# Digital Certificates and Public Key Infrastructure (PKI)

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tcg crest
Inventing Harmonious Future

$24^{th}$ June, 2025

# Outline

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- Once a single public key, belonging to a trusted party, is distributed in a secure fashion, that key can be used to "bootstrap" the secure distribution of arbitrarily many other public keys.
- Thus, at least in principle, the problem of secure key distribution need only be solved once.

# Digital Certificates

First described by Kohnfelder in 1978 in his undergraduate thesis.

**Definition (Digital Certificates)**

A ***digital certificate or identity certificate or public key certificate*** is simply a signature binding an entity to some public key.

# PKI

Charlie

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Gen: $(pk_C, sk_C)$

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Bob

# PKI

Charlie
Gen: $(pk_C, sk_C)$

Bob
Gen: $(pk_B, sk_B)$
(can be for sig. or enc. scheme)

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knows that $pk_B$ is Bob's public key

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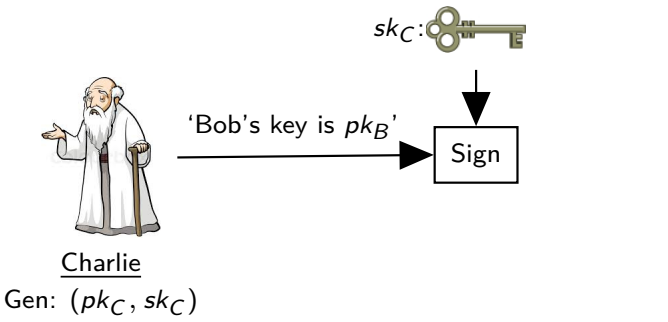


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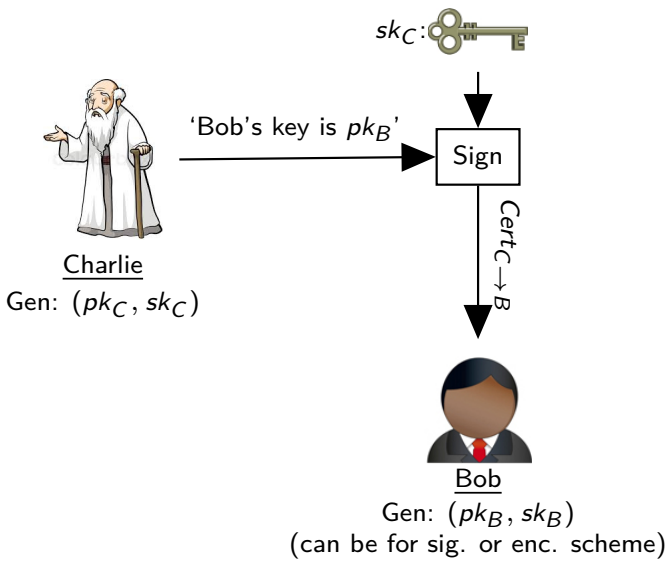


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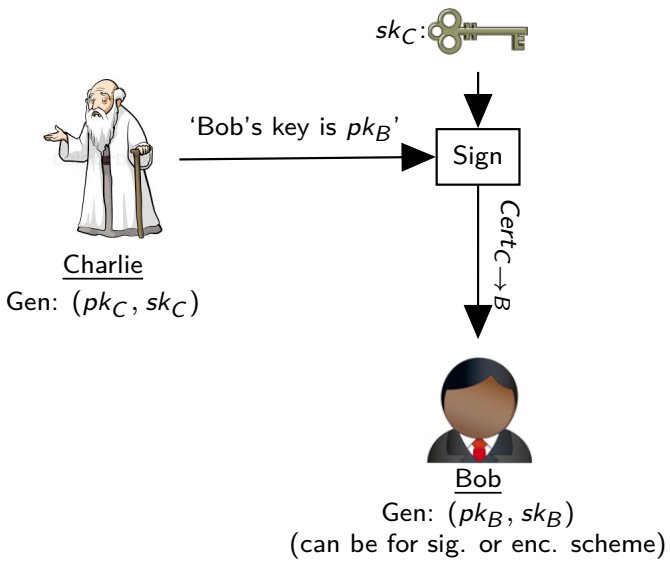


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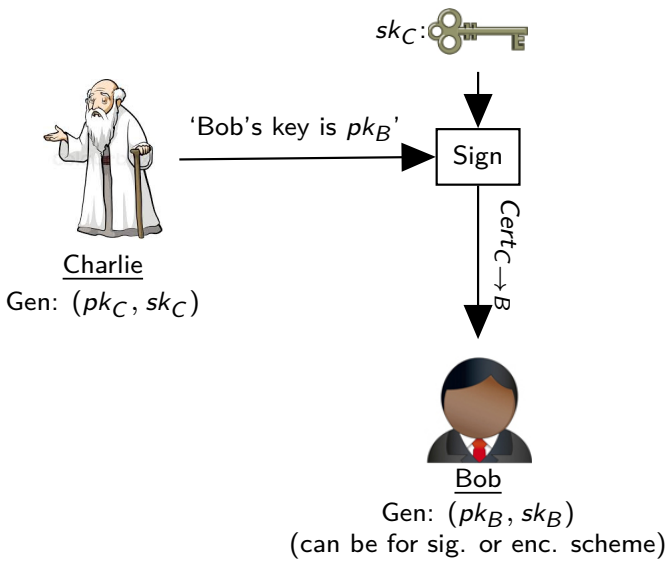


- $Cert_{C \to B}$: A certificate for Bob's public key issued by Charlie.
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- **Example:** Bob's full name and email address, or the URL of Bob's website.

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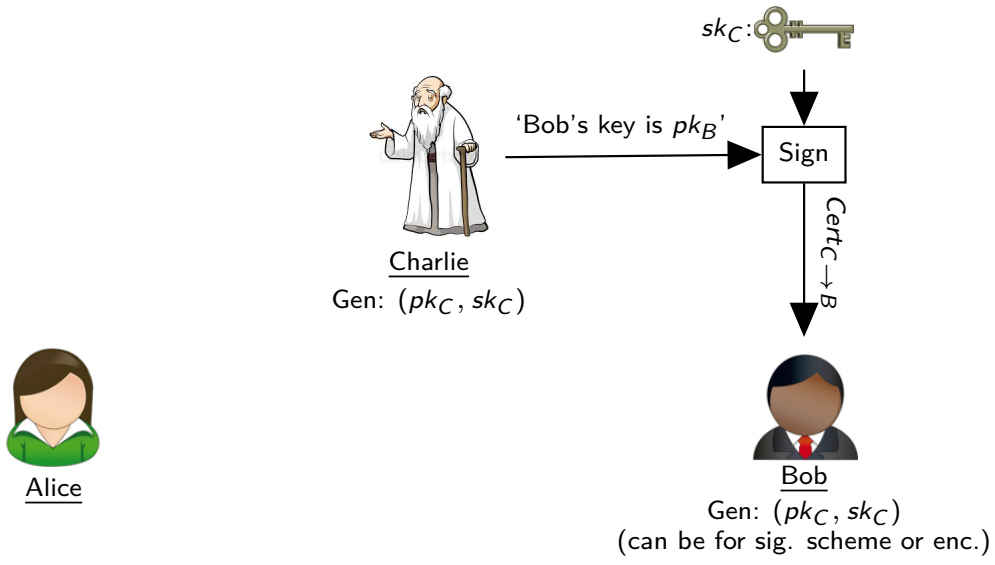
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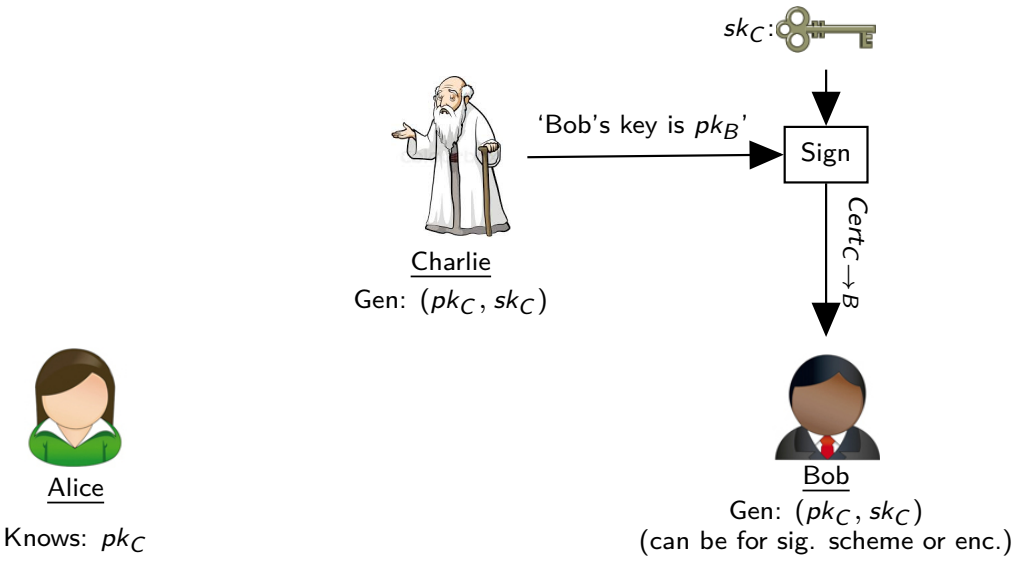
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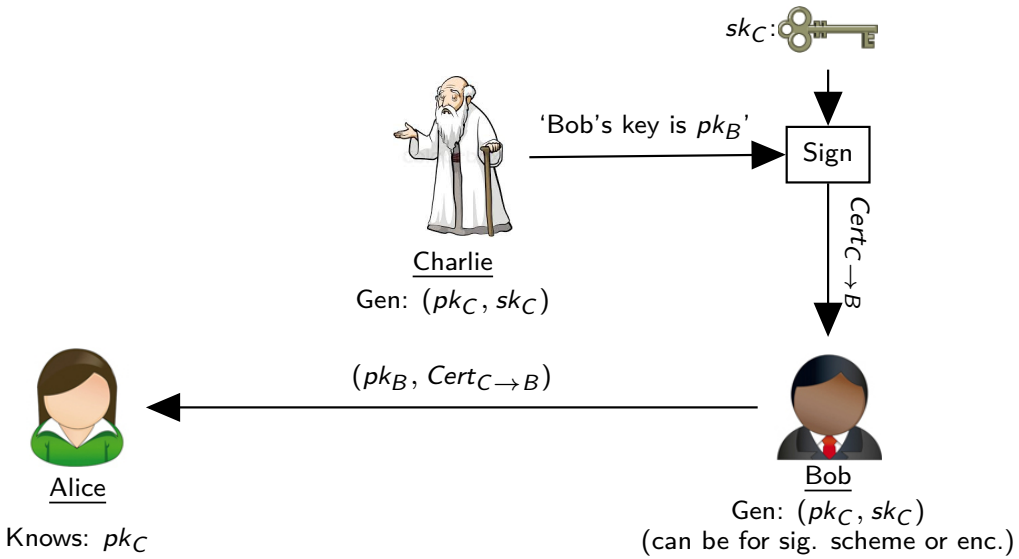
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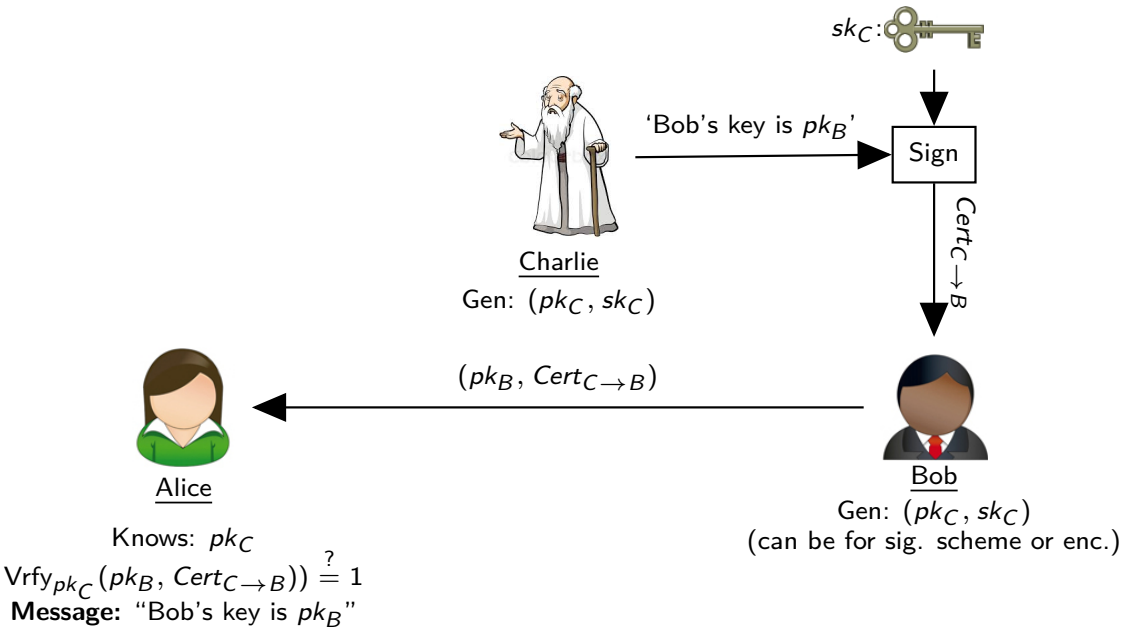
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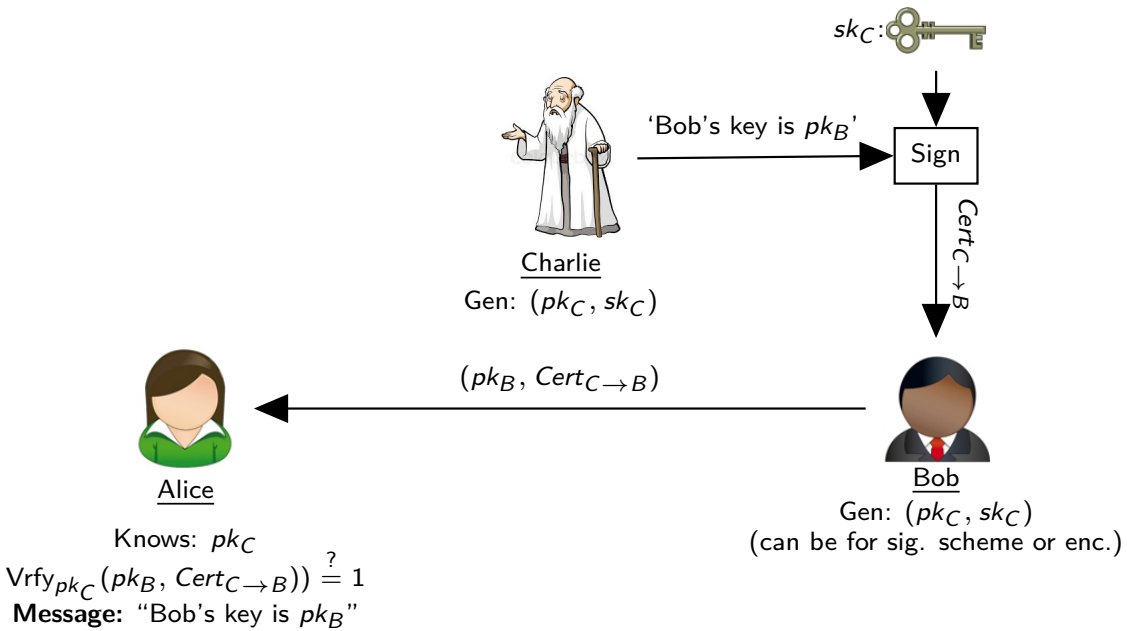


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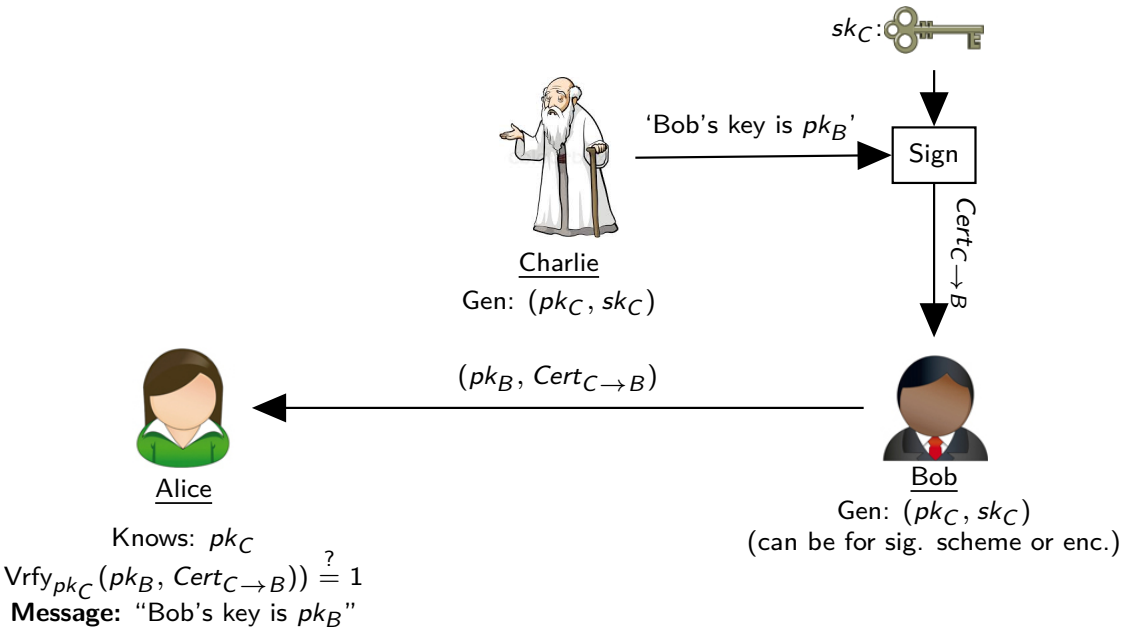


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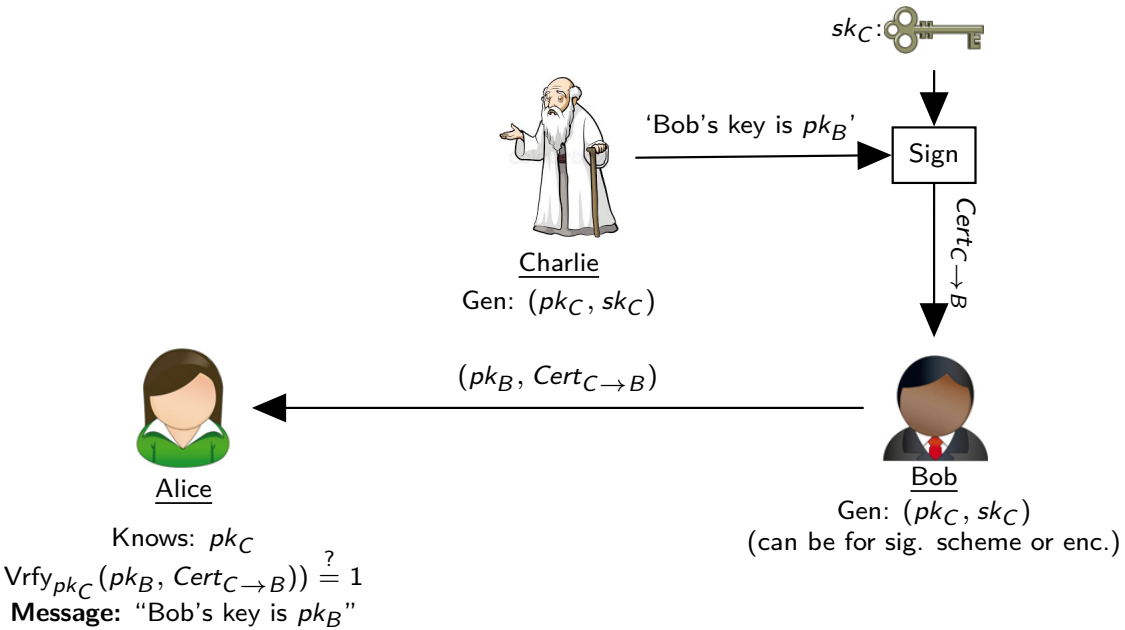


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- **Assumptions:**
  1. Charlie is honest.
  2. Charlie's private key has not been compromised.

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**Note:** Many details have been omitted!

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2. How Charlie can be sure that $pk_B$ is Bob's public key?
3. How Alice decides whether to trust Charlie?

# PKI

- Public-key infrastructure (PKI): Full specification of these details (and others) in order to enable the widespread distribution of public keys.
- Different PKI models have been suggested.
- We will mention a few of the more popular ones.
- Our treatment will be at a relatively higher level.

# Outline

# Single CA

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  - **Example:**
    - A company whose business it is to certify public keys.
    - A government agency.
    - Could be a department within an organization (intended to be used by people within the organization).

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  - Thus $pk_{CA}$ must be distributed over an authenticated channel.
  - **Easiest way:** Via physical means.
    - CA is within an organization: Employee can obtain an authentic copy of $pk_{CA}$ directly from the CA on their first day of work.
    - CA is a company: Users need to go to the company at some point and, say, pick up a USB stick that contains the CA's public key.

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  - Thus $pk_{CA}$ must be distributed over an authenticated channel.
  - **A common way:**
    - "Bundle" it with some other software.
      - **Example:** Popular web browsers like Mozilla Firefox (actually falls in "multiple CA" category).
  - This inconvenient step need only be carried out once.

# Single CA: Validation

**Validation:** The mechanism by which a CA issues a certificate to some party Bob must also be very carefully controlled.

- **Example:**
  - Bob may have to show up in person with a copy of his public key $pk_B$ along with identification proving that his name (or his email address) is what he claims.

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  - Only then would the CA issue the certificate.

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- **Validation levels:**
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     - Is validated by proving some control over a DNS domain.
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     - The organization's actual existence as a legal entity.
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     - Proves the legal entity of the owner.
     - Is signed by a CA key that can issue EV certificates.
     - EV certificates can be issued only by a subset of CAs.

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- Parties completely trust the CA to issue certificates only when appropriate.
  - Suppose Alice receives a $\text{Cert}_{CA \to B}$ certifying that $pk_B$ is Bob's public key.
  - Then, Alice accepts this assertion as valid.
  - Uses $pk_B$ as Bob's public key.

- Thus a detailed verification process is very crucial.

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- CA's verification process can be insufficient for Alice.
  - Suppose the CA asks for only one form of identification.
  - But Alice prefers two.

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- CA's verification process can be insufficient for Alice.
- Single point of failure for the entire system.
  - The CA may be *corrupt*, or can be *bribed*, or even if the CA is merely lax with the way it protects its private key.
  - The legitimacy of issued certificates may then be called into question.

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- Inconvenient for all parties to have to contact one CA.

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  - The security of her communication is ultimately only as good as the least-secure CA that she trusts.
- **Example:**
  - Suppose Alice trusts two CAs, $CA_1$ and $CA_2$.
  - Assume $CA_2$ is corrupted by an adversary.
  - This adversary will not be able to forge certificates issued by $CA_1$.
  - However, it will be able to issue fake certificates in the name of $CA_2$ for any identity/public key of its choice.

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  - The list of pre-configured CAs includes some reputable, well-established companies along with other, newer companies whose trustworthiness cannot be easily established.
  - *Therefore the user needs to manually configure their settings so as to only accept certificates from CAs the user trusts.*

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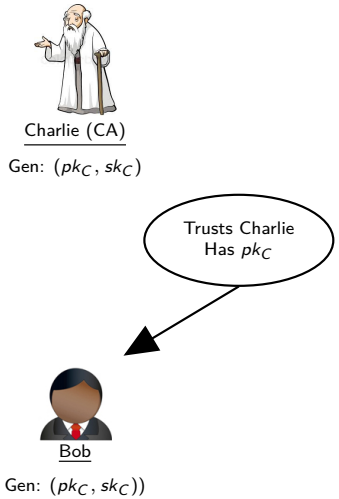

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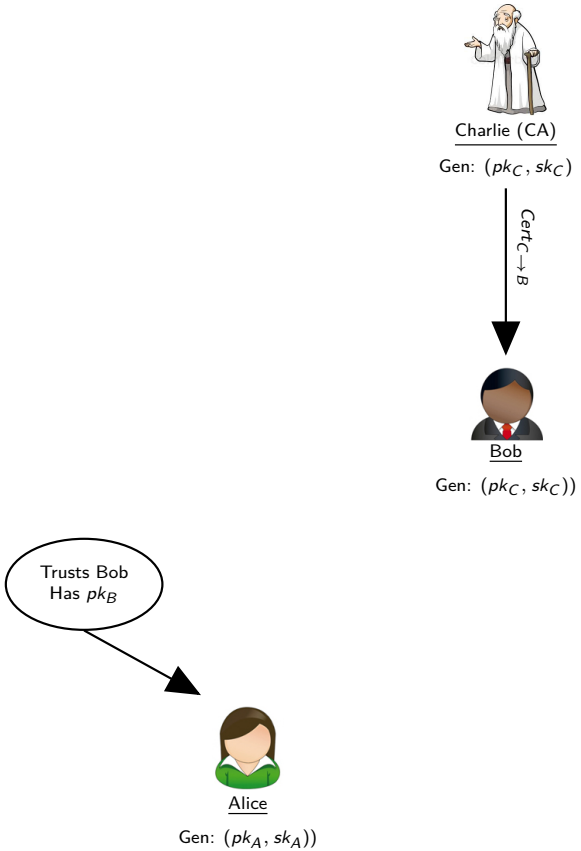

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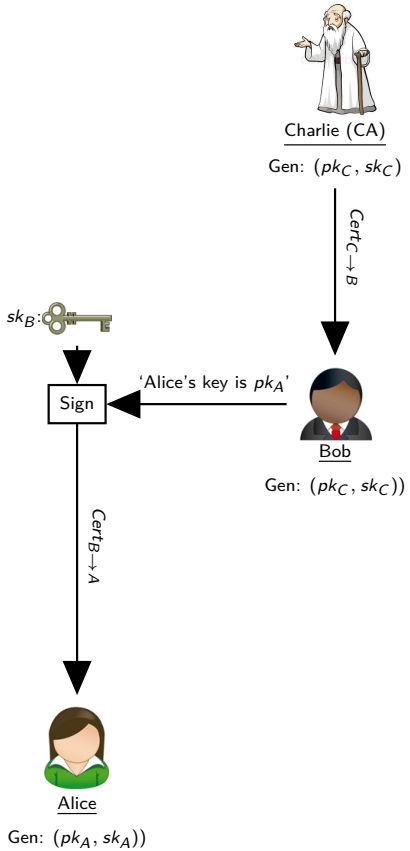

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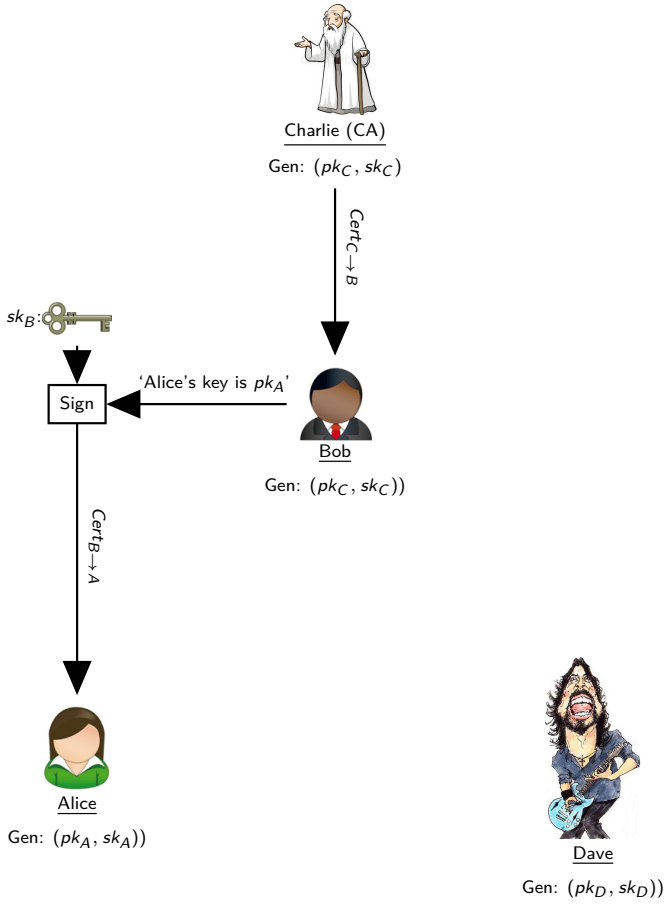

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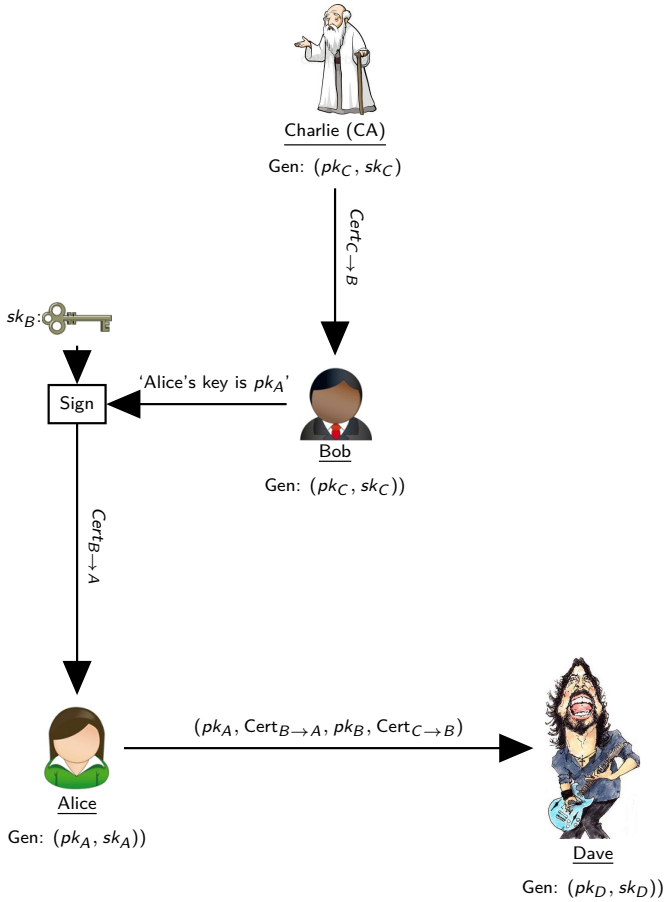

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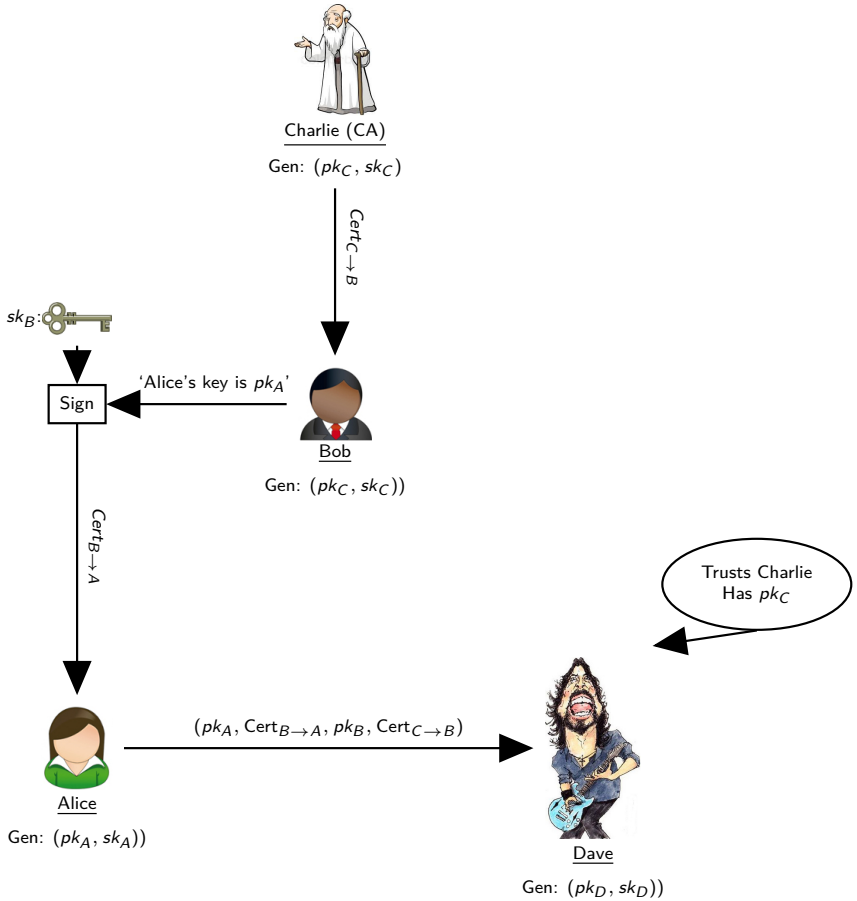

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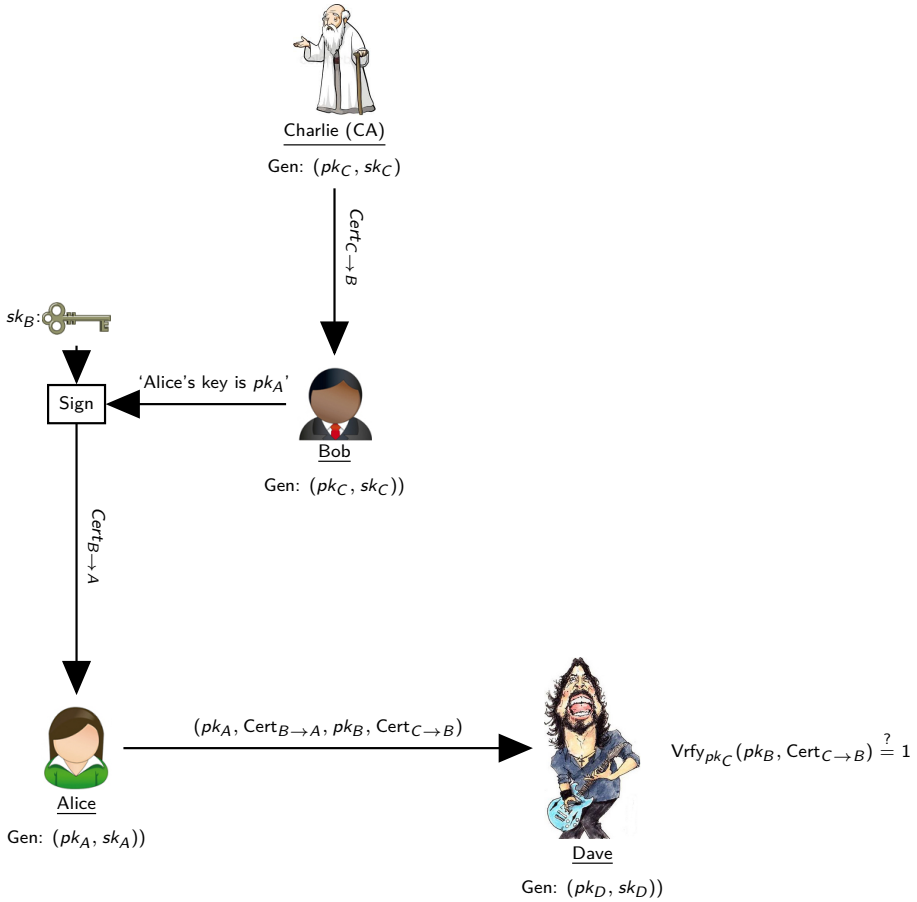

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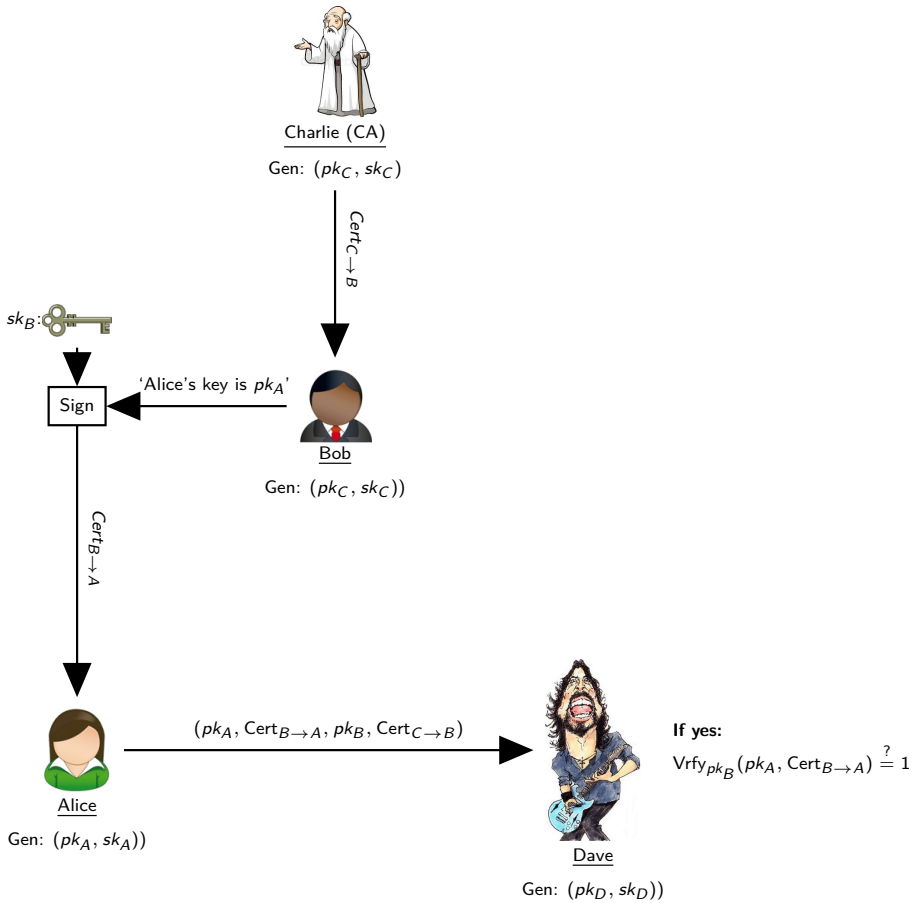

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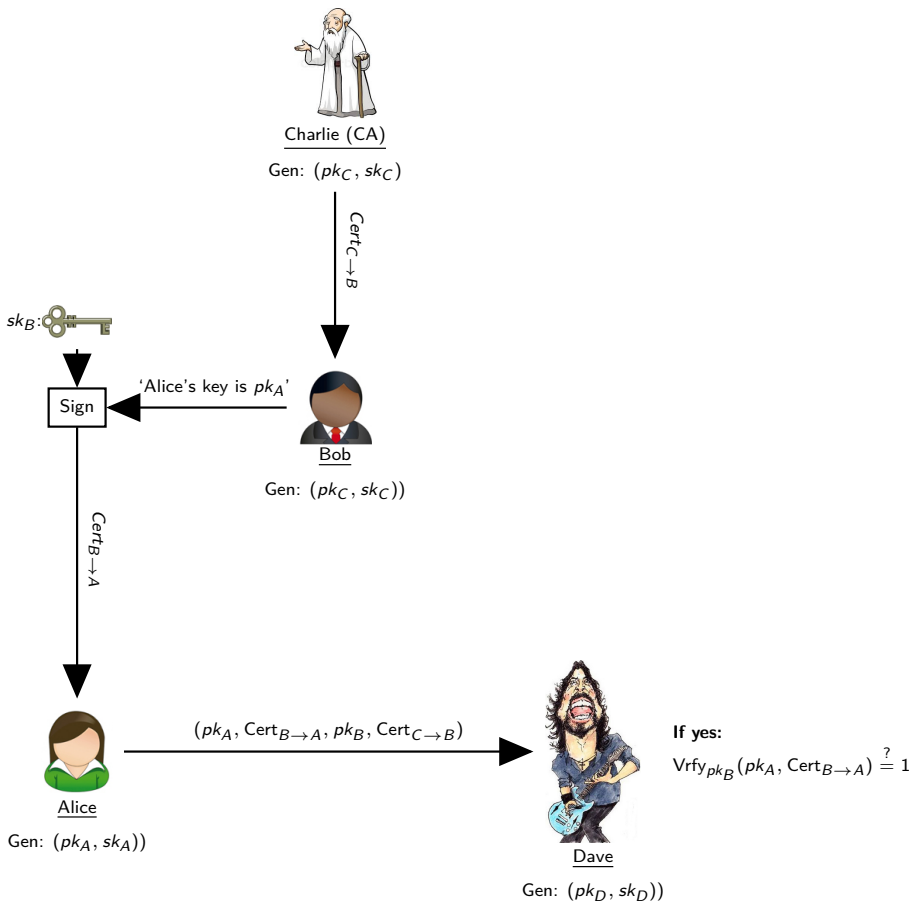


Thus, if Dave trusts Charlie then Dave may accept $pk_A$.

# Delegation and Certificate Chains

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- When Charlie signs a certificate for Bob, Charlie is, in effect, delegating his ability to issue certificates to Bob.

- Bob can now act as a proxy for Charlie, issuing certificates on Charlie's behalf.

# CA-based PKI

- Imagine one "root" CA and $n$ "second-level" CAs $CA_1, \ldots, CA_n$.
- Root CA: Can issue certificates for each $CA_i$, $1 \leq i \leq n$.
- Each $CA_i$: Then can issue certificates for other entities holding public keys.

# CA-based PKI: Pros and Cons

**Pros:**

- Eases the burden on the root CA.
- Makes it more convenient for parties to obtain certificates.
  - May now contact the second-level CA who is closest to them.

# CA-based PKI: Pros and Cons

**Pros:**

- Eases the burden on the root CA.
- Makes it more convenient for parties to obtain certificates.

**Cons:**

- But managing these second-level CAs may be difficult.
- There are now more points of attack in the system.

# Outline

# Invalidating Certificates

- Certificates generally should not be valid indefinitely.

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- **Example 1:**
  - An employee may leave a company.
  - In which case (s)he should no longer receive encrypted communication from others within the company.

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- **Example 2:**
  - A user's private key might also be stolen.
  - At which point the user (assuming they know about the theft) will want to generate a new key-pair and have the old public key removed from circulation.

# Invalidating Certificates

- Certificates generally should not be valid indefinitely.
- $\therefore$ we need a way to render previously issued certificates invalid.
- Approaches for handling these issues are varied and complex.
- We will only mention two relatively simple ideas.
- Improving these methods is an active area of real-world network-security research.

# Expiration

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- A user must contact the CA to get a new certificate issued whenever their current one expires.
- The CA then verifies the identity/credentials of the user again before issuing another certificate.

# Expiration

- Provides a very coarse-grained solution to the problem.
  - Suppose an employee leaves a company the day after getting a certificate.
  - Also assume that the issued certificate expires one year after its issuance date.
  - Then this employee can use his or her public key illegitimately for an entire year until the expiry date passes.
  - For this reason, this approach is typically used in conjunction with other methods such as **revocation**.

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- For simplicity, assume a single CA (can be generalised).
- There are many different ways revocation can be handled.
- One possibility: Every certificate includes a serial number, i.e.,

$$\mathrm{Cert}_{C\to B} \stackrel{\mathrm{def}}{=} \mathrm{Sign}_{sk_C}(\text{'Bob's key is } pk_B\text{'}, \#\#\#),$$

where $\#\#\#$ represents the serial number of this certificate.

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  - signs the CRL and the current date.
- The signed CRL is then widely distributed or is made available to potential verifiers.

# Revocation

- $\mathrm{Vrfy}_{pk_C}(\mathrm{Cert}_{C \to B}) \stackrel{?}{=} 1$:
  - Is the signature valid?
  - Does the serial number appear on recent CRL?
  - Verify the CA's signature on the revocation list itself.

# Outline

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- A formal analysis of TLS is the subject of active research.

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- As of April 2016, all major web browsers support TLS 1.0, 1.1, and 1.2, and have them enabled by default.

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- **Note:** TLS allows for clients to authenticate to servers.
- However, it is primarily used only for authentication of servers to clients because only servers typically have certificates.

# TLS: Handshake Protocol

Client ($C$)

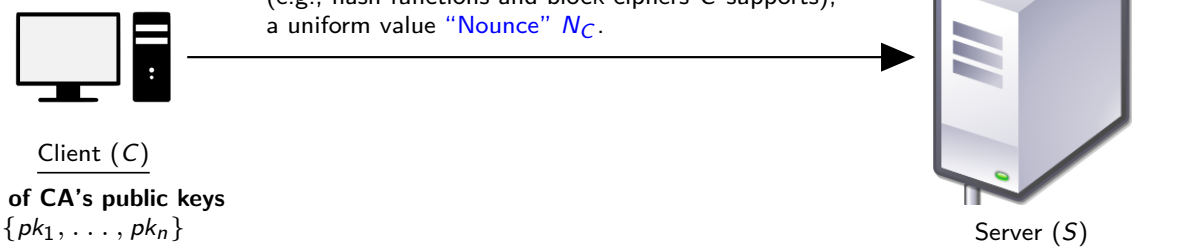
**Set of CA's public keys**
$\{pk_1, \ldots, pk_n\}$

Server ($S$)

$(pk_S, sk_S)$ for **KEM**
a certificate $\text{Cert}_{i \to S}$
issued by one of the CAs
whose public key $C$ knows.

**KEM:** Key Encapsulation Mechanism

# TLS: Handshake Protocol



# TLS: Handshake Protocol

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**Message includes:**
latest version of the protocol it supports
as well as an appropriate ciphersuite.
In addition, it sends its key $pk_S$,
its certificate $\text{Cert}_{i \to S}$, and
its own uniform value $N_S$.

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# TLS: Handshake Protocol

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$\mathsf{Vrfy}_{pk_i}(pk_S, \mathsf{Cert}_{i \to S}) \stackrel{?}{=} 1$
**If yes:** verifies the certificate (i.e., expired or revoked)
**If successful:** $pk_S$ is $S$'s key
$(c, \mathsf{pmk}) \leftarrow \mathit{Encaps}_{pk_S}(1^n)$
(pmk: *pre-master key*).

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pmk is used to derive a *master key* mk using a key-derivation function applied to pmk, $N_C$, and $N_S$.
$k_C, k'_C, k_S, k'_S \leftarrow \text{PRG}(\text{mk})$
$\tau_C \leftarrow \text{MAC}_{\text{mk}}(\text{transcript})$
transcript: messages exchanged thus far.

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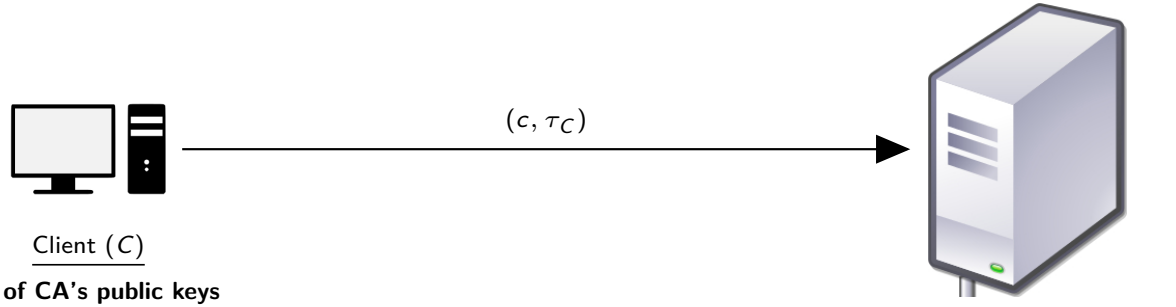

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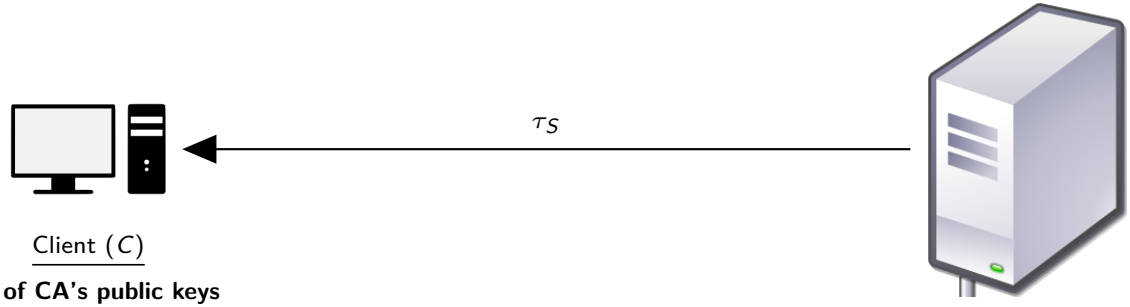
pmk $:= \text{Decaps}_{sk_S}(c)$
from pmk derive mk and $k_C, k'_C, k_S, k'_S$
as the client did.
**If** $\text{Vrfy}_{\text{mk}}(\text{transcript}, \tau_C) \neq 1$, then **abort**
**Else:** $\tau_S \leftarrow \text{MAC}_{\text{mk}}(\text{transcript}')$
transcript': messages exchanged thus far.

# TLS: Handshake Protocol



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At the end of a successful execution of the handshake protocol, $C$ and $S$ share a set of four symmetric keys $k_C, k'_C, k_S, k'_S$.

# TLS: Handshake Protocol

- TLS 1.2 supports two KEMs:
  1. CDH/DDH-based KEM or
  2. the RSA-based encryption scheme PKCS #1 v1.5

# The Record-Layer Protocol

- Once keys have been agreed upon by $C$ and $S$, the parties use those keys to encrypt and authenticate all their subsequent communication.
- $C$ uses $k_C$ (resp., $k'_C$) to encrypt (resp., authenticate) all messages it sends to S.
- Similarly, $S$ uses $k_S$ (resp., $k'_S$) to encrypt (resp., authenticate) all the messages it sends to $C$.
- Sequence numbers are used to prevent replay attacks.

# Books Consulted

1. Chapter 11 & 12 of *Introduction to Modern Cryptography* by Jonathan Katz and Yehuda Lindell, 2nd Edition, Chapman & Hall/CRC.

2. OpenSSL
   - For installation visit this "stackoverflow" page.
   - For generating certificates/basic instructions visit this "stackoverflow" page.

Thank You for your kind attention!

# Questions!!