Secure Communications

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Also part of exam revision

Contents

Asymmetric Encryption Primer

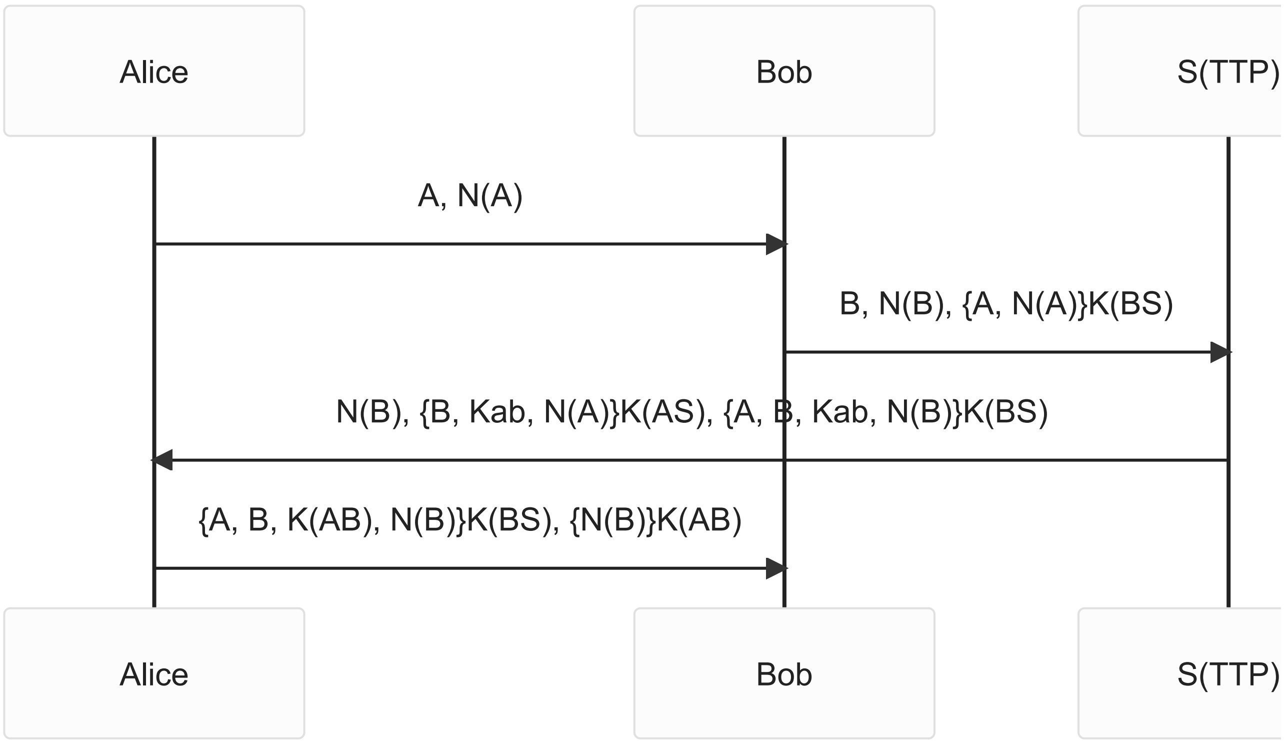
The concept of asymmetric encryption comes from several users wanting to communicate securely with the same ***shared*** *secret key*. In cases like Google for example, it would be unrealistic for them to create and keep a secure secret key for all users

Online Trusted Third Party

An **Online TTP** is a trusted third party entity that hosts secret keys for Users.

Example using *Yahalom* protocol

Say we have users $U_1, U_2, U_3, \ldots, U_n, \ldots$
Each user U_i has a shared secret key K_i with the TTP.
Users U_i and U_j can establish a key K_{ij} with the help of the TTP.


Alice
Bob
S(TTP)
A, N(A)
B, N(B), {A, N(A)}K(BS)
N(B), {B, Kab, N(A)}K(AS), {A, B, Kab, N(B)}K(BS)
{A, B, K(AB), N(B)}K(BS), {N(B)}K(AB)
Alice
Bob
S(TTP)

Let's break this down message-by-message:
0. Before any messages start:
- *Alice* has **secret key** k_{AS}
- *Bob* has **secret key** k_{BS}
- *The Trusted Third Party Server **S(TTP)*** has *Alice* and *Bob's* **secret keys** k_{AS}, k_{BS}

1. *Alice* sends A, N_A to *Bob*
   - *Alice* sends her identifier, A, and her *nonce* N_A. A *nonce* is a randomly generated number, used to *salt* messages. Mainly to prevent *replay* attacks on hash functions.
2. *Bob* sends $B, N_B, (A, N_A)k_{BS}$ to the *TTP*
   - *Bob* sends:

        - His identifier, B
        - His nonce, N_B, generated upon receiving *Alice's* message
        - The message (A, N_A) (*Alice's previous message*) encrypted under *Bob's* secret key k_{BS}

3. *TTP* sends $N_B, (B, k_{AB}, N_A)k_{AS}, (A, B, k_{AB}, N_B)k_{BS}$ to *Alice*
    - *TTP* sends:
        - *Bob's* nonce, N_B
        - The message (B, k_{AB}, N_A) encrypted under *Alice's* secret key k_{AS}
            - *Bob's* identifier, B
            - The *TTP's* **shared** secret key (also called session key), k_{AB}
            - *Alice's* nonce, A
            - **Note**: Alice *can* decrypt this message (it's her secret key)
        - The message (A, B, k_{AB}, N_B) encrypted under *Bob's* secret key k_{BS}
            - *Alice's* identifier, A
            - *Bob's* identifier, B
            - The *TTP's* shared secret key, k_{AB}
            - *Bob's* nonce, B
            - **Note**: Alice *cannot* decrypt this message (it's *Bob's* secret key)
4. *Alice* sends $(A, B, k_{AB}, N_B)k_{BS}, (N_B)k_{AB}$
    - *Alice* sends:
        - The message (A, B, k_{AB}, N_B) encrypted under *Bob's* secret key k_{BS}
            - *Alice's* identifier, A
            - *Bob's* identifier, B
            - The *TTP's* shared secret key, k_{AB}
            - *Bob's* nonce, B
            - **Note**: this is the non-decryptable message the *TTP* sent Alice before
        - *Bob's* nonce, N_B, encrypted under the *shared* secret key, k_{AB}
            - This is sent as a confirmation message

- Bob now knows both parties have the shared secret key, and can encrypt and decrypt messages with it

Negatives of TTP

This relies on trust within the *TTP* to generate secure keys and not to leak info that can be used to crack these keys. Under the above protocol, even if the messages weren't further encrypted, all an attacker could learn is Bob and Alice are talking, their nonces, and a bunch of encrypted rubbish useless without knowing the secret keys used. Even with one key leaked, the entire secure communications (*namedrop* 😎) process could be compromised.

Public Key Encryption

The idea of public-key encryption is that each user has two keys - a *public key* and a *private key*. The private key is similar to secret keys in the above example, but the difference is the *public key* is **known to everyone**. Public Key Encryption means we can establish a shared secret key without a TTP!

If we define a key generation algorithm $G :\rightarrow \mathcal{K} \times \mathcal{K}$,

and an encryption algorithm $E : \mathcal{K} \times \mathcal{M} \rightarrow \mathcal{C}$,
(when ***public*** **key** applied to **message**, produces **ciphertext**)

and a decryption algorithm $D : \mathcal{K} \times \mathcal{C} \rightarrow \mathcal{M}$,
(when ***private*** **key** applied to **ciphertext**, produces **message**)

$\forall (sk, pk) \in G$, and $\forall m \in \mathcal{M}$, $D(sk, E(pk, m)) = m$
Translation
For all *secret keys* (sk) and *public keys* (pk) that can be generated by G, (noting these keys should be generated as a *pair*, not just any random combo)

and for all *messages* (m) in the possible *message space* ($\mathcal{M}$),
(example $\mathcal{M}$: "english sentences under 15 words")

If we put m and pk into the *encryption* algorithm E, and put the result of that into the *decryption* algorithm D, alongside the corresponding *secret key* sk, we will get m in plaintext back out.

It is important $sk_{Bob} \neq pk_{Bob}$!

Evil Necessary Number Theory

Relative primes and $\phi(n)$

a and b in $\mathbb{Z}$ are **relative primes** if they have no common factors. The *Euler* function $\phi(n)$ is the **number of elements that are relative primes** with n.

$$\phi(n) = |(m|0 < m < n \text{ and } \gcd(m, n) = 1)|$$

For a prime p, $\phi(p) = p - 1$.
For primes p and q, $\phi(p \cdot q) = (p - 1)(q - 1)$

$\mathbb{Z}_n$

If we define $n \in \mathbb{N}$, we can define $\mathbb{Z}_n = \{0, \ldots, n - 1\}$. Then,
$\forall a \in \mathbb{Z}, \forall b \in \mathbb{Z}_n, a \equiv b (\text{mod } n) \iff \exists k \in \mathbb{N}. a = b + k \cdot n$
Translation

- $n \in \mathbb{N}$
  - For any natural number n
- $\mathbb{Z}_n = \{0, \ldots, n - 1\}$
  - The set of integers *modulo n*, or in English, the set of all possible *remainders* when you divide any integer (from $\mathbb{Z}$) by n.
- $\forall a \in \mathbb{Z}, \forall b \in \mathbb{Z}_n,$
  - For all integers a (from $\mathbb{Z}$). and all integers (from $\mathbb{Z}_n$ this time) b,
- $a \equiv b (\text{mod } n)$
  - a has the same *remainder* as b when dividing by n (a is *congruent modulo* to b)
- $\iff$
  - IF AND ONLY IF
- $\exists k \in \mathbb{N}.$
  - There is a natural number k that exists such that...
- $a = b + k \cdot n$
  - a is equal to b plus k lots of n

Modular inversion

The *inverse* of $x \in \mathbb{Z}_n$ is $y \in \mathbb{Z}_n$ such that $x \cdot y \equiv 1 (\bmod n)$.
We refer to this inverse as x^{-1}.

Formal Theorem:
Let $n \in \mathbb{N}$. Let $x \in \mathbb{Z}_n$. x has an inverse (x^{-1}) in Z_n if and only if gcd(x, n) = 1

$\mathbb{Z}_n^*$

We define $\mathbb{Z}_n^* = \{x \in \mathbb{Z}_n | \gcd(x, n) = 1\}$
(For example, $Z_{12} = \{1, 5, 7, 11\}$)

We can also see that $|\mathbb{Z}_n^*| = \phi(n)$

Euler's Theorems

$\forall n \in \mathbb{N}, \forall x \in \mathbb{Z}_n^* \text{ if } \gcd(x, n) = 1 \text{ then } x^{\phi(n)} \equiv 1 (\bmod n)$

For all integers n, and all elements of $\mathbb{Z}_n^*$ (which we'll call x), if the greatest common factor between x and n is 1 - if they're coprime and share no other common factors - then x to the power of the size of $\mathbb{Z}_n^*$ divided by n gives a remainder of 1.

Intractable Problems

Intractable problems are problems for which there is no known polynomial time algorithm that solves them. They can be brute forced, but this is unreliable. We can build cryptographic schemes off these problems. Some intractable problems are:

- Factoring
- RSAP
- Discrete Log
- Diffie-Hellman Protocol

Factoring

- **Input**: $n \in \mathbb{N}$
- **Output**: $p_1, p_2, \ldots, p_m$ primes *such that* $n = p_1 \cdot p_2 \cdot \cdots \cdot p_m$

RSAP

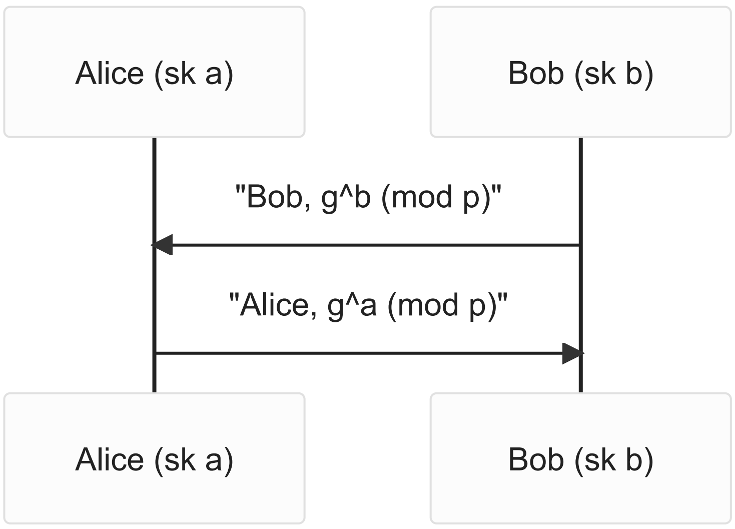
- **Inputs**:
  - n *such that* $n = p \cdot q$ with $2 \leq p, q$ primes
  - e *such that* $\gcd(e, \phi(n)) = 1$
  - $m^e \bmod n$
- **Output**: m

Discrete Log

- **Input**: prime p, generator g of $\mathbb{Z}_p^*$, $y \in \mathbb{Z}_p^*$
- **Output**: x *such that* y = $g^x \pmod p$

Diffie-Hellman Protocol

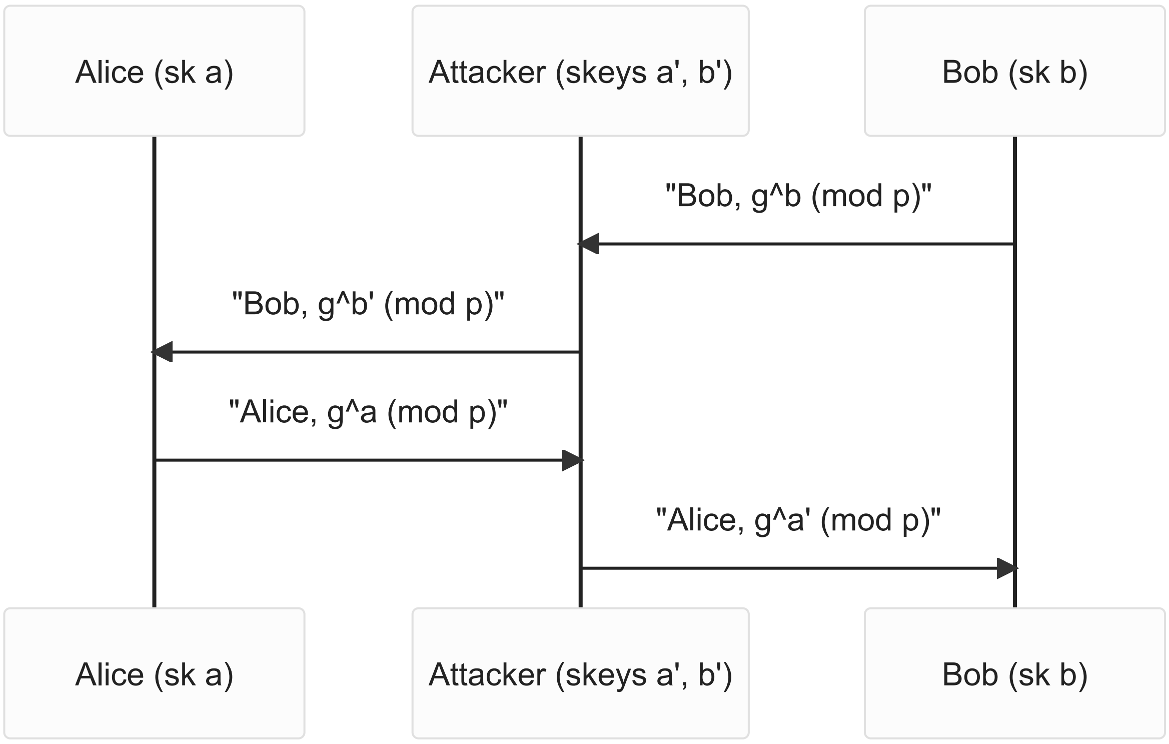
DHP is very hard in $\mathbb{Z}_n^*$ (link)
We fix a very large prime p, and a generator g of $\mathbb{Z}_n^*$, and do the following



Both *secret keys* a and b are computed by picking a number randomly from g $(a \xleftarrow{r} \{1, \ldots, p-1\}, b \xleftarrow{r} \{1, \ldots, p-1\})$
The *public keys* in this are g^a and g^b. The *shared private key* K_{AB} (session key) is $g^{ab} \pmod p$, which can be computed either $(g^b)^a \pmod p$ for *Alice*, who knows a, or as $(g^a)^b \pmod p$ for *Bob*, who knows b. The beauty of DHP is this private key is never sent over messages, and is computed at runtime for each message.

MiTM attack on Diffie-Hellman

DHP is vulnerable to a Man-in-The-Middle attack. It works by the attacker tampering with the (encrypted) communications to force their own *private keys* into the exchange, meaning they can encrypt and decrypt messages to *Alice* and *Bob*. This results in both parties independently using a *different* "shared" secret key, so the attacker must remember to switch if he is to impersonate the other party.



RSA Trapdoor Permutation

- $G_{RSA}() = (pk, sk)$ where $pk = (N, e)$ and $sk = (N, d)$
  and $N = p \cdot q$ with p, q random primes
  and $e, d \in \mathbb{Z}$ *such that*. $e \cdot d \equiv 1 \mod \phi(N)$
- $M = C \in \mathbb{Z}_N$
- $RSA(pk, x) = x^e \mod N$ where $pk = (N, e)$
- $RSA^{-1}(sk, x) = x^d \mod N$ where $sk = (N, d)$
- Consistency: $\forall (pk, sk) = G_{RSA}(), \forall x, RSA^{-1}(sk, RSA(pk, x)) = x$
  Proof: Let $pk = (N, e)$, $sk = (N, d)$. and $x \in \mathbb{Z}_N$. Easy case where x and N are relatively prime

$$\begin{aligned} RSA^{-1}(sk, RSA(pk, x)) &= (x^e)^d \mod N \\ &= x^{ed} \mod N \\ &= x^{1+k\phi(N)} \mod N \qquad \text{(for some integer } k\text{)} \\ &= x \cdot x^{k\phi(N)} \mod N \\ &= x \cdot (x^{\phi(N)})^k \mod N \\ &= x \mod N \end{aligned}$$

(by Euler's theorem, since x and N are relatively prime)

Raw RSA

RSA is deterministic! It is not secure against chosen plaintext attacks. Additionally, if we have an "idea" on what the message "is", we can easily tweak a few numbers to get slightly different outcomes to analyse.

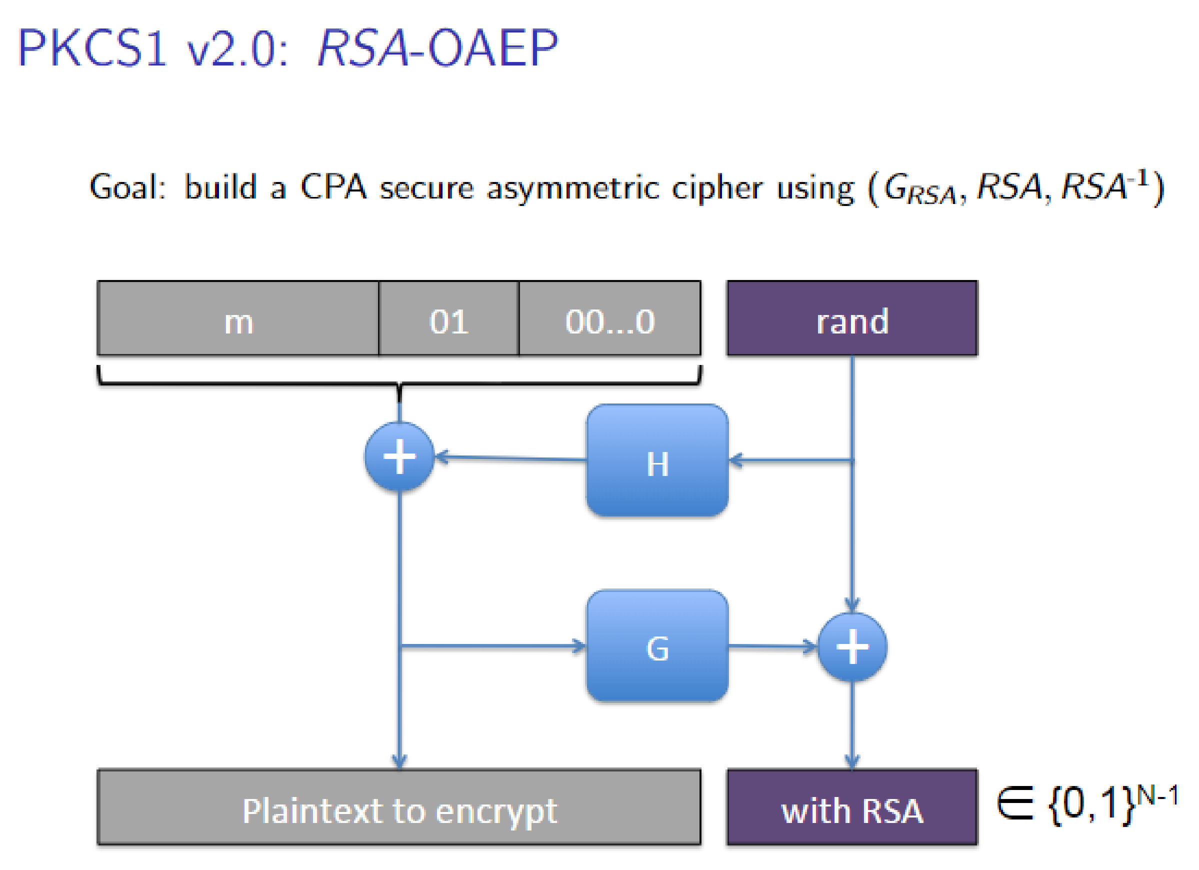
By using Trapdoor RSA, we can build a Chosen Plaintext Attack (CPA) resistant asymmetric cipher using (G_{RSA}, RSA, RSA^{-1})

Let (E_S, D_S) be a symmetric encryption scheme over $(\mathcal{M}, \mathcal{C}, \mathcal{K})$
Let $H : \mathbb{Z}_N^* \to \mathcal{K}$

Build $(G_{RSA}, E_{RSA}, D_{RSA})$ as follows

- $G_{RSA}()$ as described above
- $E_{RSA}(pk, m)$:
    - pick random $x \in \mathbb{Z}_N^*$
    - $y \leftarrow RSA(pk, x) = x^e \mod N$
    - $k \leftarrow H(x)$ - $E_{RSA}(pk, m) = y \| E_S(k, m)$
    - $D_{RSA}(sk, y\|c) = D_S(H(RSA^{-1}(sk, y)), c)$

PKCS1 v2.0: *RSA*-OAEP



PKCS1 v2.0: *RSA*-OAEP

Goal: build a CPA secure asymmetric cipher using (G_{RSA}, RSA, RSA^{-1})

ElGamal (EG)

- Fix prime p, and generator $g \in \mathbb{Z}_p^*$
- $\mathcal{M} = \{0, \dots, p-1\}$ and $\mathcal{C} = \mathcal{M} \times \mathcal{M}$
- $G_{EG}() = (pk, sk)$ where $pk = g^d \mod p$ and $sk = d$ and $d \leftarrow \{1, \dots, p-2\}$
- $E_{EG}(pk, x) = (g^r \mod p, m \cdot (g^d)^r \mod p)$ where $pk = g^d \mod p$ and $r \leftarrow \mathbb{Z}$
- $D_{EG}(sk, x) = e^{d^{-1}} \cdot c \mod p$ where $x = (e, c)$
- Consistency: $\forall (pk, sk) = G_{EG}(), \forall x, D_{EG}(sk, E_{EG}(pk, x)) = x$
  Proof: Let $pk = g^d \mod p$ and $sk = d$

$$\begin{aligned} D_{EG}(sk, E_{EG}(pk, x)) &= (g^r)^{d^{-1}} \cdot m \cdot (g^d)^r \mod p \\ &= m \mod p \end{aligned}$$

Message Authentication Codes

In larger applications, we don't just need confidentiality of messages, but also *message integrity*. Message authentication codes aim to ensure a message is actually coming from who it says it is - again, using *secret keys*.

Formally, a **MAC** is a pair of algorithms S, V *(sign, verify)* defined over $\mathcal{K}, \mathcal{M}, \mathcal{T}$ *(key-space, message-space, "tag-space")*

- $S : \mathcal{K} \times \mathcal{M} \to \mathcal{T}$
- $V : \mathcal{K} \times \mathcal{M} \times \mathcal{T} \to \{\top, \bot\}$
- Consistency: $V(k, m, S(k, m)) = \top$

The message is *unforgeable* as long as k is not known to an attacker.

Building MACs using block ciphers

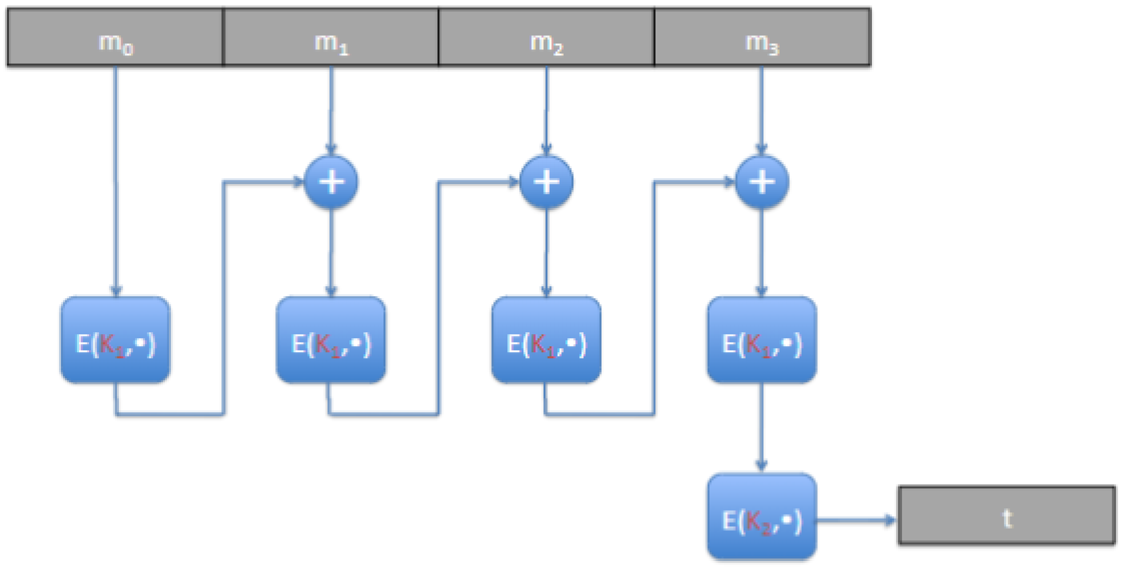
We can draw parallels between $S(k, m)$ and $E(k, m)$

$$\begin{aligned} V(k, m, t) &= \text{if } m = D(k, t) \\ &= \text{then return True} \\ &= \text{else return False} \end{aligned}$$

The problem is block ciphers can usually only process either 128 or 256 bit

ECBC-MAC

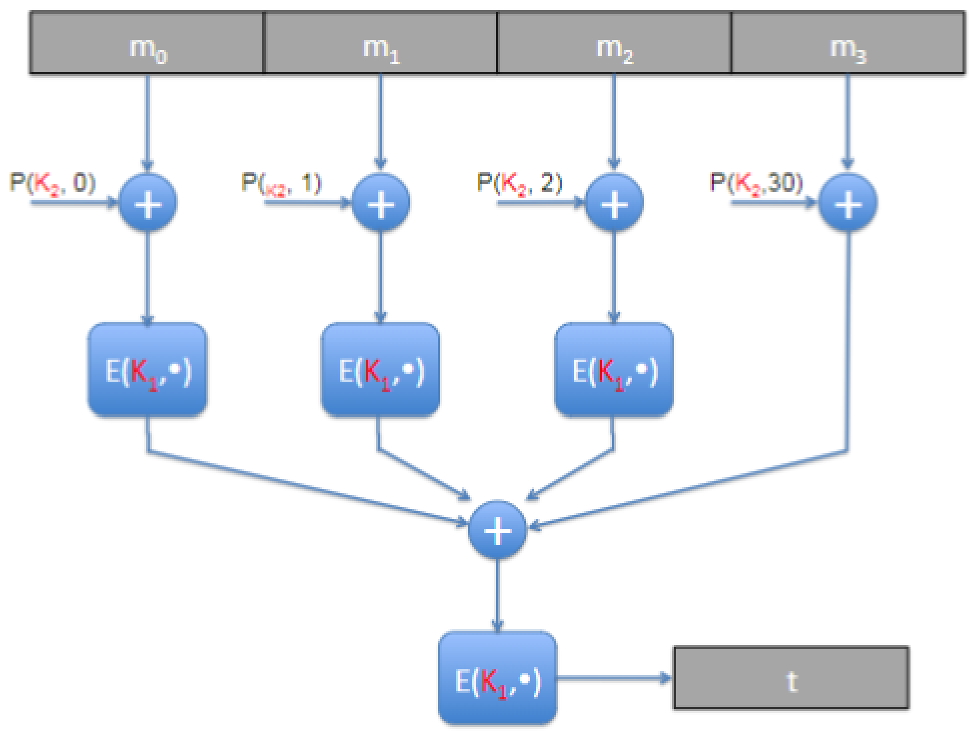
A form of CBC mode but the final message is encrypted with a different key k_2
.



- $E: \ \mathcal{K} \times \{0,1\}^n \to \{0,1\}^n$ a block cipher
- $ECBC\text{-}MAC : \mathcal{K}^2 \times \{0,1\}^* \to \{0,1\}^n$

PMAC

PMAC



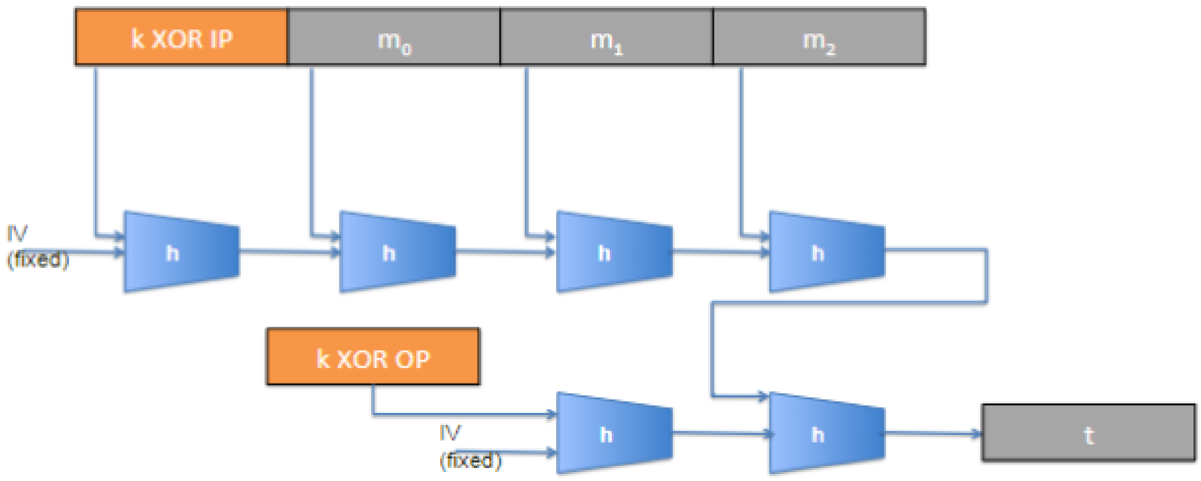
- $E : \mathcal{K} \times \{0,1\}^n \to \{0,1\}^n$ a block cipher
- $P : \mathcal{K} \times \mathbb{N} \to \{0,1\}^n$ any easy to compute function
- $PMAC : \mathcal{K}^2 \times \{0,1\}^* \to \{0,1\}^n$

HMAC

A MAC built from cryptographic hash functions

$$\mathrm{HMAC}(k, m) = H(k \oplus OP || H(k \oplus IP || m))$$

where IP and OP are publicly known padding constants. Examples of HMAC are `SSL`, `IPsec`, and `SSH`.



Authenticated Encryption

We aim to *simultaneously* provide confidentiality, integrity, and authenticity. We do this by combining decryption with integrity verification in one step by computing the MAC on the ciphertext.

Digital Signatures

The goal of digital signatures are to ensure verifiability.

Advantages over MAC

- Signatures are *publically verifiable* - in a MAC setting, only Bob can verify Alice's signature
- They are transferable
- They provide *non-repudiation* - Alice cannot later claim she never signed a document with her secret key if the signature has been generated, as only she can sign it

Textbook RSA Signatures

- $G_{RSA}() = (pk, sk)$ where $pk = (N, e)$ and $sk = (N, d)$
  and $N = p \cdot q$ with p, q random primes
  and $e, d \in \mathbb{Z}$ st. $e \cdot d \equiv 1 \mod \phi(N)$
- $\mathcal{M} = \mathcal{C} = \mathbb{Z}_N$
- Signing: $S_{RSA}(sk, x) = (x, x^d \mod N)$ where $pk = (N, e)$

- Verifying:

  $$V_{RSA}(pk, m, x) = \begin{cases} \mathrm{T} & \text{if } m = x^e \mod N \\ \perp & \text{otherwise} \end{cases}$$

  where $sk = (N, d)$
- *such that* $\forall(pk, sk) = G_{RSA}(), \forall x, V_{RSA}(pk, x, S_{RSA}(sk, x)) = \mathrm{T}$
  Proof: exactly as proof of consistency of RSA encryption/decryption

The problem with textbook RSA signatures are that they do not provide *existential inforgeability*.
Suppose *Eve* has two valid signatures $\sigma_1 = M_1^d \mod n$ and $\sigma_2 = M_2^d \mod n$ from *Bob* on messages M_1 and M_2.
Eve can produce a new valid signature for *Bob* on the message $M_1 \cdot M_2$ by multiplying the two signatures together.

To prevent this, hash the messages *before* signing them. Hashing afterwards would allow *Eve* to just hash the 2 hashed signatures to forge this message.

Public Key Authenticity

How can we be sure someone's public key is *authentic*?

Public Key Distribution methods

Public Announcements

"Participants should just broadcast their public key".
These broadcasts could easily be forged without authenticity (which public keys are needed for!)

Publicly available directories

"Participants publish public key on public directories"
Same problem as above

Public-key authority

Similar to a TTP but for public keys. "Participants contact authority for each public key needed"

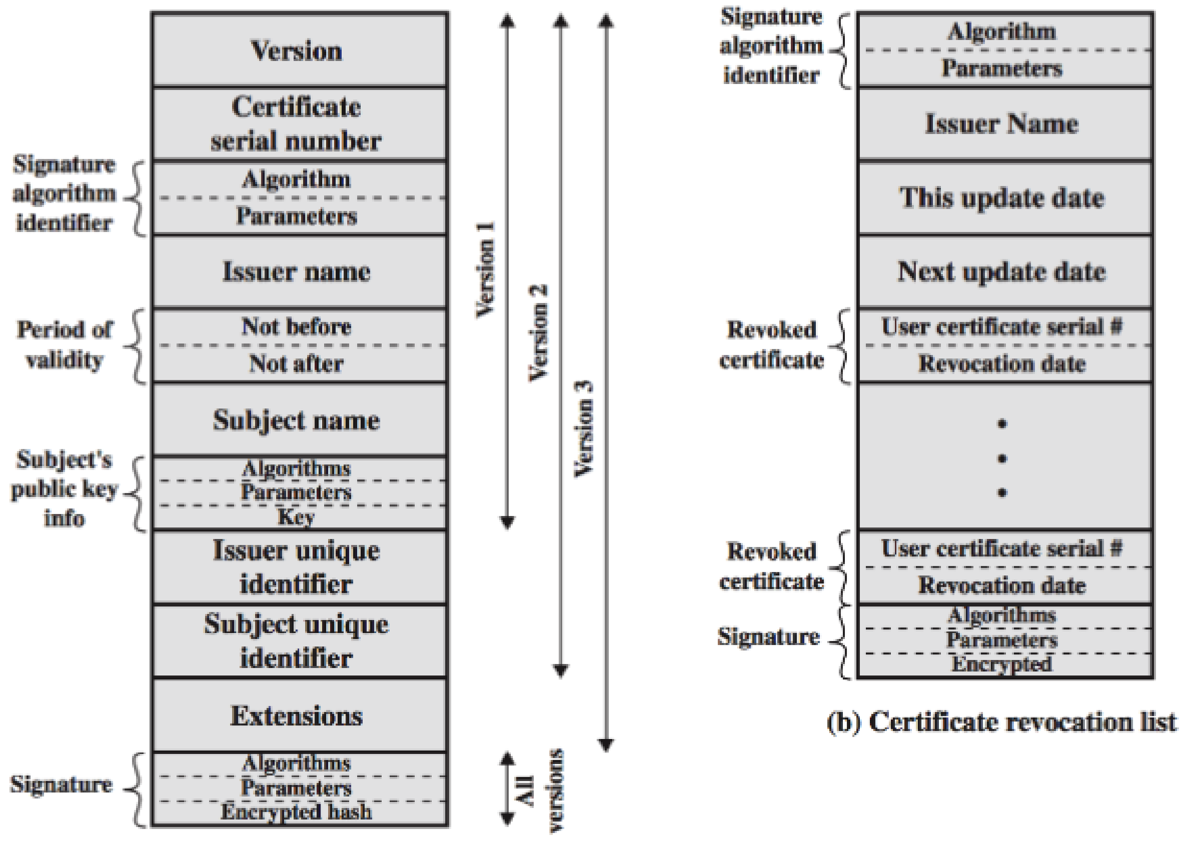
As long as the authority is trusted, this only has the issue of a major bottleneck on the authority(ies).

correct answer is ↓

Certificates

A certificate consists of a ***public key***, a ***subject*** identifying the key's *owner*, ***signature*** by the *certificate authority* on the key and subject binding them together.
Same trust issue as Public-key authority but avoids the bottleneck.

X.509 certificates



(a) X.509 certificate

X.509 is a standard used in many applications such as TLS. There are multiple levels of *certificate authorities*, all signing down, from a *root* certificate. Self-signed certificates are subject to MiTM attacks.

Revoking Certificates

If a *private key* has been *compromised*, the corresponding certificate needs to be revoked. X.509 adopts the ***Certificate Revocation List***, a list of known revoked certificates. The modern solution is ***Online Certificate Status Protocol*** - where the client will contact the server to check that the *certificate (/authority)* has not been revoked.

CA's can outsource the signing of certificates to other parties, which is why revocation is needed. This is also why the "chain of trust" exists, as if you revoke a CA, all the ones beneath them are revoked and will need to resign certificates.

SSL

See TLS. SSL was substituted by it in 1999. I don't think there's any examinable content on SSL specifically.

TLS

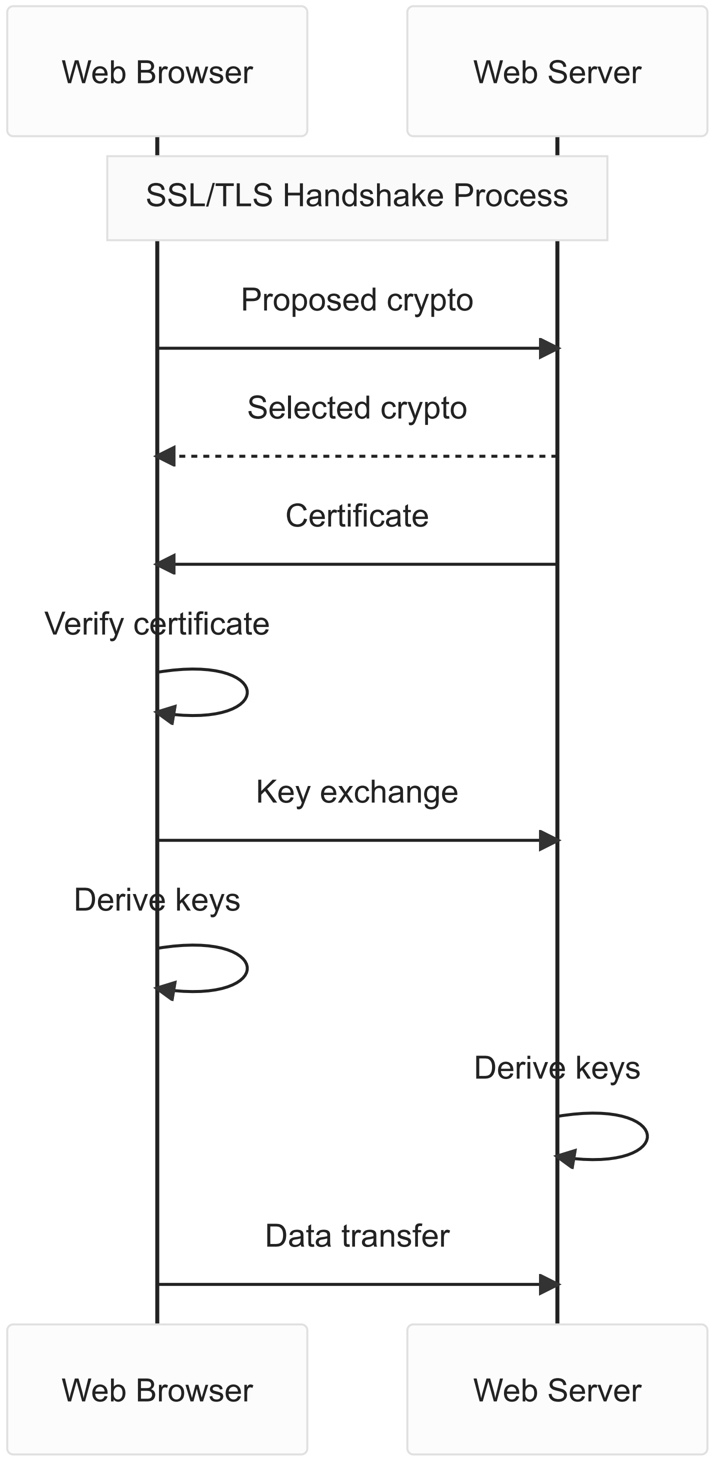
Goals of TLS

- End-to-End Confidentiality
  - Encrypt communication between client and server applications
- End-to-End Integrity
  - Detect corruption of communication between client and server applications
- Required server authentication
  - Identity of server always proved to client
- Optional client authentication
  - Identity of client optionally proved to server •
- Modular deployment
  - Intermediate layer between application and transport layers
  - Handles encryption, integrity, and authentication on behalf of client and server applications#

TLS Building Blocks

	Confidentiality	**Integrity**	**Authentication**
Setup	Public-key based key-exchange (RSA and DH)	Public-key digital signature (e.g., RSA)	Public-key digital signature (e.g., RSA)
Data transmission	Symmetric encryption (e.g., AES in CBC mode)	Hash-based MACs (e.g., HMAC using SHA256)	

TLS Overview



The browser sends the crypto algorithms it supports, and the server chooses the best one that it also supports and sends this back. It then sends back it's certificate, which the client verifies.
The client and the server, through a Basic Key Exchange, agree on a value R to exchange messages with.

Basic Key Exchange

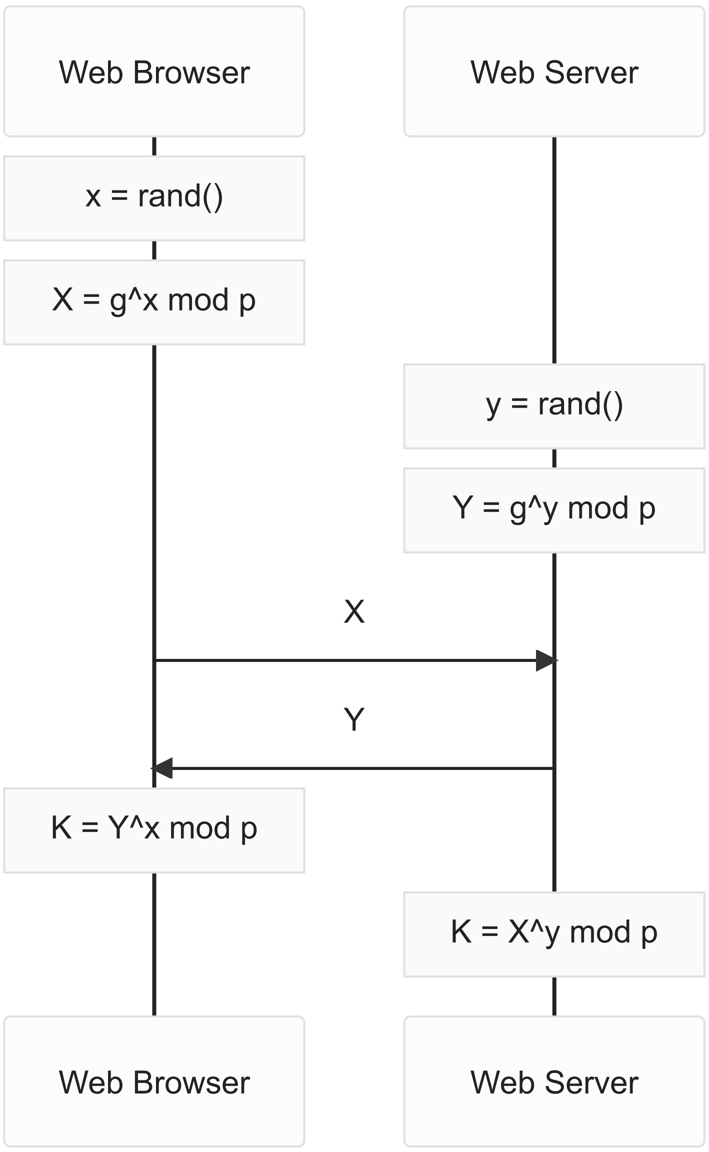
Sometimes called the *RSA key exchange* for historical reasons, the client generates a random secret value R. It encrypts R using the server's *public* *key* and sends across $C = E_{PK}(R)$, which the server decrypts to get the value of $R = D_{SK}(C)$.

Forward Secrecy

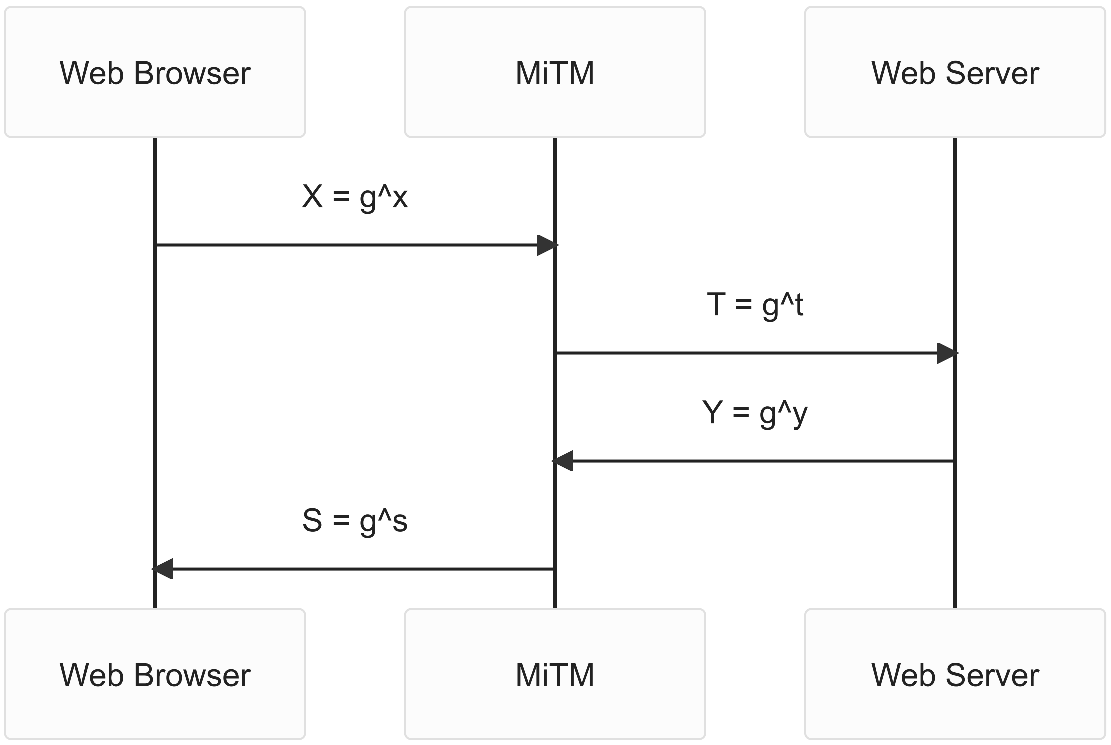
If the *secret key* SK gets compromised, all past messages can be decrypted, which is bad. To achieve forward secrecy, we use the Diffie-Hellman Key Exchange.

Diffie-Hellman Key Exchange

The public parameters are a prime p and generator g of $\mathbb{Z}_p$. The client generates random x and computes $X = g^x \mod p$, and the $Y = g^y \mod p$. Sending these between each other, they can both compute $K = g^{xy} \mod p$.

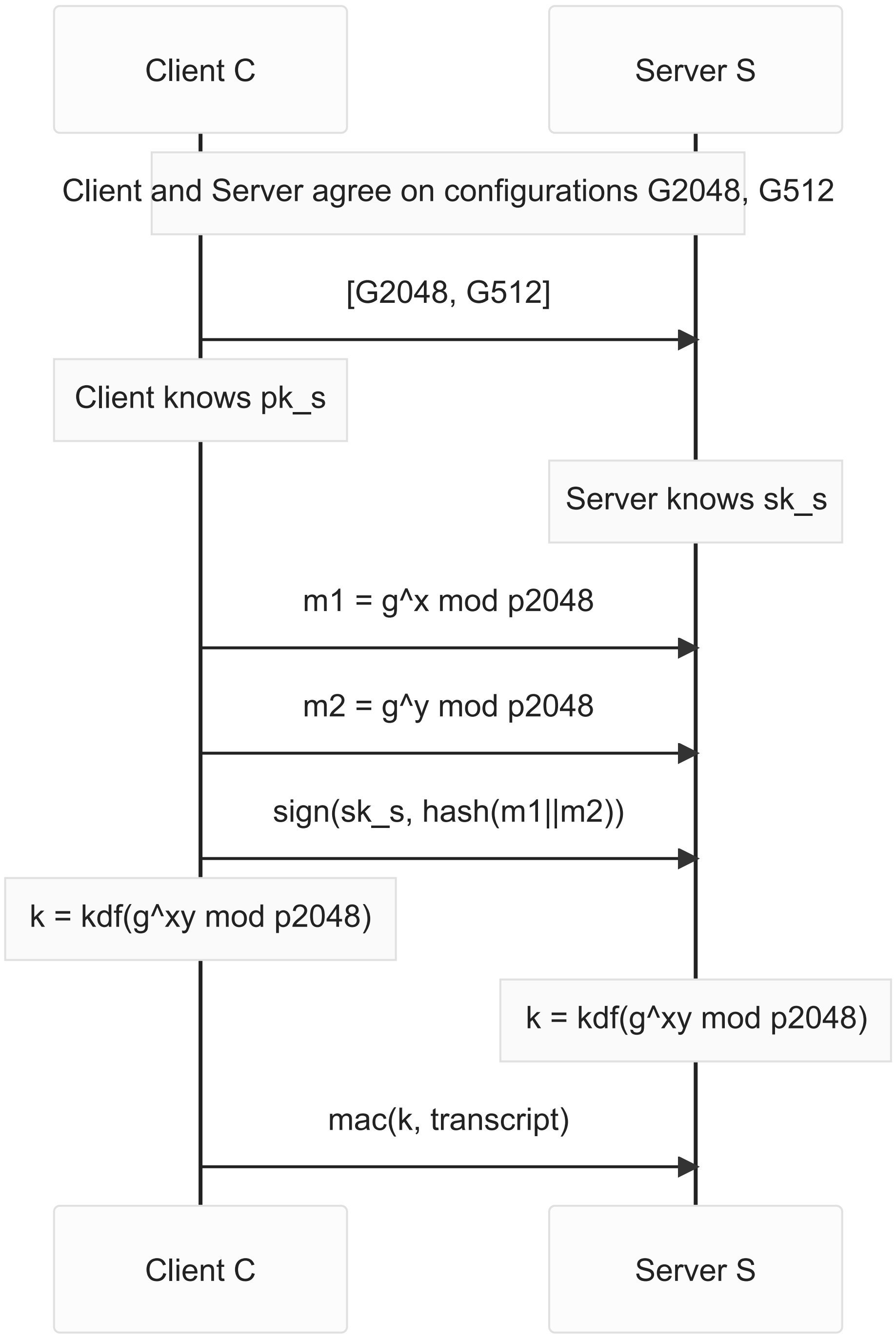


This is unfortunately subject to a MiTM attack through use of their own two keys t and s.



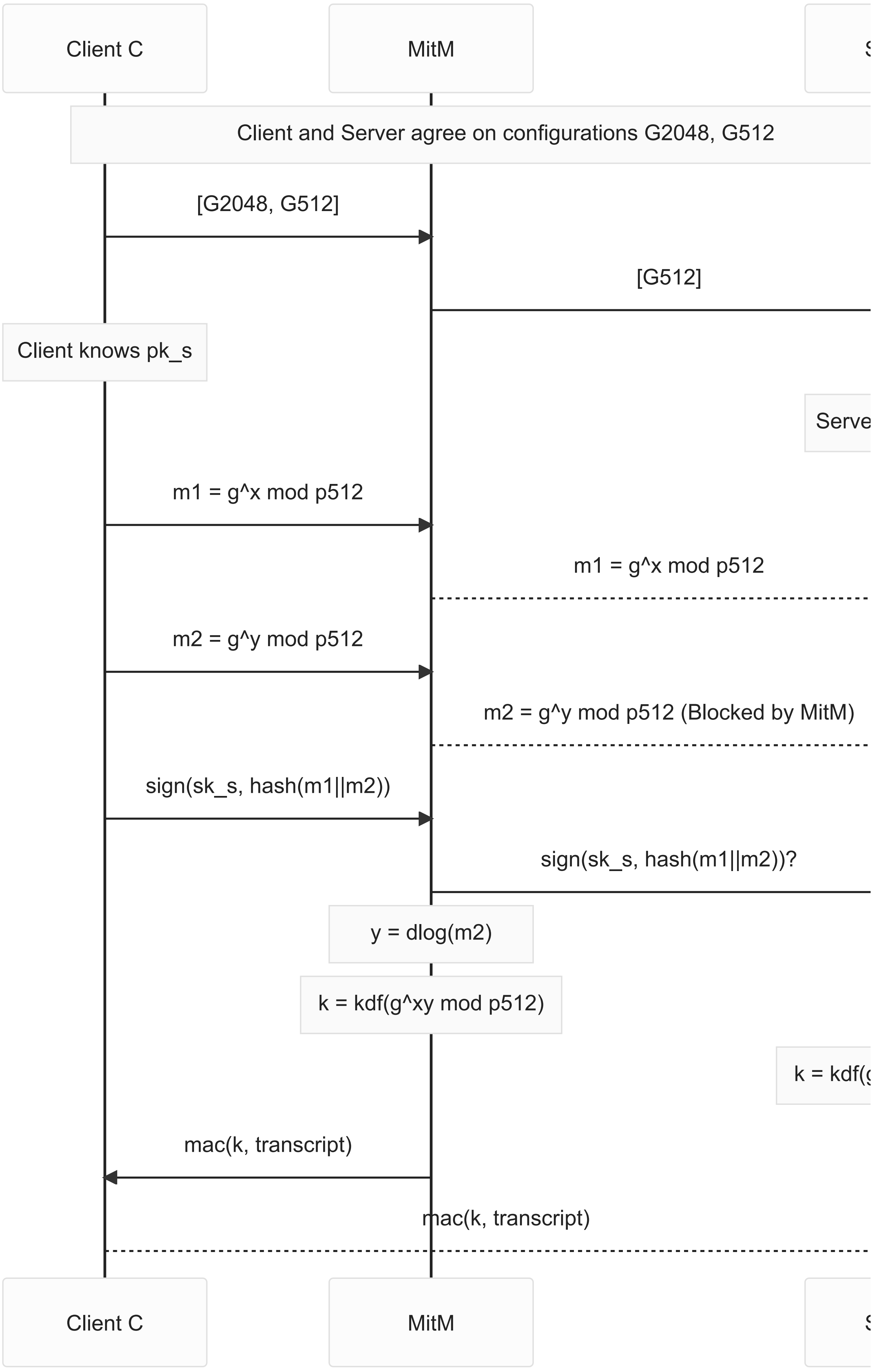
The *web browser* thinks $K_{(1)} = g^{xs}$ and *server* thinks $K_{(2)} = g^{yt}$ - the MiTM knows these both and so can encrypt/decrypt communication. This can be solved with a Signed DH key exchange

Signed DH key exchange



LOGJAM

By a MiTM downgrading the communication's security protocol, they can brute force the encryption.


Client C
MitM
S
Client and Server agree on configurations G2048, G512
[G2048, G512]
[G512]
Client knows pk_s
Serve
m1 = g^x mod p512
m1 = g^x mod p512
m2 = g^y mod p512
m2 = g^y mod p512 (Blocked by MitM)
sign(sk_s, hash(m1||m2))
sign(sk_s, hash(m1||m2))?
y = dlog(m2)
k = kdf(g^xy mod p512)
k = kdf(
mac(k, transcript)
mac(k, transcript)
Client C
MitM
S

Anonymous communication

So far, we've had ways to ensure messages are coming from a known person, and can't be read. Now, we will look over methods to ensure communications *cannot* be traced to their origin. Such methods include:

- 3DC
- Crowds
- Chaum Mixing
- Onion Routing

Three-party dining cryptographers

Premise

Three **NSA** cryptographers are having dinner.
At the end of the dinner, they are informed it has already been paid for.
They know either the *NSA paid for dinner*, or *one of the cryptographers paid*.
To find out if the NSA paid or not (while not revealing *which cryptographer paid*), we can follow the **3DC Protocol**:

3DC Protocol

Phase 1

Each pair of cryptographers flips a coin (*which only they can see*) where heads = 1 & tails = 0
Each cryptographer sees the two coin flips

Phase 2

Each participant publicly announces:

- (**did NOT pay**) - the *XOR* ($\oplus$) of the two flips they saw
- (**did pay**) - the **negation** of the *XOR* ($\neg\oplus$) of the two flips they saw

Phase 3

If the *XOR* of the *three announcements* ($a_1 \oplus a_2 \oplus a_3$) is:

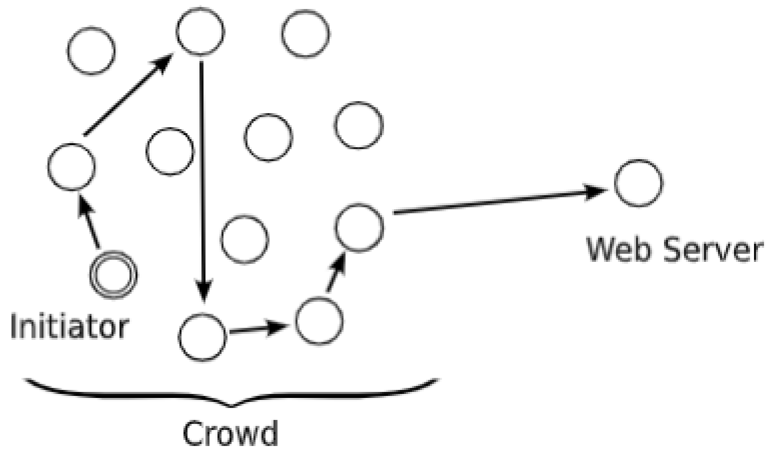
- **0**: *The NSA paid*
- **1**: A cryptographer paid (only they will know this, however)

nDC

3DC can generalise to any group size $n > 2$
The general protocol for a sender to broadcast message m, split up into each bit m_i of m:

1. Each pair of users generate a random bit $(0, 1)$
   Each user will observe $n-1$ bits
2. Each user (except sender) announces (XOR ($\oplus$) of all $n-1$ observed bits)
3. The sender announces (XOR ($\oplus$) of all $n-1$ bits and m_i)
4. m_i = XOR $\oplus$ of all announcements

Crowds



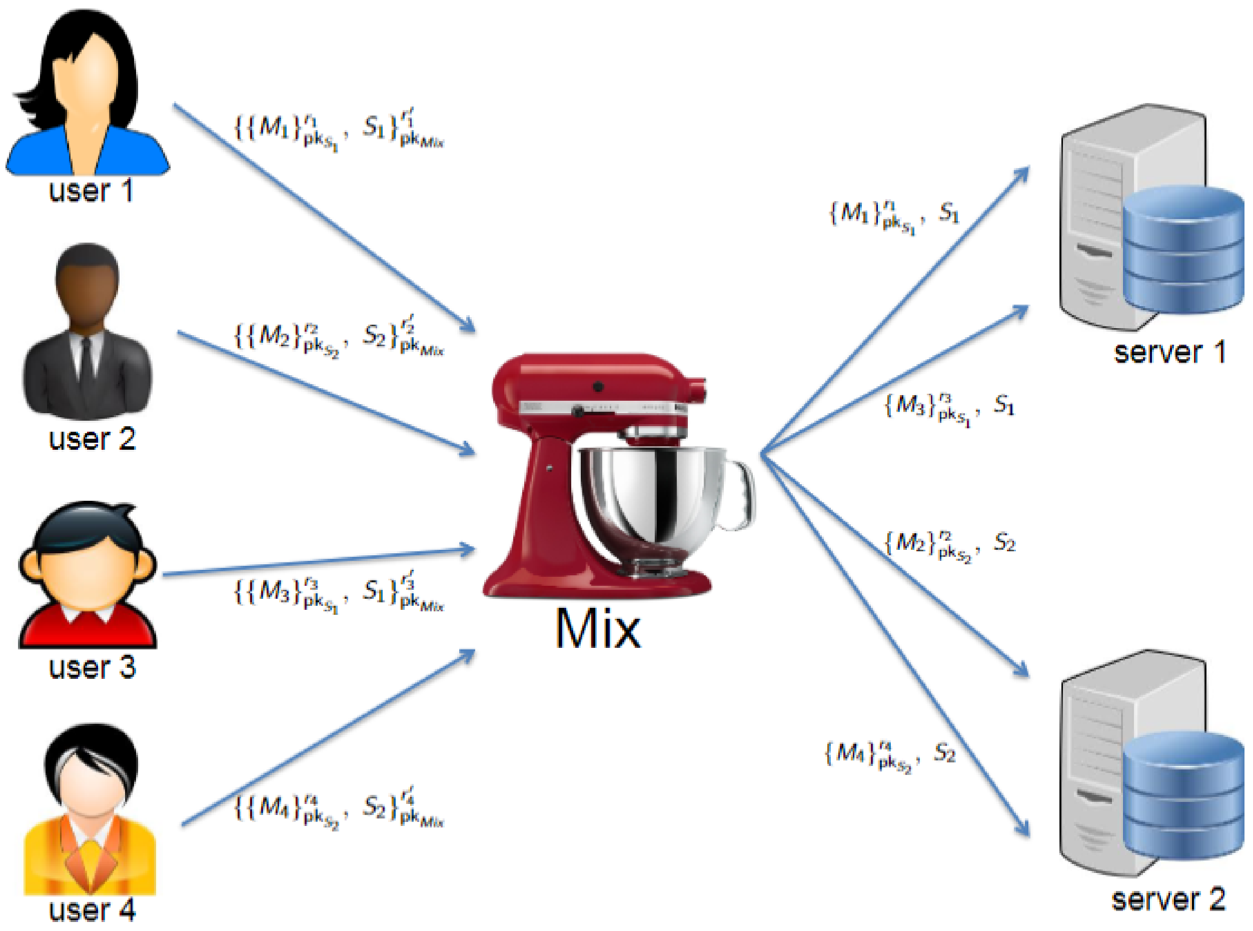
The idea behind crowds is to route the request through a *crowd* of users.

Out of a crowd of m users, c out of m may be corrupted.
An initiator who wants to request a webpage creates a path between him and the server:

1. The initiator selects a *forwarder* from the crowd and sends him his request
2. The forwarder delivers the request directly to the server with probability $1 - p_f$ and forwards the request to a new selected *forwarder* with probability p_f, who repeats the procedure

3. The response from the server follows the same route in the opposite direction.

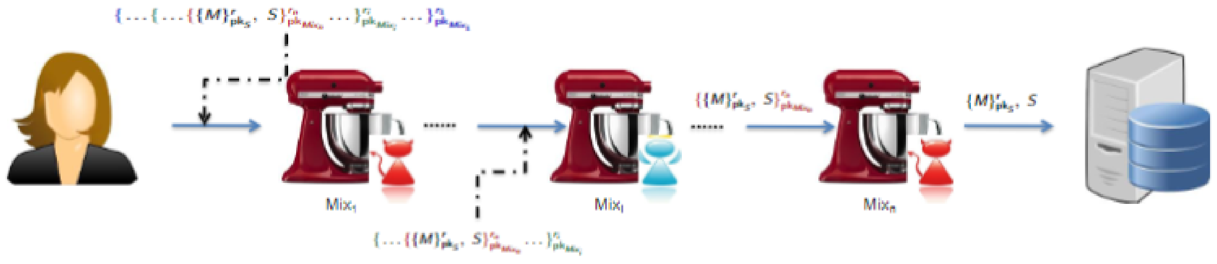
Chaum's Mix


user 1
$\{\{M_1\}^{r_1}_{\mathrm{pk}_{S_1}}, S_1\}^{r'_1}_{\mathrm{pk}_{Mix}}$
user 2
$\{\{M_2\}^{r_2}_{\mathrm{pk}_{S_2}}, S_2\}^{r'_2}_{\mathrm{pk}_{Mix}}$
user 3
$\{\{M_3\}^{r_3}_{\mathrm{pk}_{S_1}}, S_1\}^{r'_3}_{\mathrm{pk}_{Mix}}$
user 4
$\{\{M_4\}^{r_4}_{\mathrm{pk}_{S_2}}, S_2\}^{r'_4}_{\mathrm{pk}_{Mix}}$
Mix
$\{M_1\}^{r_1}_{\mathrm{pk}_{S_1}}, S_1$
$\{M_3\}^{r_3}_{\mathrm{pk}_{S_1}}, S_1$
server 1
$\{M_2\}^{r_2}_{\mathrm{pk}_{S_2}}, S_2$
$\{M_4\}^{r_4}_{\mathrm{pk}_{S_2}}, S_2$
server 2

Chaum's mix involves a *mix server*, which mixes up how it sends out messages to avoid time correlation attacks.

1. Users encrypt their message using the *server's public key*
2. Before mixing, the server provides a "blinding" operation - it removes anything that could identify the sender from it, as well as changing how it looks (a weak form of encryption).
3. It then decrypts them (possibly removing the appearance aspects of blinding, but not identity), and then shuffles the messages before sending them out.
   Mixes can also be chained, adding layers of blinding to the message

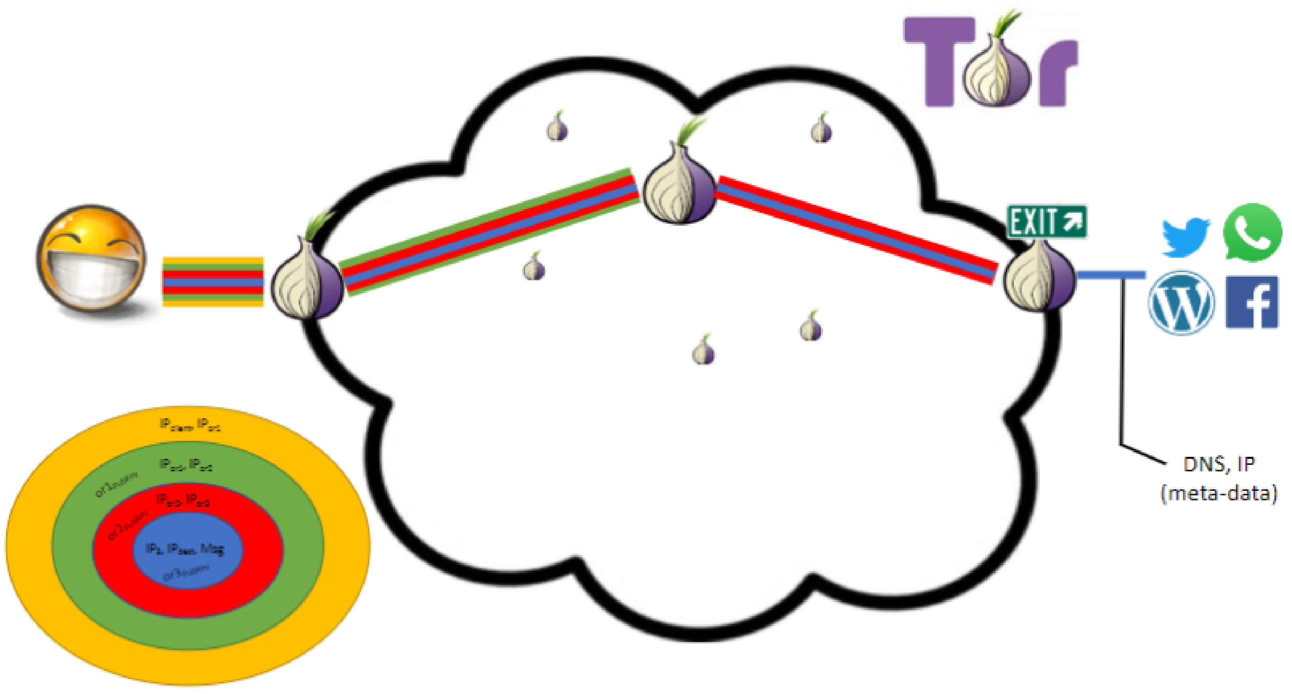
which are taken off in a chain (or layers of an onion)



TOR

TOR is much lower latency compared to mixnets. It is *source-routed*, so the user defines the path a packet takes.

TOR Relay

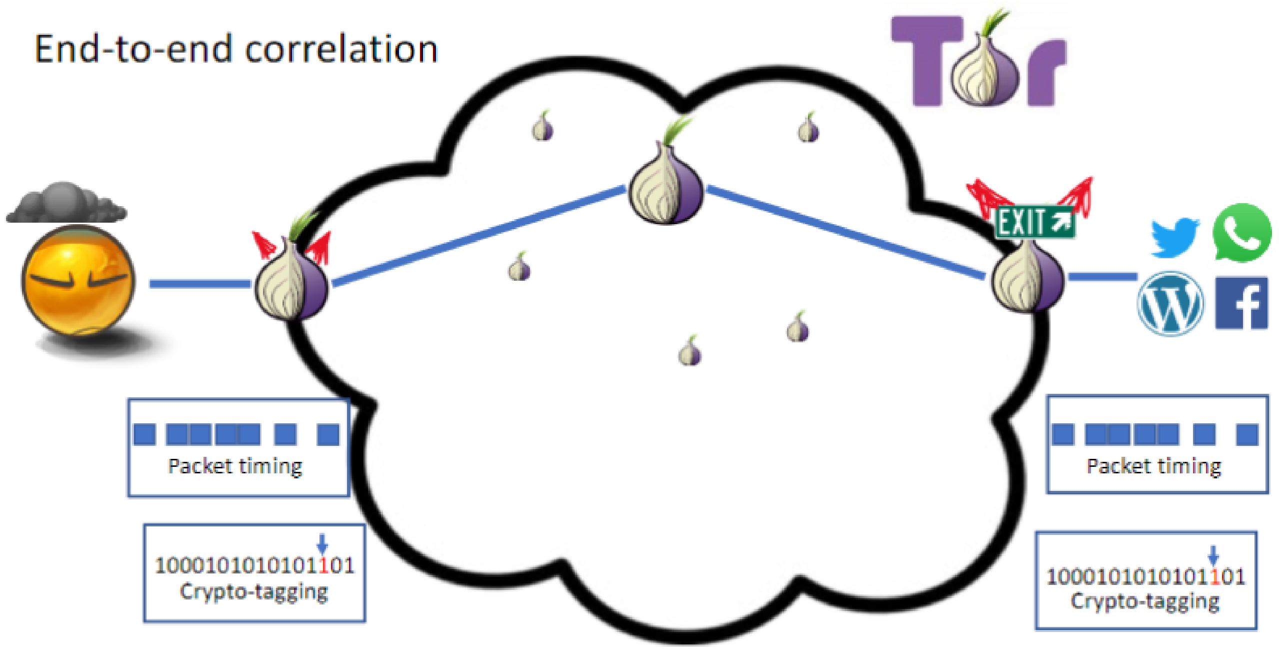


The user established a secure connection with the first hub, which sends a message to the second hub to establish the connection, and repeats until it's at the end.
Information gets encrypted for each extension, so each hub has no idea what the future hubs are meant to be doing, just who to send a big chunk of data to next. Even the endpoint has no idea *who's* connecting to them, just the *data* that's being connected.

Attacks on TOR

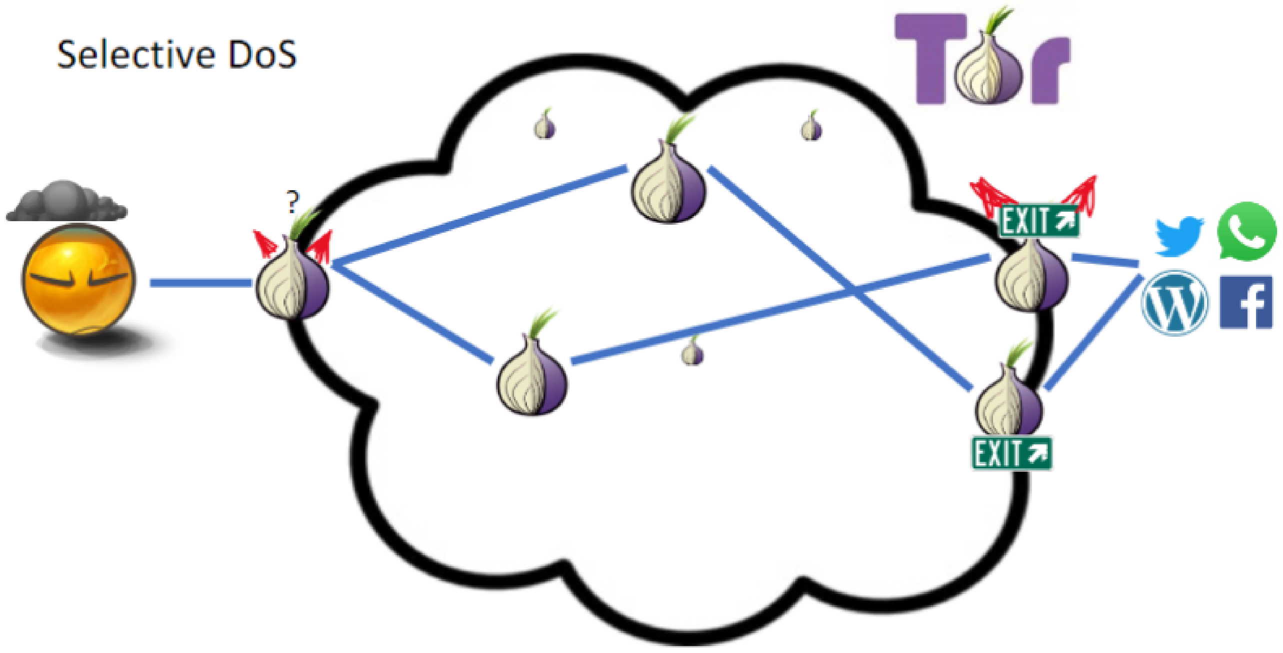
End-to-End Correlation

By tagging the packet entering the network, we can test all packets that exit the network and through checking timing and tagging, we can track the packets sent.



Selective DOS

Anyone who can control entry/exit hubs can stop any connections going through them. This could be further iterated to drop any packets that don't go through a compromised exit hub.



Website fingerprinting

This is not an attack on TOR itself, but instead on websites you can train on. If you know there are TOR users interacting, you can generate "fingerprints" that can be used to track packages coming out of the network.