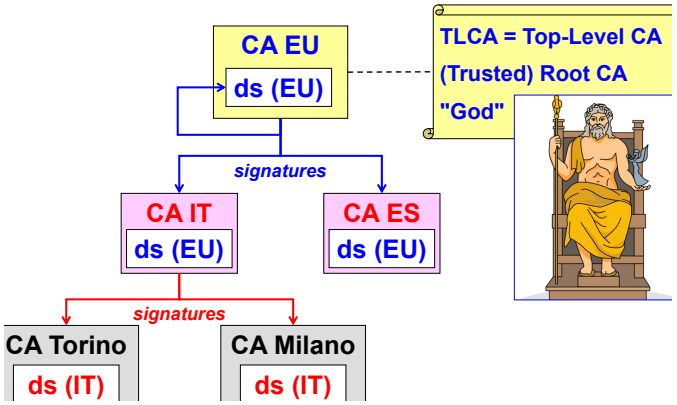


Figure 2.32: Certification hierarchy

Such a hierarchical infrastructure is depicted on Figure 2.32. For example, to check the signature of "Politecnico di Torino," which created the public key certificate for "Antonio Lioy," the certificate of "CA Torino" is needed, which contains the signature of "CA IT"; to check if this one is good, the certificate of the entity that signed the "CA IT" certificate is needed, so the "CA EU" must be obtained. This last CA ends the chain; in fact, the "CA EU" is signed by the European CA itself: this last certificate is trusted a priori (*self-signed*), it cannot be verified, and for this reason is also called **TLCA**, **Root CA**, or even **God**.

Please note that in the world there is not only one TLCA, nor are there a few: typically, in computer systems, there are quite a lot of trusted CAs, and this is due to two main reasons:

- **Security:** The one who would control the only TLCA would also control the other ones,

[10] *Quis custodiet ipsos custodes?*

by faking them;

- **Commercial:** To obtain a certificate from a certification authority, a price must be paid to it.

For the second reason, the list of trusted CAs can be different on systems produced by different manufacturers: since it is a matter of who places the trust, one system can accept or not accept a CA as a trusted one. For example, in the past, Microsoft performed only light checks on incoming trusted CAs but requested the payment of $250,000 to be in its list.

The problem that arises is: **can't an attacker fake the whole tree**? Of course, that is possible: if the device is left unattended and the attacker manages to have administrative privileges, it is possible to add another (fake) Root CA, making the whole hierarchical system useless for that device. The list of Root CAs can be managed either by the operating system or by the application being used.

Performance

Cryptographic performance is primarily dependent on the CPU, including its architecture, instruction set, and cache size. Some CPUs are equipped with specialized instructions tailored for cryptographic algorithms. Generally, client-side performance is not a significant concern, unless dealing with less powerful devices like IoT, embedded systems, or clients overloaded by multiple applications. On the other hand, server environments or network nodes (e.g., routers) may face performance challenges when implementing security measures.

In such cases, cryptographic accelerators, such as **Hardware Security Modules** (**HSMs**), can be employed. These modules offer primitive instructions to execute various security algorithms. Additionally, **special-purpose accelerators** are available, which not only handle hardware-based cryptographic operations but also support packet processing for specific security protocols (e.g., SSL, IPsec). Alternatively, **generic accelerators** may focus on expediting computations related to a particular cryptographic algorithm, such as AES, for various protocols.

CNSA In 2018, the NSA released a new suite named CNSA (Commercial National Security Algorithm Suite), which includes the following algorithms:

- **Symmetric Encryption:** AES-256 - Any key shorter than 256 bits is now considered insufficient. To protect real-time (e.g., stream) data, it suggests using mode CTR for low bandwidth applications or GCM for those requiring high bandwidth. Moreover, GCM provides authenticated encryption, offering an additional advantage.
- **Hash:** SHA-384
- **Key Agreement:** ECDH and ECMQV
- **Digital Signature:** ECDSA, with EC on the curve P-384

For legacy systems, such as old systems that are still operational and unable to perform EC or GCM, it is recommended to use:

- **Key Agreement:** DH-3072
- **Key Exchange, Digital Signature:** RSA-3072
- New quantum-resistant algorithms are expected by 2022.

Chapter 3

Authentication techniques and architectures

3.1 What is authentication

3.1.1 Definitions of authentication

There are three different definitions of *authentication:*

- **RGC-4949 (Internet security glossary)**:
  "the process of verifying a claim that a system entity or system resource has a certain attribute value"
- `whatis.com`:
  "the process of determining whether someone or something is who or what it is declared to be"
- **NIST IR 7298 (Glossary of Key Information Security Terms)**:
  "verifying the identity of a user, process, or device, often as a prerequisite to allowing access to resources in an information system"

The key aspects of these definitions are that they define the authentication of an actor, meaning that **it could be not only a human being** (interacting via software running on hardware) **but also a software component or a hardware element** (interacting via software). The common shorthand for authentication is `authN` or `authC`, while `authZ` is used for authorization, *which is different but related.*

3.1.2 Authentication factors

While authenticating an *actor*, there are three categories of **authentication factors** that can be used:

- **Knowledge**: authentication relies on something that *only the user knows*, for example a static passphrase, code, or personal identification number.

The associated risks involve the storage of this knowledge, how it can be demonstrated, and the way it is transmitted.

- **Ownership**: authentication relies on something that *only the user possesses* (often called an "authenticator"), for example, a token, smart card, or smartphone.
  The associated risks can be related to the authenticator itself, such as the possibility of infection with malware, the potential for it to be manufactured in a country that imposes government control, or the risk of it being stolen, cloned, or used without the owner's authorization (e.g., forgetting an unlocked smartphone).

- **Inherence**: *something the user is*, for example, a biometric characteristic (such as a fingerprint).
  The associated risks include counterfeiting and privacy concerns. Inherence factors pose a greater risk than the previous cases because, for example, a biometric characteristic cannot be replaced when compromised. For this reason, inherence factors should be limited to very secure environments, typically used only for local authentication, as a mechanism to unlock a secret or a device.

3.2 Digital authentication model (NIST SP800.63B)

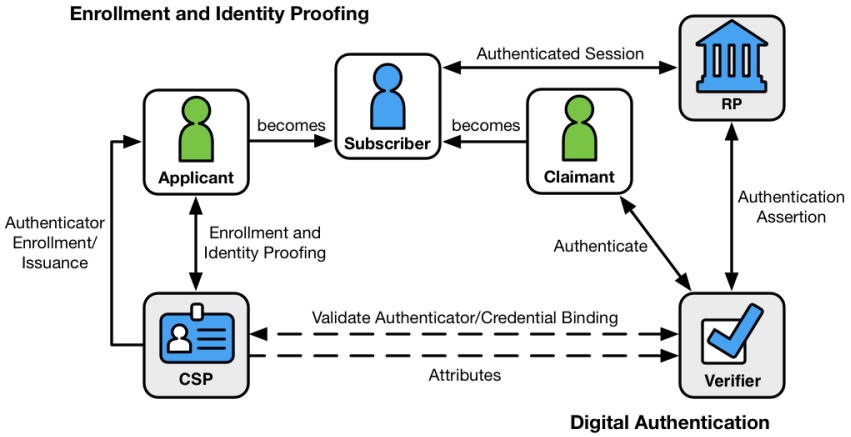


Figure 3.1: General model for digital authentication as described in NIST SP800.63B

- In this model, an actor who wants to use a system is called an **applicant**: if it possesses an authenticator it can provide it to the *CSP* (Credential Service Provider), or it can get one (for example, when a student is enrolled in Politecnico, he is given a smart card that works as an authenticator). The CSP is that component that will issue or enrol user credential and authenticator, and verify and store associated attributes.
  When this procedure is completed successfully, the actor becomes a **subscriber**, which is an entity recorded in the authentication system.

- Later, when the actor wants to use some network service, typically the actor is called a **claimant**, because they claim to be a valid user. Typically, an authentication protocol against a verifier is run to verify this claim. When this process ends successfully, the actor becomes **a subscriber with an open authenticated session** with the relying party, that will request and receive an authN assertion from the Verifier to assess user identity (and attributes).

  The relying party, which requests the actor to be authenticated, is the end application. The verifier may have communication with the CSP to validate the binding between the authenticator used in the authentication protocol and the credential claimed.

Recap

- **The credential binds an authenticator to the subscriber via an ID**:
  - for example, an X.509 certificate can be considered the credential, as it binds the identity and attributes written inside the certificate with the authenticator. In this case, the authenticator is the private key that the user controls.
- **CSP (Credential Service Provider)**:
  - will issue or enrol user credential and authenticator
  - verify and store associated attributes
- **Verifier**:
  - executes an authN protocol to verify possess of a valid authenticator and credential
- **Relying party**:
  - will request/receive an authN assertion from the Verifier to assess user identity (and attributes)

These roles may be separate or collapsed together. Thinking about a *Linux machine* used locally, the enrollment phase involves creating a new user with a username (the credential) and a password (the authenticator). In this scenario, the CSP is the operating system itself, and when a user wants to use a server on this machine, they need to perform login, which is the verifier. The relying party is any software running on that machine that uses the identity as proven by the login service of the operating system.

Another example is the use of Google Identity for different services, such as the Doodle Service to schedule an appointment. For Doodle, there is an option to use Google or Facebook Credentials. In this case, the relying party is Doodle, while the verifier (as well as the CSP) is Google or Facebook.

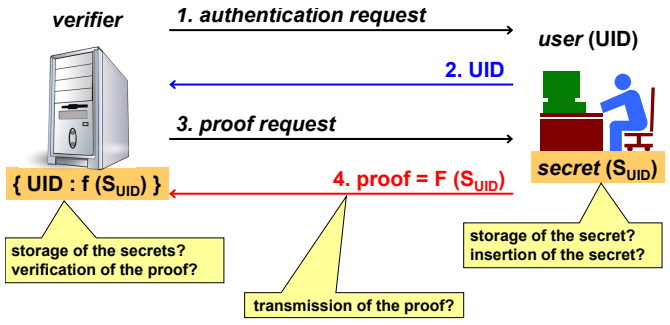


Figure 3.2: Generic authentication protocol

3.3 Generic authentication protocol

Suppose that the user wants to access an application server (Relying Party). In this case, the server will include both the Relying Party and Verifier. The user has been identified with the User ID and has a secret associated with that User ID. The server's identifier contains a table with the User ID and the result of the function f applied to the secret. Normally, the secret should never be stored in cleartext; of course, if the function f is the identity function, it means you are storing the secret in cleartext, which is not recommended.

When the user wants to access the service, they receive an **authentication request**. Initially, they provide the **User ID**, and then the verifier asks for a **proof request**; the user replies with the **proof** $= F(S_{\text{UID}})$, which is the result of the computation with the function F applied to the user's secret.

In this scenario, several problems need to be addressed:

- On the user side, how is the secret stored? How is the secret provided (e.g., if it is a password entered via a keyboard, a keylogger could disclose it)? Is the transmission of the proof secure?
- On the server side, how are the secrets related to the user stored? When a proof is received, how is it verified to be the correct proof?

3.3.1 Passwords (reusable)

Imagine that the secret is a **reusable password** (meaning that it is always the same), and the user is identified by their User ID, with the secret being the password associated with that user. On the server side, there is a table containing usernames and passwords in plain text or a function H computed over the password.

Once again, there will be an **authentication request**, followed by the user sending their **UID**. Then, a password request is made, and the user responds with $P_{\mathbf{UID}}$.

Assume the network is secure and focus on the verifier's side. The secret is the user's password, and the client creates and transmits the proof, typically using a function $F = I$, which is the identity function. The proof is the password sent in plain text, which is, of course, dangerous.

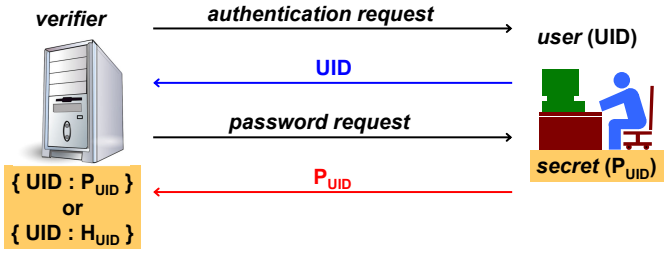


Figure 3.3: Authentication with password

Now, looking at the server, when the server receives the password, it needs to check if it is correct or not:

1. first case: if the function f used to store the password is the **identity function** ($f = I$), then the proof is the password in cleartext. In this scenario, the server knows all the passwords in plain text, and verifying their correctness is simple. However, it is risky; if someone copies the database, they will gain access to all data.

2. second case (the suggested one): f is not the identity function but a **one-way hash** (a digest of the password), and the server does not know the password in plain text but only the (unprotected) digest H_{UID}. This means that access control is a bit more complex, as when the proof is received, the hash of the proof is computed and compared with the hash stored in the password database. If the database is stolen, the attacker will not have a copy of the plain-text passwords.

Problems of reusable passwords

Password-based authentication is usually convenient for the user, but only if they have to remember just one password, a reusable one. The current situation is unfortunate because in some applications, there is a need for several passwords that cannot be remembered by a person, so they would need to be stored on the user's side, which is a source of insecurity. The **disadvantages** of password-based authentication are:

- **The user-side password storage**: it could be written on a post-it or on a client-side password manager (also called password wallet), that stores it encrypted typically using only one passphrase;
- **Guessable passwords**;
- **Server-side password storage**: the server must know the password in cleartext or an unprotected digest of it (dictionary attack);
- **Sniffing**: Password can be sniffed while it is sent across the network;
- **DB attacks**: There could be attacks to the password DB at the verifier (if DB contains plaintext or only obfuscated password);

- **Password guessing**: it is very dangerous if it can be done offline, for example against a list of password hashes;
- **Password enumeration**: if the password is limited in length or character type, or if authN protocol doesn't block;
- **Password duplication**: using the same password for different services, due to user password reuse. This could be a problem because if the user has the same password for a high-security service and for a weaker one, an attacker could discover it on the weaker system and have access to the high-security one;
- **Cryptography aging**: the solution adopted for verifying the secret should not be tied to a specific cryptographic algorithm, because it could be then difficult to adapt to the need for changing the algorithm used, due to new attacks and more computing power;
- **Password capture** via server spoofing and phishing;
- **MITM attacks**.

Password best practice

- Use a **mixture** of alphabetic characters (both uppercase and lowercase), digits, and special characters. Unfortunately, there are many systems that don't allow the use of special characters or impose limits on password length.
- Use a **long** password, preferably at least 8 characters in length.
- **Avoid using dictionary words**, as attackers often employ dictionaries from multiple languages.
- **Change your password frequently**. If the same password is kept for an extended period, attackers have more time to perform their computations. It's advisable to change your password at least once or twice a year to reduce the window of exposure.
- Whenever possible, **consider not using passwords**. However, this may be unavoidable unless biometric techniques are employed.

Storing passwords

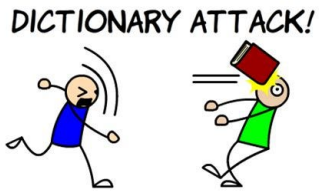
Storing passwords on the server-side

- Never store passwords in cleartext.
- If the password is **encrypted**, the server must have access to the encryption key in cleartext, which can be a security concern. To enhance security, it's recommended to **store a password digest**. However, be cautious of dictionary attacks that can be expedited by techniques such as **rainbow tables**. To mitigate these types of attacks, you can introduce an unpredictable element known as a "**salt**".

Storing passwords on the client-side

- Passwords should be memorized by the user.
- If there are numerous passwords to manage, consider using an encrypted file or a password wallet.

3.3.2 The "Dictionary" Attack



If you store the plain hash of a password, dictionary attacks are possible. This is possible under two hypotheses:

1. known hash algorithm;
2. leakage of information, so that the attacker has a copy of the **password hash values**.

Hashes are not invertible functions, but it is possible to make a **pre-computation**. Therefore, even if there is no copy of any password hash yet, it is possible to decide that it would be worthwhile to attack passwords stored as plain SHA-1 hashes in the future.

You must obtain a dictionary containing not only the Italian language but all possible languages. For each word in the dictionary, you compute the hash of the word and store it in a database paired with the corresponding word. By "word," we mean a potential passphrase, not a part of it. Typically, attackers have dictionaries extended to include words such as names of famous people.

The main hypothesis is that the user has chosen one of the words contained in the dictionary. The attack proceeds as follows:

1. At some point, the attacker obtains a hash value due to a leakage.
2. The attacker performs a simple **lookup** as follows: $w = \text{lookup}(\text{DB}, \text{HP})$, where DB is the database and HP is the computed hash of a word in the database, if any of the hash passwords appears in any tuple.
3. If the response is positive, the password is equal to that word. If not, the password is not from the dictionary.

Pre-computation is the key because if you wait until you get a copy of the password hash, and only at that point you start computing all the possible hash values, it could be too late because the password could have changed.

3.3.3 Rainbow table

A dictionary attack can be made faster and more effective by the **Rainbow table** technique. It is still a *dictionary attack*, but it involves a trade-off between space and time. Trying all possible passwords and computing the hash would be fast, but the result would be a huge database. If you have a complete database, the lookup would be fast, but fewer passwords are stored, and a bit more time is taken to compute the password if the corresponding hash is present. This is an improvement because it makes an exhaustive attack feasible for certain password sets.

Imagine creating a rainbow table to attack a password that we know contains 12 digits. The exhaustive attack would require 10^{12} rows, which is a huge number of lines containing passwords and the corresponding hash values. A rainbow table could be used to reduce the number of rows in the database by a factor of 1000. In this way, we get a 10^9 rows database, where each line represents 1000 passwords. To achieve that, we use the **reduction function**:

$$r : h \Rightarrow p$$

It is a function r that takes a hash as input and creates one possible password. **Beware that this is NOT the inverse of the hash (h^{-1})**, because the inverse of the hash does not exist. It is just a mapping function that, from a hash, creates one of the possible passwords of the whole set; in other words, the reduction function is a different function with a swapped domain and codomain of the hash function.

For other informations, check `https://en.wikipedia.org/wiki/Rainbow_table`.

Pre-computation Then, the pre-computing is the following:

- **pre-computation:**
  - for (10^9 distinct P)
    - for (p=P, n=0; n<1000; n++)
      - k = h(p); p = r(k);
    - store (DB, P, p) // chain head and tail

1. Select 10^9 distinct passwords (the desired size) called P.
2. For each of them, initialize the computation starting from that specific password, and then iterate 1000 times; each time the hash of the current password is computed (called k), and then the reduction function is used to go from k to another possible password.
3. At the end, the password P of the first cycle is stored in the database together with the last computation of the reduction function (called p).
4. Then, the entry implicitly represents all the 1000 passwords tried. Note that there is no more hash to be stored.

```
attack:
    let HP be the hash of a password
    for (k=HP; n=0; n<1000; n++)
        p = r(k)
        if lookup( DB, x, p ) then exit ( "chain found!" )
        k = h(p)
    exit ( "HP is not in any chain of mine" )
```

Attack Then the attack rises in this way:

1. HP is the leaked hash of a password;
2. Start an iteration of at most 1000 times, and each time, the reduction function is used to derive a possible password from the hash value;
3. Next, search the database to check if there is a row where p (the result of the reduction function) is at the end of the chain. In that case, we found the chain containing that hash; otherwise, a new value k is calculated by performing the password hash;
4. After finding the chain, the computation of the hash must be done again to identify which hash matches the one we have.

The problem is that since the reduction function is going from a hash to one possible password, there could be two different hashes that generates the same password, and this is called **fusion**. Rather than using a reduction function, a set of n reduction functions is used, one for each reduction step. On internet there are on sale pre- computed rainbow tables for various hash functions and password sets (e.g., SHA1 for alphanumeric).

This technique is used by various attack programs.

3.3.4 Using salt in storing passwords

The critical point in the previous kind of attack is that the attacker performs pre-computation. Without the rainbow table and without the database created by the dictionary, it would take a lot of time. For this reason, **do not provide the attacker with the information needed for pre-computation**, because it is based on the idea that the attacker may know which is the password (through the dictionary).

- Using the following technique, even if it can be possible to guess what a possible password is, the attacker does not get the hash table because every time a User ID is created, the system generates a **salt** that is different for each user.
  The salt is a random (unpredictable) and long (increased dictionary complexity) string of bytes. Users do not have to memorize the salt, which should contain rarely used or control characters.
  Then the hash is computed using the password concatenated with salt:
  HP = $hash(pwd|salt)$;

- The verifier stores UID, HP_{UID} and $salt_{\text{UID}}$.
  If someone gets the information in the database, he also gets the salt, but only then the computation can start, which will require a lot of time and in the meanwhile the password could have been changed. Additionally, there are different HP for users having the same password.

This makes the dictionary attacks nearly impossible (including those based on rainbow tables).

Example: Passwords in Linux

Originally stored in `/etc/passwd`, hashed with a DES-based hash function named `crypt()`. Since `/etc/passwd` needs to be world-readable (contains usernames, UID, GID, home, shell, etc.), passwords have been moved to `/etc/shadow`, readable only by system processes. Passwords are stored in the following form - see `crypt(5)`:

```
$id$salt$hashedpwd
```

Different hash functions are used depending on the ID, for example:

- 1 = MD5, ..., 5 = SHA-256, 6 = SHA-512, ...

If `$id$salt` is absent, the old DES-based hash is used (with a 12-bit salt, and the password is truncated to 8 characters) - danger! Some algorithms have adjustable complexity (to counter brute-force attacks).

Case history: The LinkedIn Attack

In June 2012, someone was able to copy 6.5 million passwords from LinkedIn, which were unsalted plain SHA-1 hashes. The person published those hashes on the internet and asked for crowdsourcing, used for cooperative password cracking (which means trying to compute SHA-1 hashing of words and looking if someone has a match). At least 236,578 passwords were found before Interpol was able to ban the website that published the password hashes.
Note that simultaneously LinkedIn found out that the LinkedIn app for iPad/iPhone was sending in clear sensitive data (not relevant to LinkedIn!).

Example: Passwords in MySQL

MySQL is a database where usernames and passwords are stored in the "user" table. MySQL (from v4.1) uses a **double hash (without salt!)** to store passwords:

```
SHA-1(SHA-1(password))
```

Then, the hex encoding of the result is stored, preceded by * (to distinguish this case from MySQL versions < 4.1). For example, for the password "Superman!!!," the field `user.password` is

```
user.password = *868E8E4F0E782EAA610A67B01E63EF04817F60005
```

To verify that this is the double hash of the word, you can use the following command on Linux:

```
$ echo -n "Superman!!!" | sha1sum | xxd -r -p | sha1sum
```

This is the standard way for MySQL to store passwords, which is not secure. It is advisable to change the standard way MySQL uses to store passwords by using a salted approach.

3.4 Strong (peer) authN

Recently, there has been a growing emphasis on the requirement to move away from standard authentication methods and adopt strong peer authentication. While this is consistently requested in specifications, it is often not formally defined or defined in multiple, potentially confusing ways.

3.4.1 ECB Definition for Internet Banking

According to the European Central Bank (ECB), strong customer authentication (authN) is a procedure based on the use of two or more of knowledge, ownership, and inherence. The selected elements must be mutually independent, ensuring that the breach of one does not compromise the others. At least one element should be non-reusable and non-replicable (except for inherence), and not capable of being surreptitiously stolen via the Internet. The strong authentication procedure should be designed to protect the confidentiality of the authentication data; for example, if a password is used, it cannot be sent in clear text.

3.4.2 PCI-DSS Definition for Payment with Credit Cards

According to the PCI-DSS definition, which applies to payment with credit cards, starting from v3.2, multi-factor authentication (MFA) is required for access into the cardholder data environment (CDE). This requirement is applicable regardless of whether the network is trusted or untrusted, and it is also mandatory for administrators accessing the CDE.

The only exception is for direct console access, which involves physical security measures, such as entering the room where the server is located. However, for remote access, MFA is always required, especially from untrusted networks, and for users and third parties (e.g., maintenance).

This best practice was in effect until January '18 and became mandatory thereafter.

Remember: MFA does **not** mean using the same factor twice, like using two passwords.

3.4.3 Other definitions

According to the *Handbook of Applied Cryptography*,
authentication is a **cryptographic challenge-response identification protocol**.

More in general, it is a technique resisting to a well-defined set of attacks.

An authN technique can be classified as strong or weak depending on the attack model:

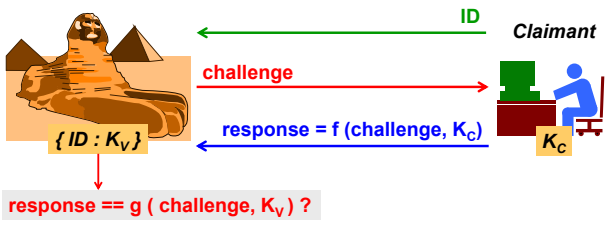
- E.g., users of Internet Banking follow the ECB definition;

- E.g., employees of PSP adhere to the PCI-DSS definition.

In general, pay attention to your specific application field because it defines the types of risks and the level of strength required for your strong authentication.

3.5 Challenge-Response Authentication (CRA)

Challenge-response protocol is a possible way to implement strong authentication. CRA means that there is a challenge sent to the Claimant from the Verifier. The Claimant replies with the solution computed using some secret knowledge and the challenge. The Verifier compares the response with a solution computed via a secret associated with the Claimant.

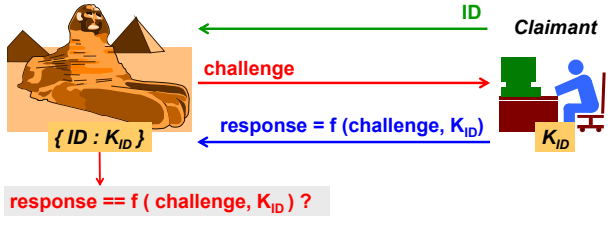


Someone claims to own the identifier (ID). The verifier looks that there is a row associated with that ID and sends to the claimant the challenge. The claimant has a key (K_c) and uses it to perform some kind of computation (function f) and generates a response. The response can be checked by applying the function g to the challenge and to a well-known key (K_V) of the Verifier. The keys can be different or the same.

General issues of CRA

- **The challenge must be non-repeatable to avoid replay attacks**. For this reason, usually, the challenge is a (random) nonce.
- **The function f must be non-invertible**, otherwise, a listener can record the traffic and easily find the shared secret by using the function $K_c = f^{-1}(response, challenge)$.

3.5.1 Symmetric CRA



In this case, there is a common key shared between Claimant and Verifier, which is typically the password or passphrase of the user. The function f is computed two times: once from the user to make the response, and once from the verifier to verify the match.

General issues of Symmetric CRA

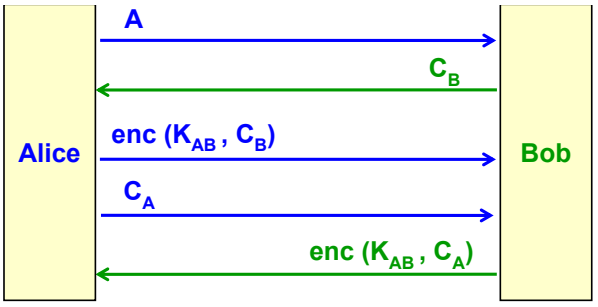
General issues with Symmetric CRA are:

- The easiest implementation uses a hash function (faster than encryption) such as SHA1 (deprecated), SHA2 (recommended) or SHA3 (future);
- K_{ID} must be known in cleartext to the Verifier and this may lead to attacks against the $\{ID : K_{ID}\}$ table at the Verifier;

There is a technique called **SCRAM** (Salted CRA Mechanism) which solves this problem by using hashed passwords at the Verifier, which also offers channel binding and mutual authentication, while we are always talking about single authentication

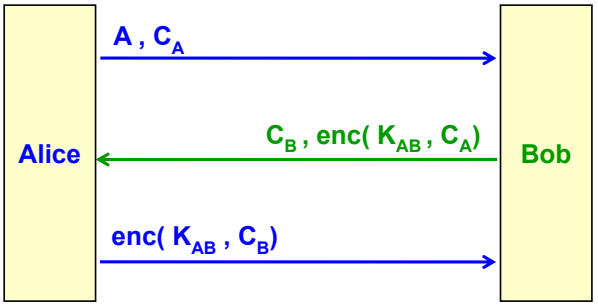
Mutual symmetric CRA (v1)

Imagine that we are not using a hash but encryption (although it would work in the same way), and let's consider the scenario of mutual authentication.
Alice and Bob share a key K_{AB}, and Alice sends a message A to Bob (which means: "Hey, I'm Alice!"). Bob responds with a challenge C_B, and Alice replies with enc(K_{AB}, C_B), which is the encryption of the challenge using the shared key. Then, Alice could create a challenge (C_A), and Bob would respond in the same way by computing enc(K_{AB}, C_A). This approach provides protection against MITM attacks because, if the challenges are nonces, the Replay Attack is not possible.
Beware! This protocol is outdated and insecure.



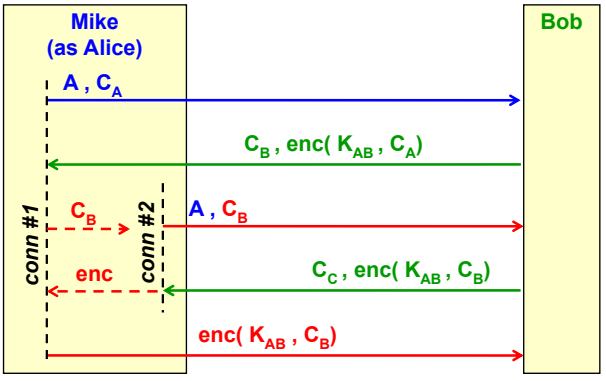
Mutual symmetric CRA (v2)

IBM, in its SNA network system, employed a similar technique with a different implementation: they reduced the number of messages for improved performance without compromising security.
In the initial step, Alice transmits both the identity (A) and the challenge (C_A). The response from Bob includes both the challenge (C_B) and the encryption enc(K_{AB}, C_A). Finally, Alice responds with enc(K_{AB}, C_B). Although this may appear equivalent to the previous solution in terms of functionality and security, it is not.



Attack to the mutual symmetric CRA (v2)

Here, Mike pretends to be Alice. Mike sends to Bob Alice's identity (A) and Alice's challenge (C_A). Bob replies with C_B and enc(K_{AB}, C_A).
At this point, Mike does not know K_{AB} and cannot compute the response to the challenge. However, Mike opens a new connection with Bob, sending Alice's identity (A) again but, this time, sends the challenge sent from Bob (C_B). Bob replies again with another challenge (C_C) and enc(K_{AB}, C_B), which is the answer to the challenge of the 1st connection. Mike can finally provide the correct answer.
Of course, this can be countered if there is a limit on connections.



GSM (in)security

In our discussion on improved authentication methods beyond basic passwords, we highlighted the effectiveness of the challenge-response approach with symmetric keys. To illustrate this concept

in a real-world scenario, let's delve into GSM authentication and its relevance to security.

GSM (*Global System for Mobile Communications*) has been designed violating the principle of security through obscurity and relies on three confidential algorithms:

- A8, operating within the SIM (Subscriber Identity Module), focuses on symmetric key generation, laying the foundation for secure connections.
- A3, also embedded in the SIM, handles authentication processes, providing a robust framework for verifying user identities.
- Additionally, A5, a stream cipher implemented in the mobile device, contributes to data encryption, safeguarding sensitive information during transmission.
  - GSM's security approach introduces some level of secrecy through the implementation of A5/1 and A5/2, where A5/1 is the more commonly used variant and A5/2 is intentionally weakened in specific regions for surveillance purposes.
  - A5/3, based on the Kasumi block cipher, offers an alternative encryption method, but it's not widely used.

Implementing **security through obscurity**, as highlighted, is inherently problematic. This approach is not only detrimental in terms of the algorithm's efficacy but also raises concerns about the design process itself. The fact that a limited group of individuals crafted the process without seeking revisions, reviews, or insights from external experts resulted in a suboptimal design. This underlines the importance of inclusive and collaborative design practices for creating robust and effective security measures.

Furthermore, the discretion of Mobile Network Operators (MNOs) comes into play, allowing them to choose algorithms for A8, A3, and A5. Typically, A8 and A3 are constructed using the COMP128 secret function, involving the computation of

$$Z = \text{COMP128}(X, Y)$$

with each variable being 128 bits. A8 extracts the least significant 54 bits of Z to generate the connection key

$$Kc = lsb(54, Z)$$

while A3 utilizes the most significant 32 bits of Z to produce a "*Signed RESponse*"

$$SRES = msb(32, Z)$$

actually this is not a digital signal because it is not using any public key.

GSM Security Overview In GSM authentication, a symmetric Challenge-Response Authentication (CRA) is employed to verify the identity of the Mobile Station (**MS**),such as a mobile phone, to the Base Station (**BS**) through its SIM. The SIM holds an **individual subscriber authentication key** (Ki), a confidential 128-bit secret shared with the Authentication Centre (AC).

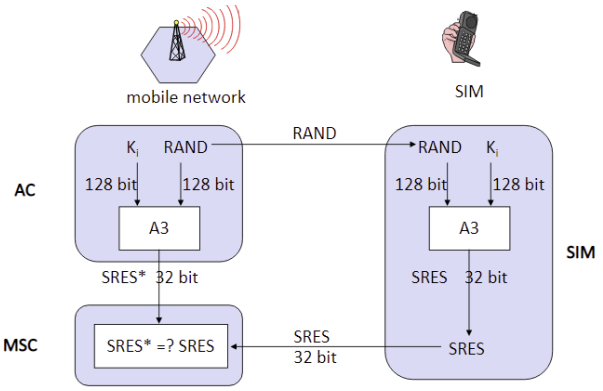


Figure 3.4: GMS authentication

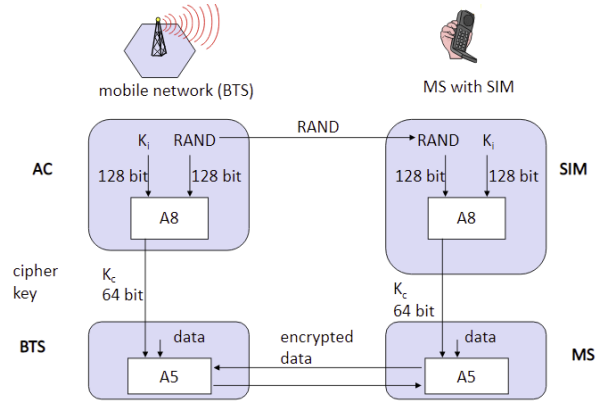


Figure 3.5: GMS encryption

The process unfolds as the BS transmits a random 128-bit challenge (C) to the SIM, and in response, the SIM computes the 32-bit Signed Response (SRES) using the A3 algorithm with inputs C and Ki:

$$\text{SRES} = A3(C, Ki)$$

This value is, in fact, a keyed digest, as it is computed based on a key.

However, a notable vulnerability arises with COMP128-1, which is identified as weak. Exploiting chosen-challenge and differential cryptanalysis techniques, a relatively modest number of challenges, around 150,000, are adequate to compute Ki. This weakness opens the door to potential security breaches, enabling actions such as SIM cloning, where an unauthorized party can replicate the SIM, sharing the same Ki.

Consequently, with the compromised Ki, the attacker gains the ability to decrypt the communication traffic by computing the Connection Key (Kc) for that specific Ki and the challenge (C) sent by the BS. This vulnerability highlights the importance of addressing weaknesses in authentication protocols to ensure the integrity of GSM security.

3.5.2 Asymmetric CRA

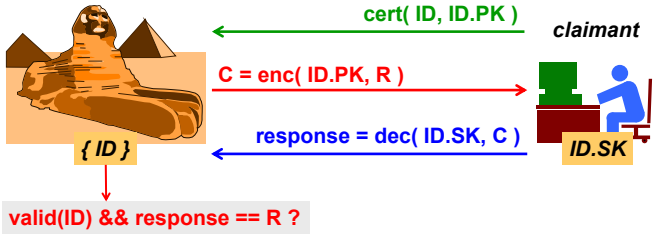


Figure 3.6: Asymmetric CRA

It is also possible to employ an asymmetric challenge-response mechanism. In this scenario, the user does not transmit their identity directly but rather provides their X.509 certificate, which declares both their identity and public key (the claimant possesses the corresponding private key, $ID.PK$). The Verifier initiates the process by generating a challenge, employing a random nonce R encrypted with the public key. The claimant decrypts the challenge using their private key and returns the decrypted value to the Verifier. If the response matches the R value specified in the challenge, it confirms possession of the private key. The only necessary verification involves checking if a valid ID is registered in the Verifier's database.

Asymmetric CRA: analysis Asymmetric Challenge-Response Authentication (CRA) is the strongest usable mechanism, eliminating the need for storing any secrets at the Verifier. It is consistently implemented for *peer authentication* (client and server) in protocols such as IPsec, SSH, and TLS. Additionally, it serves as a fundamental component for user authentication in a new authentication system named FIDO (Chapter 3.5.6).

However, it comes with certain downsides:

- **Slowness**, stemming from the inherent sluggishness of asymmetric cryptography.
- Inaccurate design may result in **unintentional signature creation by the Claimant**. The Claimant, while receiving something, performs a computation with the private key. This computation, used both for decryption and creating a signature, poses a risk of inadvertently signing a document. To mitigate this risk, the data provided as input for decryption on the claimant-side must follow a specific format.
- Public Key Infrastructure (**PKI**) **issues**, including concerns related to *trusted roots*, *name constraints*, and *revocation*, since it relies on certificates. These issues can be avoided if the Verifier stores $ID.PK$, however this strategy shifts the equivalent PKI effort to the Verifier. This approach is adopted by SSH, wherein the public key is taken and made public on the server, despite with the significant risk of someone potentially altering the key stored on the server.

3.5.3 One-time password (OTP)

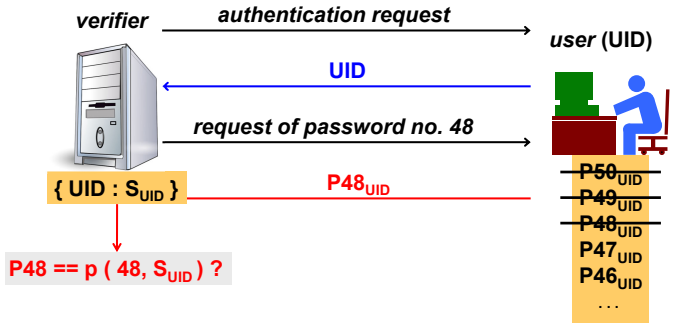


Figure 3.7: One Time Password (OTP)

Instead of employing reusable passwords, users are assigned passwords that are valid for a single login session. When a claimant seeks access to the server, they respond by providing their userID. Subsequently, the server issues a request for a specific password from an extensive list, for instance, password number 48. If passwords $P49_{UID}$ and $P50_{UID}$ have already been utilized, the user transmits $P48_{UID}$ and marks it as used in the table.

At this juncture, the server maintains a table containing user identifiers (UID) and the undisclosed secret (S_{UID}) that the user is unaware of. This secret is utilized for password generation. The Verifier, in turn, replicates the function used to generate the password to regenerate it and verifies if it aligns with the one transmitted by the user. This methodology renders passwords **immune to** potential **sniffing attacks**, as they can be transmitted in plaintext, knowing that the subsequent login will involve a different password.

Summary

- The password in this authentication protocol is **only valid for a single run**, necessitating a new password for each subsequent authentication session.
- This characteristic makes it **immune to sniffing attacks**, as the intercepted password becomes obsolete after one use.
- However, it is **subject to** Man-in-the-Middle (**MITM**) attacks when an entity assumes the role of the verifier. To mitigate this risk, Verifier authentication is essential.
- Provisioning for subscribers involves managing a large number of passwords, leading to potential password exhaustion.
- Additionally, **inserting passwords can be challenging** due to their typically random and complex nature, designed to prevent guessing attacks.

OTP provisioning to the users For OTP provisioning to users, additional precautions may be necessary when the claimant operates on a device lacking computational capabilities or on an insecure/untrusted workstation. In such cases, physical safety measures can include:

- A sheet of paper containing pre-computed passwords.
- Hardware authenticator (crypto token): a device where passwords are stored or generated.

By contrast, when working on an intelligent and secure/trusted workstation, OTPs can be **automatically computed** by a dedicated application (commonly found in smartphones, tablets, laptops, etc.).

The S/KEY system

This was the first OTP definition and implementation by Bell Labs (1981).

- The user generates a secret S_{ID}.
- Then the user autonomously computes N one-time passwords where $P_1 = h(S_{ID})$, $P_2 = h(P_1)$, ..., $P_N = h(P_{N-1})$ (associated hash).
- The Verifier stores the last one P_N. This password will never be used directly for authentication but only indirectly.
- When the user wants to access the server, the Verifier (which has P_N) asks for P_{N-1} and gets X from the user. Then the following check is performed:

$$\text{if } (P_N \neq h(X)) \text{ then FAIL}$$
$$\text{else OK; store } X \text{ as } P_{N-1}$$

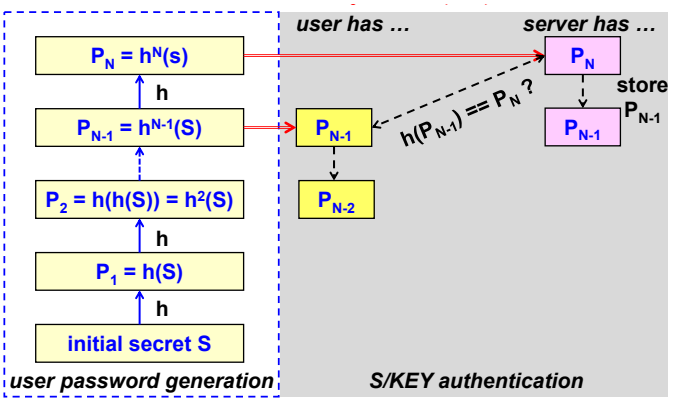


Figure 3.8: The S/KEY System

The technique employed here involves the Verifier requesting passwords **in reverse order**. This approach allows the Verifier to operate without the need to possess knowledge of the user's

secret, placing the responsibility on the user to be familiar with all passwords. This methodology is detailed in RFC-1760 and employs MD4 (although alternative options are possible). S/KEY serves as an illustration of an Off-line / Pre-computed OTP.

It is crucial to note that **MITM** (Man-in-the-Middle) **attacks are possible with OTP**. Consequently, S/KEY should be utilized in conjunction with **server authentication**.

S/KEY - generation of the password list The user inserts a passphrase (PP), which must be a minimum of 8 characters long and kept secret. If disclosed, the security of S/KEY is compromised. The passphrase is concatenated with a server-provided seed (sent in cleartext from S to C), allowing the use of the same passphrase for multiple servers (using different seeds). It is also possible to safely reuse the same passphrase by changing the seed.

A 64-bit quantity is extracted from the MD4 hash, which generates a 128-bit result (by XORing the first/third 32-bit groups and the second/fourth groups).

S/KEY - passwords 64-bit passwords represent a compromise, and entering them in hexadecimal form requires 16 characters. Typically, they are input as a sequence of six short English words selected from a dictionary of 2048 (e.g., 0 = A, 1 = ABE, 2 = ACE, 3 = ACT, 4 = AD, 5 = ADA).

This entails choosing 11 bits from the computed hash and utilizing a dictionary with simple words corresponding to the combinations (2048 in this case). **It is crucial that the client and server share the same dictionary**. For instance:

- **Password (text)**: "YOU SING A NICE OLD SONG," not because it serves as a password but because "YOU" is one of the words in the dictionary, representing 11 bits. In total, there are 6 words, resulting in 66 bits (more than 64, ensuring security).
- **Password (numeric)**: 1D6E5001884BD711 (hex) or 2,120,720,442,049,943,313 (decimal).

This is merely an illustrative example of encoding a lengthy bit string in a user-friendly manner.

Time-based OTP

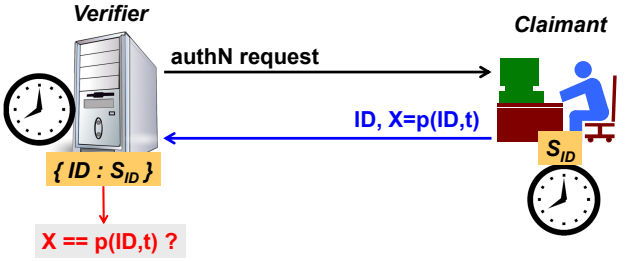


Figure 3.9: Time Based OTP

In this solution, the password depends on time and the user's secret:

$$p(ID, t) = h(t, S_{ID})$$

When the claimant wants to authenticate, it receives a request from the verifier and submits its own ID plus the value generated by a device (authenticator), which tells the claimant which is the correct password to be entered at that moment. At that point, the verifier needs to check if the value is the current OTP for the current time. Since the verifier has a large table containing, for each user, the corresponding secret, it can perform the same computation and compare it.

This type of OTP requires local computation at the subscriber and clock synchronization (or keeping track of time-shift for each subscriber). Due to the fact that the password needs time to be sent, the time needs to be quantized (considering timeslots, usually ranging from 30 to 60 seconds), and an authentication window is established. Usually, the verifier considers the password as correct if it is generated one timeslot before or one timeslot after the correct timeslot according to its own time. In formulas, the authentication succeeds if[1]

$$X == p(ID, t) \quad \| \quad X == p(ID, t-1) \quad \| \quad X == p(ID, t+1)$$

(where t is the timeslot). Typically, only one authentication run per timeslot is allowed, which might not be suitable for some services, for example, a broker that needs to perform many transactions concurrently.

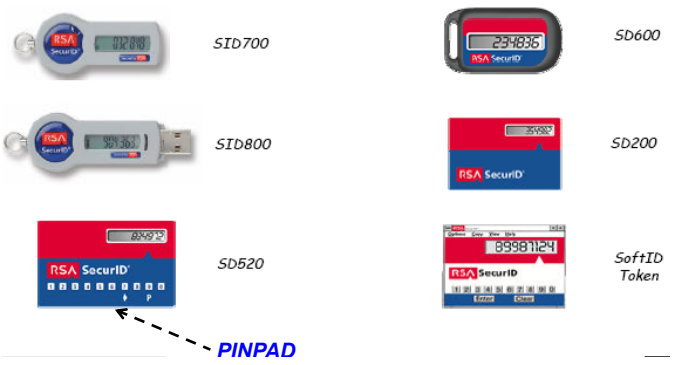
This system is **susceptible to time-based attacks** against both subscribers and the Verifier. Typically, servers and clients synchronize their time with an external source, and an attack can be executed using a fake NTP server or a mobile network femtocell. For instance, if an attacker successfully deceives the subscriber into providing a password for a future timeslot, they can exploit it at that specific time.

Since the Verifier stores the secret for each user, it must manage a highly sensitive database. In the event of a security breach where the database is compromised, the attacker gains the ability to impersonate users and compute the passwords for any user. An incident of this nature occurred in an attack against a TOTP system named *RSA SecurID*.

A TOTP example: RSA SecurID In this system, the Claimant sends the triple {*user*,*PIN*, *tokencode(seed, time)*} in clear to the Verifier. As *RSA SecurID* is a physical device continuously displaying the correct password, if someone other than the subscriber reads and uses it, an attacker could gain access with the subscriber's identity. This emphasizes the need for an additional authentication factor. Therefore, one factor is "*owning the device*" while the other is "*knowing the (reusable) password*".

Since it could be possible for the PIN to be sniffed while sent across the network, there is a variant of the *SecurID* authenticator that includes a "pin pad" (a sort of small keyboard just for entering the PIN). When the PIN is entered, the value of the PIN is taken into account for the generation of the OTP. In this case, it is possible to send just the user and the modified token code (the tuple {*user, token-code*(seed, time, PIN)*}), which is also a function of the PIN. Based on the user and PIN, the Verifier checks against three possible token codes: TC_{-1}, TC_0, TC_{+1}, as in any TOTP system.

[1]Here "||" means `logical or` instead of `concatenated`



Moreover, each device is associated with two PINs: the first one is the one used normally for authentication, while the second is called duress code, and it is used to generate an alarm when the subscriber is under attack (for example, when the user is forced by a criminal to authenticate).

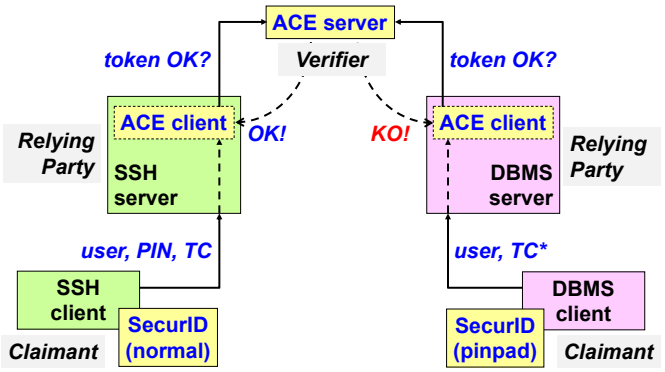


Figure 3.10: SecurID: architecture

SecurID: architecture Besides providing the hardware authenticator which computes the token code, RSA also provides some component called **ACE** (Access Control Engine):

- **ACE client** is installed at the Relying Party, which is the server that wants to use the authentication system;
- **ACE server** implements the Verifier.

In the illustration (Figure 3.10), the ACE server positioned at the top serves as the verifier, possessing the comprehensive information required to validate a token code. The service servers represent the Relying Party, entities necessitating access control integration with RSA SecurID. To interact with the verifier and authenticate user credentials, these servers must implement the ACE client. On the left of the depicted scenario, remote access to an SSH server is illustrated: the user, equipped with a standard SecurID device, submits the triple `{user, PIN, TC}`. Upon

receiving this information, the Relying Party forwards it to the verifier, which subsequently delivers a response indicating the validity of the provided credentials. On the right side of the picture, an unsuccessful authentication attempt is exemplified, employing a device with a pin pad.

The significance of examining this architecture extends beyond its role as a SecurID implementation. It serves as a comprehensive model, highlighting the need for server enhancements to accommodate specialized authentication methods (e.g., DBMS software in the provided example). When a company aims to deploy a uniform authentication technology across various servers, a centralized verifier becomes essential. This verifier can offer authentication verification services for all relaying parties, drawing parallels with the *NIST schema* (Chapter 3.2) in this regard.

Event-based OTP

The principal problem with TOTP is that only one authentication per timeslot is allowed. This solution introduces a monotonic integer counter, denoted as C, as an additional input alongside the seed:

$$p(ID, C) = h(C, S_{ID})$$

It requires local computation at the subscriber, where the counter is incremented (e.g., through a button press), allowing for frequent authentication runs. While this system enables OTP pre-computation, even by adversaries with temporary access to the authenticator, it poses challenges for the Verifier in handling **desynchronization** issues. For instance, if the subscriber unintentionally triggers the button, desynchronization may occur. To address this, a counter window is considered, defining a set of counters with a fixed and typically small size. In formula terms, a password is deemed correct if

$$X == p(ID, C)||X == p(ID, C+1)||X == p(ID, C+2)||\dots$$

with a maximum of ten subsequent counters to resist exhaustive attacks. Verifiers can adapt to desynchronization, storing the counter that matched the password sent by the user. If none of the passwords generated on the user side is acceptable, a counter reset may be required, such as in cases where a child presses the button more than ten times.

Out-of-band OTP

The solutions illustrated so far require the user to receive something: a list of passwords in the case of S/KEY or a device in the case of TOTP and EOTP. In situations where these options are not feasible, such as the inability to securely provide the list or a lack of trust in the user's device, Out-of-Band OTP can be utilized. This method is based on generating the OTP without using the normal communication channel.

In the schema depicted in the figure, the user is provided with a secret key, which is a *reusable password*. During authentication, the user sends the user ID and the reusable password, necessary for clear user identification. Although reusable passwords may not be very robust, the verifier can ensure the user's authenticity through the third step: it looks up the registered phone number

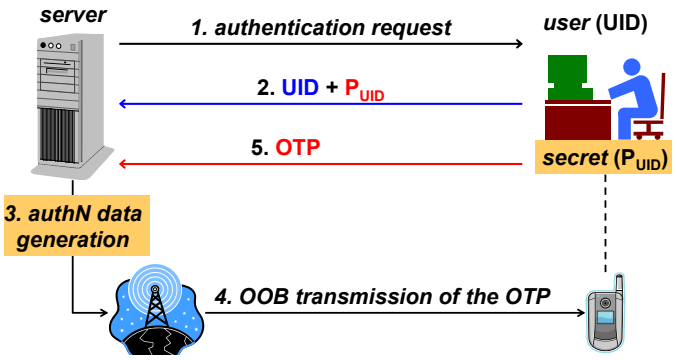


Figure 3.11: Out-of-band OTP

in its database. Subsequently, the verifier generates an OTP and sends it (out of band) to the user's cell phone, typically via SMS (step four). This process is considered out of band because the OTP transmission uses a different medium than the communication between the server and the user. Finally, in step five, the user provides the OTP just received.

This is a widely used system by many banks and identity providers, such as those involved in SPID. This system also reduces the burden on the user, who does not need to have a modern smartphone but just a minimal device to receive the message: the OTP is generated by the server only when needed and then sent in a trusted way to the user. However, be aware that at step five, a secure channel with server authentication is needed to avoid MITM attacks. The Out-of-Band (OOB) channel is frequently a text via SMS message. Since most mobile networks are nowadays implemented with VoIP, mobile user identification, and SS7 protocol (which are quite insecure), NIST suggests using the Push mechanism over a TLS channel to the registered subscriber device. This is done by putting the message inside a notification, the confirmation of which is made by inserting the user's fingerprint.

Two-/Multi- Factors AuthN (2FA/MFA)

It has already been pointed out that, if we want to provide strong authentication, more than one factor should be used. This is also named **2FA**, or more generally, **MFA**. MFA is used both to increase authentication strength and to protect the physical authenticator, as seen with OTP. Usually, a **PIN** is used for authenticator protection.

- **PIN transmitted along with OTP:** As seen, the possible problem is that it can be sniffed when entered or transmitted across the network.
- **PIN entered to compute the OTP itself:** Like in RSA SecurID.
- **PIN (or inherence factor) used to unlock the authenticator,** which is very risky if:
  - No protection from **multiple unlock attempts**.

- **The lock mechanism** is weak, for example, the fingerprint sensor is not strong enough to recognize only the device owner's fingerprint.
- **Unlocking is valid for a time window**: if someone has access to the authenticator in the time window in which it is unlocked, then they can use the user identity.

Importance of MFA: the Iphone ransomware In May 2014, a security incident occurred involving iCloud accounts with single-factor authentication, resulting in unauthorized access. The attackers employed a "remote lock" feature through the "Find My Device" functionality. Users of affected devices, such as iPhones and iPads, received a menacing message indicating the breach: "*Device hacked by Oleg Pliss!*" The attackers demanded a payment of 100 USD/EUR via a specified PayPal account (lock404(at)hotmail.com) for the restoration of control.

Alternatively, users were informed of the option to use "recovery mode," although this came at the cost of losing all device data and applications. It's crucial to note that even complying with the payment demand did not guarantee a resolution, as the attackers provided a fake PayPal account. This incident highlighted the vulnerabilities associated with single-factor authentication and emphasized the importance of robust security measures in safeguarding user accounts.
More info here.

3.5.4 Authentication of human beings

Ensuring that the subscriber is a human rather than a program can be achieved through two solutions:

- **CAPTCHA** techniques (*Completely Automated Public Turing test to tell Computers and Humans Apart*): for example, a picture with images of distorted characters;
- **Biometric** techniques: for example, fingerprints.

Biometric systems

The main idea is to measure a biological characteristic of the user, such as fingerprint, voice, retinal scan, iris scan, hand's blood vein pattern, heart rate, and hand geometry. EHowever, it is important to note that each technique can potentially be circumvented. Moreover, biometrics is not replaceable, highlighting the necessity of implementing additional security measures to mitigate potential vulnerabilities. Regardless of the chosen biometric solution, two parameters must be considered:

- **FAR (False Acceptance Rate):** the rate at which the system incorrectly accepts a biometric signal as valid.
- **FRR (False Rejection Rate):** the rate at which the system erroneously rejects a valid signal as if it were fake.

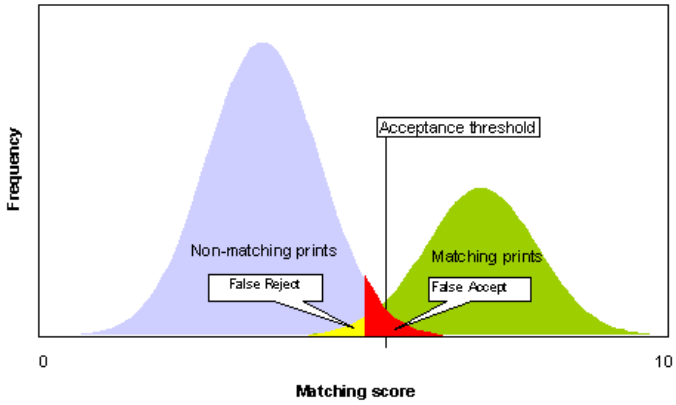


Figure 3.12: FAR and FRR

The two normal distributions refer to fingerprints that match (green) and those that do not. The two distributions overlap, necessitating the establishment of a threshold. Regardless of where the threshold is set, it is important to note that FAR and FRR cannot both be equal to zero. They may be partly tuned, but they heavily depend on the cost of the device. Moreover, some biological characteristics are variable; for example, the user can have a finger wound, the voice altered due to emotion, or retinal blood pattern altered due to alcohol or drugs.

Other than technical challenges, there are also various non-technical issues:

- **Psychological acceptance**:
  - "Big Brother" syndrome, related to personal data collection.
  - Some technologies are intrusive and could be harmful; for example, retinal scans may not be suitable for everyone.
- **Privacy concerns** arise since, at this point, it is not just a matter of authentication but of identification, making it irrepudiable.
- Biometric features **cannot be changed** if copied. Unlike passwords, which can be changed if there is a fear of disclosure, a biometric authentication cannot. Therefore, it should not be sent across the network and can only be useful for locally replacing a PIN or a password.
- **Lack of a standard API/SPI** leads to:
  - High development costs.
  - Heavy dependence on single/few vendors.

3.5.5 Kerberos (and SSO)

Kerberos, named after the three-headed dog from Greek mythology that guarded the entrance to the underworld, is an authentication system based on a *Trusted Third Party* (**TTP**). Originally

developed as part of the MIT project Athena, Kerberos holds significance beyond the realm of HTTP-based services.

One of its distinguishing features is its innovative approach to user password management; rather than transmitting passwords across the network, Kerberos utilizes them only locally, as **symmetric cryptographic keys**. In the Kerberos framework, there are two important concepts:

- the term "**realm**" denotes the Kerberos domain, which represents the collection of systems employing Kerberos as their authentication system.
- Additionally, a **credential** within Kerberos is identified as `user.instance@realm`, resembling an email address but specific to the Kerberos domain. This structure attaches to each user the role that the user is assuming at this moment for a given operation.

Ticket Kerberos employs a data structure known as a ticket for client authentication to servers. These tickets possess a **variable lifetime**. In the earlier Version 4, the maximum duration was restricted to 21 hours, structured around five-minute time slots, totaling 255. However, in the more recent Version 5, the validity period is explicitly defined, allowing tickets to be valid for an extended duration, even years. Despite being potentially unlimited, it is recommended to opt for shorter duration tickets to mitigate potential security risks associated with prolonged authentication privileges.

One notable characteristic of Kerberos tickets is their encryption with the **symmetric key of the target server**. This encryption ensures that the ticket remains secure and can only be decrypted at the destination server, adding an extra layer of protection to the authentication process.

In the initial Kerberos *Version 4*, **tickets were bound to the IP address of the client**, serving as an identifier for accessing a specific server. However, recognizing the vulnerability of IP addresses to spoofing, this association with IP addresses was eliminated in Version 5, enhancing the robustness of the Kerberos authentication system.

It's essential to highlight that each ticket is uniquely tied to a single credential. If a user possesses multiple credentials, they must obtain distinct tickets for each credential. While the primary purpose of tickets is to facilitate client authentication, Kerberos also offers the optional feature of server authentication using these tickets.

Protocol description

The protocol is described in detail below[2]. See Figure 3.13.

[2]Editor's note: This section is taken from `https://en.wikipedia.org/wiki/Kerberos_(protocol)`. I thought it could be simpler and more concise, and it aligns with the content in the slides

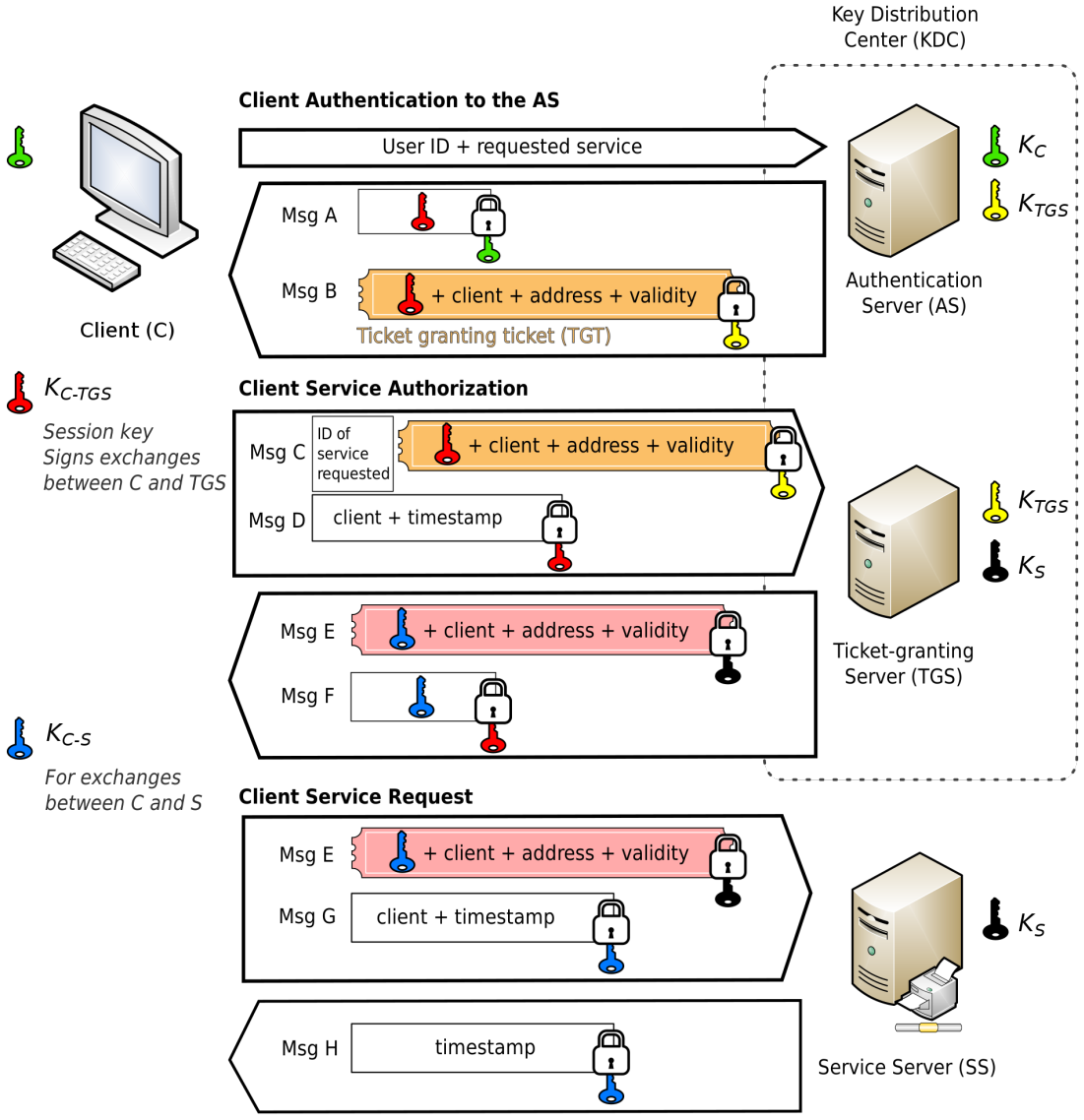


Figure 3.13: Kerberos protocol

User Client-based Login example without Kerberos

1. A user enters a username and password on the client machine(s). Other credential mechanisms like pkinit (RFC 4556) allow for the use of public keys in place of a password. The client transforms the password into the key of a symmetric cipher. This either uses the built-in key scheduling, or a one-way hash, depending on the cipher-suite used.

2. The server receives the username and symmetric cipher and compares it with the data from the database. Login was a success if the cipher matches the cipher that is stored for the

user.

Client Authentication

1. The client sends a cleartext message of the user ID to the AS (Authentication Server) requesting services on behalf of the user. (Note: Neither the secret key nor the password is sent to the AS.)
2. The AS checks to see whether the client is in its database. If it is, the AS generates the secret key by hashing the password of the user found at the database (e.g., Active Directory in Windows Server) and sends back the following two messages to the client:
   - Message A: `Client/TGS Session Key` encrypted using the secret key of the client/user.
   - Message B: `Ticket-Granting-Ticket` (TGT, which includes the client ID, client network address, ticket validity period, and the `Client/TGS Session` Key) encrypted using the secret key of the TGS.
3. Once the client receives messages A and B, it attempts to decrypt message A with the secret key generated from the password entered by the user. If the user entered password does not match the password in the AS database, the client's secret key will be different and thus unable to decrypt message A. With a valid password and secret key, the client decrypts message A to obtain the `Client/TGS Session Key`. This session key is used for further communications with the TGS. (Note: The client cannot decrypt Message B, as it is encrypted using TGS's secret key.) At this point, the client has enough information to authenticate itself to the TGS.

Client Service Authorization

1. When requesting services, the client sends the following messages to the TGS:
   - Message C: Composed of the message B (the encrypted TGT using the TGS session key) and the ID of the requested service.
   - Message D: Authenticator (which is composed of the client ID and the timestamp), encrypted using the `Client/TGS Session Key` (found by the client in Message A).
2. Upon receiving messages C and D, the TGS retrieves message B out of message C. It decrypts message B using the TGS secret key. This gives it the Client/TGS Session Key and the client ID (both are in the TGT). Using this `Client/TGS Session Key`, the TGS decrypts message D (Authenticator) and compares the client IDs from messages B and D; if they match, the server sends the following two messages to the client:
   - Message E: `Client-to-server ticket` (which includes the client ID, client network address, validity period, and Client/Server Session Key) encrypted using the service's secret key.
   - Message F: `Client/Server Session Key` encrypted with the `Client/TGS Session Key`.

Client Service Request

1. Upon receiving messages E and F from TGS, the client has enough information to authenticate itself to the Service Server (SS). The client connects to the SS and sends the following two messages:

   - Message E: From the previous step (the `Client-to-server ticket`, encrypted using service's Secret key by the TGS).
   - Message G: A new Authenticator, which includes the client ID, timestamp and is encrypted using `Client/Server Session Key`.

2. The SS decrypts the ticket (message E) using its own secret key to retrieve the `Client/Server Session Key`. Using the sessions key, SS decrypts the Authenticator and compares client ID from messages E and G; if they match server sends the following message to the client to confirm its true identity and willingness to serve the client:

   - Message H: The timestamp found in client's Authenticator (plus 1 in version 4, but not necessary in version 5), encrypted using the `Client/Server Session Key`.

3. The client decrypts the confirmation (message H) using the `Client/Server Session Key` and checks whether the timestamp is correct. If so, then the client can trust the server and can start issuing service requests to the server.

4. The server provides the requested services to the client.

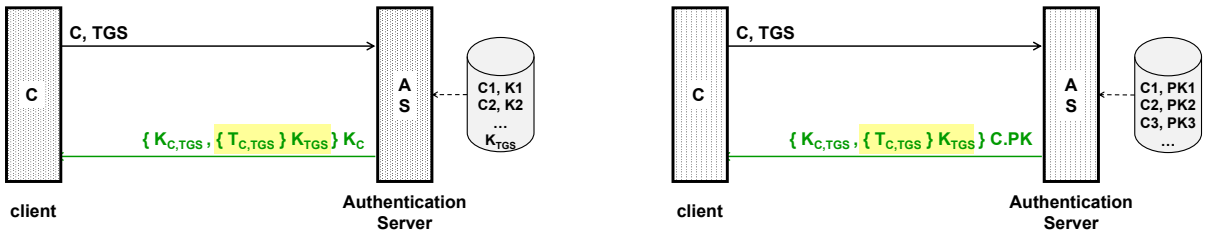
Kerberos versions Kerberos has evolved through various versions, with MIT V4 marking its original implementation. The subsequent version, MIT V5 (also known as RFC-1510), introduced significant enhancements. Unlike its predecessor, MIT V5 supports encryption beyond DES, offering increased security options. Notably, it extended the ticket lifetime by specifying explicit begin-end validity periods. Additionally, MIT V5 introduced features such as inter-realm authentication, forwardable tickets, and extendable tickets. This version enabled users to achieve a single login for access to all Kerberized services. These services encompassed a diverse range, including K-POP, K-NFS, K-LPD, K-telnet, K-ftp, and K-dbms. Furthermore, Kerberos found adoption in Windows domains, with Microsoft incorporating it into their systems starting from Windows 2000.

The subsequent evolution of Kerberos is reflected in `RFC-4120`, which supersedes `RFC-1510`. One notable improvement is the introduction of algorithm flexibility, allowing clients and servers to support different encryption algorithms. Originally, Kerberos utilized DES-CRC32, but over time, it expanded its repertoire to include 3DES, RC4, AES, Camellia, MD4, and MD5.

To enhance security, `RFC-4120` introduced pre-authentication measures, aiming to thwart password enumeration or dictionary attacks on the Ticket Granting Ticket (TGT). For instance, in Windows, the `AS_REQ` must contain encrypted forms of the user's key and timestamp.

TGT request with PKINIT `RFC-4120` (v5) brings support for asymmetric cryptography, applicable specifically in the `AS_REQ` phase, the initial phase of the protocol when making a request to the authentication server.

This feature, known as `PKINIT` (Public Key Initialization), modifies the Ticket Granting Ticket (TGT) request. In this process, a user seeks a ticket for the Ticket Granting Server (TGS). Unlike previous versions, the authentication server no longer stores user passwords, significantly improving security. Even in the event of an attack on the authentication server, no clear passwords are compromised. Instead, the server stores the public keys of users. Consequently, the server's response to the user's request is encrypted not with a password but with the user's public key. To decrypt this response, the user employs their private key, eliminating the need for storing passwords. In essence, the user relies on a key pair—public and private—rather than a password, and the authentication server utilizes the public key for encryption in the initial step of the authentication process. This paradigm shift represents a substantial advancement in security and authentication within the Kerberos framework.



(a) TGT request

(b) TGT request with PKINIT

Figure 3.14: Client authentication

SSO (Single Sign-On)

Kerberos is an example of a more general concept of *SSO* (Single Sign-On), where users possess a single "credential" to authenticate themselves and gain access to various services in the system.

- **Fictitious SSO:**
  - Client for automatic password synchronization/management (alias "password wallet").
  - Specific for some applications only.
- **Integral SSO:**
  - Multi-application authentication techniques (e.g., asymmetric CRA, Kerberos), likely requiring a change in the applications.
  - Multi-domain SSO (e.g., with SAML tokens, that generalize Kerberos tickets).

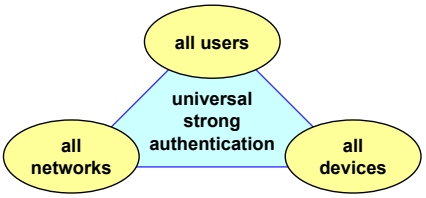


Figure 3.15: OATH

3.5.6 Authentication interoperability: OATH

As mentioned, companies that manage numerous servers aim to implement a unified authentication system for all their relying parties, namely the application servers. However, this implies the ability to purchase a verifier and use it with devices created by different companies. In the past, achieving such interoperability was challenging. For instance, when acquiring RSA SecurID devices, it was necessary to also procure the ACE client and ACE server from RSA. Moreover, RSA did not disclose the hash algorithm used in generating the token code.

To address this challenge, an initiative called OATH was introduced. The primary goal of OATH is to establish interoperability among authentication systems based on One-Time Passwords (OTPs) and symmetric or asymmetric challenges. This is achieved through the development of standards for the client-server protocol and the data format on the client, aiming to realize universal strong authentication.

So far, OATH has provided the following specifications:

- **HOTP** (HMAC OTP, RFC-4226)
- **TOTP** (Time-based OTP, RFC-6238)
- **OATH Challenge-Response Protocol** (OCRA, RFC-6287)
- **Portable Symmetric Key Container** (PSKC, RFC-6030): When using OTP, the shared secret must be protected. This solution offers an XML-based key container for transporting symmetric keys and key-related metadata.
- **Dynamic Symmetric Key Provisioning Protocol** (DSKPP, RFC-6063): It is a client-server protocol for provisioning symmetric keys to a crypto-engine by a key-provisioning server.

HOTP

Let us define:

- K: shared secret key (between Verifier and Subscriber);
- C: counter (monotonic positive integer number);
- h: cryptographic hash function (by default is SHA1);

- sel: function to select 4 bytes out of a long byte string.

The HMAC-based OTP is computed in the following way:

$$\text{HOTP}(K, C) = \text{sel}(\text{HMAC} - h(K, C)) \;\&\&\; \texttt{0x7FFFFFFF}$$

where the mask `0x7FFFFFFF` is used to set $MSB = 0$ (to avoid problems if the result is interpreted as a signed integer). Then to generate an N-digit (6-8) access code:

$$\text{HOTP code} = \text{HOTP}(K, C) \mod 10^N$$

In this way, we implement an event-based OTP.

TOTP

To create a Time-based OTP (TOTP), the process is similar to HOTP, but the counter C is the number of intervals TS elapsed since a fixed origin T_0. In formulas:

$$C = \frac{(T - T_0)}{TS}$$

Where, in the default (RFC-6238), T_0 is the Unix epoch (1/1/1970), T is `unixtime(now)` seconds elapsed since the Unix epoch, TS is equal to 30 seconds, h is `SHA1` (but may use SHA-256 or SHA-512), and N is equal to 6.

The crucial point is that with the same base functions, *it is possible to implement both TOTP and EOTP.*

Moreover, this standard is essential because Google provides free open-source implementations of both HOTP and TOTP, for both the client and the server. In **Google authenticator**, K is provided base-32 encoded (most often as a QR code), C is provided as `uint_64`, TS is equal to 30 seconds, N is equal to 6, and the function `sel`(X) is such that: an offset with the 4 least-significant-bits of X is considered, then it returns X[`offset...offset + 3`]. If the generated code contains less than 6 digits, then it is left padded with zeroes (e.g., 123 $\rightarrow$ 000123). The availability of this code from Google has significantly contributed to the widespread usage of this standard.

FIDO

One of the most recent attempts to increase the security of authentication is the standard named **FIDO** (*Fast IDentity Online*). It is an industry standard of the FIDO Alliance for:

- biometric authentication (referred to as *passwordless user experience* in FIDO terminology);
- 2-factor authentication (referred to as *2nd factor user experience* in FIDO terminology).

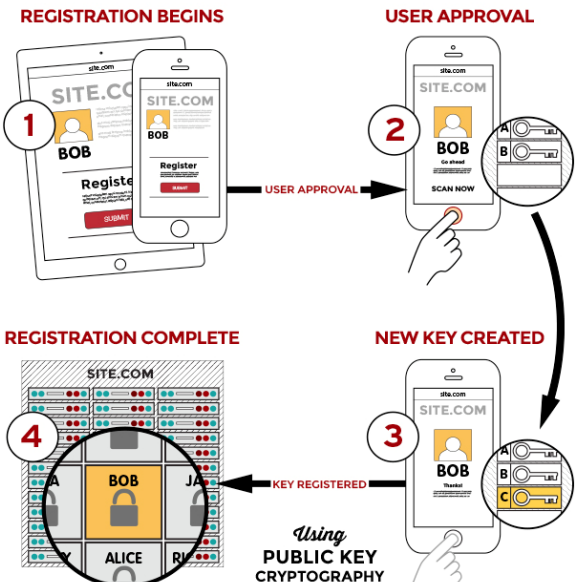
So, the focus of FIDO is to simplify the user experience in authentication, allowing them to use a biometric system and more than one factor. The main concept of FIDO is not to invent another device but to let the user exploit any personal device capable of asymmetric cryptography (e.g., laptop or smartphone). Inside FIDO, it will be used:

- for responding to an asymmetric challenge;
- for the digital signature of texts.

The FIDO protocols are designed from the ground up to protect user privacy. The protocols do not provide information that can be used by different online services to collaborate and track a user across services. Biometric information, if used, never leaves the user's device.

FIDO registration Differently from other systems, in which registration is usually performed by a new classical username and password creation, or by reusing the user's Facebook or Google identity, FIDO uses the user's device with asymmetric cryptography. When registering with FIDO:

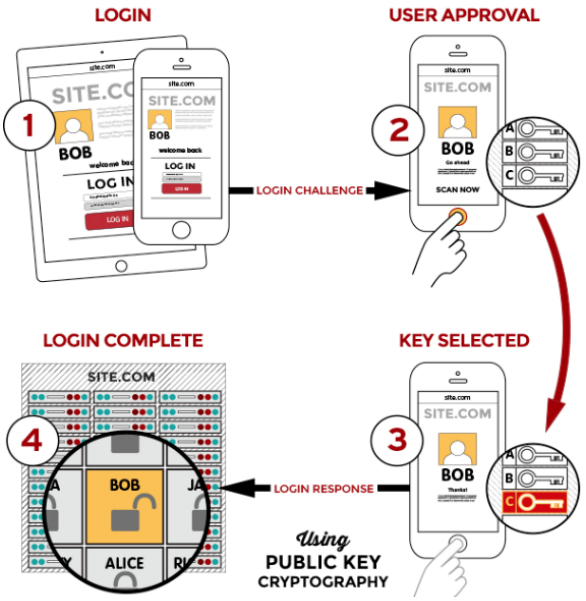
1. User is prompted to choose an available FIDO authenticator that matches the online service's acceptance policy.
2. User unlocks the FIDO authenticator using a fingerprint reader, a button on a second-factor device, securely-entered PIN or other method.
3. User's device creates a new public/private key pair unique for the local device, online service, and user's account.
4. Public key is sent to the online service and associated with the user's account. The private key and any information about the local authentication method (such as biometric measurements or templates) never leave the local device.



Please note that the real user's identity can be fictitious! However, the real identity of the user is not important, only the key is: the private key is stored inside the device and the public key is sent to the web server and associated with the name decided for authentication. There is the use of asymmetric cryptography but no X509 certificates (it is not needed), because the public key is stored at the server, associated with a name.

FIDO login After signing up, there are four steps to be performed to log in:

1. Online service challenges the user to log in with a previously registered device that matches the service's acceptance policy: in this phase, the username and (reusable) password are provided by the user;
2. User unlocks the FIDO authenticator using the same method as at Registration time.
3. Device uses the user's account identifie to select the correct key and sign the service's challenge: this identifier is retrieved by considering the pair username-password;
4. Client device sends the signed challenge back to the service, which verifies it with the stored public key and logs in the user.



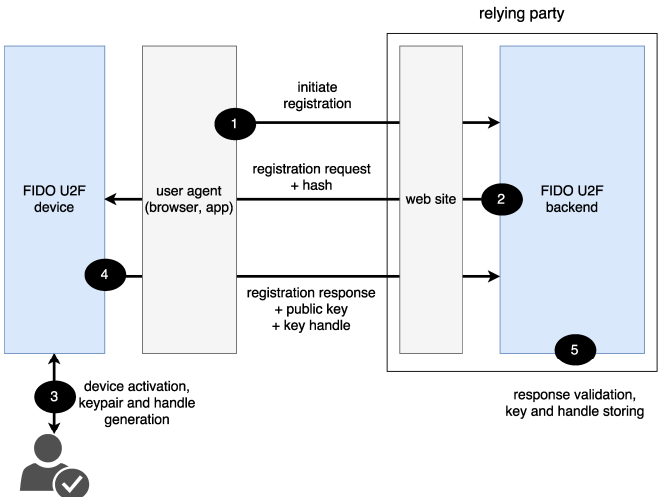


Figure 3.16: FIDO U2F registration

FIDO U2F registration In the registration phase, typically, the work starts with the browser or with an application that typically communicates with the server. The user registration phase means that the website on which the users try to sign up **must** have a FIDO U2F backend, which is something that can manage the FIDO protocol.

When a registration request arrives, the backend will send a registration request to the device, including a hash (like a nonce, to protect the integrity of transmission). The browser/app will pass it to the FIDO U2F device (which can be software or hardware). Then the user must explicitly activate the device, authorize the keypair generation and the handle generation, which is an identifier for this specific key (typically the hash of the public key).

The registration response is then sent along with the public key and the key handle. These items are validated in the final step (5), and the key-handle pair is stored.

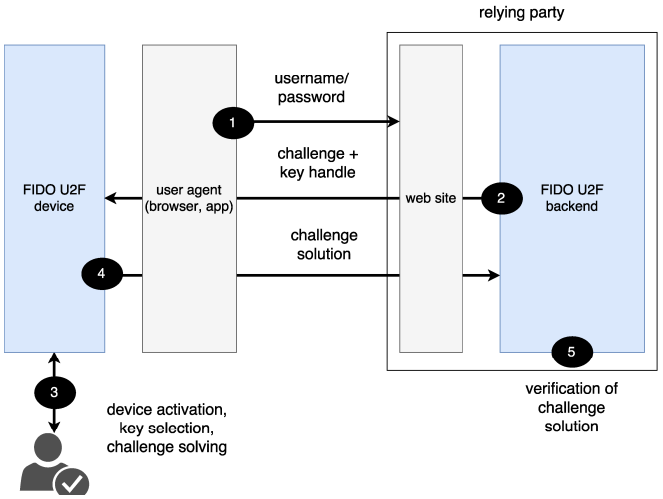


Figure 3.17: FIDO U2F authentication

FIDO U2F authentication Authentication typically begins with the submission of the username and reusable password to the FIDO U2F backend. The backend initiates a challenge that must be addressed using the key associated with the provided username. Upon receiving the challenge, the user activates the device once again, selects the key (based on the key handle submitted by the server), and resolves the challenge. Subsequently, the solved challenge is sent to the server for verification.

FIDO: Other Characteristics & Security Analysis FIDO uses:

- **Biometric techniques**: local authentication method to enable the FIDO keys stored only on the user device;
- **Secure transactions**: digital signature of a transaction text (in addition to the response to the challenge) with the same key used for authentication. This is done to avoid MITM attacks;
- FIDO backend (or server): to enable the use of FIDO on an application server;
- FIDO client: to create and manage credentials FIDO on a user device.

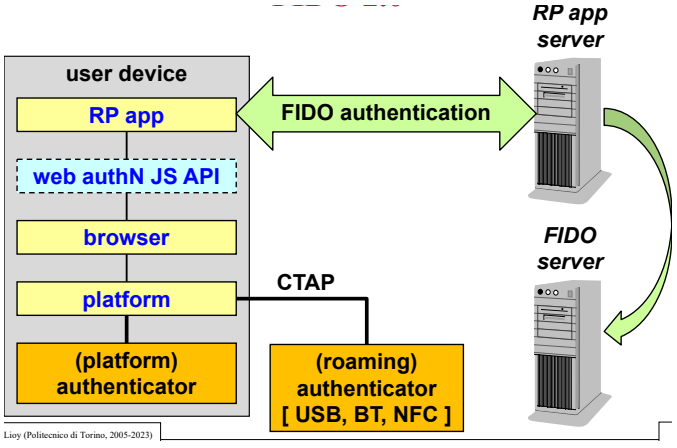
About security and privacy, FIDO provides:

- **Strong authentication** (asymmetric cryptography);
- **No 3rd party in the protocol:** since there is no use of X509 certificates. It's a sort of direct trust between user and web server;
- **No secrets on the server side**: not exposed to any confidentiality attack. Of course, since it stores public keys and identifiers of the users, authentication and integrity for those data is needed;
- **Biometric data** (if used) **never leave user device**;
- **No phishing because authN response cannot be reused**: it is a signature over the transaction text, including the RP identity (which means that the same response cannot be used on another server);
- Since one new keypair is generated at every registration, we obtain **no link-ability among**: different services used by the same user; different accounts owned by the same user.
- There is no limit in private key generated, because **private keys are not stored in the authenticator but recomputed** (generated on-the-fly) as needed based on an **internal secret** and **RP identity**. Using a proper internal function with the secret, it can be possible to use RP identity to compute private key.

FIDO Evolution The evolution of FIDO is as follows:

- Feb 2013: FIDO alliance launched;
- Dec 2014: FIDO v1.0;
- Jun 2015: Bluetooth and NFC as transport for U2F;
- Nov 2015: submission to W3C of the Web API for accessing FIDO credentials;
- Feb 2016: W3C creates the Web Authentication WG to define a client-side API that provides strong authentication functionality to Web Applications, based on the FIDO Web API;
- Nov 2017: FIDO v2.0.

FIDO 2.0 With FIDO 2.0, a new protocol, the **CTAP** (*Client To Authenticator Protocol*), is defined for connecting an external authenticator to the platform. During authentication initiation, the RP application can utilize the `web authN JS API` to access FIDO. The API operates within the browser, on top of a platform (such as Linux, iOS, Android). Two choices are available: **a local authenticator** (e.g., a private key stored in a file on Windows) or an **external device paired with the device using the CTAP protocol**. This protocol operates through USB,



FIDO 2.0

BT, NFC, etc., and keys are always present. This represents a kind of *roaming authenticator* as the device can be used with multiple application devices.

In case of using an internal authenticator, there are cryptographic elements (more or less secure) capable of storing and using asymmetric keys. For example:

- **Packed attestation**: an authenticator with limited resources (e.g., a Secure Element in Android);
- **TPM attestation**: a special chip providing robust security features, capable of generating and using asymmetric keys;
- **Android Key attestation**: an authenticator available from Android Nougat onward;
- **Android SafetyNet attestation**: an authenticator for Android via the SafetyNet API;
- **FIDO U2F attestation**: an authenticator for FIDO U2F using the FIDO-U2F Message Format.

Chapter 4

Security of IP networks

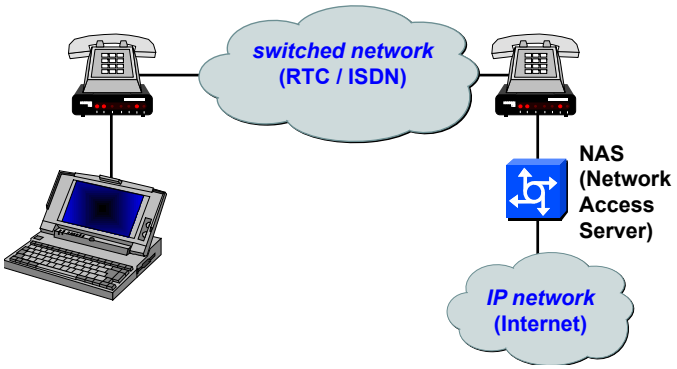


Figure 4.1: Remote access via dial-up lines

The first point regarding the security of IP networks involves controlling who can access the networks. In the past, it was primarily used for residential users who utilized a modem to connect to a telephone line (switched network). This process involved transforming bits into sound and having equivalent equipment on the ISP side, which would accept the telephone call and convert it into network packets. To facilitate this, devices known as **NAS** (*Network Access Server*) were employed. NAS had the responsibility of authenticating users, performing access control, and subsequently providing users with access to the IP network - typically the internet, but in some cases also allowing access to a company's internal network from home. Nowadays, this system is no longer widely used, at least in Western countries, although some countries still rely on it.

Today, it is possible to access the Internet in different ways, which basically depends on the device. For example, a smartphone typically uses technologies such as 3G, 4G, or 5G to connect to the base station, which runs an **authentication protocol** with the **AAA server** to check if the user is authorized for an internet connection. It is also possible to use Wi-Fi to connect to access points, which provide the translation from a wireless to a wired network and can again verify access. Alternatively, there could be a home gateway, which provides access to the Internet using both Ethernet and Wi-Fi (only if properly authenticated). In all these scenarios,

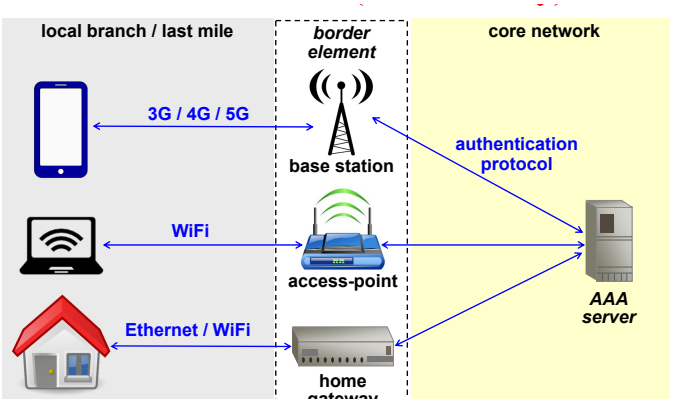


Figure 4.2: Network access (modern way)

authentication is always required before permitting traffic from a specific user. Therefore, there is a difference between the *local branch / last mile*, *border element*, and *the core network*.

4.1 Authentication of PPP channels

There is a need to authenticate a user before enabling network transmission. The authentication process begins when someone attempts to connect, and at this point, the physical layer (Layer 1) for physical transmissions is already available. Since we are working at a logical level, Layer 2 (data layer connectivity) is also accessible.

On top of data layer connectivity, a protocol specific to transporting data is usually running. Typically, this protocol is **PPP** (*Point-to-Point Protocol*), designed to **encapsulate network packets** such as Layer 3 (e.g., IP) and **carry them over a point-to-point link**. This PPP link can be a physical connection like an ISDN line or a telephone network; alternatively, it can be a virtual layer, as is the case when starting from a home gateway with access to ADSL using PPPoE (PPP over Ethernet) to transport packets between the home gateway and the provider.

Moreover, PPP is utilized to carry packets within virtualized Layer 3 connections with a specific and somewhat complex[1] protocol named L2TP (Layer 2 Tunnel Protocol). L2TP is a Layer 2 encapsulated inside UDP/IP (which is Layer 4), which deviates from the normal behaviors of a network.

Regardless, once PPP is enabled, numerous virtual point-to-point connections extend from the device to an access point. PPP activation occurs in three steps:

1. **LCP (Link Control Protocol):** Establishes the ability to transmit data, and can also negotiate authentication protocols and algorithms.
2. **Authentication (optional; PAP, CHAP, or EAP):** Performs user authentication.
3. **L3 encapsulation:** Handles Layer 3 encapsulation via various **NCP**s (Network Control Protocols), such as IPCP (IP Control Protocol).

[1]The professor described it as "horrible"

4.1.1 Authentication of a network access

There are three methods to authenticate network access over PPP:

- **PAP (Password Authentication Protocol):** This is the oldest method; in this case, the user sends the username and password in clear over the PPP channel. If someone is sniffing the channel, they can acquire the password.
- **CHAP (Challenge Handshake Authentication Protocol):** It uses a symmetric challenge-response based on the user's password. In this case, the password cannot be copied, but the channel is not protected. Instead of inventing other protocols tied to a specific authentication mechanism, a generalization has been made by introducing EAP.
- **EAP (Extensible Authentication Protocol):** It is a authentication framework that does not implement any specific method. The authentication method is external; for example, challenge-response, OTP, or TLS can be used.

Nowadays, PAP and CHAP should never be used, while EAP is the most widely adopted method for authenticating network access.

4.1.2 LCP Authentication - Protocol Configuration Option

If the Protocol Configuration Option in LCP Authentication exists, it includes several components:

- **Type (8-bit):** Denotes the option type.
- **Length (8-bit):** Represents the length of the option in bytes.
- **Authentication Protocol (16-bit):** Specifies the protocol identifier.
- **[Algorithm (8-bit)]:** Optional field for algorithm identifier, required when a protocol supports various algorithms.

  For PAP (Password Authentication Protocol):

  - **Type:** 3
  - **Length:** 4
  - **Protocol:** `0xC023`

  For CHAP (Challenge Handshake Authentication Protocol):

  - **Type:** 3
  - **Length:** 5
  - **Protocol:** `0xC223`
  - **Algorithm:** 5 (for MD5)

PAP

PAP, or *Password Authentication Protocol*, is defined in RFC-1334 "PPP Authentication Protocols" (Oct 1992). This RFC also introduces the initial version of CHAP.

In PAP, the user-id and password are transmitted in clear text between the Peer and the Authenticator, posing a significant security risk. Authentication occurs only once when the channel is created, making it a potentially vulnerable method. Due to the clear transmission of sensitive information, PAP is considered very dangerous and is not recommended for secure network communication.

PAP: 2-way Handshake Protocol PAP employs a 2-way handshake protocol involving communication between the Peer and the Authenticator.

- ($Peer \rightarrow Authenticator$) `Authenticate-Request` ($code = 1$)
  - Code (8-bit) + Identifier (8-bit) + Length (16-bit)
  - Peer-ID Length (8-bit) + Peer-ID (0-255B)
  - Passwd-Length (8-bit) + Password (0-255B)
- ($Authenticator \rightarrow Peer$) `Authenticate-Response` ($code = 2, 3$)
  - Code (8-bit) + Identifier (8-bit) + Length (16-bit)
  - Msg-Length (8-bit) + Message (0-255B)
  - Code=2 (ACK), Code=3 (NAK)

An identifier is essential for correlating the `Authenticate-Request` with its corresponding `Authenticate-Response`. Given the potential loss of either loss of either request or response, it becomes imperative for the Authenticator to accommodate multiple requests. Therefore, to mitigate the risk of lost messages, the Authenticator **MUST** allow for the submission of multiple `Authenticate-Request` or `Authenticate-Response` messages. This identifier is also pivotal in preventing replay attacks. Without it, an adversary could intercept and replay the message, potentially granting unauthorized access.

CHAP

CHAP, or *Challenge Handshake Authentication Protocol*, is defined in RFC-1994 "PPP Challenge Handshake Authentication Protocol (CHAP)" (Aug 1996). It introduces a symmetric challenge (password-based) authentication mechanism.

In CHAP, the initial challenge is compulsory and occurs at channel creation. The authentication request can optionally be repeated, with a different challenge, during transmission. The decision to repeat the authentication request is taken by the Network Access Server (NAS). It's important to note that the challenge MUST be a nonce.

For systems supporting both PAP and CHAP, the Authenticators must offer CHAP as the preferred authentication method.

CHAP: 3-way Handshake Protocol CHAP employs a 3-way handshake protocol involving communication between the Authenticator and the Peer. After the link is established:

- (*Authenticator* → *Peer*) `Challenge` (*code* = 1)
  - Code (8-bit) + Identifier (8-bit) + Length (16-bit)
  - Challenge-Size (8-bit) + Challenge-Value (0-255B)
- (*Peer* → *Authenticator*) `Response` (*code* = 2)
  - Code (8-bit) + Identifier (8-bit) + Length (16-bit)
  - Response-Size (8-bit) + Response-Value (0-255B)
- (*Authenticator* → *Peer*) `Result` (*code* = 3 Success, 4 Failure)
  - Code (8-bit) + Identifier (8-bit) + Length (16-bit)

Response-Value is calculated using `md5(Identifier || pwd || Challenge-Value)` (in the version specified in 1996). The server checks the response by comparing it with its own calculation of the expected hash value. If the values match, the authentication is acknowledged; otherwise, the connection is usually terminated.

The identifier is crucial for correlating the Request and Response. In case of lost `Challenge` or `Response`, the Authenticator **MUST** resend the Challenge until the retry limit is reached.

Packet Loss in PPP Implementation One interesting point to consider is the idea that challenges or responses could be lost in a PPP (point-to-point protocol). You might wonder why, especially when we have a direct connection between two peers using an Ethernet cable or Wi-Fi. Usually, in such direct connections, we expect very little or no loss of information.

The confusion arises due to the varied ways PPP can be used. We mentioned earlier that PPP can operate on different types of transport, including a virtual setup within UDP. Here's the catch: UDP, unlike other more reliable protocols, doesn't ensure that your data reaches its destination every time. Moreover, UDP is built on top of IP, which also doesn't guarantee that your information will be reliably delivered.

This becomes apparent when we consider how PPP packets are implemented in real-world situations. In some cases, instead of sticking to the logical layering (PPP being at layer 2), PPP packets may be placed inside layer 4 due to certain implementation choices. This might seem like a strange decision, but it happens. As a result, even though you might think a direct point-to-point connection is rock-solid, these implementation choices could lead to some data loss. So, when designing such protocols, it's crucial to account for all possible scenarios, even the ones that might seem unlikely at first.

MS-CHAP MS-CHAP, or Microsoft PPP CHAP Extensions, is a set of protocols developed by Microsoft to enhance the functionality of the Challenge Handshake Authentication Protocol (CHAP) in PPP connections[2].

[2] "The usual approach from Microsoft, in which they take something standard and make it non-standard".

- **MS-CHAPv1:**
  - RFC 2433 "Microsoft PPP CHAP Extensions" (October 1998).
  - Initially included but later discontinued by Microsoft starting with Windows Vista.
- **MS-CHAPv2:**
  - RFC 2759 "Microsoft PPP CHAP Extensions, v2" (January 2000).
  - Continued the evolution of MS-CHAP, dropped by Microsoft starting with Windows 11 22H2.

LCP negotiates the CHAP algorithm, with `0x80` for MS-CHAPv1 and `0x81` for MS-CHAPv2, using option 3 (Authentication Protocol).

MS-CHAP is a Microsoft-specific implementation of CHAP concepts. Despite its origin, MS-CHAP is supported by many other vendors, including CISCO.

MS-CHAP: Extensions over CHAP MS-CHAP extends the principles of CHAP but operates as a distinct protocol with unique features.

- **Common Features (v1 and v2):**
  - Authenticator-controlled password change.
  - Authenticator-controlled authentication retry.
  - Specific failure codes.
- **MS-CHAPv2 Mutual Authentication:**
  - Achieved by piggybacking a peer challenge on the Response packet.
  - Includes an authenticator response on the Success packet.

In order to implement this protocol, each peer must know the plaintext password or an MD4 hash of the password. Note: This approach is not compatible with most password storage formats.

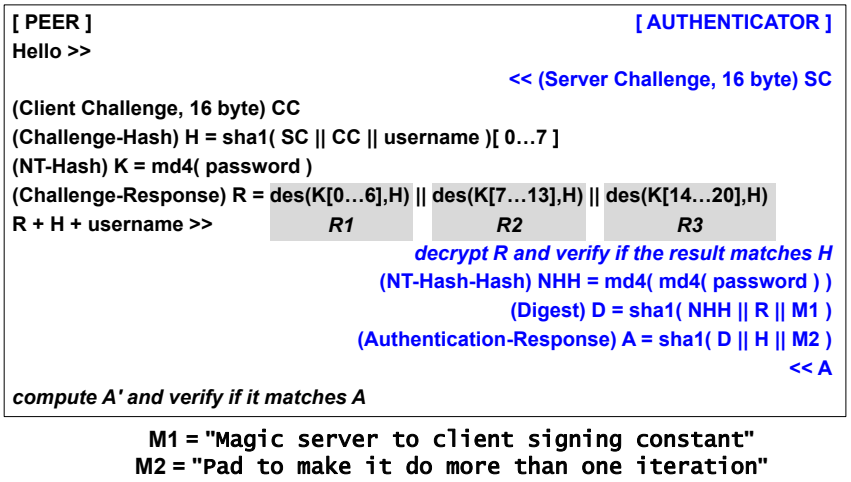


Figure 4.3: The MS-CHAPv2 protocol

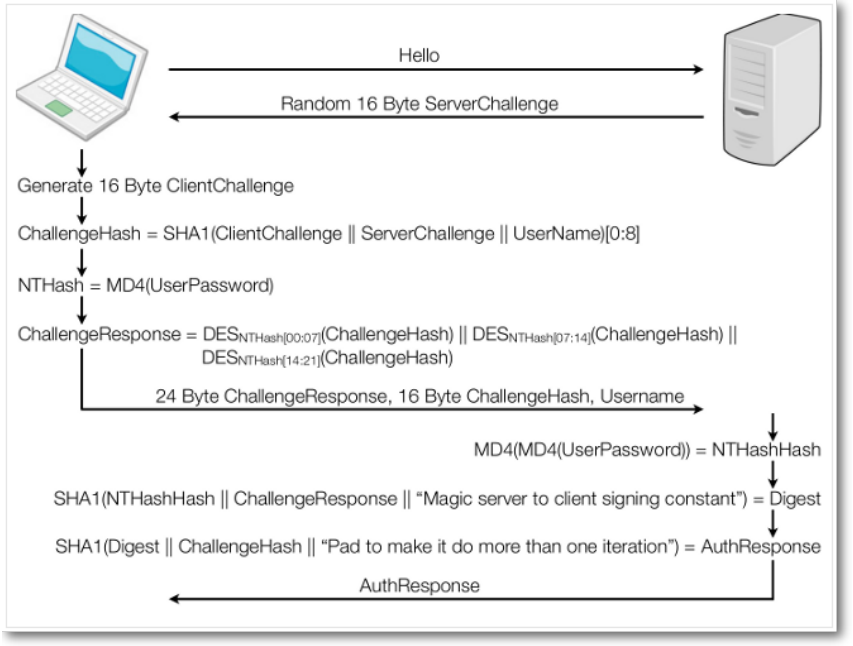


Figure 4.4: MS-CHAPv2 - Another frame of reference. Please consider the professor's slide. Taken from
`https://web.archive.org/web/20160316174007/https://www.cloudcracker.com/blog/2012/07/29/cracking-ms-chap-v2/`

MS-CHAPv2: an attack MS-CHAPv2, once deemed a secure authentication protocol, is susceptible to a specific attack exploiting a known ciphertext-plaintext pair denoted as R and

H. The primary objective is to decipher the three keys, namely K_{0-6}, K_{7-13}, and K_{14-20}. Directly employing a brute-force approach on the password is considered impractical due to the significant time involved. Alternatively, a brute-force attack on the keys poses a challenge, requiring approximately $2^{56} + 2^{56} + 2^{56}$ operations.

However, it's crucial to note that K is only 128 bits (MD4 output), i.e., 16 bytes, and K_{14-20} has only two bytes (K_{14-15}) padded with zeros. To find K_{14-20}, 2^{16} operations are needed. The process involves 2^{56} operations to find K_{0-6} and K_{7-13}, followed by a comparison with $R1$ and $R2$. Utilizing a divide-and-conquer strategy reduces the effort to approximately 2^{56} operations (less than 23 hours with DES FPGA).


```
keyOne = NULL;
keyTwo = NULL;

for (int i=0;i<2^56;i++) {
  result = DES_key[i](plaintext);

  if (result == ciphertext1)
    keyOne = result;
  else if (result == ciphertext2)
    keyTwo = result;
}
```

In conclusion, MS-CHAPv2 should NEVER be used anymore and has been officially deprecated, including its removal in Windows 11 22H2.

EAP

EAP (*Extensible Authentication Protocol*) is the PPP authentication mechanism defined in RFC-3748, providing a **flexible Layer 2 (L2) authentication framework**. This L2 authentication occurs before accessing the internet, which operates at Layer 3 (L3). EAP supports various predefined authentication mechanisms, such as *MD5-challenge* (symmetric and akin to CHAP), *generic OTP*, and *generic token card*. Additional mechanisms, such as RFC-2716 "PPP EAP TLS authentication protocol" and RFC-3579 "RADIUS support for EAP," have been incorporated.

As EAP performs authentication before reaching L3, it requires its encapsulation protocol for transporting data, including usernames, challenges, or responses, over L2.

- EAP introduces a small L3 protocol exclusively for its use, offering **independence from IP** and compatibility with diverse link layers (e.g., old PPP and 802.x).
- Due to the absence of L3, EAP **provides ACK/NAK** for packets but lacks windowing (as seen in TCP). EAP assumes that packets won't be reordered, a guarantee provided by

PPP, but if EAP is utilized over virtual channels like UDP and raw IP, datagrams may arrive out of order, potentially disrupting EAP functionality.

- **Retransmission** is essential to ensure packet delivery, with a typical limit of 3 to 5 retransmission attempts; authentication fails if this limit is exceeded.
- EAP **does not handle fragmentation**, dependent on the MTU of the underlying L2 network. EAP methods must manage payloads exceeding the minimum EAP MTU.

When authentication fails in EAP, it does not necessarily indicate a failure in the authentication process; rather, it could be attributed to a network problem. When troubleshooting EAP, the expertise of a network specialist may be required to identify and address any issues causing the failure.

In EAP, the assumption is that the link is not inherently physically secure, requiring each authentication method to ensure its security. Some EAP methods include:

- **EAP-TLS (RFC-5216):**
- **EAP-MD5 (RFC-3748):** Symmetric challenge-response providing only EAP peer authentication without mutual authentication.
- **EAP-TTLS:** TLS tunneling that allows the operation of any method protected inside a secure TLS channel.
- **EAP-SRP (Secure Remote Password)**
- **GSS-API (includes Kerberos)**
- **AKA-SIM (RFC-4186, RFC-4187):** Subscriber Identity Module, the system used in mobile networks.

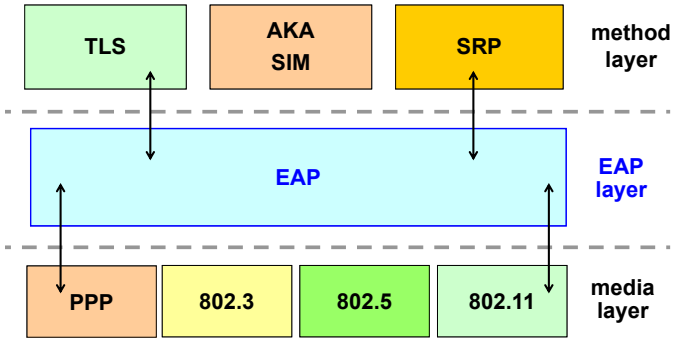


Figure 4.5: EAP - architecture

In Figure 4.5, the general architecture of EAP is depicted. The lower part represents various L2 channels supported by EAP, including PPP, 802.3 (Ethernet), 802.5 (Token Ring), and

802.11 (Wi-Fi). EAP extends its authentication methods, such as TLS, AKA-SIM, and SRP authentication, to these specific networks independently of the L2 layer.

4.2 Authentication for network access

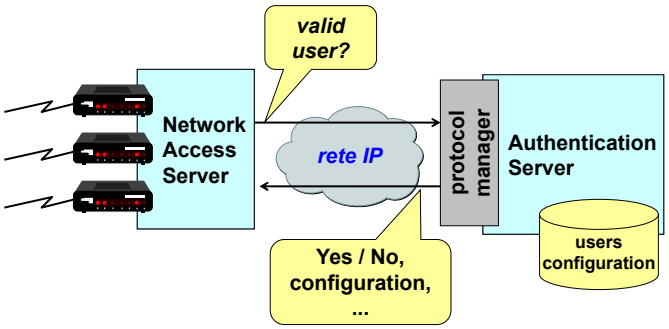


Figure 4.6: Authentication for network access

Authentication for network access operates as illustrated in the architecture in Figure 4.6. On the left, various communication links (modems, access points, or ADSL/Fiber) terminate at a device hosted by the ISP. These devices, designed to connect multiple users, are controlled by a NAS (Network Access Server), which receives requests from clients and determines the validity of the user. The NAS employs a protocol on the backend IP network local to the NAS and subsequently communicates with the centralized authentication server. This approach is necessary as ISPs have multiple points of presence with numerous NAS devices that must share consistent user information.

The authentication server possesses access to a database containing user credentials and configuration details for each user, based on the contract between the user and the ISP. The Authentication Server responds to the NAS with the user's authentication status (valid/invalid) and the configuration that the NAS must enforce on the user's traffic.

AAA NAS manufacturers claim that security needs three functions briefly named as AAA:

- **Authentication:** entity's identity is authenticated based on credentials (e.g., password, OTP);
- **Authorization:** determining whether an entity is authorized to perform a given activity or gain access to the resources or services;
- **Accounting:** tracking network resource usage for audit support, capacity analysis, or cost billing.

The AS performs exactly these three functions talking with one or more NAS via one or more protocols.

Network Authentication Protocols Basically, there are three protocols that AS (Authentication Server) and NAS can use to communicate:

- **RADIUS:** It is the de-facto standard and the most widely used one, with a feature that allows it to act as a proxy towards other authentication systems. It can serve as both an authentication system and use external AS.
- **DIAMETER:** This protocol is the evolution of RADIUS, emphasizing roaming among different ISPs. Since it is more modern, it pays better attention to security.
- **TACACS+ (TACACS, XTACACS):** A competitor of RADIUS, technically superior, but achieved lower acceptance due to being a proprietary solution implemented only by Cisco with no public specification.

4.2.1 RADIUS

RADIUS stands for **Remote Authentication Dial-In User Service**. It is a legacy protocol developed nearly 30 years ago, initially designed for Dial-In scenarios when users connected to an ISP using modems. Over time, RADIUS has evolved and **now supports authentication, authorization, and accounting (AAA)** to control network access for various types of ports:

- **Physical ports** (analogical, ISDN, IEEE 802): RADIUS can be utilized for access control on Ethernet networks as well.
- **Virtual ports** (tunnel, wireless access): It enables centralized management of a network of access points.

RADIUS, as a concept, implements **centralized administration and accounting** to store information about resource usage. It operates as a **client-server protocol** *between the NAS and AS*, utilizing `port 1812/UDP` for *authentication* and `port 1813/UDP` for *accounting*. Since UDP is unreliable, each transmission of a RADIUS packet is subject to timeout. If no ACK is received after the *timeout*, the same packet is *retransmitted*, with a maximum number of attempts before declaring communication impossible. RADIUS supports architectures with a main server and numerous *secondary servers*, enhancing system performance, and resilience (also against DoS attacks).

- RFC-2865 (Protocol): Specifies the RADIUS protocol for remote authentication and accounting.
- RFC-2866 (Accounting): Defines additional attributes and guidelines for RADIUS accounting.
- RFC-2867/2868 (Tunnel Accounting and Attributes): Describes extensions for handling tunnel attributes and accounting in RADIUS.
- RFC-2869 (Extensions): Provides extensions to RADIUS to support additional attributes.

- RFC-3579 (RADIUS Support for EAP): Outlines RADIUS support for the Extensible Authentication Protocol (EAP).
- RFC-3580 (Guidelines for 802.1X with RADIUS): Presents guidelines for using RADIUS with the IEEE 802.1X standard.

From the list above it is possible to see that from the basic protocol there have been a lot of extensions (also the EAP support) and in particular it supports also 802.1X (Chapter 4.2.2) which is a network access control security architecture.

RADIUS proxy

The **RADIUS server** may act as a **proxy** towards other authentication servers. In the depicted scenario (Figure 4.7), there are two NAS on the left, each sending an access request from users. RADIUS consults its *local RADIUS DB* on the right and checks if, for example, "Barbara" is a valid registered user. If it receives an access request, perhaps from another NAS, in the form of an email address (although it is not an email address), such as alice@WIN.polito.it, it indicates that the user Alice is not registered in the local RADIUS DB. Instead, Alice is a user defined in the security domain WIN.polito.it to which the RADIUS server is associated somehow.

This implies that **RADIUS will act as a proxy for the authentication part** and redirect the request to the Windows domain controller. The authorization/accounting could then be managed locally by the RADIUS server. RADIUS can also be associated with another domain, such as a UNIX NIS server.

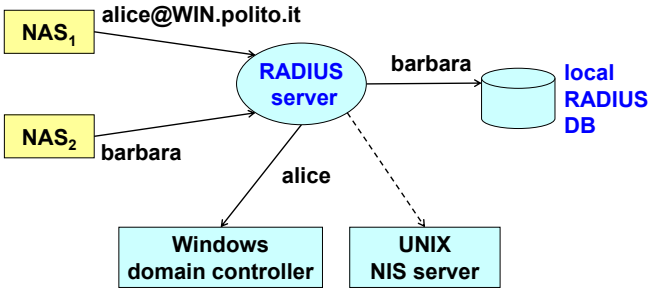


Figure 4.7: Radius proxy

RADIUS security functionalities

RADIUS requires security functionalities due to various potential threats:

- **Sniffing NAS Requests (if contains passwords):**
  This poses a *confidentiality* problem, as sniffing a request containing a password in clear text could lead to unauthorized access. Even in scenarios where passwords are not sent in clear text (e.g., OTP systems), a privacy concern arises, as sniffing the traffic could reveal

user actions without revealing the actual password. There are no issues with sniffing the response, as it only indicates the validity of the request.

- **Fake AS Response (to block valid or allow invalid user):**
  Attackers could exploit the UDP nature of RADIUS to provide faster responses than the legitimate server. The first received response is considered valid, allowing for potential denial-of-service (DoS) attacks to block valid users or provide positive responses to invalid ones. Authentication of responses is crucial in such cases.

- **Changing AS Response (Y $\rightarrow$ N or N $\rightarrow$ Y):** Unauthorized modification of responses from valid to invalid or vice versa is a possibility. Authentication and integrity checks for responses are necessary to mitigate this type of attack.

- **Replay of AS Response (if not properly tied to NAS req):**
  Replay attacks could occur if responses are not properly tied to specific requests. If a response is generic (e.g., only "valid" or "invalid"), attackers could replay a valid response to another user. To prevent this, responses should contain user identification (e.g., "Antonio Lioy, who connected at XX:XX time, is valid").

- **Passwords Enumeration (from fake NAS):**
  If an attacker gains access to the back-end network between the NAS and RADIUS server, they might create a fake NAS and send requests to the RADIUS server to enumerate passwords. Authentication from NAS requests is required to mitigate this risk.

- **DoS (many NAS requests from fake NAS):**
  An attacker with access to the back-end network could flood the RADIUS server with numerous requests, rendering it unavailable. NAS are configured with a list of various RADIUS servers, and if a response delay occurs, the NAS assumes the server is busy and switches to the next one. The system's resistance to this attack is proportional to the number of secondary servers configured.

RADIUS characteristics

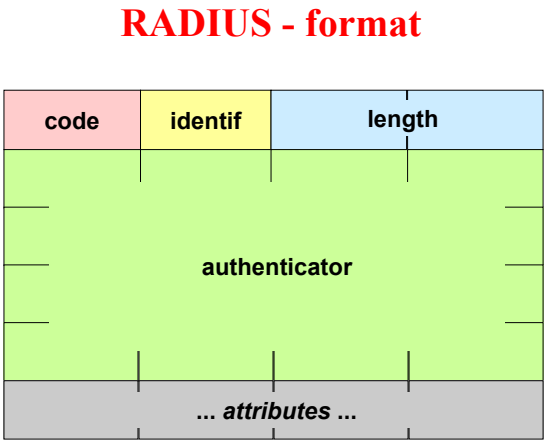
For **data protection**, RADIUS employs packet integrity and authentication via **keyed-MD5**:

- The key is a shared secret between the NAS and the RADIUS Server, ensuring that inserting a fake NAS server into the network will result in the rejection of its requests.

- In cases where packets contain a password (e.g., if a user decides to use PAP and the password is sent in clear), the password is transmitted in an "encrypted" manner (not true encryption, but rather obfuscated using MD5, which is a digest algorithm, not an encryption algorithm): password $\oplus$ md5(key + authenticator). This is padded with NULL bytes until a multiple of 128 bits is reached.

RADIUS supports various authentication methods (PAP, CHAP, token-card, and EAP). Cisco provides a free server for CryptoCard, and others also support SecurID. Importantly,

RADIUS is an **extensible protocol** because each packet carries attributes described in TLV form `(attribute type - length - value)`. This allows the introduction of new types without breaking compatibility.



The format of a RADIUS packet includes the following components:

- `Code` (8 bits)
- `Identifier` (8 bits)
- `Length` (16 bits)
- `Authenticator` (128 bits)
- `TLV` (Type-Length-Value) list of attributes

RADIUS supports various packet types, and some of them include:

- `ACCESS-REQUEST:` Contains access credentials (e.g., username and password).
- `ACCESS-REJECT:` Access is denied (e.g., due to bad username/password).
- `ACCESS-CHALLENGE:` Requests additional information from the user (e.g., PIN, token code, secondary password).
- `ACCESS-ACCEPT (parameters):` Access is granted, and some network parameters are given (e.g., IP address, netmask, MTU, host, port, ...).

RADIUS - authenticator Inside packets, the `authenticator` serves a dual purpose:

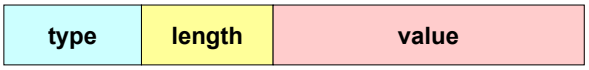
1. in the *server reply*, it provides *authentication* and *protection from replay*;
2. while also *masking the password*.

In `Access-Request`, it is named Request Authenticator and is 16 bytes randomly generated by the NAS. In `Server Responses`, besides being named Response Authenticator, it is not random but computed via a keyed digest:

```
MD5(code || ID || length || RequestAuth || attributes || secret)
```

Note that the presence of `RequestAuth` in the computation links a response to a request, preventing replay attacks.

Attributes in RADIUS Packets Attributes in RADIUS packets follow the TLV (Type-Length-Value) form, and some of them are:



- **Type = 1 (User-Name):**
  The value could be a text *string*, *network access identifier* (NAI), or *Distinguished Name* (DN).
- **Type = 2 (User-Password):**
  The value is the `password` $\oplus$ `md5(key || RequestAuth)`.
- **Type = 3 (Chap-Password):**
  The value is the user CHAP response (128 bits).
- **Type = 60 (CHAP-Challenge):**
  The value is the challenge from the NAS to the user.

NAI in Radius The *Network Access Identifier* (**NAI**) serves to distinguish whether the request is from a local user or belongs to a different security domain. The NAI takes the form of a username and is optionally followed by a security realm [@realm]. According to rules, all devices must support NAIs up to 72 bytes long. The exact syntax for the username and realm is detailed in the RFC, allowing only ASCII characters < 128. All ASCII characters are permitted, including non-printable characters. The username corresponds to the one used in the PPP authentication phase, which may differ from the application username used when opening the connection to the layer.

Example - CHAP + RADIUS

CHAP is utilized for authentication, and RADIUS is employed to verify the authentication. In the scenario, a *user* is on the left, the *NAS* is in the middle, and the *RADIUS* server is on the right.

When a user connects to the system, the NAS sends a CHAP packet containing a `challenge request`. The client enters the password and provides the `challenge response`. It is important to note that the NAS does not possess the password and cannot verify if the response is valid. Consequently, the NAS creates a `RADIUS Access Request` packet with all relevant information: `CHAP-Username` is the one provided by the user, `CHAP-Challenge` is the challenge that the NAS sent to the user, and `CHAP-Password` is the response to the challenge. With this information, the RADIUS Server can verify if the response to the challenge is valid. Assuming the response is valid, the RADIUS Server sends a response, `RADIUS Access Accept`, with network parameters for the specific user. This acceptance is then translated to CHAP in the form of a `CHAP Success` packet, enabling Layer 3 (e.g., IPCP). The NAS engages in a dialogue with the user seeking access to the network, transforming information from one protocol to another.

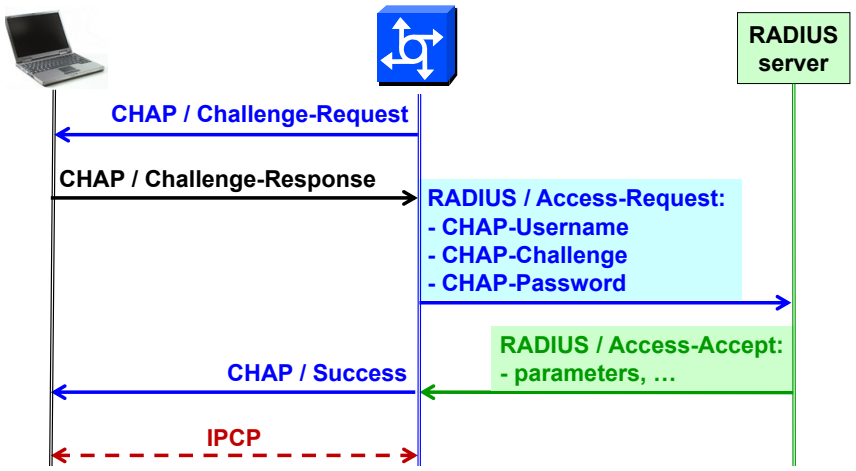


Figure 4.8: CHAP + RADIUS

RADIUS assumes that the system operates within the network access infrastructure of a single provider.

4.2.2 IEEE 802.1x

Radius (Chapter 4.2.1) and Diameter (Chapter **??**) have been employed in defining `IEEE 802.1x`, which constitutes a more comprehensive architecture known as **Port-Based Network Access Control**. This authentication architecture operates at *Layer 2*, verifying the identity and authorization of users before permitting communication. While it could prove useful in a wired network to prevent unauthorized access, its significance becomes paramount in **wireless networks**. Initial implementations were promptly introduced by Windows XP and Cisco wireless access points.

IEEE 802.1x functions as a framework, signifying that it does not enforce a specific authentication solution but supports multiple alternatives. Notably, it serves as a framework for executing **authentication** and **key management**. The latter is crucial for wireless networks, where the radio component of communication is susceptible to eavesdropping. With key management, a shared symmetric key can be established for encrypting traffic and deriving session keys for packet authentication, ensuring integrity and confidentiality. It employs standard algorithms for key derivation (e.g., TLS, SRP, ...) and offers optional security services, including authentication or a combination of authentication and encryption.

802.1x - architecture

On the left, Figure 4.9 illustrates the **semi-public network**, also known as the enterprise edge, housing devices seeking network access—referred to as supplicants. The element situated at the interface between the core network and the edge, called an **authenticator or etherNAS** (which can be an *access point* or a *switch*), allows supplicants to connect in various ways.

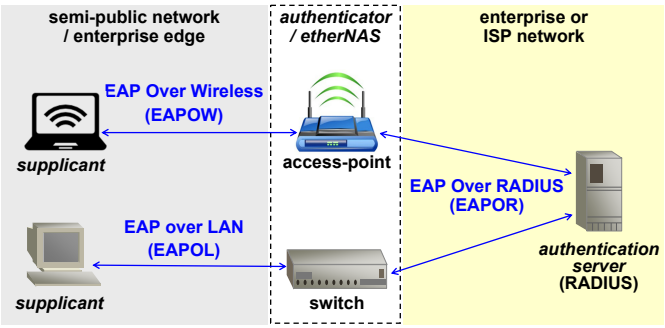


Figure 4.9: 802.1x - architecture

802.1x uses EAP for authentication, named EAP Over Wireless (**EAPOW**) for wireless or *EAP over LAN* (**EAPOL**) for wired networks. When the authenticator receives the EAP request from a supplicant, it verifies its validity by performing packet decapsulation and re-encapsulation in another protocol (Radius). On the backend, *EAP Over Radius* (**EAPOR**) checks the user's validity.

802.1x - advantages

802.1x leverages the application level for the actual implementation of security mechanisms. It facilitates a direct dialogue between the supplicant and the Authentication Server (AS), allowing user devices to communicate directly with the Radius Server. The network card (NIC) and Network Access Server (NAS) function as **"pass-through devices"**, limiting themselves to encapsulation and decapsulation. This is crucial as no changes are required at the NIC and NAS to implement new authentication mechanisms. The responsibility for implementing these mechanisms lies solely with the Radius Server and the supplicant.

This aspect is significant because it ensures that the security architecture remains unchanged even if there are future advancements in authentication techniques. Additionally, the system seamlessly integrates with AAA architectures, providing accounting functionalities.

802.1x - messages

In the provided example in Figure 4.10, a laptop is connected via Ethernet to a switch, where, by default, all Ethernet ports are locked. In 802.1X architecture, the switch acts as a pass-through device, translating EAP messages to and from RADIUS. The authentication process maintains an *end-to-end connection*.

The supplicant initiates the negotiation using `EAPOL-Start`. The switch responds with `EAP-Request/Identity`, and the supplicant, in turn, provides his identity with `EAP-Response/Identity`. This information is relayed to the Radius Server via a `Radius-Access-Request`, with the switch acting as a pass-through element.

Subsequently, the Radius Server responds with a challenge through a `Radius-Access-Challenge` packet, which is translated into an `EAP-Request` packet by the switch. The supplicant, once

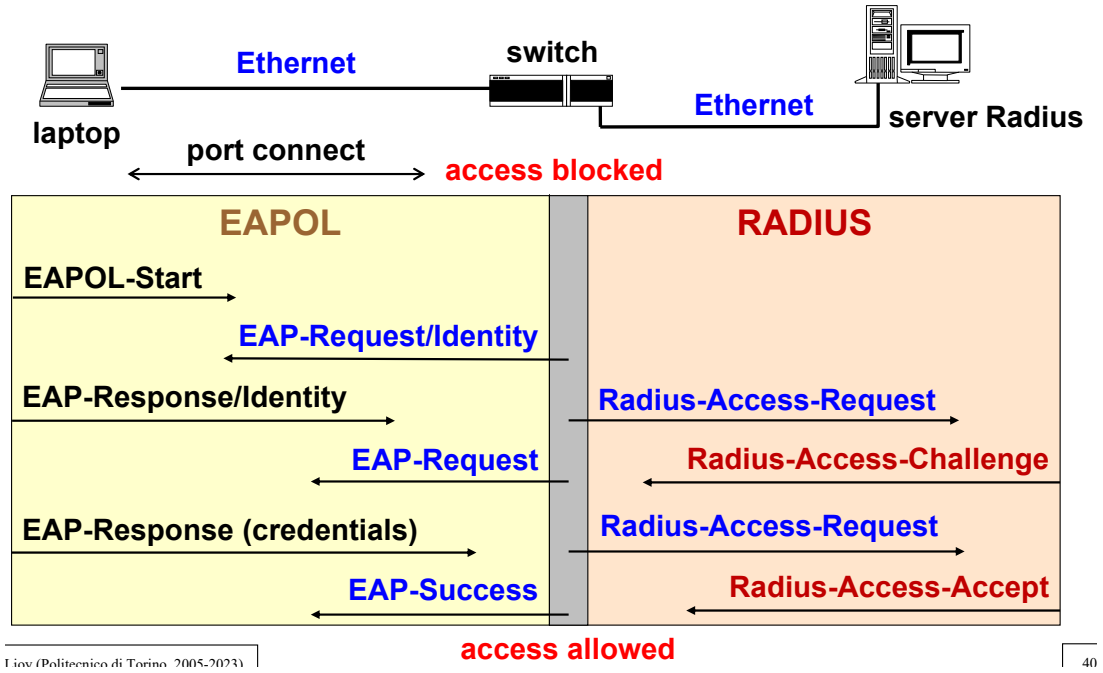


Figure 4.10: 802.1x - messages

again, responds to the challenge with a `EAP-Response (credentials)` packet, leading to another `Radius Access Request`. The Radius Server then authenticates the user with a `Radius-Access-Accept` to the switch, and the exchange concludes with an `EAP-Success` packet sent to the user. The user is now granted access to communicate with Layer 3 and above.

Eduroam example A major example of the usage of Radius is the **Eduroam** network. It is a worldwide network access control network that involves all universities and many research centers around the world. Nearly one year ago, 101 countries were connected, and 18 other countries were under test. Eduroam uses 802.1x plus the Radius federation.

The supplicant can identify an access point in a university named Eduroam and connect to it. The access point is related to the local AS, known as the **visit AS**. Using the Network Access Identifier (NAI) syntax, the supplicant provides its identifier (e.g., `s123456@studenti.polito.it`), and the local Radius Server determines that it must go through the **Eduroam hierarchy** (national, international, etc.) until it reaches the Radius AS where the supplicant has created their credentials (e.g., the PoliTO Radius Server), known as the **Home AS**. Once found, a direct connection is established through an End-to-End (E2E) virtual secure channel (e.g., EAP-TTLS) between the supplicant and the Home AS to perform authentication. The Home AS then provides the answer to the access point, allowing the user to access the network.

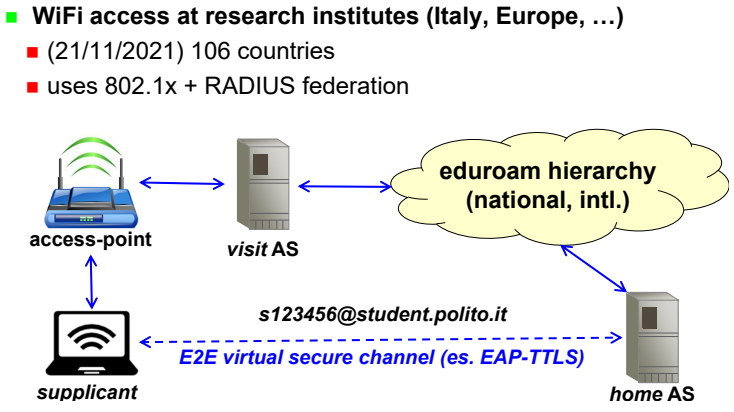
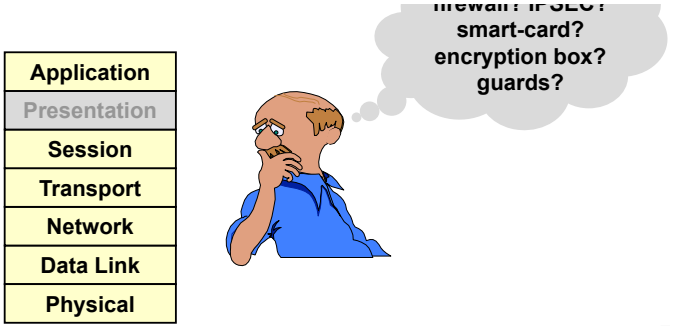


Figure 4.11: Eduroam

4.3 Security implementation in OSI levels



The main question is, "*Which is the best OSI level to implement security?*" with many possibilities and answers. Typically, the "Presentation" layer is the only one in which security measures are not useful.

Unfortunately, there is not a single optimal level. **The higher we go in the stack, the more specific our security functions can be**. For example, at the application level, it is possible to identify the user, commands, and data. Security functions are also independent of the underlying network, but if the functions are placed at the application level only, attacks at lower levels are possible (in particular, DoS attacks are available).

The lower we go in the stack, the more quickly we can "expel" the intruders, but the fewer data are available for the decision (e.g., only the MAC or IP addresses, no user identification, no commands).

In short, there is not an optimal level. You can decide whether to take one of these two risks or make a mixture by placing some security features at lower levels and then focus most of the security at the application level.

4.3.1 DHCP (in)security

When Layer 3 is reached, one of the first things activated is *DHCP* because access to the network is given, and now the user needs to know the network parameters. DHCP is the protocol by which a device can ask to be assigned a valid network address. Unfortunately, the protocol is **non-authenticated** and a **broadcast protocol** that provides a response carrying *IP address, netmask, default gateway, local nameserver,* and *local DNS suffix.*

For this reason, the activation of a fake DHCP server is trivial because the DHCP request is a Layer 2 broadcast frame, and the only thing an attacker needs to do is to stay in the same broadcast domain as the victim and sniff the DHCP request.

Possible attacks from the fake DHCP are:

- **Denial-of-service**:
  - This can be done by providing a wrong network configuration.
- **(Logical) Man-in-the-Middle (MITM)**:

  - A valid IP address is provided to the victim, but it will be assigned a subnet with only the last two bits equal to zero. Therefore, only two addresses are valid: one of them is given to the user, and the other to the attacker as his default gateway. In that way, the attacked machine is isolated in a subnet of its own (logically, not physically). To communicate with all the nodes in the world, the victim has to send everything through the attacker.
  - The replies could reach the original node without passing through the attacker. For this reason, it is possible to activate NAT, and it is possible to also intercept the replies.

- **Malicious name-address translation**:
  - The attacker declares himself as the local name server. Then, whenever the user needs to perform a name-to-address translation, the attacker will provide the wrong address. This is used, for example, for phishing and pharming.

Various manufacturers have tried to provide some security improvement, such as switches (e.g., Cisco) that offer:

- **DHCP Snooping**:
  - Accepts only replies from "trusted ports."
- **IP Guard**:
  - Provides room only for IP addresses obtained from a valid DHCP server (but there is a limit on the number of recognized addresses).

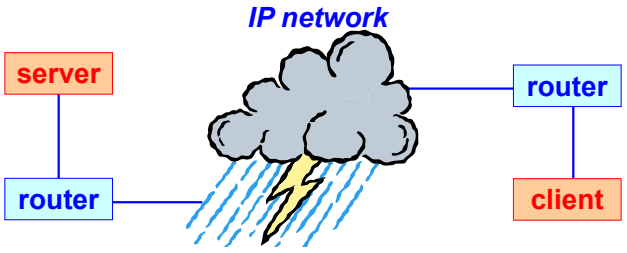
There is also RFC-3118 "Authentication for DHCP messages," which uses HMAC-MD5 to authenticate the messages, but it is rarely adopted because it is hardly configurable. Since HMAC is a symmetric protocol, it is needed to install a key on all the machines that need to use DHCP. This leads to the problem of key distribution. Furthermore, there is a problem of key management because if a key is captured, then it will be reusable, and since it is symmetric, any DHCP client could work as a DHCP server too.

4.3.2 VPN

Security at Network Level (Layer 3)

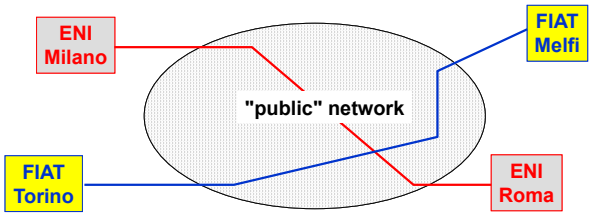
Layer 3, which, given today's widespread use of the Internet, is predominantly IP, provides a crucial layer where meaningful security features can be implemented in a general sense. This is because it is the first layer that offers end-to-end connectivity. It allows for the creation of both **end-to-end protection** for Layer 3 homogeneous networks, such as IP networks, and **Virtual Private Networks (VPNs)**.

If it is possible to provide Layer 3 end-to-end protection, ensuring that data are secured as soon as they exit the server/client, it becomes irrelevant whether routers are properly managed



or if the network being traversed is insecure. This is because the data are protected from the moment they exit the network interface until they reach the final network interface. Therefore, the only potential attacks are those originating from within the client/server. Hence, security at Layer 3 allows us to disregard other attacks at the network level (except for Denial of Service - DoS).

What is a VPN?



A *Virtual Private Network* (VPN) is a technique, employing both hardware and/or software, that allows the creation of a private network while utilizing shared (or otherwise untrusted) channels and transmission devices. Instead of laying down their own cables and managing dedicated infrastructure, companies may prefer to establish a virtual segment of the network.

For instance, one could designate FIAT packets as "blue", allowing them to be exchanged only between blue endpoints. Similarly, packets from ENI could be labeled as "red" and permitted to be exchanged exclusively through red endpoints. While this conceptualization is beneficial, the devil lies in the details. Since it is impossible to visualize packets as blue or red, and the exact mechanism of their switching is uncertain, implementation details become crucial.

There are three techniques for creating a VPN:

- **Private addressing**
- **Protected routing (IP tunnel)**
- **Cryptographic protection of network packets (secure IP tunnel)**

VPN via Private Addresses In this basic VPN implementation, the networks included in the VPN use non-public addresses, making them unreachable from other networks (e.g., private

IANA networks as listed in RFC-1918). Consequently, these networks are considered private, as they do not require authorization, and the packets in this case are not globally routable.

For example, a telecom provider wishing to share its infrastructure with various customers might allocate a distinct class of addresses to each customer. Access control lists (ACLs) on routers could then be implemented to ensure that packets are directed only to the allowed destinations.

However, this protection can be compromised under several circumstances:

- **Guesses or discovers the addresses:** If the addresses are guessed or discovered, there is a risk of unauthorized access. If a class of addresses from another customer is found, an attacker could switch its own address to infiltrate that network.
- **Sniffing packets during transmission:** Since packets lack intrinsic protection, if network traffic can be sniffed, it may be possible to read the content of the packets.
- **Access to communication devices:** If someone gains access to the communication devices, they can read, change, or inject any type of packet.

There is minimal protection for packets, customers, and even for the infrastructure maintainer in this scenario. Consequently, the actual level of security is close to zero, despite the commercial availability of such services.

VPN via Tunnel This solution represents an improvement over the previous one. In this approach, routers encapsulate the entire Layer 3 packet as a payload within another packet, which can be **IP in IP**, **IP over MPLS**, or other techniques. Before encapsulation, border routers implement access control to the VPN via *Access Control Lists* (**ACL**s). For instance, if a network belongs to the 10.1 address range, the destination can only be another network within the 10.1 range.

With this solution, providers gain protection against malicious end-users, as it prevents customers from changing the subnet to which they belong. However, this protection can be circumvented by anyone managing a router or capable of sniffing packets during transmission. For instance, it does not provide protection to customers against attacks originating from within the geographical network (→ protection for providers but not for customers).

If robust protection is desired, alternative techniques need to be considered.

VPN via IP Tunnel Network 1 and Network 2 are depicted in the same color because they belong to the same subnet. When utilizing an IP tunnel, as the packets traverse from node A in subnet 1 to node B in subnet 2, they reach the border routers of subnet 1, which are responsible for encapsulation.

Router R1 identifies that B is in subnet 2, reachable through the border router R2. R1 then creates another packet that travels from R1 to R2, containing the original packet as its payload. The external IPv4 header of the tunnel is illustrated in the diagram. Upon receipt at router R2, the packet is decapsulated and forwarded to the final destination.

Throughout transmission, the packet remains susceptible to being readable, manipulated, or injected, signifying a lack of real security for the end user of the VPN.

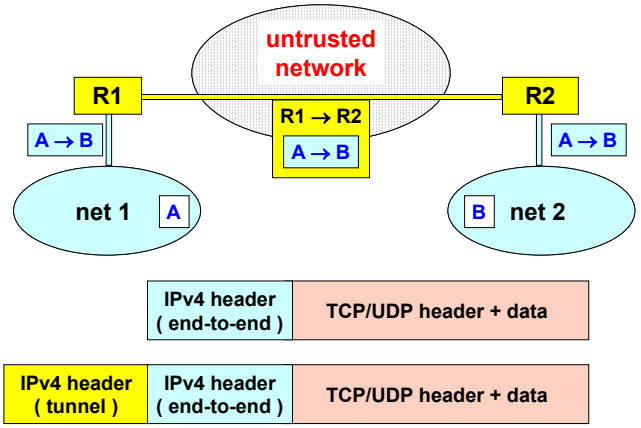


Figure 4.12: VPN via IP tunnel

The IP tunnel also presents a performance challenge: **fragmentation**. If the packet size equals the Maximum Transmission Unit (MTU), encapsulation will require fragmentation. In such instances, the maximum performance loss is 50%, as two packets are generated instead of one. This impact is more pronounced for applications with large packets, typically non-interactive applications like file transfers. Consequently, this solution can also be a performance killer.

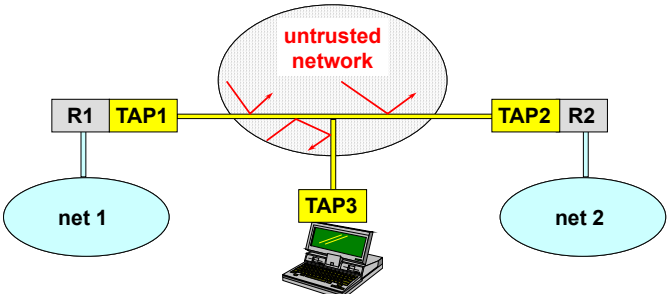


Figure 4.13: VPN via secure IP tunnel

VPN via secure IP tunnel While the performance issue remains unresolved, the final solution offers enhanced security for end users. Prior to encapsulation, packets are protected with the following measures:

- **MAC (Message Authentication Code):** Provides integrity and authentication.
- **Encryption:** Ensures confidentiality.
- **Numbering:** Guards against replay attacks.

No digital signature is employed due to its slowness, which would not align with the speed of current networks. If robust cryptographic algorithms are selected, the only viable attack is

to disrupt communications (Denial of Service - DoS). This type of VPN is often referred to as **S-VPN** (*Secure VPN*), representing the only VPN that can be considered secure (→ caution with VPNs promoted online).

In Figure 4.13, there is a router and a **TAP** (*Tunnel Access Point*). Responsibilities are divided: the router oversees encapsulation/decapsulation, while the TAP is responsible for cryptographic protection. If this solution is implemented, and the TAP is managed by an external network provider, the security is compromised. Ideally, two separate devices should be in place: the client manages the TAP, and the ISP manages the router.

4.4 IPsec

IPsec is the IETF architecture for Layer 3 security in IPv4/IPv6 designed to **create a Secure VPN (S-VPN) over untrusted networks** and **create end-to-end secure packet flows**. This is achieved through the definition of two specific packet types:

- **AH (Authentication Header):** Provides integrity, authentication, and protection against replay attacks.
- **ESP (Encapsulating Security Payload):** Offers functions similar to AH, with the addition of payload confidentiality.

It is crucial to emphasize that **confidentiality can only be provided for the payload**; it is never possible to encrypt the header. Otherwise, intermediate systems would be unable to process the packets.

There is also a dedicated protocol for key exchange, named **IKE (Internet Key Exchange)**, to create and distribute keys in IP networks.

The IPsec security services include:

- **Authentication of IP packets:**
  - *Data integrity*: The receiver can *detect* if the packet has been manipulated. It is not designed to prevent manipulation.
  - *Sender authentication*: A formal proof of the sender's identity. Note that this does not correspond to an IP address; IP addresses must not be trusted, as they can be completely fake (IP spoofing).
  - *(Partial) protection against "replay" attacks*: Challenges arise due to working at Layer 3, where packets can be lost or duplicated.
- **Confidentiality of IP packets:**
  - Data encryption (for the payload only).

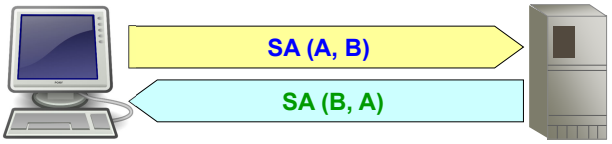


Figure 4.14: IPsec Security Association (SA)

4.4.1 Security Associations (SA)

These security features are associated with the concept of **Security Association (SA)**, which is a **unidirectional logical connection between two IPsec systems**. Each SA is associated with different security services. To achieve full protection for a bidirectional packet flow between two nodes, **two SAs are needed** (one from A to B and one for the packets from B to A).

In theory, it is possible to have different security features and different algorithms for the two directions, but normally, even if there are two distinct SAs, the same kind of protection/algorithms are used. Imagine that the sender (node A) is transmitting data (which may require confidentiality), but the response from B is a very simple thing (e.g., "received" or "bad") that does not need confidentiality. In this case, it is possible to avoid the encryption of the returning packet.

Security Associations are managed through two local databases, **which are not real databases** (i.e., no implementation of servers like SQL, Oracle; it means that it is just a collection of data):

- **SPD (Security Policy Database):**
  - It contains a list of security policies to apply to different packet flows.
  - A-priori configured (e.g., manually) or connected to an automatic system (e.g., ISPS, which stands for Internet Security Policy System).
- **SAD (SA Database):**
  - It is a runtime database that contains the list of active SAs and their characteristics (e.g., algorithms, keys, parameters) to create protected traffic for that specific SA.

Suppose to be at a sending node within the TCP/IP stack. An IP packet has been created to be sent at L2, but on this node there's IPsec. When the packet is ready to be sent, the IPsec module starts working. The first question is: *which policy should be applied for this packet?*

The answer is provided by the **SPD**. It can be *"you should apply these security rules"* or *"you don't need any kind of protection for this packet; go straight to L2"*. If protection is needed and this is the first packet of this specific network flow, IPsec proceeds in creating a Security Association. Otherwise, there is already an existing SA, and it proceeds in reading the parameters associated with that SA by consulting the **SAD**. This will provide it with the algorithms and parameters to enrich the packet, and finally, the IP packet will be protected with IPsec and sent to L2 for the actual transmission.

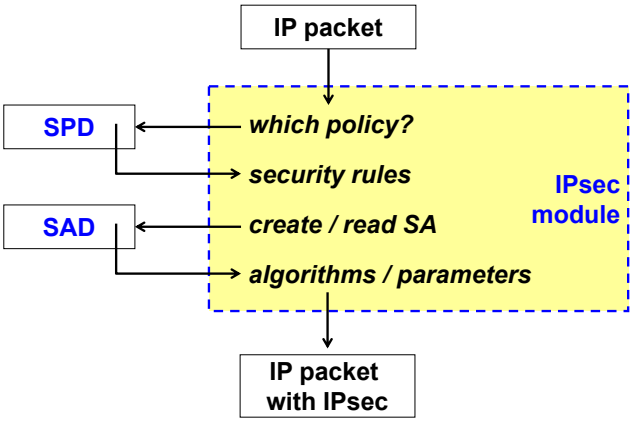


Figure 4.15: Local operations performed by a IPsec module when sending a packet

4.4.2 Transport mode IPsec

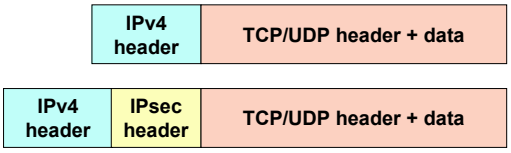


Figure 4.16: IPsec used for end-to-end security in transport mode

Transport Mode IPsec is used for **end-to-end security**, primarily employed by hosts rather than gateways (with the exception of traffic for the gateway itself, e.g., SNMP, ICMP). The original packet is split into two parts, and a new header is inserted between the IPv4 header and the TCP/UDP header. Thus, the IPv4 header will indicate that it is transporting IPsec (instead of TCP/UDP). Inside the IPsec header, there will be another field specifying the actual payload being transported.

- **Pro:** It is computationally light.
- **Con:** No protection of header variable fields.

4.4.3 Tunnel mode IPsec

Tunnel Mode IPsec is utilized to **create a VPN**, typically among gateways. It is not created among routers; the correct term is gateway, which serves as a contact point between a network assumed to be secure and a network that is not secure. The gateway enhances protection by establishing the secure IPsec tunnel. It takes the original packet with the end-to-end header and encapsulates it inside a tunnel. This tunnel is initiated by the sending gateway and has

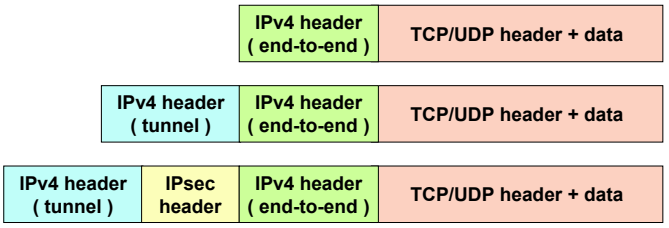


Figure 4.17: IPsec used for end-to-end security in transport mode

the destination gateway protecting the network where the destination is located. The sending gateway applies IPsec to this IP in IP packet.

- **Pro:** Complete protection of the packet, including header variable fields.
- **Con:** Computationally heavy.

Although not as common, IPsec in tunnel mode can also be used for end-to-end communication, even though it is typically adopted between border elements of larger networks. This setup is also known as a **site-to-site VPN** since the entities involved are typically entire networks.

4.4.4 Authentication Header (AH)

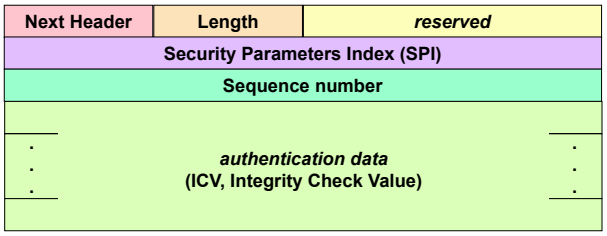


Figure 4.18: IPsec AH header format according to RFC-4302

AH stands for **Authentication Header**. There have been three major versions of IPsec.

Mechanism of the first version (RFC-1826):

- Data integrity and sender authentication
- Compulsory support of keyed-MD5 (RFC-1828)
- Optional support of keyed-SHA-1 (RFC-1852)

Mechanism of the second version (RFC-2402):

- Data integrity, sender authentication, and (partial) protection from replay attacks
- HMAC-MD5-96
- HMAC-SHA-1-96

Header format of the third version (RFC-4302) The format of the header added to the IPsec packet includes:

- `Next header` field because this is a pseudo-protocol. In the IP header, it will indicate that it is transporting AH. Inside the AH, there is the real transporting packet field.
- `Length` parameter of 1 byte to describe the length of the packet.
- `Reserved` bytes for future uses.
- `Security Parameters Index (SPI)`: 32 bits to refer in a quick and easy way to all the parameters needed to verify in the packet.
- `Sequence number` to avoid replay attacks.
- `Integrity Check Value (ICV)`: Variable number of 4-byte words to provide authentication data (digest).

Receiving IPsec packet As shown in Figure 4.19, when an IPsec packet is received, it is protected with AH. The process begins with the **extraction** of the `AH`, and from it, the `ICV` is extracted — the `received authentication value` (the digest computed by the sender). Subsequently, the received packet undergoes **normalization**, which involves putting the packet in the same condition as it was at the sender to compute the same kind of hash.

Once the `normalized IP packet` is available, it is necessary to **compute the authentication value (ICV)**. For this purpose, the *Security Parameter Index (SPI)* is used inside the *Database of the Security Association (SAD)*. It serves as a pointer indicating the algorithm and parameters to be used. These parameters are employed to compute the authentication value, and then it is checked whether the two values (the one computed and the one received from the sender) are the same.

If the two values are equal, then the sender is authenticated, and the packet is integral. However, if the two values are not equal, there could be a fake sender and/or manipulated packet.

An authentic sender is identified in the previous picture, but there is no explicit mention of where the sender is authenticated. So, who is the sender authenticated here? The answer lies in the fact that a specific entry in the Security Association Database (SAD) is being utilized. This entry is negotiated with a specific node. For this reason, authentication is implicit in the process. The actual authentication comes into play when we create the Security Association: this is the point at which the sender must prove its identity. The Security Association (SA) ensures this form of authentication through the use of the correct algorithm/parameters.

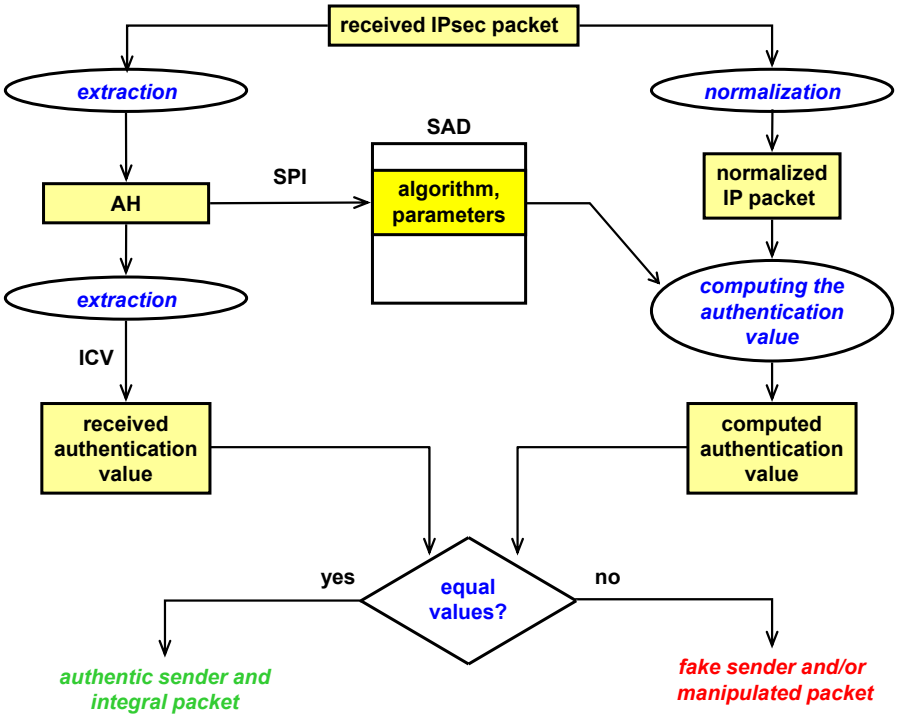


Figure 4.19: The processing of a received IPsec packet

HMAC-SHA1-96 The key digest is based on HMAC, which includes an additional parameter '96' at the end. The HMAC-SHA1-96 is generated in the following way:

1. Given M, normalize it to generate M'.
2. Pad M' to a multiple of 160 bits (by adding 0x00 bytes) to generate $M'p$.
3. Compute the authentication base: $B = \texttt{HMAC-SHA1}(K, M'p)$ (where K is the key agreed upon with the sender).
4. ICV = **the leftmost 96 bits of** B.

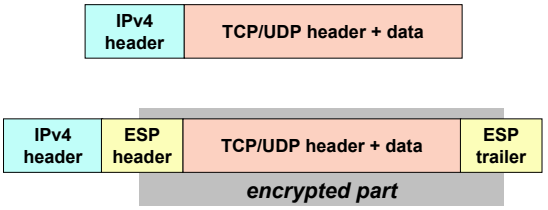
Although we mentioned that a longer digest is needed to avoid various types of attacks, the decision to use only 96 bits may seem reckless. The reason behind this is a conflict of interest between security and network managers. Network managers prefer a header with a **fixed size**. If different algorithms are used for the digest, they may produce digests of varying lengths, posing a problem for router manufacturers dealing with variable-size headers. This approach might make it nearly impossible to process the header, resulting in lower resistance to replay attacks. In IPsec version 3, this aspect is further addressed.

4.4.5 Encapsulating Security Payload (ESP)

If confidentiality is desired, *Encapsulating Security Payload* (*ESP*) is required. The first version (RFC-1827) provided only confidentiality. The basic mechanism operates on DES-CBC (RFC-1829), but other mechanisms are also possible. The second version also provided authentication, but not for the IP header, so the coverage is not equivalent to that of AH. The advantage is that the packet dimension is reduced, and one Security Association (SA) is saved.

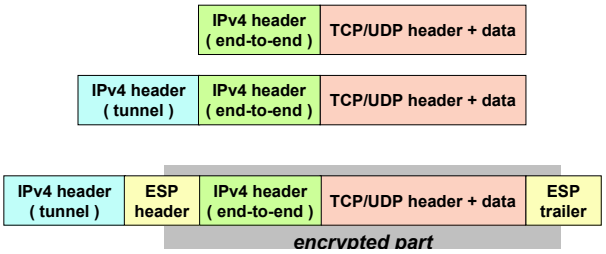
REMINDER: IPsec is an architecture that is implemented with two kinds of packets: AH or ESP, and they may be used simultaneously.

ESP can be used in transport mode and tunnel mode as well.



ESP in transport mode If used in transport mode, ESP is inserted between the header and the payload. After a brief clear part, all the subsequent content will be encrypted, up to a **trailer** that concludes it.

- **Pro:** The payload is hidden, including information needed for Quality of Service (QoS), filtering, or intrusion detection.
- **Con:** The header remains in clear.



ESP in tunnel mode If used in tunnel mode, the tunnel is first created, and then protection is applied to the tunnel payload. In this case, everything from the original packet is encrypted, including the end-to-end header.

4.4.6 IPsec implementation details

Since there are many algorithms that can be used, RFC-4308 defines two crypto-suites that anybody should implement for interoperability:

- **VPN-A:** Uses ESP with 3DES-CBC and HMAC-SHA1-96. This is a legacy VPN for compatibility with old systems.
- **VPN-B:** Uses ESP with AES-128-CBC and AES-XCBC-MAC-96. This is the one used nowadays.

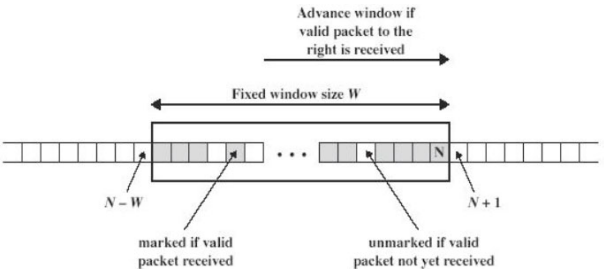
It is also possible to use **NULL algorithms** for ESP. You can specify `NULL` for one of the two parts: authentication or privacy, but not simultaneously. This allows for some kind of *'protection against performance'* trade-off. Regarding the sequence number, it provides partial protection against replay attacks and works on a minimum window of 32 packets (64 suggested).

4.4.7 IPsec Replay (partial) Protection

When the sender is transmitting packets sequentially, they are numbered. However, since the network uses IP, these packets can be lost, duplicated, or arrive out-of-order, posing significant challenges. For instance, if the receiver has received packets 0-1-2 and then 4, can it declare that packet 3 was canceled by an attacker? The answer is uncertain due to the possibility of packet loss. Similarly, when the receiver has already received packet 53 and then receives packet 3, can it confidently claim that packet 3 is duplicated? No, as it could be an out-of-order packet.

To determine if a packet preceding the last received one is a duplicate, the only viable method is to maintain a list of received packets and check if the packet has already been received or not. However, maintaining a list of all received packets is impractical due to the potentially large number.

Hence, a sliding window is employed, consisting of a **fixed window of size W**. In this window, received packets are marked, while unmarked packets remain unreceived. When an old packet is received, it is accepted if it belongs to an unreceived slot (indicating an out-of-order packet) and discarded if it was already received (indicating duplication from the network or an attacker).



If an old packet (outside the window) is received, there is no way to check its validity. This poses a significant risk because accepting it could result in a replay attack, while discarding it could lead to communication issues. If the protected traffic is TCP, accepting an old packet is less risky, as it will be discarded at the upper level if already received. However, for UDP packets, accepting old packets is not allowed, and the sender is usually requested to resend with a fresher sequence number.

The window progresses: when all packets up to 20 are received and packet 21 arrives, the window shifts one packet to the right. **Whenever a new packet with a sequence number greater than the current one is received, the window slides**. **Waiting for unreceived** packets is **not feasible**, as they could be lost (and IP does not handle retransmission).

4.4.8 IPsec v3

IPsec v3 changes the paradigm by providing equal support to the two headers. In fact, ESP is mandatory, and AH is optional. This means that it is possible to find implementations of IPsec that do not support AH, i.e., integrity and authentication for the payload only, not for the header. IPsec v3 has also added support for single-source multicast.

Moreover, since IPsec has been mainly used to create site-to-site VPNs, which involve channels with a lot of traffic, to avoid overflow of the sequence numbers, IPsec v3 has introduced **ESN** (Extended Sequence Number). ESN consists of 64 bits, even though inside packets there are still only 32 bits transmitted; the 32 least significant bits are the ones transmitted, and this is the default when using **IKEv2**.

Additionally, rather than having the separate encryption of the payload plus the **MIC** (Message Integrity Code), support for authenticated encryption (**AEAD**) has been introduced. Some clarifications about SA (Security Association) and SPI (Security Parameter Index) have been added to achieve faster lookup.

The algorithms used in IPsec are the following:

- For integrity and authentication:
  - (MAY) HMAC-MD5-96;
  - (MUST) HMAC-SHA-1-96;
  - (SHOULD+) AES-XCBC-MAC-96;
  - (MUST) NULL (only for ESP).
- For privacy:
  - (MUST) NULL;
  - (MUST- i.e., discouraged) TripleDES-CBC;
  - (SHOULD+) AES-128-CBC;
  - (SHOULD) AES-CTR;
  - (SHOULD NOT) DES-CBC.
- For authenticated encryption (AEAD mode):
  - AES-CCM;
  - AES-CMAC;
  - ChaCha20 with Poly1305.
- For authentication and integrity, it is possible to support longer digest:
  - HMAC-SHA-256-128;
  - HMAC-SHA-384-192;
  - HMAC-SHA-512-256.

TFC (Traffic Flow Confidentiality) in IPsec v3

TFC is padding in ESP that is added after the payload and before the normal padding: this is necessary to avoid disclosing the real size of the payload in the packet. The receiver must be able to compute the original size of the payload, which is possible with IP, UDP, and ICMP payloads thanks to the "length" field.

For the same confidentiality reasons, IPsec v3 introduces support for "**dummy packets**". This is in the form of a nested pseudo-protocol (next header 59), and it is needed so that it is possible to keep transmitting even in the absence of real data to send. Obviously, it makes sense to use dummy packets only if they are encrypted.

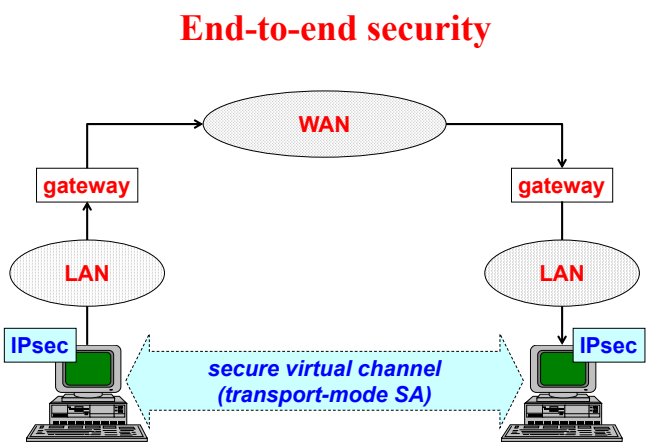
The reasoning behind having dummy packets is that sometimes just the fact that peers are communicating can be valuable information. For instance, imagine a scenario where a general wants to give an attack command, and there are various squadrons. If the enemy could see that the general is communicating with a specific site, they might suppose that an action will be taken in that site. Sending dummy packets to the other squadrons will make the messages indistinguishable for the enemy.

Of course, this reduces global performance by increasing the data sent over the network, but it is a price that needs to be paid to achieve this level of confidentiality.

4.4.9 Ways to use IPsec

End-to-End security

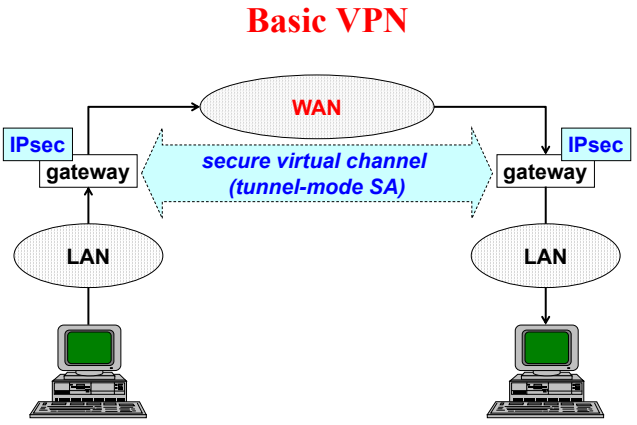
It involves activating the IPsec module on the end nodes that are communicating. These nodes require a secure virtual channel, so they create a transport mode Security Association (SA) between them. This ensures that packets are protected with the selected security level as soon as they leave the network interface of the sender. This approach eliminates concerns about the LAN being insecure, the gateway being managed by an untrusted party, or the WAN being untrusted.



The significant **advantage** is that security is implemented independently of the rest of the network, with the only possible attack being a Denial of Service (DoS). The **drawback** is the requirement to install IPsec on both communicating machines. While most operating systems support IPsec natively, some devices, such as mobile devices (Android and iOS) and embedded systems, may lack the module. Therefore, the choice of devices needs consideration, not only in terms of the availability of the IPsec software module but also in relation to the computational power required for its use.
Another critical aspect is security management. If IPsec is used to protect all computers in a large LAN, an efficient system for managing IPsec configurations on all those nodes is necessary. Finally, if ESP with a non-null encryption algorithm is adopted for the secure virtual channel, the traffic cannot be sniffed even from inside the LAN. For example, adopting an Intrusion Detection System (IDS) within either of the two LANs becomes impossible, as one would not see the real content of the transported data. In this case, the IDS needs to be placed directly onto the nodes rather than in the network.

Basic VPN

The IPsec modules are placed directly on the gateways that protect the internal network from the external one. In this case, since the channel must protect all the traffic between the two networks, it must be a tunnel-mode SA because packets coming from one network to another need to be encapsulated.

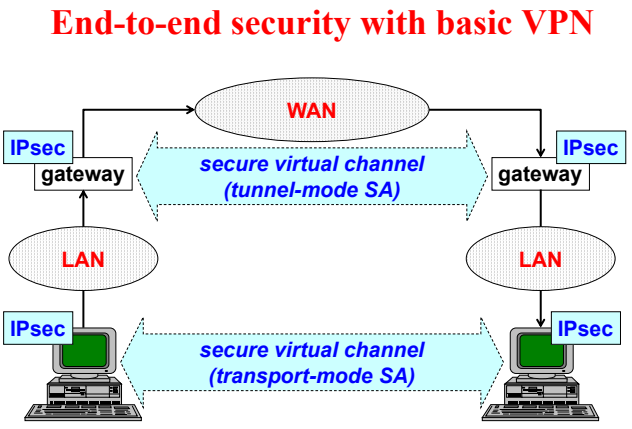


The main assumption in this architecture is that the internal network is secure and trusted, so the only concern comes from attacks over the WAN. It means leaving an open door for internal attacks, and it is not possible to perform authentication of the real endpoints of the communication; only the intermediate elements, which are the gateways, are authenticated. This model is also called a **site-to-site VPN**.

In this scenario, gateways usually do not suffer from the problem of lacking IPsec capabilities, but there is still a computational capacity issue. Since the gateways must handle tunneling for all communications, they could be overloaded. Typically, in this case, the gateways are equipped with powerful CPUs or hardware accelerators, such as an HSM. On the other hand, management is greatly simplified because there is no need to manage configurations for all end nodes, but only for the gateways. Since there is no end-to-end security among peers, there is also the possibility to inspect internal traffic.

End-to-end security with basic VPN

This is an example of the principle of "*defense in depth*", creating more than one line of defense. In this scenario, IPsec is activated both between end nodes and between the gateways. This setup allows for two lines of defense or the option to balance security. For instance, the end-to-end connection, represented by the transport mode SA, could be utilized for authentication and integrity only (e.g., to clearly identify the sender), while encryption might be activated solely between the gateways to protect against sniffing in the WAN, maintaining the ability to inspect traffic on the LAN.

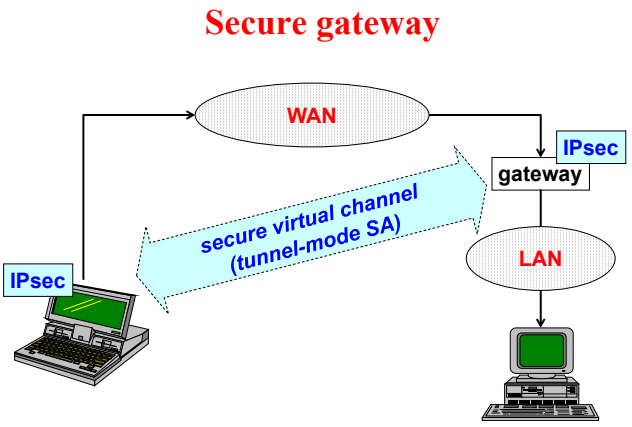


The challenge lies in managing the entire structure, which involves handling the maximum

number of systems (as in the first architecture) and all the gateways (as in the second one).

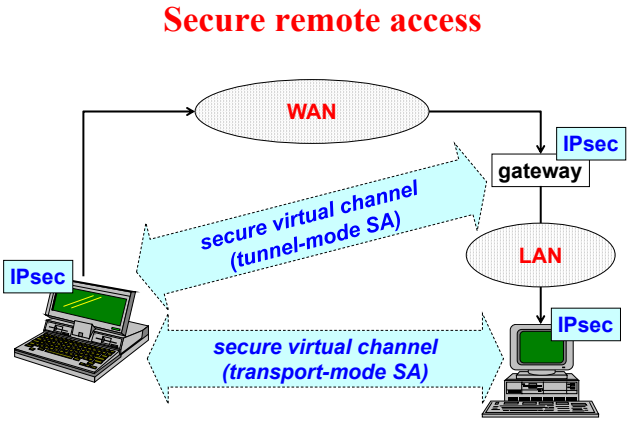
Secure gateway

The concept of a secure gateway involves mobile users, such as employees who travel and require connection to the internal company network. In this scenario, IPsec can be deployed on the user's mobile device to establish a secure virtual channel using tunnel mode SA between the device and the company gateway. This setup allows all traffic from the user to any internal server in the company network to be protected. Moreover, it enables the gateway to perform authentication and authorization.



Secure remote access

In this scenario, there is again the possibility of a double defense line: there is tunnel mode between the mobile node and the gateway, plus an end-to-end virtual channel between the mobile node and the final destination. Typically, the tunnel mode is used only for authentication and authorization (to grant access to the internal network), while the transport mode SA is typically employed for end-to-end protection, depending on the required level of protection.



4.4.10 IPsec key management

It is an important component that provides symmetric keys used for packet authentication and, if necessary, encryption to all the parties involved. To distribute these keys, it is possible to use an OOB (out-of-band) approach, such as passing the keys manually. This is physically possible when there is a limited number of nodes, and there is the ability to directly inject the keys into those nodes. However, with many nodes, some **automatic in-band key distribution** is needed, and this, in turn, requires a protocol.

ISAKMP, OAKLEY, and IKE

An integral part of the IPsec architecture is the **ISAKMP** protocol (*Internet Security Association and Key Management Protocol*). Described in RFC-2408, it contains the procedures needed to negotiate, set up, modify, and delete an SA. Unfortunately, there is no information about the key: the key exchange method is not fixed, and it can be an OOB one (and ISAKMP is used just to select the proper key) or an in-band method by using OAKLEY, a protocol for authenticated exchange of symmetric keys.

The combination of ISAKMP and OAKLEY, widely adopted, has been renamed **IKE** (*Internet Key Exchange*). It is one of the most complex security protocols because it works in the following way:

1. First, there is the creation of an SA to protect the ISAKMP exchange.
2. The created SA is used to protect the negotiation of the SA needed by IPsec traffic.

The same ISAKMP SA may be reused several times to negotiate other IPsec SAs.

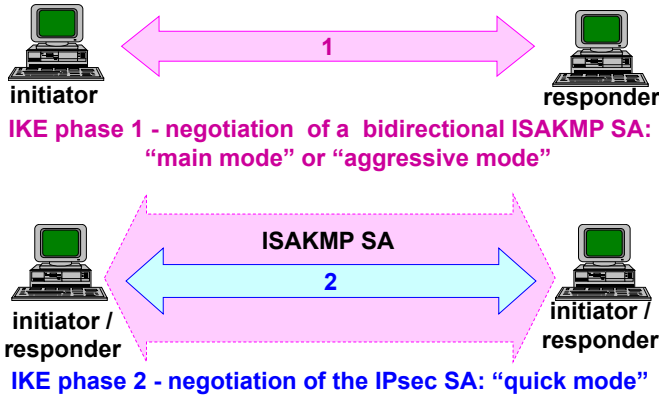


Figure 4.20: IKE: operations

In Figure 4.20, a potential schema of IKE operations is presented. During phase one, there is a node referred to as the **initiator**, as it takes the initiative to establish the IPsec channel with another machine known as the **responder**. In IKE phase 1, bidirectional ISAKMP SA negotiation is possible to protect traffic in both directions, and a choice can be made between main mode and aggressive mode.

Once the SA is established, either of the two nodes can take on the role of the initiator to create an IPsec SA. Phase two negotiation can employ quick mode since all traffic is already protected by the SA.

The main modes of operation are:

- **Main Mode**
  - It requires the exchange of 6 messages (→ quite slow)

  - Protects the parties' identities: IP addresses are, of course, always visible to an attacker, but remember that in IPsec, the authentication is given by what has been used during the authentication phase to create the key. Those "cryptographic" identities are not disclosed.

- **Aggressive Mode**
  - 3 messages (but does not protect the parties' identities)
- **Quick Mode**
  - 3 messages
  - Negotiation only of the IPsec SA
- **New Group Mode**: used to communicate with the other peer to inform it about a change in the algorithm or the key that is being used to protect the traffic.
  - 2 messages only

When an SA is opened, authentication is needed, and there are four ways to perform authentication:

- **Digital Signature**
  - Non-repudiation of the IKE negotiation, which means it is not possible to deny the request to open the secure channel.
- **Public Key Encryption**
  - Identity protection provided in the aggressive mode
- **Revised Public Key Encryption**
  - Less computationally expensive, only 2 public-key operations
- **Pre-Shared Key**
  - The party ID may only be its own IP address (which creates problems with mobile users)

VPN concentrator

IPsec is mostly used today to create site-to-site VPNs, posing a problem in terms of gateway performance. To address this concern, the concept of a **VPN concentrator** has been proposed. A VPN concentrator is a **special-purpose hardware appliance that acts as a terminator of IPsec tunnels**. It serves either for *remote access by individual clients* or to *establish site-to-site VPNs*. Implementing this functionality in hardware provides high performance at relatively low costs. It is particularly suitable for scenarios such as company or campuses, where substantial traffic is exchanged and numerous individuals work remotely.

Applicability of IPsec

IPsec can **only be applied to unicast packets**, (*no broadcast, no multicast, no anycast*) as the identification of the peer and key exchange are necessary. Although IPsec v3 introduces support for single-source multicast, this is an exception. Reciprocal authentication is required for IPsec, applying between parties that have activated a Security Association (SA) using shared keys or X.509 certificates. IPsec is well-suited for **"closed" groups**, making it unsuitable for scenarios like e-commerce services, where users are unknown, and there is no information about keys or certificates.

In essence, IPsec provides security for upper-layer traffic carried within IP packets. However, many protocols transported over IP inherit its inherent insecurity, as **IP addresses are not authenticated**, and **packets are unprotected** without IPsec. For these reasons, all protocols using IP as a carrier can be susceptible to attacks. Attackers often target neglected protocols, the so-called *"service" protocols* (e.g., ICMP, IGMP, DNS, RIP), taking advantage of the lack of protection.

4.5 "Service" protocols security

4.5.1 ICMP Security

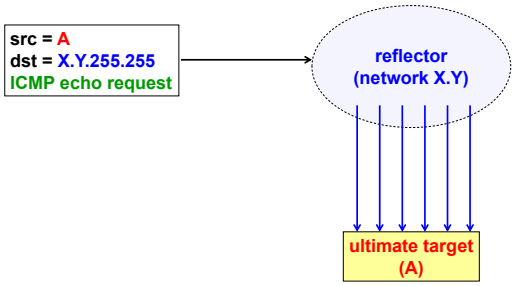
ICMP, or the Internet Control and Management Protocol, plays a crucial role in network management, yet **it lacks authentication**, making it vulnerable to various attacks. Examining ICMP functions reveals several potential security issues:

- **ICMP echo request/reply:**
  - Ping flooding or Ping bombing attacks can be conducted.
- **Destination unreachable (network/host/protocol/port unreachable):**
  - As packets lack authentication, fake nodes may send destination unreachable messages to the sender, leading the sender to terminate the communication, assuming the destination is genuinely unreachable, resulting in a Denial of Service (DoS) attack.
- **Source quench (deprecated with RFC-6633, year 2012):**
  - Originally intended for congestion control, Source Quench messages required senders to slow down transmission in response. As these ICMP Source Quench messages lack authentication, attackers could send fake packets to deliberately slow down the destination, causing a DoS.
- **Redirect:**
  - An intermediate node can send an ICMP Redirect message when it detects that the packet has taken a wrong path, allowing attackers to create a logical Man-in-the-Middle (MITM) scenario. An attacker can redirect the sender to a malicious node under its control, facilitating a MITM attack.

- **Time exceeded for a datagram:**
  - Sent by an intermediate node when processing a packet with `TTL=0`, usually indicating routing plan loops. Receiving this message suggests potential network issues, and faking this message could lead to a DoS for the sender.

It is not possible to protect ICMP with IPsec, and these types of problems remain possible. The recommended approach is to collaborate with the network manager and monitor all ICMP packets passing through the network.

4.5.2 Smurfing attack



ICMP can be exploited to execute a *Smurfing attack*, a type of Denial of Service (DoS) attack. The attack involves a target (A) being overwhelmed by creating an `ICMP echo request` (*ping*) with a fake sender, making it appear as if the ping was sent by the victim. The destination for this ping is set to the broadcast address of an entire network. The broadcast is received by all active nodes inside the network, referred to as the **reflector**, as it sends back an `ICMP echo reply` (*pong*) for each received ping. Since it is directed to the broadcast address, all active nodes inside the network respond, resulting in an amplification effect. With a single ping packet, it is possible to trigger responses from thousands of nodes, overwhelming the final target. Meanwhile, the reflector network becomes busy with the increased ICMP traffic it needs to forward.

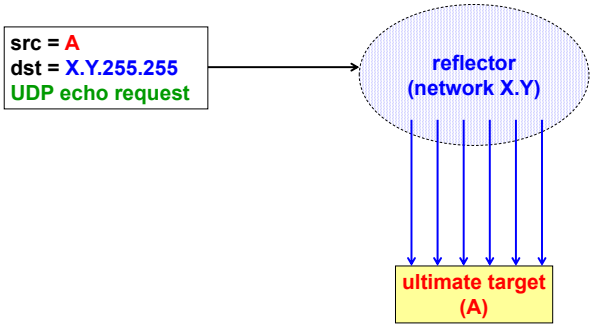
To counteract this attack, external attacks are typically mitigated by **rejecting IP broadcast packets** at the network border. For example, on a border router with a serial0 interface in the external network, the following configuration can be applied:

```
interface serial0
no ip directed-broadcast
```

This configuration ensures the discard of all broadcasted IP packets. However, this solution is effective for external attacks. The network remains vulnerable to an attack originating from within the intranet, as disabling LAN broadcast is not feasible due to protocol requirements. In such cases, countering an internal source of smurfing involves identifying the attacker using Network Management Tools and subsequently taking measures to halt the offending machine.

4.5.3 Fraggle attack

The Fraggle attack is quite similar to smurfing, but it is executed using UDP instead of ICMP. The underlying philosophy remains the same: a malicious node sends a `UDP echo request`. Currently, these UDP echo requests are disabled by default. As a result, the success of this type of attack depends on the number of clients within the reflector network that still have the UDP echo request functionality enabled.



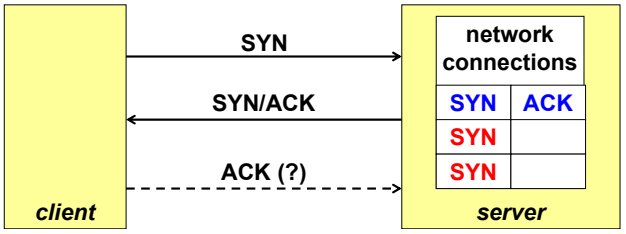
4.5.4 ARP poisoning

ARP (Address Resolution Protocol) is used to discover the Level-2 address by exploiting the Level-3 address knowledge. The result is then cached inside the ARP table. ARP poisoning is executed as follows:

- Nodes accept `ARP reply` even if they did not send an `ARP request`, as it could avoid the need to send an ARP request in the future when contacting that node.
- Thus, it is possible to send unsolicited incorrect ARP replies to nodes.
- Nodes will overwrite static ARP entries with the dynamic ones obtained from ARP replies.
  - Most stacks do not check that the source hardware address inside the ARP field coincides with the source field in the 802.3 packet.

This technique is exploited by many attack tools, such as `Ettercap`.

4.5.5 TCP SYN flooding



Remembering the three-way handshake to open a TCP connection, a first packet is sent containing the `SYN` flag. The receiver will answer back with a segment with both ACK and SYN (`SYN/ACK`) flags. Normally, the client would close/open the channel with a final `ACK`.

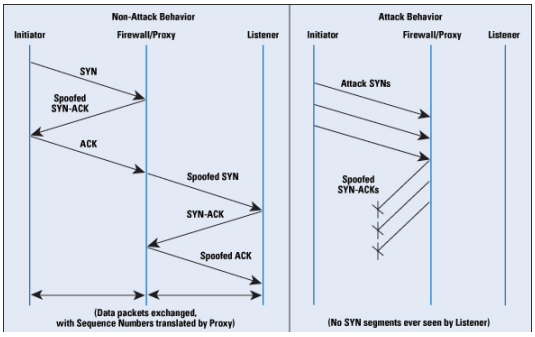
However, a malicious client can send a SYN but never send the final ACK back. The server proceeds to another line on its table of connections, and the client goes back to the first step and sends another SYN. At some point, the **table of connections will be full** (maximum size reached), and it will not be able to open new connections for real users. This results in a Denial of Service (DoS) for clients attempting to connect to the server.

It's important to note that the absence of the final ACK can also be due to a network problem. TCP/IP documents state that after a specific duration (typically 75 seconds), the server will check its connection table, and if half of the connections are open, those will be reset.

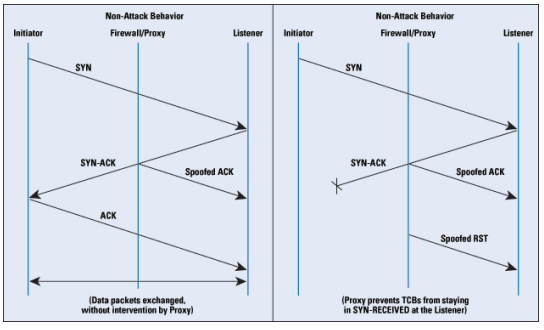
To protect against SYN flooding, it is possible to:

- **Decrease the timeout**
  - there is a risk of deleting requests from valid but slow clients.
- **Increase the table size**
  - which can be circumvented by sending more requests.
- **Use a router in front of the server as a "*SYN interceptor*"**:
  - It substitutes the server in the first phase.
  - If the handshake completes successfully, it then transfers the channel to the server.
  - Implement an "aggressive" timeout (risky!).
- **Use a router as a "*SYN monitor*"**:
  - It kills the pending connection requests (RST).

If the network manager notices a huge quantity of SYN requests (more than the usual amount), that should be the right time to start investigating.



(a) SYN interceptor (or firewall relay)



(b) SYN monitor (or firewall gateway)

Figure 4.21: Protection against SYN flooding

SYN cookie

Currently, *SYN cookie* is considered the most effective solution against SYN flooding. Proposed by D. J. Bernstein, it addresses the vulnerability in which the server stores information about a client upon receiving a SYN. Instead of maintaining the connection state on the server, SYN cookie places this responsibility on the client side. The concept employs the TCP sequence number of the SYN-ACK packet to transmit a cookie (keyed-digest) to the client, allowing the server to recognize clients that have already sent a SYN without storing any information about them.

This process is feasible because the client responds with an ACK containing the `sequence number + 1` (indicating the `keyed-digest + 1`). The server then checks if the keyed-digest is a valid one generated earlier. In more detail, the server's initial sequence number is constructed as follows:

- Let t be a slowly incrementing timestamp; $t \mod 32$ yields the top 5 bits of the sequence number.
- Let m be the *Maximum Segment Size* (MSS) value stored in the SYN queue entry.
- Let s be the result of a cryptographic hash function computed over the server IP address and port number, the client IP address and port number, and the value t. The returned value s must be a 24-bit value.

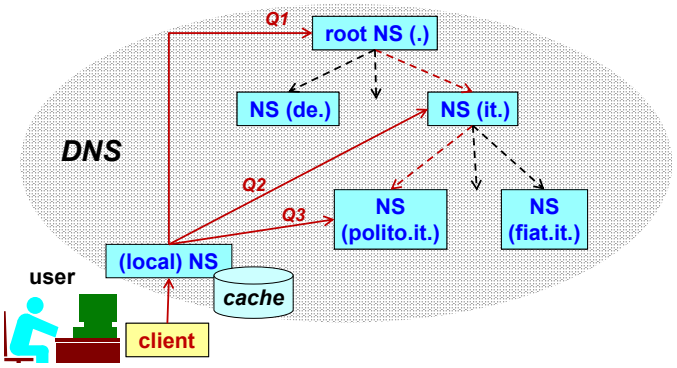
Upon receiving the ACK and retrieving the keyed digest, the server:

- Checks the value of t against the current time to determine if the connection has expired.
- Recomputes s to validate the SYN cookie.
- Decodes the value of m from the 3-bit encoding in the SYN cookie, enabling the reconstruction of the SYN queue entry.

4.5.6 DNS security

The *Domain Name System* (**DNS**) is a crucial service that provides the translation of names to addresses and vice versa. It plays a vital role as users commonly utilize names rather than IP addresses to access websites. DNS operates through **queries**, executed over port `53/UDP`, and **zone transfers** (information transfers between servers) over port `53/TCP`. As of now, DNS **lacks intrinsic security**, and while *DNS-SEC* is in development, it has not been fully implemented.

The DNS architecture follows a **hierarchical structure of servers**, beginning with the local DNS server (within the client's network). When a user intends to access a website, the local DNS server checks its caches. In the event of a `cache miss`, the local DNS server queries the root *Name Server* (**NS**). Typically, the root NS does not have the answer, as it manages only top-level domains represented by `dots` (`"."`). The query is then redirected from the root NS to the appropriate domain server (first to it., then, for example, to `polito.it`) to obtain the answer.



The diagram in Figure 4.22 illustrates the logical path for retrieving the IP address. However, in reality, the name server always responds to the local DNS, which usually caches the newly answered queries.

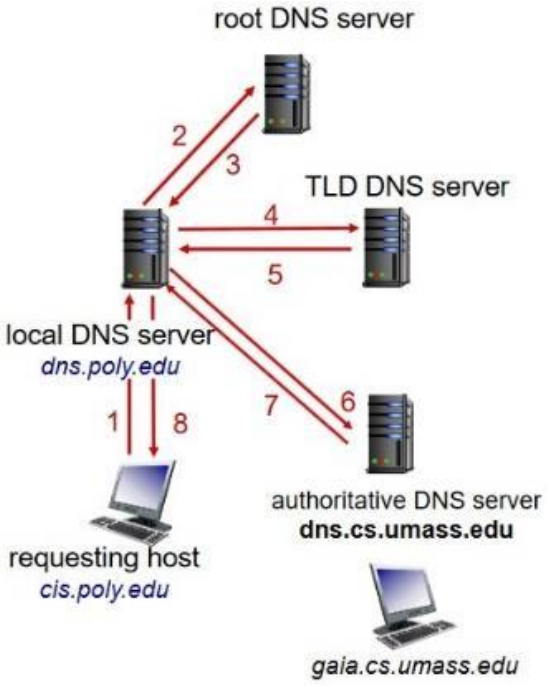
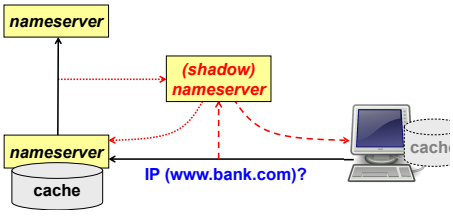


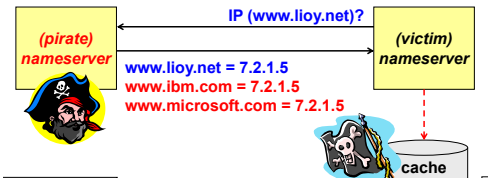
Figure 4.22: DNS name resolution with iterated query

DNS shadow server



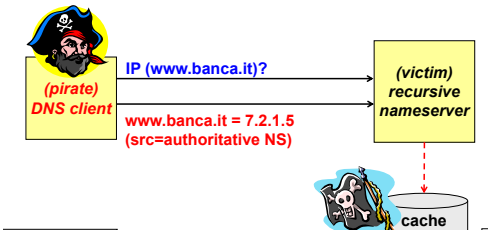
One form of attack is a *shadow/fake DNS server*. If an attacker can intercept and sniff the request sent to the local DNS, it may be possible to provide a fake response. This can result in the victim receiving a false IP address.
Conversely, if an attacker can intercept the request from the Local DNS to the Root DNS, they can provide a fake response to the local DNS. Consequently, all clients in that network making the DNS query will receive the fake IP address from the local DNS.
Microsoft has implemented a DNS cache on Windows, which deviates from the general DNS rules. In this scenario, an attack of this nature is more effective because the cache on the client is not frequently updated.

DNS cache poisoning



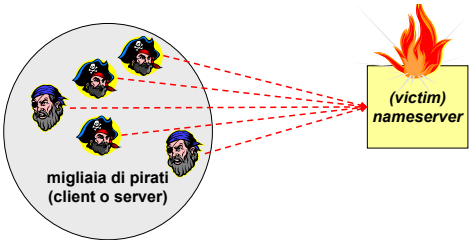
DNS employs caching to avoid redundant queries. In this type of attack, a domain (e.g., www.lioy.net) is created, and a corresponding *nameserver* is set up. However, in this case, the nameserver is a rogue or pirate nameserver. Whenever a request is made for the nameserver (e.g., the address of www.lioy.net), the pirate nameserver responds with the correct information along with additional incorrect data. If the victim nameserver is not correctly programmed or configured, it may accept the additional answers, potentially overwriting the information stored in its cache.
One limitation of this attack is that the victim must specifically request the pirate address resolution. To overcome this limitation, attackers can exploit another version of cache poisoning.

DNS cache poisoning (2nd version)



In this attack scenario, the attacker employs a pirate DNS client to request address resolution from the victim's recursive nameserver. Knowing that the resolution process takes time, the attacker preemptively self-provides the answer with a fake source address, making it appear as if the address originates from the authoritative Name Server (NS).
This form of attack is notably more effective, as it does not require the victim to be deceived into initiating the resolution for the pirate's nameserver.

(DNS) flash crowd



The primary method for executing a Denial-of-Service (DoS) attack on DNS involves overwhelming a nameserver with a significant volume of client queries. DNS is a common target for such attacks, as incapacitating the nameserver renders all associated domains unreachable.

Name-address translation

The process of translating names to addresses typically initiates from a device running an operating system. Within the OS, various applications require name resolution to obtain the corresponding address. To accomplish this, the OS utilizes a component known as the **name switch**, which determines the service responsible for translating a name into the corresponding address. For instance, the `/etc/hosts` file is a local data source. If an individual manages to add a name-address pair to this file, they can potentially redirect applications to connect to a fraudulent server.

The name switch typically determines the priority between the internal file and external services. The most common external service is accessed by the **resolver**, a component that implements the DNS client and communicates with the DNS infrastructure.

If the name is not found in the local data, the resolver will reach out to an external service, often a **caching server**. The caching server may be recursive, meaning it independently handles all the queries. It contacts various servers in accordance with the hierarchy described earlier, which is organized into specific zones. Each zone is overseen by a **zone master** (primary name

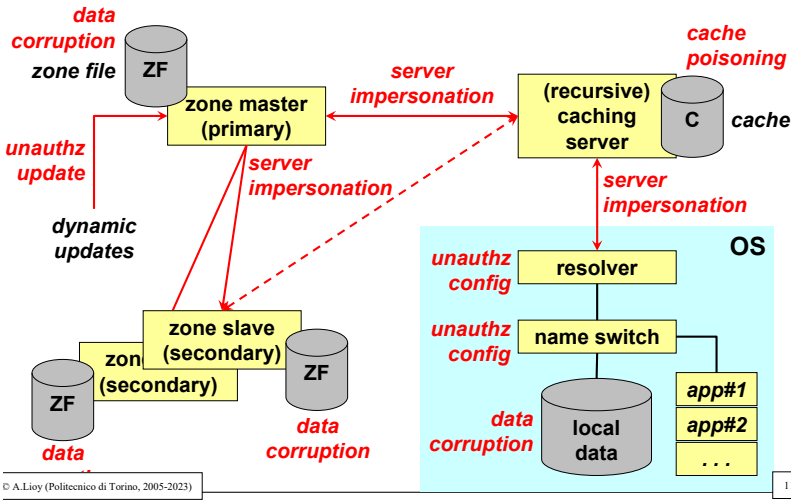


Figure 4.23: Name-address translation

server) and several **zone slaves** (secondary name servers) that maintain a database named **zone file**. This file contains the mappings between names and addresses. The caching server may interact with either the primary or secondary servers, depending on the availability or load of the primary server.

Typically, the zone master is manually updated by the administrator. Unfortunately, Microsoft introduced the capability for dynamic updates directly by clients. When a Microsoft network is joined, and an address is assigned, clients can inform the DNS master about the received IP address. This poses a significant risk as it allows uncontrolled modifications to DNS data.

Potential attacks on this infrastructure include:

- **Data Corruption to Local Data:** If an attacker gains access to a client (e.g., through a keyboard or malware), they can attempt to insert incorrect information into its local data to create a false mapping.
- **Unauthorized Configuration of Name Switch/Resolver:** Instead of pointing to the actual external name server, an attacker can redirect the name switch/resolver to a fake one, providing incorrect answers.
- **Server Impersonation in Communication:** In the communication between the resolver and server, as well as between the caching server and zone server, server impersonation (someone posing as the real server) can occur because DNS lacks any form of authentication.
- **Cache Poisoning:** Whenever there is a cache, there is a risk of cache poisoning.
- **Data Corruption on Zone File:** An attacker penetrating the zone master could corrupt data on the zone file.

- **Unauthorized Dynamic Updates:** Dynamic updates could be performed by unauthorized nodes.
- **Server Impersonation in Zone File Transfer:** Since the master sends a copy of the zone file to secondary servers, there could be server impersonation, where a fake master sends a wrong copy to the secondary servers.

As evident, there are numerous potential local attacks, such as data corruption, and some are network attacks primarily due to the lack of authentication.

DoT and DoH

Apart from the attacks against from the DNS server which is providing wrong information, DNS has got another problem for user privacy, because when you are performing a query and there is someone who are sniffing that query, he can see the site that you rare going to visit and that can be read while your query is in transit, but i t can be read in the name server, so the attacker can track your activity. DNS over TLS means that the query and the response between the client and the local NS are encapsulated in a secure TLS channel, so that is protecting information from sniffing, but it still evident that it is a DNS exchange and the NS can still track your activities.

An alternative is DNS over HTTPs, queries and responses are part in normal HTTPS exchange, so an external observer it looks like that you are visiting a secure webpage, they don't even understand that you are making a DNS request. They are adopted by cloudflare and google. These things protect against sniffing attack but not for the privacy for the server that you are contacting.

DoT and DoH

There is another thing called DNS over TLS or DNS over HTTPS. Apart from the attacks against the DNS server which may provide incorrect information, DNS presents another issue for user privacy. When you perform a query and someone is sniffing that query, they can see the site you are going to visit. This information **can be intercepted** while your query is **in transit** or even **within the name server**, allowing the attacker to track your activity.

DNS over TLS (**DoT**) ensures that the query and response between the client and the local name server are encapsulated in a secure TLS channel, protecting the information from sniffing. However, it is still evident that it is a DNS exchange, and the name server can still track your activities.

An alternative is *DNS over HTTPS* (**DoH**), where queries and responses are part of a normal HTTPS exchange. To an external observer, it appears as if you are visiting a secure webpage, making it indistinguishable from regular HTTPS traffic.

These protocols are adopted by Cloudflare and Google. While these methods protect against sniffing attacks, they do not guarantee privacy from the server you are contacting.

Protection from IP spoofing

It is not possible to prevent a host from changing its own address, but it is possible to try to limit the spread of IP spoofing. Several RFCs provide guidance to network managers on how

to enhance protection from IP spoofing, both to protect a host from external impostors and to protect the external world from impostors internal to the local network. These include:

- RFC 2827 "Network Ingress Filtering: Defeating Denial of Service Attacks Which Employ IP Source Address Spoofing"
- RFC 3704 "Ingress Filtering for Multihomed Networks"
- RFC 3013 "Recommended Internet Service Provider Security Services and Procedures"

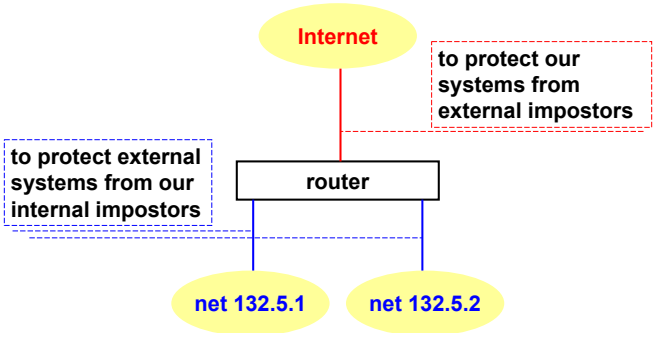


Figure 4.24: Filters for IP spoofing protection

Looking at Figure 4.24, it is possible to notice two networks: `132.5.1` and `132.5.2` (they are 2 subnets connected to a border router connected to the internet).

- **Red Cable (Internet Connection):** In this case, the filter set on incoming packets allows accepting any address coming from the Internet, except for those belonging to the internal subnets. This is important because we do not want to accept packets with internal addresses from external sources, as they could be spoofing attempts.
- **Blue Cables (Internal Subnet Connections):** Here, the filter configuration is more restrictive. We only accept incoming packets that originate from the corresponding subnets. For example, on the blue cable connection for subnet 1, we only accept packets coming from that same subnet, and the same applies to subnet 2.

In essence, it involves configuring filters so that incoming packets are allowed only if they meet certain conditions, thereby ensuring that packets with spoofed or unauthorized IP addresses are not accepted. By placing filters on the lines, it is possible to protect against both external and internal impostors. If all providers would apply this simple rule, **it would be possible to avoid IP spoofing globally**.

Possible syntax (CISCO language) in which it is possible to apply filters is the one shown in Figure 4.25.

```
access-list 101 deny ip
  132.5.0.0 0.0.255.255 0.0.0.0 255.255.255.255
interface serial 0
ip access-group 101 in

access-list 102 permit ip
  132.5.1.0 0.0.0.255 0.0.0.0 255.255.255.255
interface ethernet 0
ip access-group 102 in

access-list 103 permit ip
  132.5.2.0 0.0.0.255 0.0.0.0 255.255.255.255
interface ethernet 1
ip access-group 103 in
```

Figure 4.25: Example of IP spoofing protection

Chapter 5

Firewall

5.1 What is a firewall

A firewall is a **"wall to protect against fire propagation"**: this concept originates from regulations common in countries where houses are primarily constructed with wood. According to these regulations, a brick wall must be inserted between two houses under specific conditions to prevent the spread of fire. Similarly, in the realm of information systems security, a firewall is positioned to prevent the easy propagation of an attack from one network to another in the event of a network being compromised (akin to being "on fire"). This is particularly relevant when two networks have varying security levels, with one considered untrusted, and an attack on it could potentially spread to a more secure network.

Therefore, in addition to placing firewalls at the boundaries of networks with different security levels, it is crucial to consider the **directionality** of the **controlled flow**.

An important aspect to consider is the directionality of the flow being controlled:

- **Ingress Firewall**:
  - It is a filter that checks **incoming connections** from the untrusted network.
  - The purpose is typically to select (public) services offered; it limits which internal services are offered to the external network.
  - The problem is that sometimes the request to open a connection is part of an application exchange initiated by internal users.
- **Egress Firewall**:
  - It is a filter that checks **outgoing connections**.
  - The purpose is typically to check the activity of the personnel. This can include control of websites visited, verifying that confidential documents are not sent outside the network, or ensuring that a user is not downloading potentially dangerous files.

This classification is straightforward for channel-based services (e.g., TCP applications) but challenging for message-based services (e.g., ICMP, UDP applications). In such cases, the firewall is typically bidirectional, as a clear distinction between ingress and egress would be meaningless.

5.2 Firewall design

5.2.1 The Three Commandments of Firewall

When designing a firewall, the primary consideration is the desired security level. However, there exists an inverse relationship between the level of protection and the functionalities offered. **The higher the protection level, the fewer functionalities can be provided**. Consequently, all solutions are compromises between these two objectives.

Moreover, when designing a firewall, one should adhere to the principles articulated by the pioneers of the firewall (D. Cheswick and S. Bellovin):

I. **The firewall must be the only contact point of the internal network with the external one**.

II. **Only the "authorized" traffic can traverse the firewall**. This implies having a precise list of the allowed traffic, including protocols, ports, or external nodes. Failure to do so may result in either blocking valid traffic (thus limiting functionalities) or being too permissive and exposing the network to potential attacks.

III. **The firewall must be a highly secure system itself**. Many companies use a powerful general-purpose computer for the firewall and gradually load additional components (e.g., web server, database server) onto it. This practice should be avoided, as adding more software increases the likelihood of introducing bugs that could be exploited in an attack.

Authorization policies

For the second principle, when designing a firewall, authorized traffic must be identified. In expressing the authorization policy, there are two possible strategies:

- **Whitelisting: "All that is not explicitly permitted is forbidden"**
  - The firewall opens only a few kinds of communication, leading to higher security.
  - More difficult to manage, especially if users were accustomed to free connectivity. This could require providing explanations about things that are no longer permitted.
  - This is the recommended strategy.
- **Blacklisting: "All that is not explicitly forbidden is permitted"**
  - Implies studying what can be a security problem and forbidding that kind of traffic, typically leading to lower security (open gates). It is like saying that the vulnerability is kept until it is discovered.
  - Easier to manage.

5.3 Basic components of a firewall

As mentioned earlier, a firewall comprises several components:

- **Screening router (choke):** A router that filters traffic at the network level.
- **Bastion host:** A secure system that undergoes periodic auditing. It serves as the first line of defense against attacks.
- **Application gateway (proxy):** A service that operates on behalf of an application, facilitating communication outside the network with access control.
- **Dual-homed gateway:** A system with two network cards, acting as a bridge between two different networks. Normal routing is disabled, and components on top decide whether to forward or block traffic.

Depending on the network stack layer considered by a firewall, different terms are used to refer to it:

- **Packet filter:** Analyzing traffic at the network level, exploiting information contained in that level.
- **Circuit gateway:** Operating at layer 4, considering TCP streams or UDP datagrams as units for filtering.
- **Application gateway:** Examining application data in detail.

Usually, the higher we go in the stack, the more accurate the detection of attacks becomes, but the slower the process.

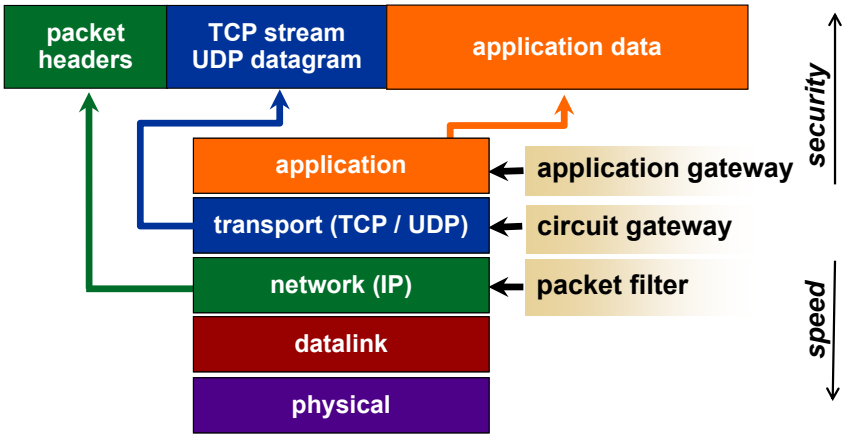


Figure 5.1: A which level the controls are made?

5.3.1 Firewall technologies

Firewall Technologies Depending on the network level at which controls are performed, different terms are used:

- (Static) packet filter
- Stateful (dynamic) packet filter
- Cut-off proxy
- Circuit-level gateway/proxy
- Application-level gateway/proxy
- Stateful inspection

Differences are observed in terms of:

- Controls to be performed (= threats detected):
  - They are related to the threats that can be detected.
- Performance:
  - Understanding the different performance levels provided by various technologies is important, typically because security comes with a price.
- Protection of the firewall O.S.:
  - Various solutions offer different levels of protection for the firewall itself.
- Keeping or breaking the *client-server model*:
  - The discussed firewalls are placed between the client and the server. It could be transparent, meaning that if the traffic is permitted, the client can directly communicate with the end server. Alternatively, the firewall can act as a proxy, allowing the client to communicate with the firewall, which then communicates with the server. The second model, where the firewall acts as a proxy, is more secure, but the firewall itself becomes an element prone to attacks.

(Static) Packet filter

Originally, it was available on routers and performed packet inspection at the network level by checking just the IP header and, when available, also the transport header. The reason for this is that once a packet is received, it should be forwarded or discarded in the minimum possible time.

This kind of solution has pros and cons:

- **It is independent of the kind of applications**

  - Good scalability (if throughput increases).
  - Approximate controls: easy to "fool" (e.g., IP spoofing, fragmented packets).
- **Good performance**
- **Low cost** (available on routers and in many OS).
- **Difficult to support services with dynamically allocated ports** (e.g., FTP).
- **Complex to configure**: all the rules are expressed in terms of IPs, port, and protocols.
- **Difficult to perform user authentication**: it comes from the fact that it uses only information available at L3.

Stateful (dynamic) packet filter [REMOVED?]

- **Conceptually similar to packet filter but "state-aware":** it means that it remembers the previous packets in order to be faster in processing the new ones. It can look inside packets for commands that define the ports that will be used (e.g., FTP PORT command).
- **It can distinguish new connections from those already open:**
  - Keeps state tables for open connections;
  - Packets matching one row in the table are forwarded without any further control (fast transmission).
- **Better performance than a packet filter:**
  - SMP (Symmetrical Multi-Processing) support can be enabled, thanks to the use of state tables.
- **Still has many of the static packet filter limitations**.

Application-level gateway

It is composed of a set of proxies that inspect the packet payload at the application level. The gateway often **requires modifications to the client application** and may optionally **mask/renumber the internal IP addresses**. When used as part of a firewall, it usually also performs **peer authentication** (typically for egress firewall). Since the proxy understands the application-level commands, it can provide **top security**, for example, against buffer overflow attacks on the target application. There are differences between forward-proxy (egress) and reverse-proxy (ingress).

In general, when working at the application level, there may be rules that are **more fine-grained and simpler** than those of a packet filter because it is possible to express rules in terms of application-level commands and data. However, every application needs a specific proxy because it will have its own commands and data. This implies:

- Delay in supporting new applications.
- Heavy reliance on computational resources: a separate process is needed for each connection, typically running in user mode.
- Low performance (because they are user-mode processes).

It is possible to use SMP that may improve performance. However, this completely breaks the client/server model, which means:

- More protection for the server.
- Ability to authenticate the client.
- Not transparent to the client: the application needs to be configured to use the proxy.

Since it is not transparent, the OS of the firewall may be exposed to attacks because it needs to process all the packets. Additionally, there is also a problem with application-level security techniques (e.g., SSL) that will not allow inspecting the traffic. For this reason, there are some variants:

- **Transparent Proxy:**
  - Less intrusive for the client.
  - Requires more effort (packet rerouting + destination extraction).
- **Strong Application Proxy** (checking semantics, not just syntax):
  - Only some commands/data are forwarded. For example, in the case of the HTTP protocol, this could allow only GET and POST commands to be allowed.
  - This is the only correct configuration for a proxy[1].

Circuit-level Gateway

Between the packet filter and the application-level gateway, there is also the **circuit-level gateway**. It is a generic proxy (which is not "application-aware") that **creates a transport-level circuit** between the client and server, but it does not understand or manipulate the payload data in any way. It simply copies TCP segments or UDP datagrams (if they match the access control rules), but in doing this, it re-assembles the IP packets, providing protection against some L3/L4 attacks.

For the server, all attacks related to the TCP handshake are no longer possible because there is no TCP handshake between the client and server. The client performs the TCP handshake with the gateway, and then the gateway performs a correct handshake with the server.

In conclusion, it breaks the TCP/UDP-level client/server model during the connection and provides:

[1] according to Lioy.

- **More Protection for the Server:**
  - Isolated from all attacks related to the TCP handshake.
  - Isolated from all attacks related to IP fragmentation; an attacker could fragment a packet with which they perform the attack, and such an attack will not be detected by a simple packet filter.
- **May Authenticate the Client:**
  - But this requires modification to the application.

However, it still exhibits many limitations of the packet filter. A well-known example is **SOCKS**.

HTTP (forward) proxy

A forward proxy, typically HTTP, acts as an HTTP server, functioning as a front-end and passing requests to the real external server. In addition to network *Access Control Lists* (**ACL**), the benefits include:

- Shared cache of external pages for all internal users.
- Authentication and authorization of internal users.
- Various controls (e.g., allowed sites, transfer direction, data types, ...).

It is a typical component of the **egress** firewall. By contrast, the *reverse proxy* is used for the **ingress firewall**.

HTTP reverse proxy

An HTTP server acts as a front-end for the real server(s) to which the requests are passed. It can implement ACL again in case it is possible to limit clients, but typically, an ingress firewall does not limit clients that can contact the server. It is possible to perform **content inspection**. Benefits of this proxy include:

- **Obfuscation** (no info about the real server): Since the server proxy is responding to the client, it can declare that it is a generic proxy without providing any information to the real software that implements the final server.

- **SSL accelerator** (with unprotected back-end connections . . .):
  Reverse proxy can be the endpoint for SSL/TLS. In that sense, it is an SSL accelerator because if the channel is terminated here, it is possible to place an HSM and then get the additional benefit that the traffic comes in clear after the TLS channel is terminated. This permits performing content inspection.
- **Load balancer**
- **Web accelerator** (=cache for static content)
- **Compression**
- **Spoon feeding**:
  Gets from the server a whole dynamic page and feeds it to the client according to its speed, thus unloading the application server.

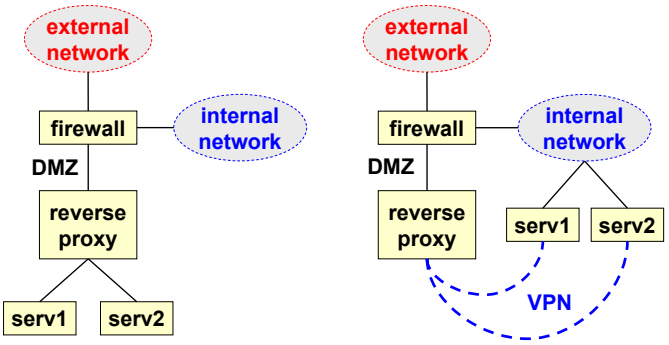


Figure 5.2: Reverse proxy: possible configurations

There are two possible configurations for a reverse proxy (Figure 5.2).

left. The best solution is that, if conceptually a *three-legged firewall* (see Chapter 5.4.4) is used, **the reverse proxy should be placed on the DMZ because it will be the public interface**. Behind it, the equivalent servers (which are the application servers being accessed by external users) can be placed. The problem arises when the application server needs access to data located inside the internal network. In this case, the server should pass back through the proxy, traverse the firewall, and finally enter the internal network.

right. To handle this case and avoid the issues just explained, an alternative solution is also possible: **the reverse proxy is on the DMZ, and then a VPN connection is established between the reverse proxy and the servers, which are in the internal network**. This approach should limit the risks because there is no direct access to those servers, only through the reverse proxy. However, the first solution is the suggested one, as in that case, an attack against the (public) servers is confined to the DMZ.

WAF (Web Application Firewall)

Since web applications are widely used nowadays, there is an increasing number of threats. WAF is a module installed at a proxy (forward and/or reverse) to **filter the application traffic**. It checks:

- HTTP commands
- Header of HTTP request/response
- Content of HTTP request/response

The most widely known and used WAF is **ModSecurity** (opensource project), which is a plugin for Apache and NGINX (representing 5% and 30% of worldwide HTTP servers). ModSecurity is so popular that OWASP (Open Web Application Security Project) has developed a specific **ModSecurity Core Rule Set (CRS)**. This means that OWASP studied the most frequent and well-known attacks and wrote a set of rules that permit ModSecurity to detect and drop those attacks.

5.4 Architectures

5.4.1 "Packet filter" architecture

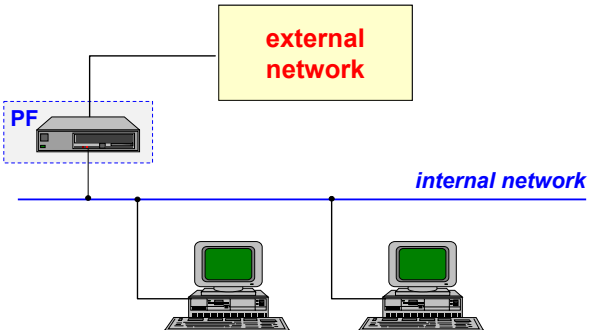


Figure 5.3: "Packet filter" architecture

The core concept is to equip the switching element with filtering capabilities. Typically, since this is a Layer 3 (L3) network device, the kind of filtering it can perform is at the IP and upper levels, implementing a packet filter. The advantage of this architecture is that there is no need for dedicated hardware. Moreover, since this filter does not address the application level in any way, there is no need for a proxy, and hence, there is no need to modify the applications. It is a simple, easy, cheap, and... *insecure* solution since the kind of controls it can make are very trivial, usually based on protocols, ports, and addresses. One final drawback is that the router is a single point of failure, meaning that a bug could allow the attacker to bypass the control and access the internal network.

5.4.2 "Dual-homed gateway" architecture

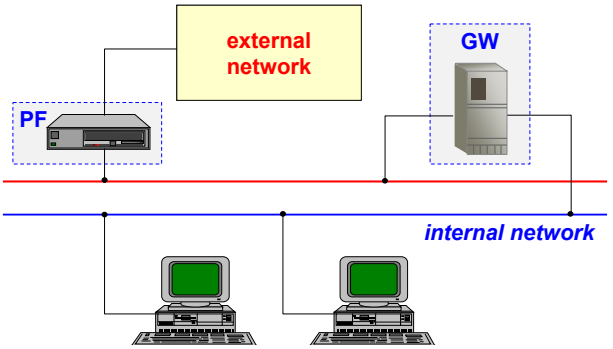


Figure 5.4: "Dual-homed gateway" architecture

Because relying solely on filtering at the network layer does not provide high security, another element is needed to improve the architecture, performing inspections at higher levels. In this architecture, the traffic permitted by the packet filter will not directly enter the internal network. Instead, it will be further checked by a second element, generally referred to as a "gateway". This gateway is actually "dual-homed" because it has two network cards, with routing disabled. A packet coming from one interface goes to the other if it respects the imposed rules.

This architecture is still easy to implement because two different components deal with separated aspects. It requires small additional hardware requirements; just a general-purpose machine with the proper gateway software installed will suffice. Moreover, since the gateway is the frontend for the entire internal network, it can masquerade the internal addresses, even without using NAT.

The big problem with this solution is its rather inflexibility. Even if traffic is permitted in the packet filter, it must also pass the check at the gateway. Taking electronic mail as an example, typically, in incoming mail, it is difficult to limit the sender (other than forbidding well-known sites that send spam). Therefore, it is checked at the mail server, which is internal to the network. The gateway would reconstruct the application-level packet just to see that it is an email, and it is not its job to inspect it. Consequently, it will send it to the internal network. The inflexibility lies in the fact that a packet is double-checked even if the second check is useless because nothing can be decided with the information that the gateway has. The actions performed by the gateway lead to a large work overhead. One thing to note is that this solution implements a **double line of defense**, applying the "*defense in depth*" principle.

5.4.3 "Screened host" architecture

Improving the "dual-homed gateway" architecture means avoiding the bottleneck at the gateway. In the "screened host" architecture, the packet filter is also connected to the internal network, but there is also the gateway, which is connected to the packet filter. This arrangement allows packets that do not need a double-check to be directly forwarded to the internal network. However, it

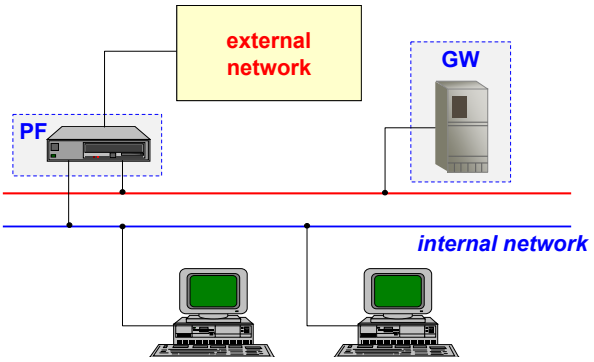


Figure 5.5: "Screened host" architecture

reintroduces the problem of a single point of failure in the packet filter, and a double line of defense is implemented only for those packets that need to be processed more in-depth.

To summarize:

- The *router*:
  - Blocks traffic from internal to external unless it comes from the bastion.
  - Blocks traffic from external to internal unless it goes to the bastion.
  - Exception: directly enabled services.
- The *bastion host* runs a circuit/application gateway to control authorized services.
- This architecture is more expensive and complex to manage because the work of the two systems must be synchronized.
- It is more flexible (skip control over some services/hosts).
- Only the hosts/protocols passing through the bastion can be masked (unless the Packet Filter (PF) uses NAT).

5.4.4 "Screened Subnet" Architecture

The main problem introduced with the "screened host" architecture is the single point of failure in the packet filter. In the "screened subnet" architecture, the packet filter is split because it conceptually performs two different operations:

- Deciding if incoming traffic should be permitted or denied.
- Deciding if traffic should be forwarded to the internal network.

In this solution, one packet filter is connected to the external network, while the other one acts like a bridge from the "intermediate" network to the internal one. First, an incoming packet

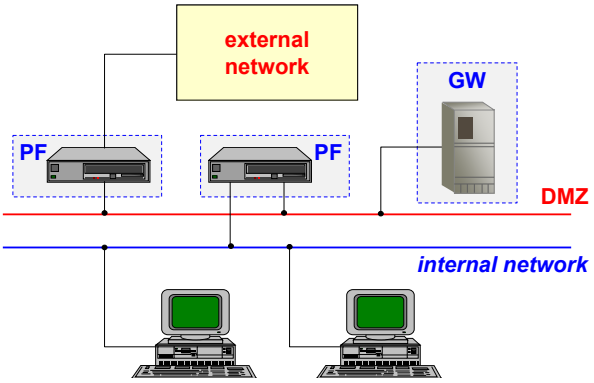


Figure 5.6: "Screened subnet" architecture

is checked. If it is permitted, it is forwarded to the second packet filter that will still verify if the rule is valid and then forward it to the internal network. This way, there is a double defense, even for packets that will be directly transmitted to the internal network. For packets that need further inspections, there will be three defense lines, as the second packet filter will send them to the bastion. Please note that, to have a proper double line of defense implemented by the two routers, they should be sourced from different vendors. If they are equal, the same bugs may affect security.

In this scheme (Figure 5.6), there is **a network that is completely decoupled from both the external and the internal network** (highlighted in red in the figure): this is called the **DMZ** (*De-Militarized Zone*). Typically, the DMZ is not only home to the gateway but also to other hosts, such as public servers (e.g., web servers or remote access systems). This implies that public servers should be placed in the DMZ. This solution is more expensive than the others because it is more complex.

"Screened Subnet" Architecture (Version 2)

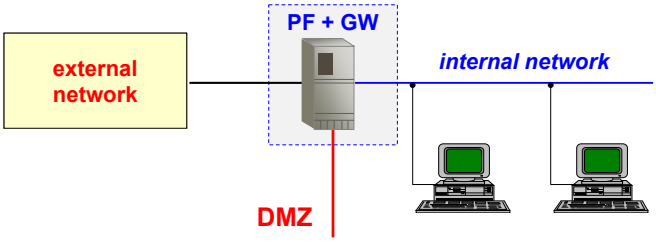


Figure 5.7: "Screened subnet" architecture v2

To reduce costs and simplify management, often the routers are omitted, and their function is incorporated into the gateway: this solution is also called the "**three-legged firewall**". In this solution, the firewall is a single element, typically a general-purpose computer, equipped

with **three network cards**: one connects to the external network, one to the internal, and the third one implements the DMZ.

The components of the previous solution are software modules inside a single element. From a functional point of view, there are the same functionalities, but the solution is intrinsically less secure because:

- There is again a *single point* of failure, the single machine hosting all the processes.
- The *complexity* of this node makes room for attacks due to implementation or configuration errors.

Despite these considerations, many companies tend to implement this solution because it provides numerous functionalities while keeping costs limited, and the management is simple due to having only one interface for overseeing everything. Some companies claim to have implemented a *"four-legged firewall"* or a *"five-legged firewall"*: the number of legs comes from having multiple interfaces toward the internal network or from deploying multiple DMZs. Each one can be assigned to a different department of the company, mostly for administrative decisions.

5.5 Local/personal firewall

Until now, we discussed the network firewall, which is a filter situated between two networks (internal and external). However, this kind of firewall faces a problem with HTTPS, as channels are encrypted, making it difficult to inspect packets.

This has led to moving the firewall to a location where traffic can be inspected. In HTTPS, traffic is encrypted on the client and server sides. This implies that the firewall should be moved to the client or server: a **local firewall** if installed on the server or a **personal firewall** if installed on the client. It is **directly installed at the node to be protected**, safeguarding a single node instead of a whole network. It is **typically a packet filter** but, concerning a normal network firewall, it may **limit the processes** that are allowed to:

- Open network channels towards other nodes (i.e., act as a client)
- Answer network requests (i.e., act as a server)

For example, this firewall can limit traffic going to an unknown process because it might be malware on the client attempting to gather information.

It is crucial to limit the spread of malware and trojans or detect plain configuration mistakes (for example, some services installed by default on the operating system that send or receive data). Firewall management must be separated from system management; otherwise, the people installing a service may also activate the firewall to permit that kind of traffic (a decision that should be made by the security manager).

5.6 Protection offered by a firewall

The analogy presented here illustrates that in the areas of the wall where bricks are removed to allow traffic, that is the part where fire can enter the system. For all channels enabled through the firewall, additional protections are necessary:

- VPN
- "Semantic" firewall / IDS (Intrusion Detection System)
- Application-level security

5.7 Intrusion Detection System (IDS)

IDS is another critical component of contemporary security solutions; it is a **system designed to identify actors using a computer or a network without authorization**. Depending on the features, it can be extended to **identify authorized actors violating their privileges**.

IDS is based on a crucial hypothesis: **the behavioral "pattern" of non-authorized users differs from that of authorized ones**.

An IDS can base its behavior on two strategies.

- **Passive IDS**:
  Tries to identify visible signs of an attack, using:
  - Cryptographic checksum (e.g., tripwire) checking for modified files on the server that should not be modified;
  - Pattern matching ("attack signature") looking for specific packets which are typical of an attack;
- **Active IDS**:
  Tries to identify unknown attacks or known attacks but before they produce their negative result. It goes through three steps:
  - "Learning" = accurate statistical analysis of the system behavior;
  - "Monitoring" = active statistical info collection of traffic, data, sequences, actions;
  - "Reaction" = comparison against statistical parameters (reaction when a threshold is exceeded).

An Active IDS always has someone who looks at IDS statistics. This is necessary because statistics may not be accurate. An attack is detected if it significantly diverges from the statistics related to the behavior of the system, so there is a chance to have undetected attacks but also false positives. This means that human intervention is often needed to check the alarms raised by the IDS, carefully analyze the problem, and understand if there is an attack or if it is just a false positive, given the strict threshold. Typically, IDS have both an active and passive part.

Topological features of IDS:

- **HIDS (host-based IDS)**, looks for statistics inside a single node:
  - Log analysis (OS, service, or application);
  - Internal OS monitoring tools;
- **NIDS (network-based IDS)**, looks at the network traffic:
  - Network traffic monitoring tools.

5.7.1 NIDS

NIDS components

- **Sensor (host/network based):**
  - Checks traffic and logs looking for suspect patterns;
  - Then generates the relevant security events;
  - Could also interact with the system (modifying ACLs, performing TCP reset, ...);
- **Director:**
  - Coordinates the work of all sensors;
  - Manages the security database (e.g., statistics, attack signatures);
- **IDS message system (to make director and sensors communicate):**
  - Provides secure (authentication and integrity) and reliable (nobody should be able to drop a message that was sent by sensors or vice versa) communication among the IDS components.

To achieve reliability in communication, if possible, it is performed on a separate physical network. If it is not possible, a VLAN or VPN is used.

NIDS architecture

The schema (Figure 5.8) shows how IDS should be configured. Conceptually, there is always the three-legged firewall with a connection to the external, one to the internal, and one to the DMZ. In the internal network, **sensors** on the most critical hosts are inserted (e.g., databases, application servers). **Net sensors** are also needed to check if some malicious traffic succeeds in passing the network, but it is also necessary to check the behavior of users in the internal network.

On the DMZ, there is the server reachable from the outside and those are easily attackable. Therefore, a **host sensor** on each server placed on the DMZ should be inserted. The last sensor is the **net sensor** on the external interface of the firewall. Some think that it is not needed because it is outside, but placing it outside of the firewall permits the analysis of which attempts are made, to gather statistics (e.g., the firewall blocks 98% of attacks).

On the top right, the IDS director collects all the information from sensors.

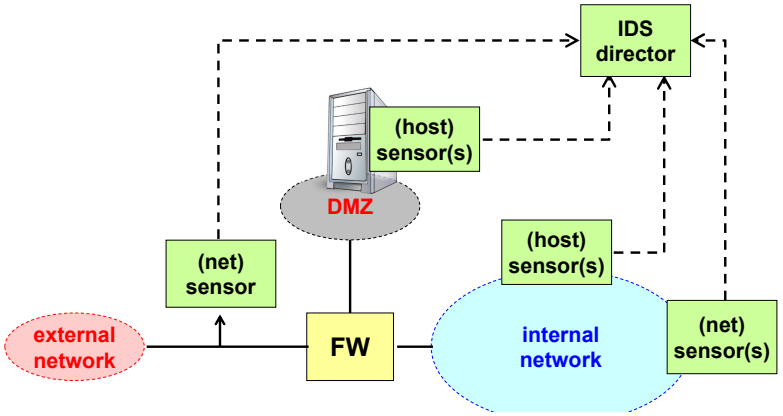


Figure 5.8: NIDS architecture

5.7.2 IPS - Intrusion Prevention System

IPS is a system used to **accelerate and automate responses to intrusions**. It combines an *IDS* with a *distributed dynamic firewall*. The IDS sends alarms related to a specific type of traffic; then, when the distributed dynamic firewall receives an alarm, it can block all traffic of that particular kind or isolate a node. This approach is effective when the intrusion detection system's detection is 100% certain. However, if it is not, IPS can be risky because **it may make incorrect decisions and block innocent traffic**. It is a technology, not a product, with a significant impact on many elements of the protection system. It is often integrated into a single product called *IDPS*.

5.7.3 Next-Generation Firewall (NGFW)

NGFW is a kind of firewall that attempts to **identify applications independently of the network port used**. Consider a scenario where users are only allowed to use `HTTPS (443/TCP)`, and all other traffic is blocked. There might be someone using port 443 to send traffic other than HTTPS. **With a packet filter, it is not possible to detect that**. In contrast, with NGFW, it is possible to inspect traffic on any port and try to understand the actual application being carried out on that port. If possible, NGFW tries to decipher/re-cipher the traffic.

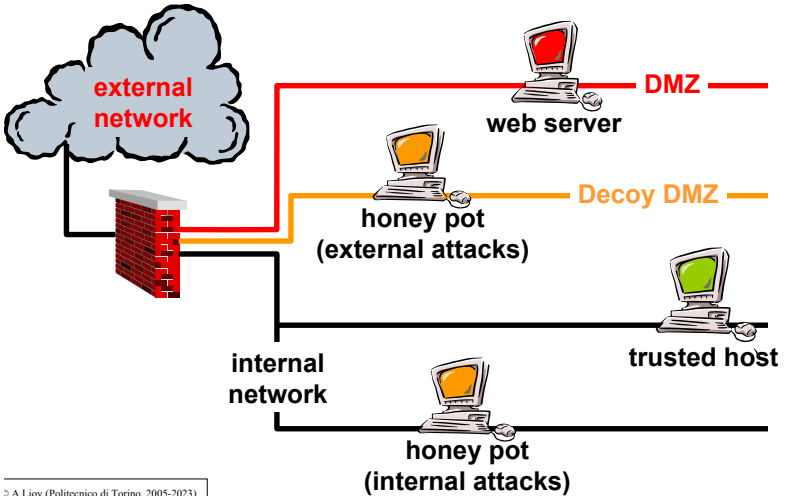
NGFW offers integration with authentication systems such as captive portal, 802.1x, or end-point authentication (Kerberos, Active Directory, LDAP, ...). This integration allows the firewall to write policies based on user identities rather than IP addresses. By associating IP addresses with specific users through integration, it becomes possible to create **per-user policies**. Similarly, the ability to identify applications independent of the port used allows the application of **per-application policies**. Additionally, NGFW can perform filtering based on known vulnerabilities, threats, and malware.

5.7.4 Unified Threat Management (UTM)

It is an **integration of several products into a single device** that simplifies management. The device provided is named *UTM appliance/Security* appliance and can contain firewall, VPN, anti-malware, content-inspection, IDPS, and other features.

The actual capabilities depend on the manufacturer. UTM is mainly targeted to reduce the number of different systems, thus reducing management complexity and cost.

5.7.5 Honey Pot / Honey Net



A Honey Pot is a method to **attract attackers**. The external network is protected with a firewall, which contains the real DMZ. Additionally, there is a second DMZ called the **decoy DMZ** where there is a **honey pot** — *an easily attackable machine*. The purpose is to attract attackers and then have an inspection system that monitors what the attacker is doing to **understand their behavior** and new types of attacks or to collect malware. Honey pots are placed worldwide by antimalware manufacturers just to collect new malware.

The honey pot can also be placed inside the internal network to detect if there are internal users attempting to attack the system. For example, it is possible to create a fake duplicate salary server just to check if someone is trying to increase their own salary or to access someone else's salary.

Chapter 7

Security of network applications