



Get the slides!

Thierry Sans

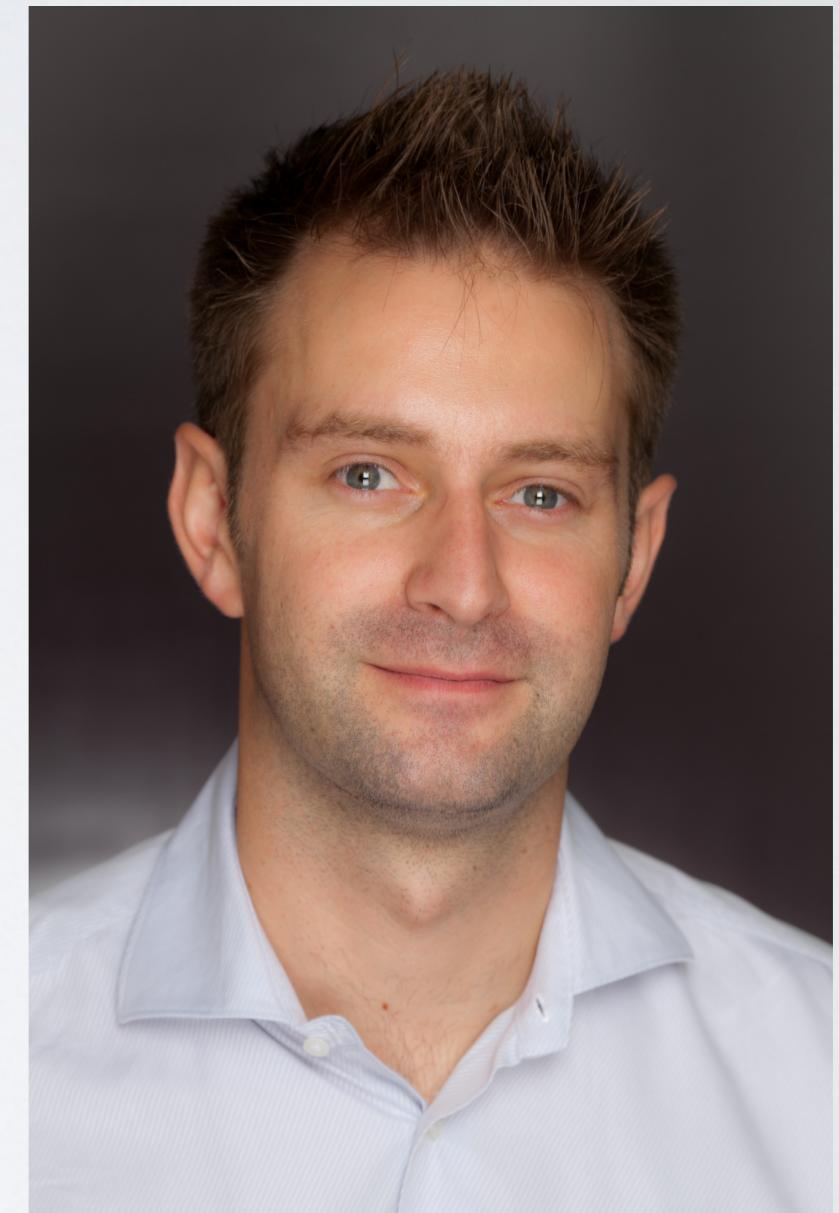
Associate Professor - Teaching Stream

Teaching

- Computer and Network Security
- Blockchain and Decentralized Applications
- Web Development
- Operating Systems

Research

- Cryptography Protocols
- Zero-Knowledge Proofs
- Blockchain Protocols and Applications



Understanding the "s" in "https://"

An introduction to
modern cryptography

Thierry Sans

You are using cryptography everyday

- **Browsing the web** with HTTPS://
- **Text messaging** apps
- **Authentication** (passwords, biometrics, one-time code and so on)
- Connecting to a remote server **using SSH**
- **Bitcoin** and other cryptocurrencies

The Internet

1980's - few hosts connected : government institutions and universities

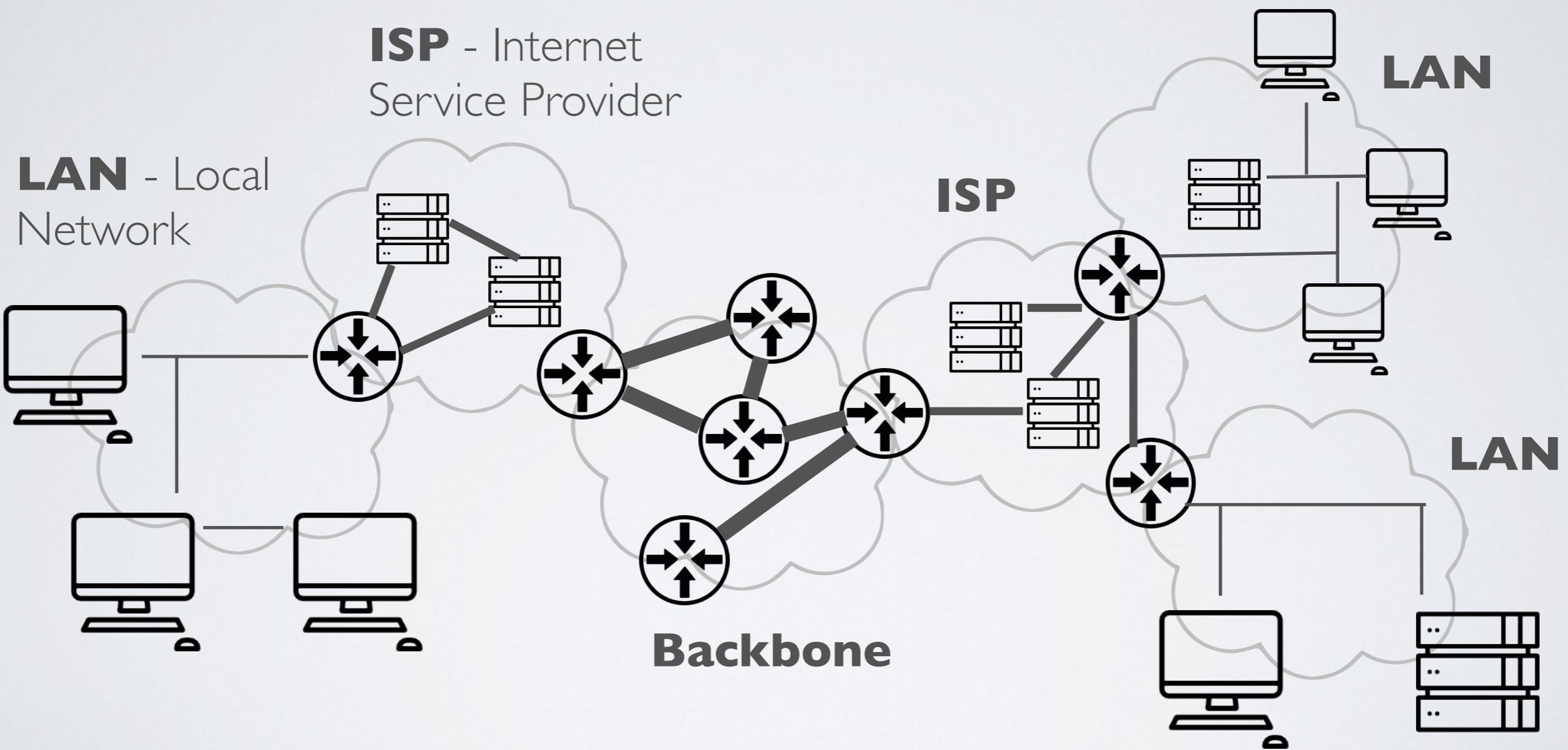
→ Trustworthy environment

2025 - ~ 5.6 billion internet users : network of networks

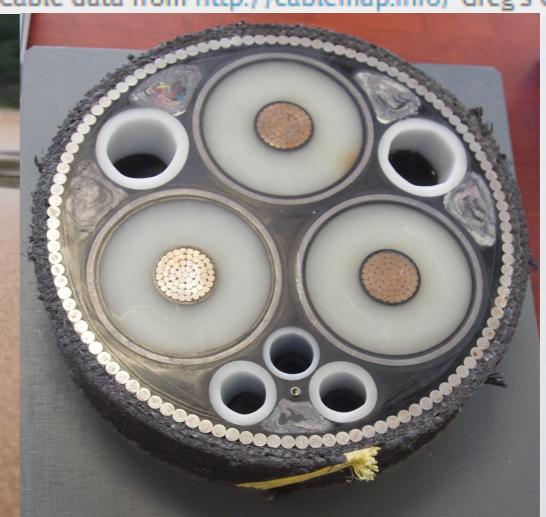
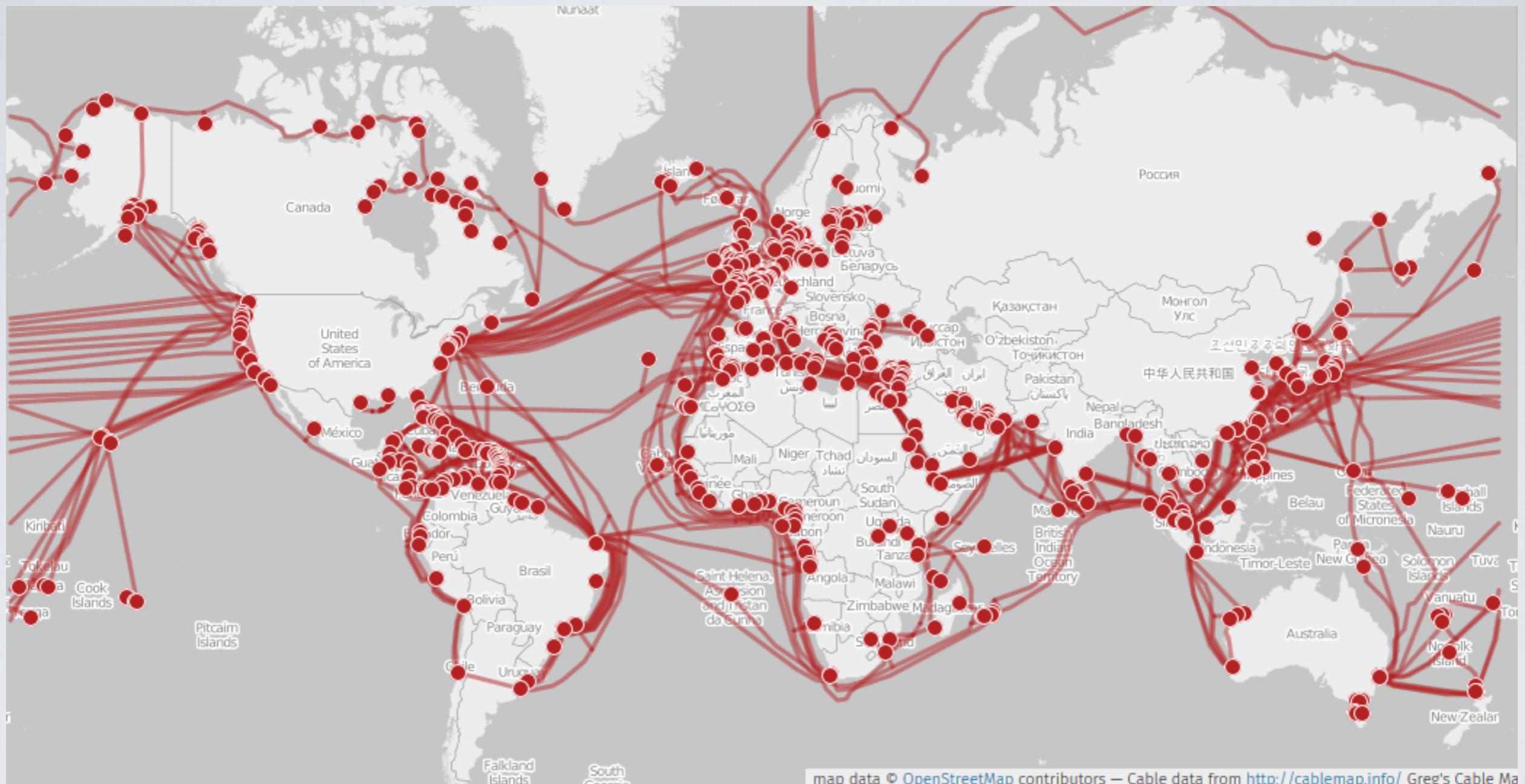
→ Untrustworthy environment

→ Internet (and its protocols) was
not designed for untrustworthy environment

A network of networks



The Internet Backbone

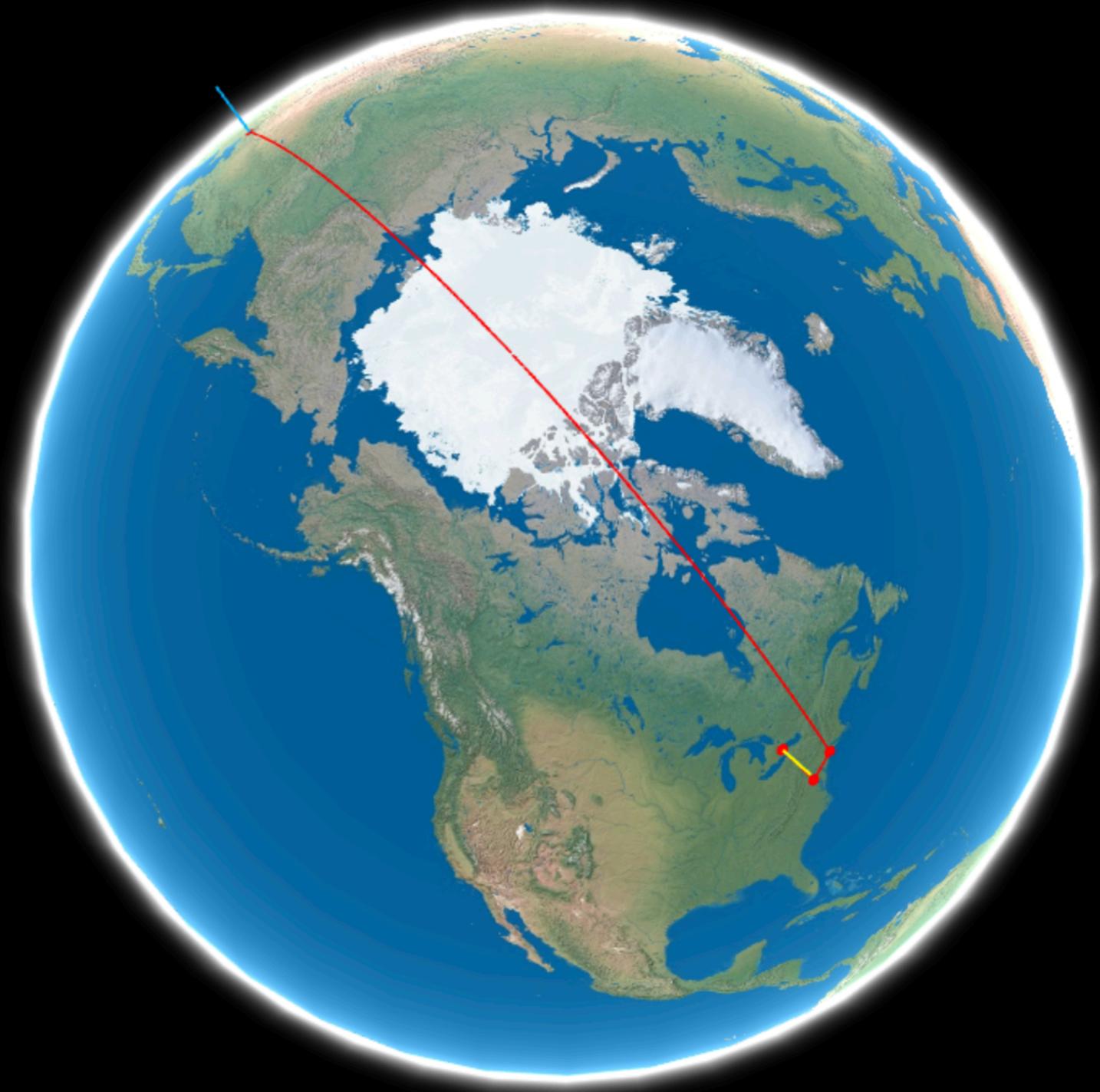


GeoTraceroute to:

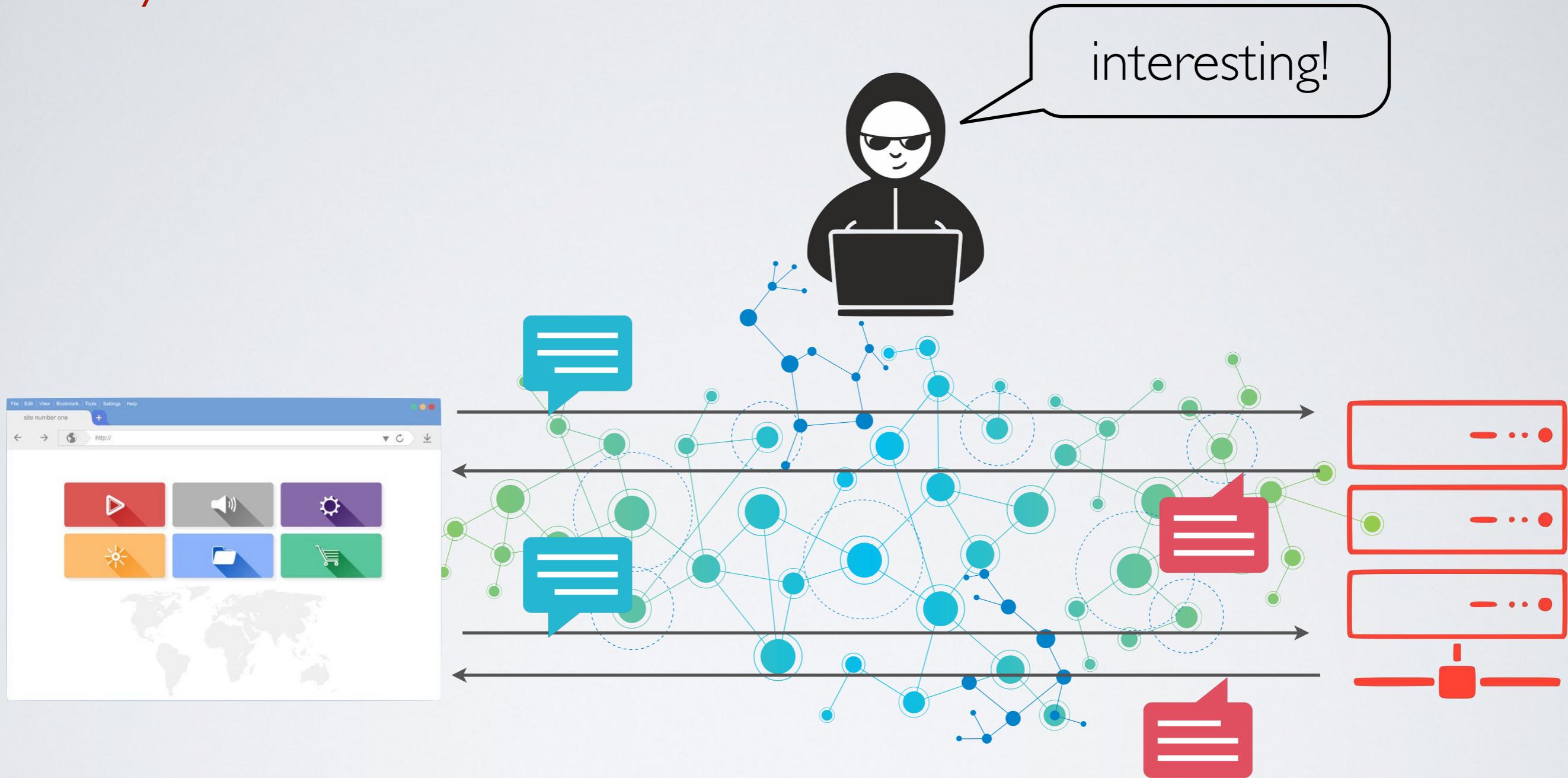


baidu.com

-
- #1 🇨🇦 CA - Toronto (0 km)
159.203.1.207 [AS14061] (0 ms)
143.244.192.138 [AS0] (1 ms)
143.244.224.37 [AS0] (1 ms)
157.238.227.100 [AS2914] (1 ms)
 - #2 🇺🇸 US - Washington (564 km)
129.250.2.141 [AS2914] (15 ms)
 - #3 🇺🇸 US - New York (340 km)
129.250.3.213 [AS2914] (16 ms)
129.250.9.222 [AS2914] (22 ms)
 - #4 🇨🇳 CN - Beijing (11012 km)
202.97.63.98 [AS4134] (71 ms)
202.97.41.49 [AS4134] (218 ms)
202.97.12.49 [AS4134] (218 ms)
36.110.251.78 [AS23724] (222 ms)
106.38.196.190 [AS23724] (222 ms)
182.61.255.66 [AS38365] (221 ms)
182.61.255.45 [AS38365] (221 ms)
182.61.201.211 [AS38365] (244 ms)

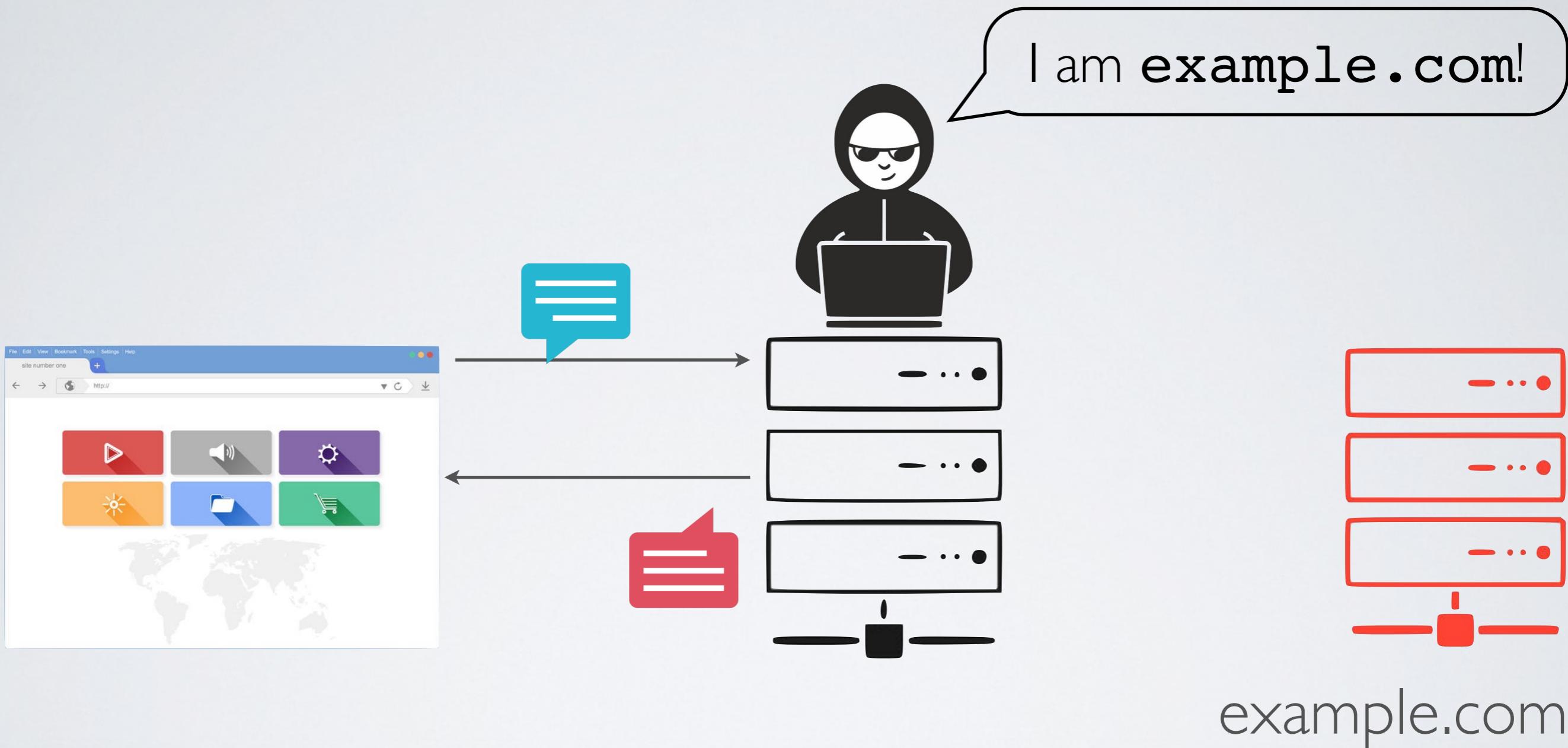


Do you trust the network?



- Threat I : an attacker **can eavesdrop** messages sent back and forth

Do you *really* trust the network?



- Threat 2: an attacker **can tamper with** messages sent back and forth

Confidentiality and Integrity

- Threat 1: an attacker **can eavesdrop** messages sent back and forth

Confidentiality: How do we exchange information secretly?

- Threat 2: an attacker **can tamper** with messages sent back and forth

Integrity: How do we exchange information reliably?

HTTPS = HTTP + TLS

- Transport Layer Security (formerly SSL) provides
 - **confidentiality:** end-to-end secure channel
 - **integrity:** authentication handshake
- ✓ Prevents all kinds of eavesdropping and tampering protecting many internet protocols

An introduction to cryptography

Protecting confidentiality

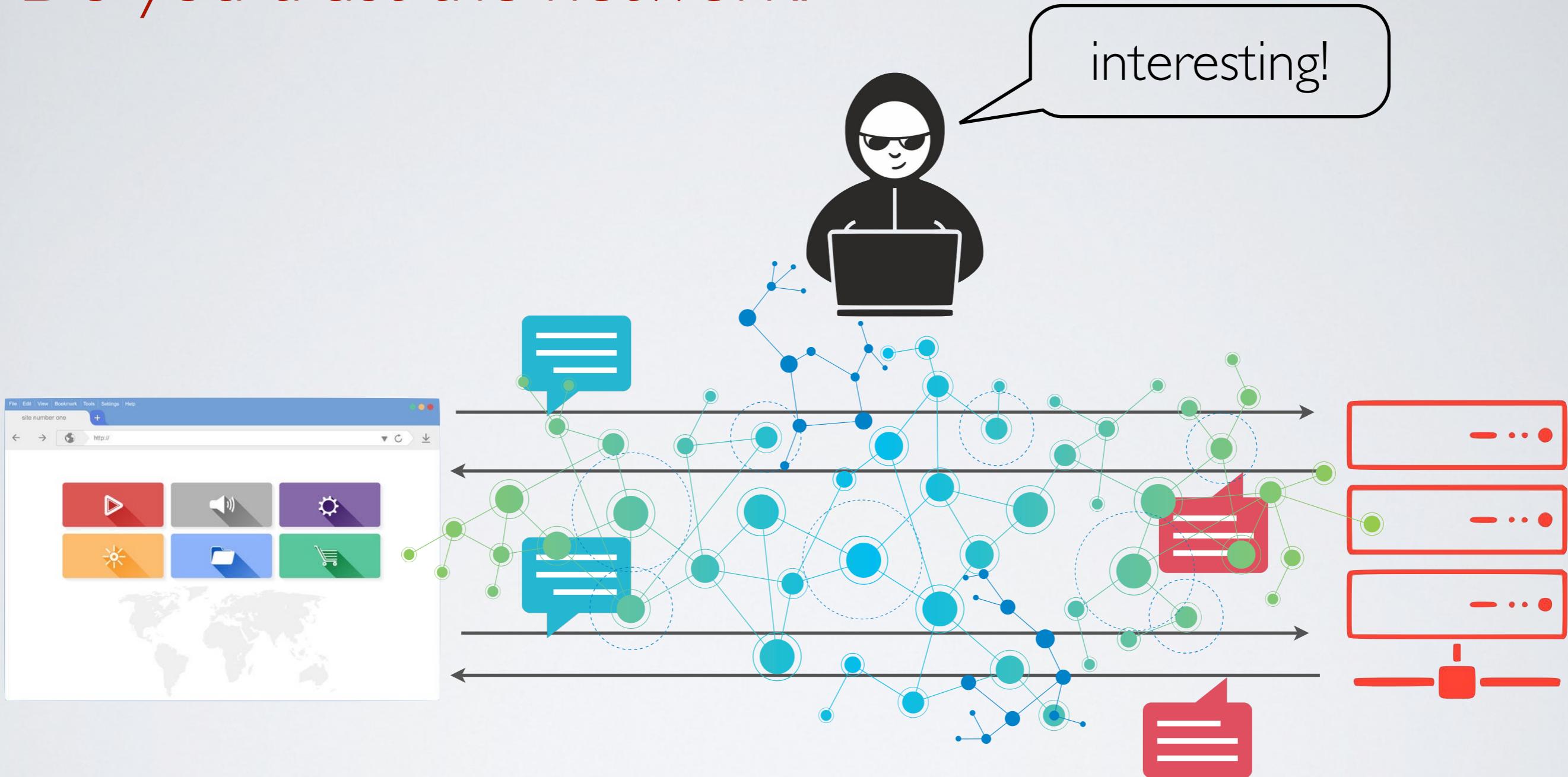
- Symmetric Encryption
- Asymmetric Encryption
- Key Exchange

Protecting Integrity

- Digital Signatures
- Public Key Infrastructure

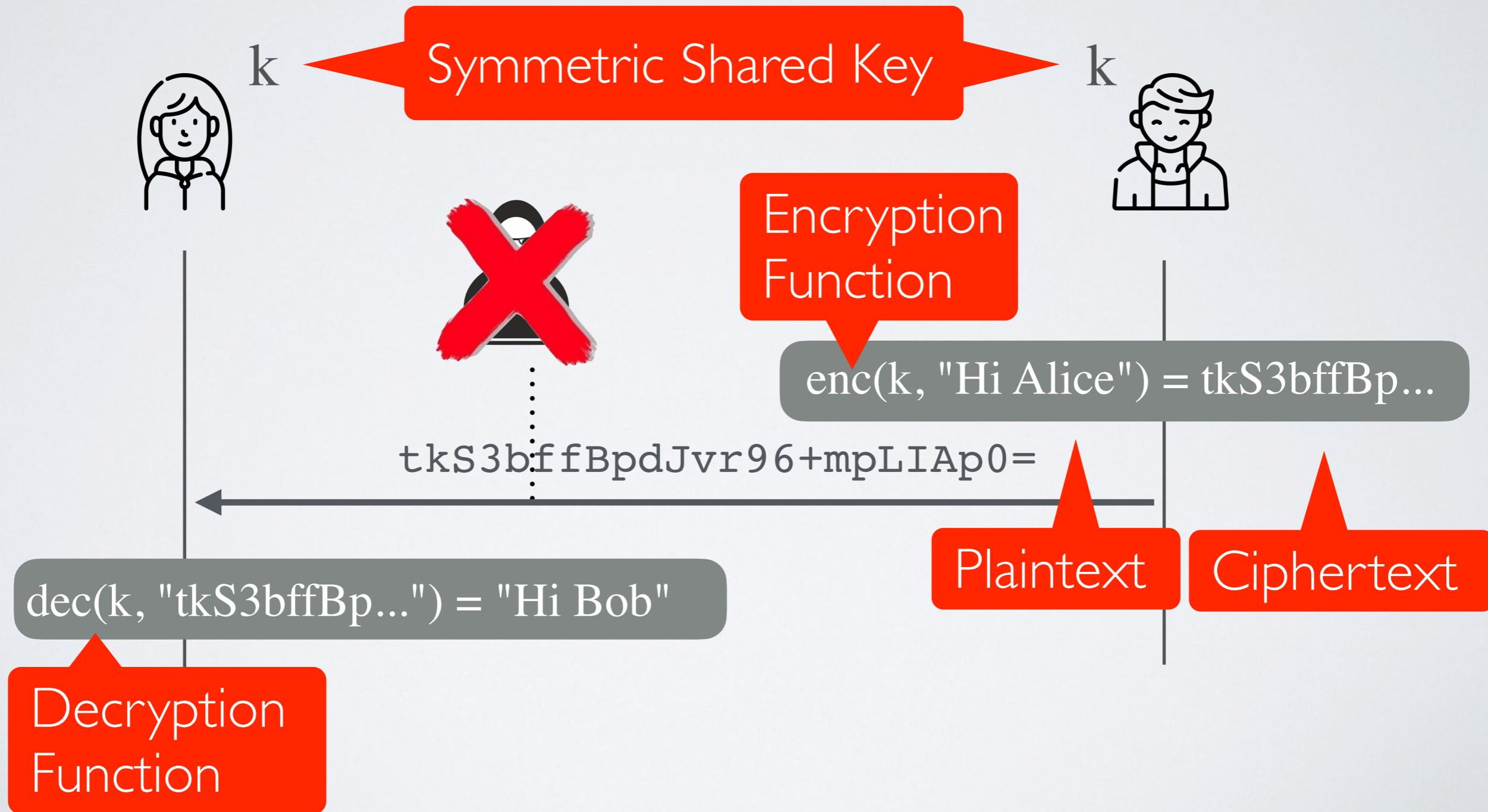
Protecting Confidentiality

Do you trust the network?



- Threat I : an attacker **can eavesdrop** messages sent back and forth

Symmetric Encryption to protect confidentiality



Definitions

Plaintext

The message in its original form (a.k.a "in clear")

Ciphertext

The message in its encrypted form

Encryption Function

Transform a plaintext into ciphertext

Decryption Function

Transform a ciphertext into a plaintext

Definitions

Cryptographic algorithm

The method to do encryption and decryption

- ✓ The cryptographic algorithm is public

Cryptographic key

An input variable used by the algorithm for the transformation

- The key must remain secret between the two parties

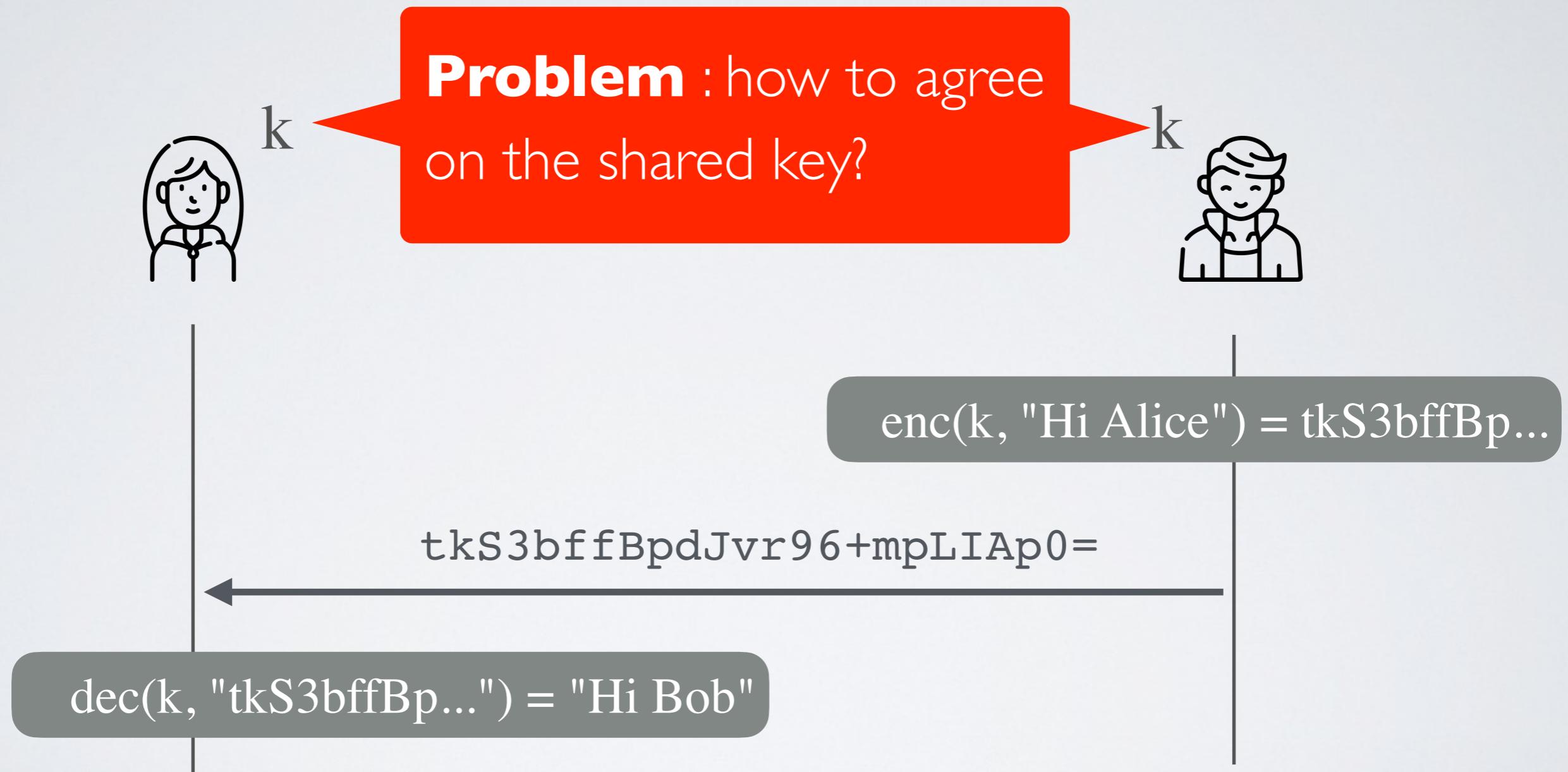
The Kerckhoffs' principle (1883)

“The enemy knows the system” - the security of a communication should **not** rely on the fact that the algorithms are secrets

- A cryptosystem should be secure even if **everything about the system, except the key, is public knowledge**

No security by obscurity

The big challenge with symmetric encryption



Asymmetric Encryption a.k.a Public Key Cryptography



K_{sA}, K_{pA}



K_{pA}



K_{pA}

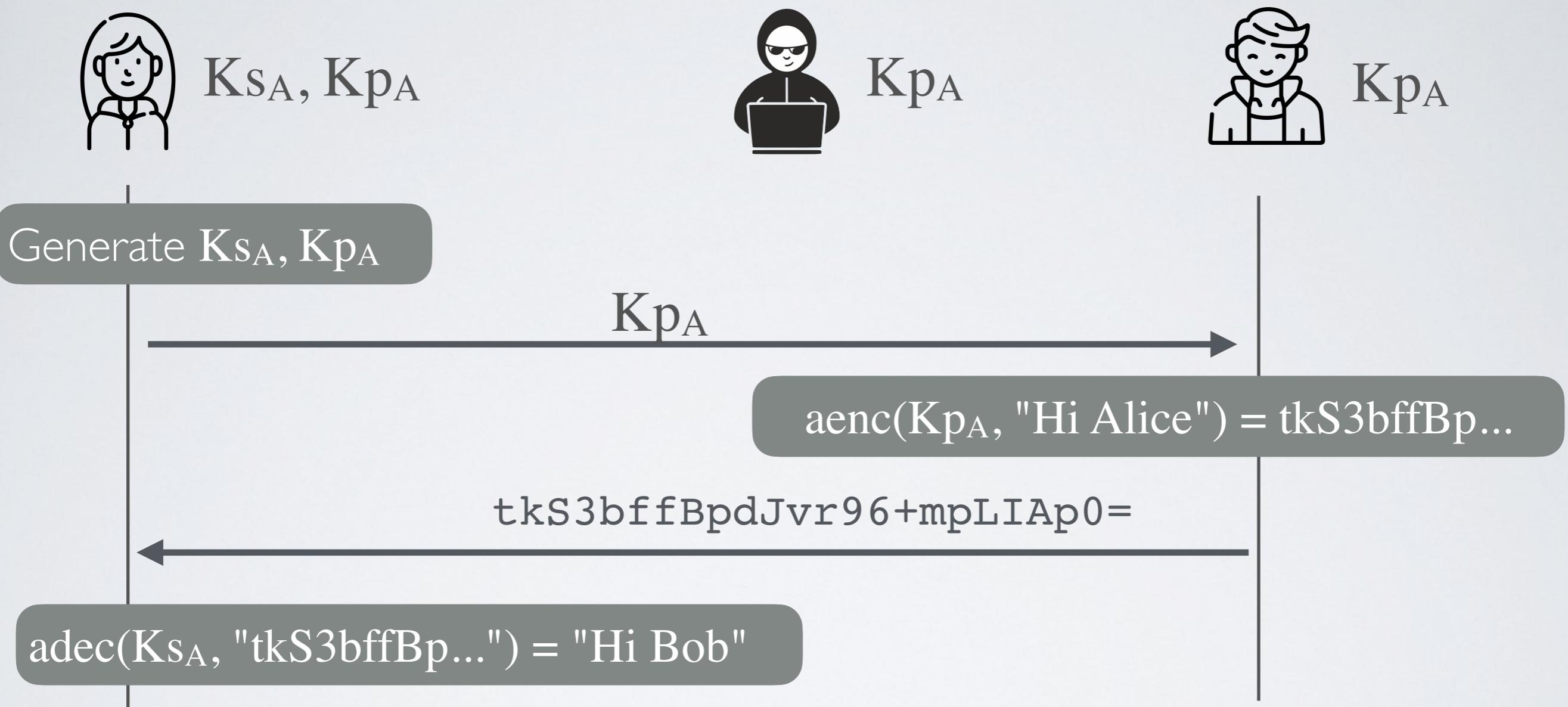
Generate K_{sA}, K_{pA}

K_{pA}

Alice generates a pair of asymmetric keys

- K_{sA} is the secret key that Alice keeps for herself
 - K_{pA} is the public key that Alice gives to everyone (even Mallory)
- These two keys K_{sA} and K_{pA} work together

Asymmetric encryption **for confidentiality**



- Nobody can decrypt m, except Alice with her private key K_{sA}
- ✓ Confidentiality without the need to exchange a secret key

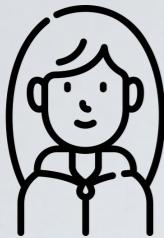
Asymmetric vs Symmetric

	Symmetric	Asymmetric
pro	Faster	No key agreement
cons	Key agreement	Slower and works on small messages only

The best of both worlds

- Use asymmetric encryption to encrypt a shared key
- Use symmetric encryption to encrypt message

(naive) key exchange using asymmetric encryption



Generate K_{sA}, K_{pA}

K_{pA}

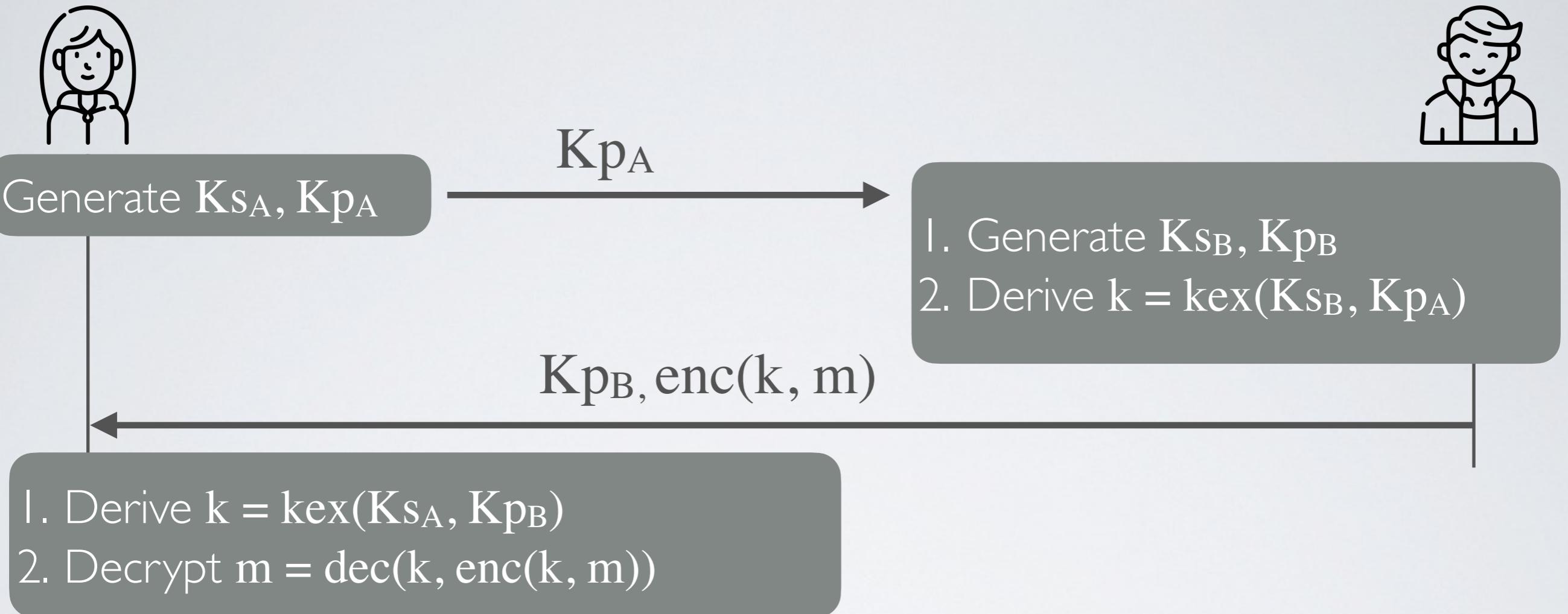
Generate k

$aenc(K_{pA}, k), enc(k, m)$

1. Decrypt $k = denc(K_{sA}, aenc(K_{pA}, k))$
2. Decrypt $m = dec(k, enc(k, m))$

- Protecting the shared key is the **responsibility of Alice only**
- Generating the shared key is the **responsibility of Bob only**

(better) key exchange using Diffie-Hellman-Merkle key exchange protocol

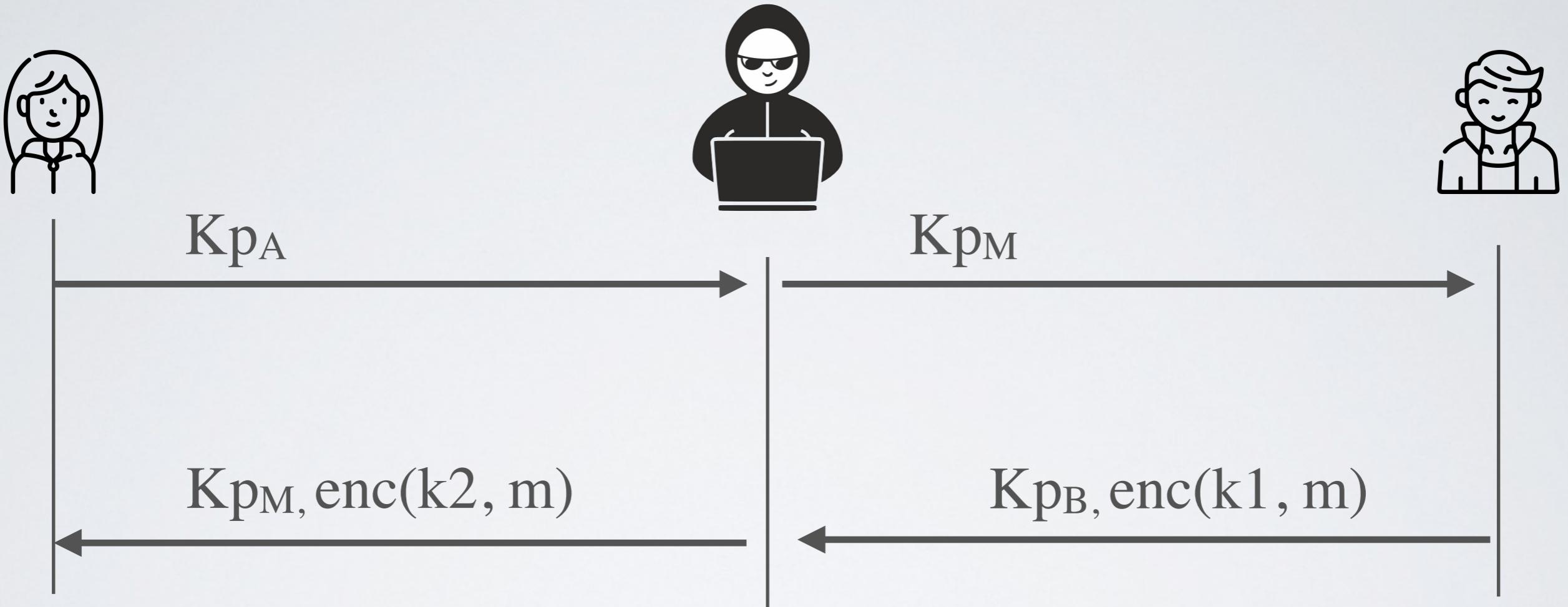


Diffie-Hellman-Merkle provides a way to generate a shared key from two asymmetric key pairs

$$kex(K_{sA}, K_{pB}) = kex(K_{sB}, K_{pA}) = k$$

- ✓ Mutual contribution to the key generation
- ✓ No need to send the encrypted shared key

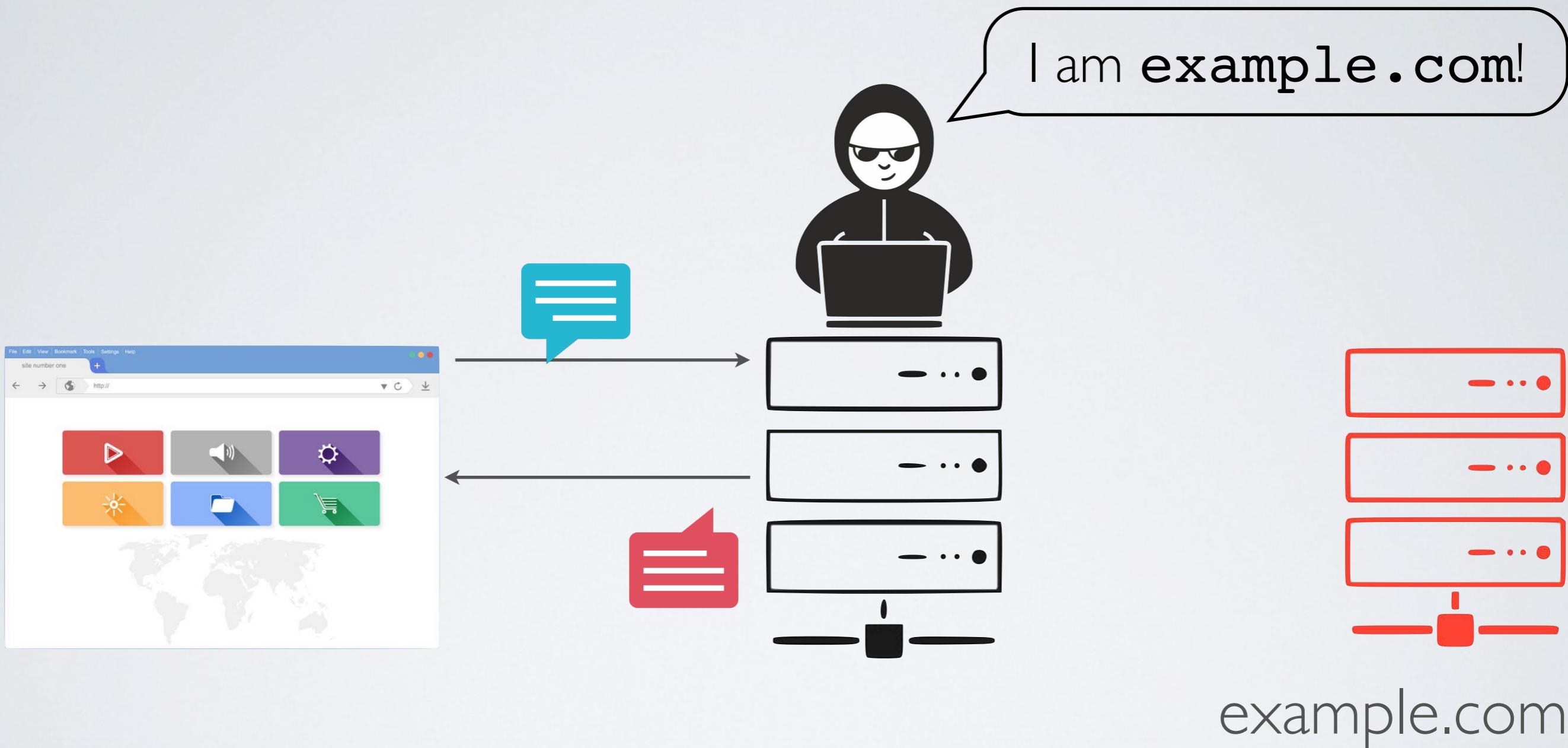
Are we done yet?



- ✓ Encryption and key exchange protects against confidentiality ...
- ... but not **does not protect integrity**

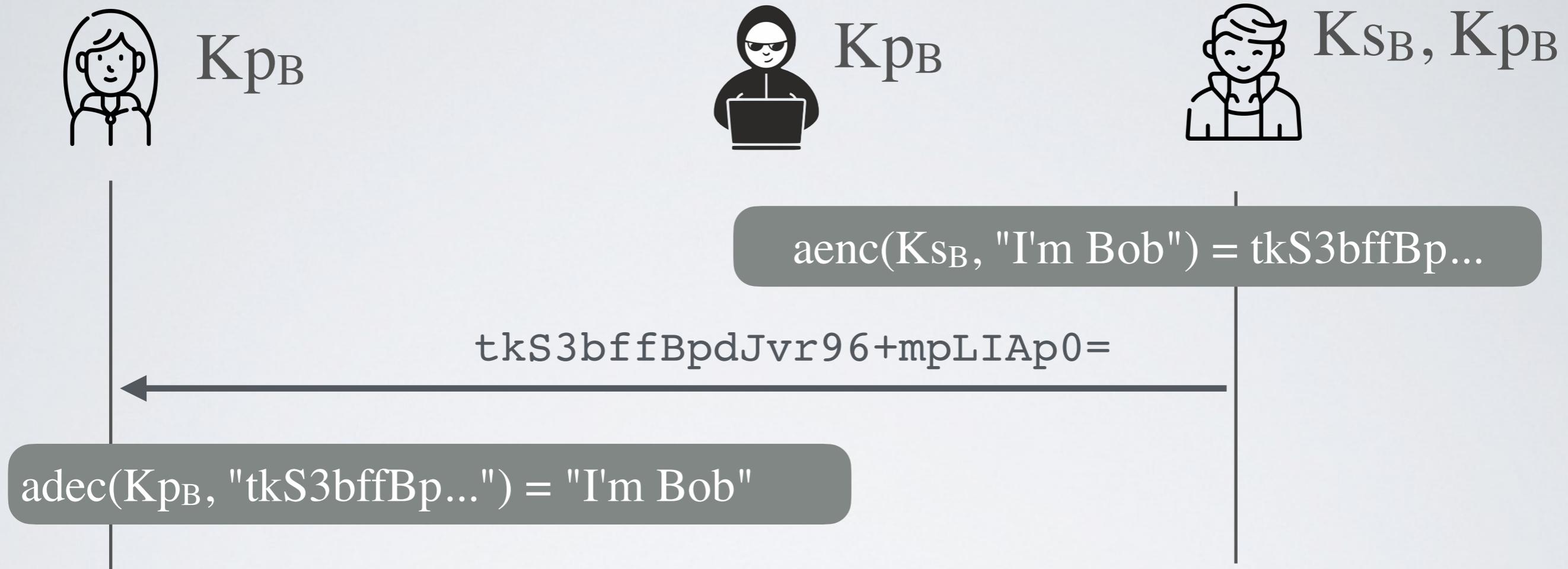
Protecting Integrity

Do you *really* trust the network?



- Threat 2: an attacker **can tamper with** messages sent back and forth

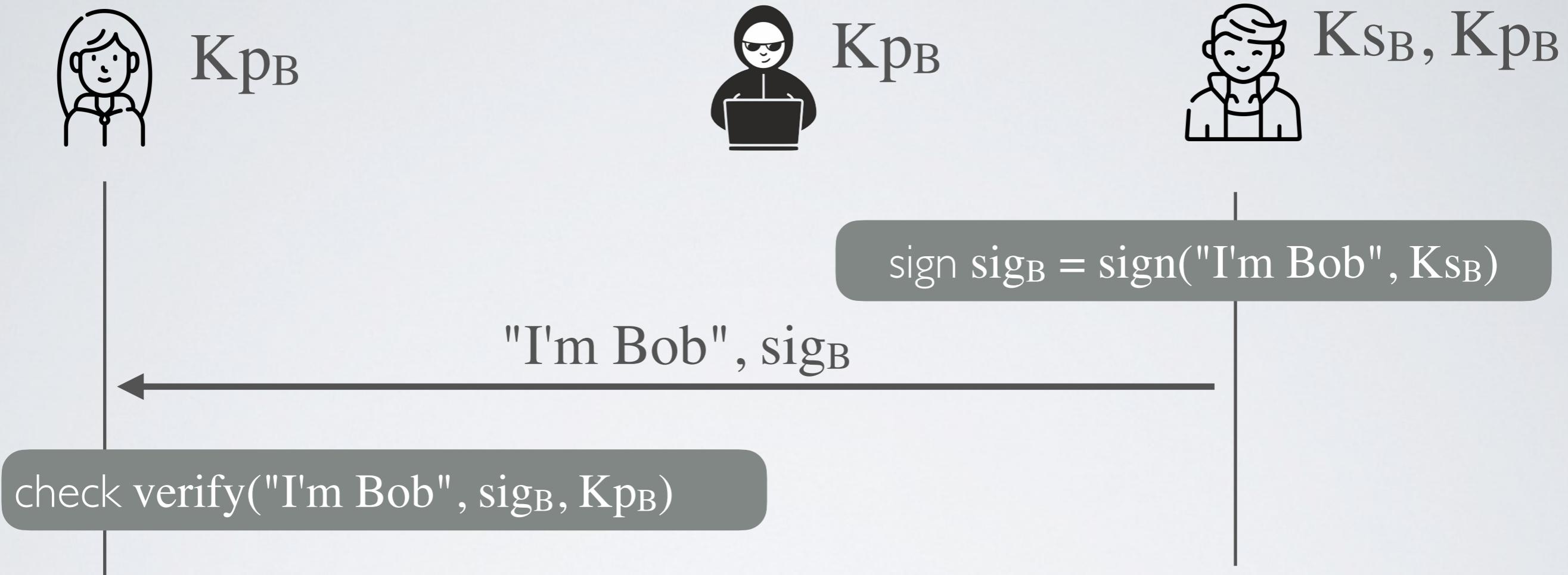
Asymmetric encryption **for Integrity**



→ Everybody can decrypt m using Bob's public key K_{pB}

✓ Authentication with non-repudiation (a.k.a Digital Signature)

Digital Signatures

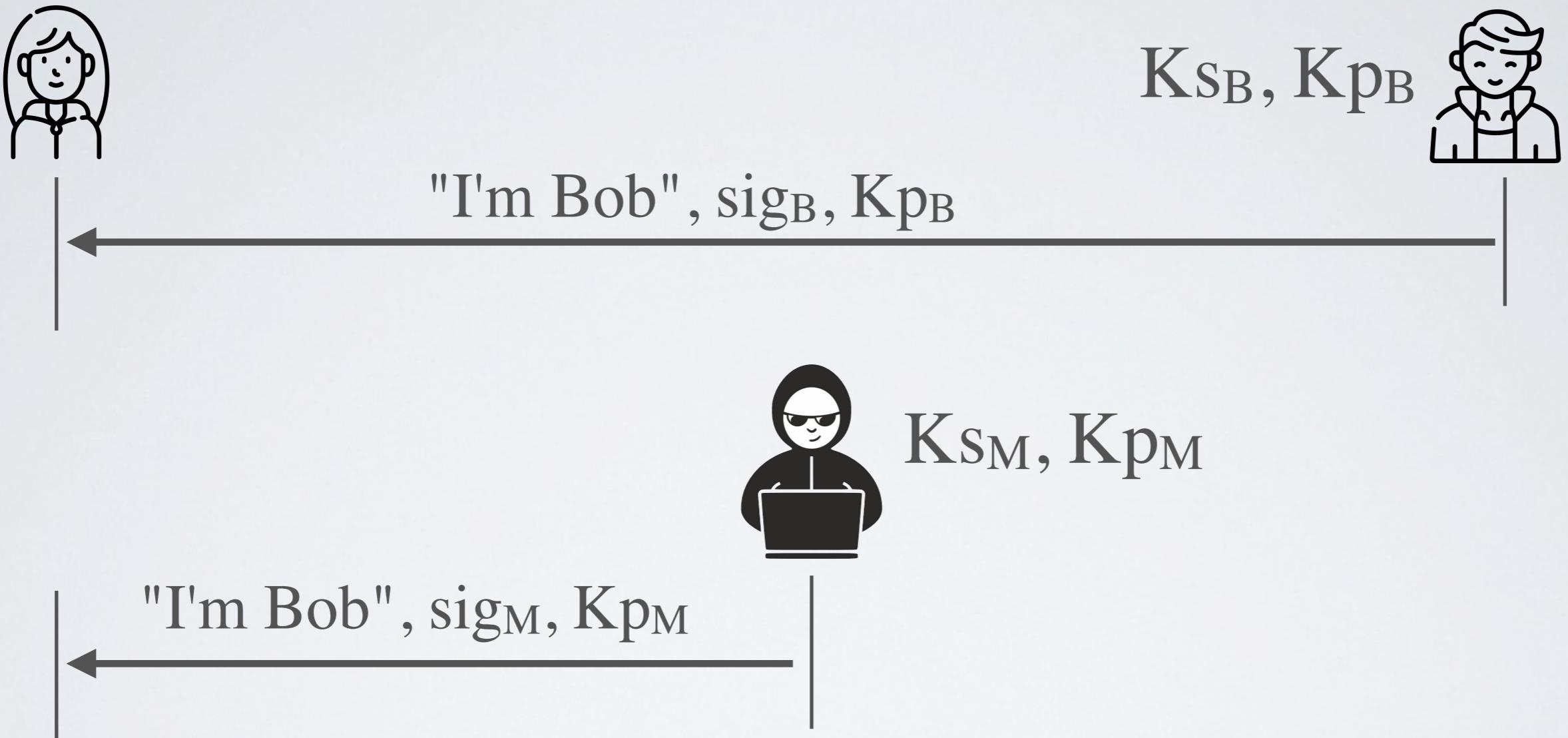


Only Bob can sign a message m with his secret key K_{sB}

→ Everybody can verify m and its sig using Bob's public key K_{pB}

Problem :

How does everyone know Bob's public key?



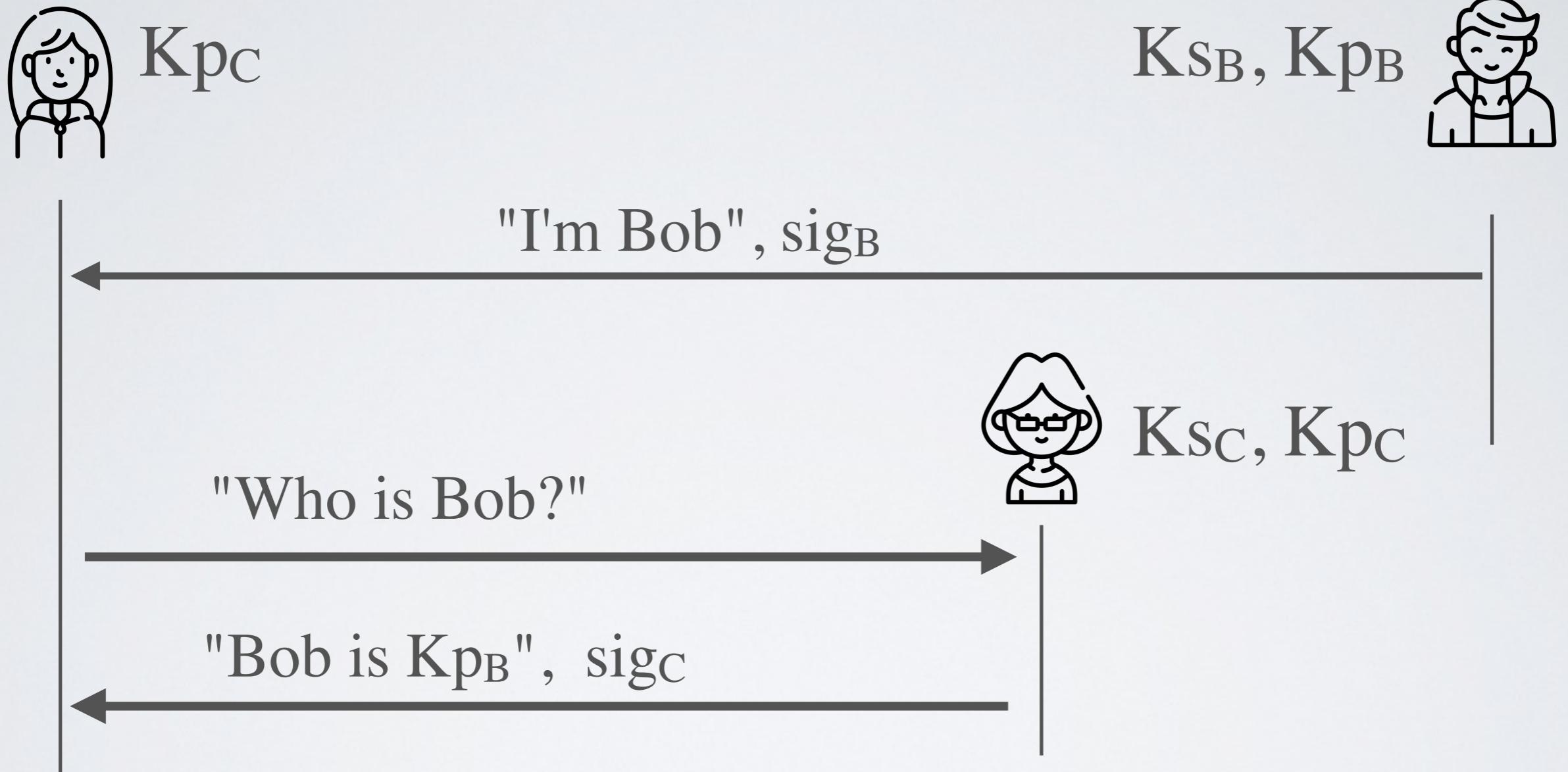
- If Alice does not know Bob in the first place, Bob cannot just send his key and ask Alice to trust it

Transitive Trust

If Alice does not know Bob maybe **she knows Charlie that knows Bob** and can vouch for him

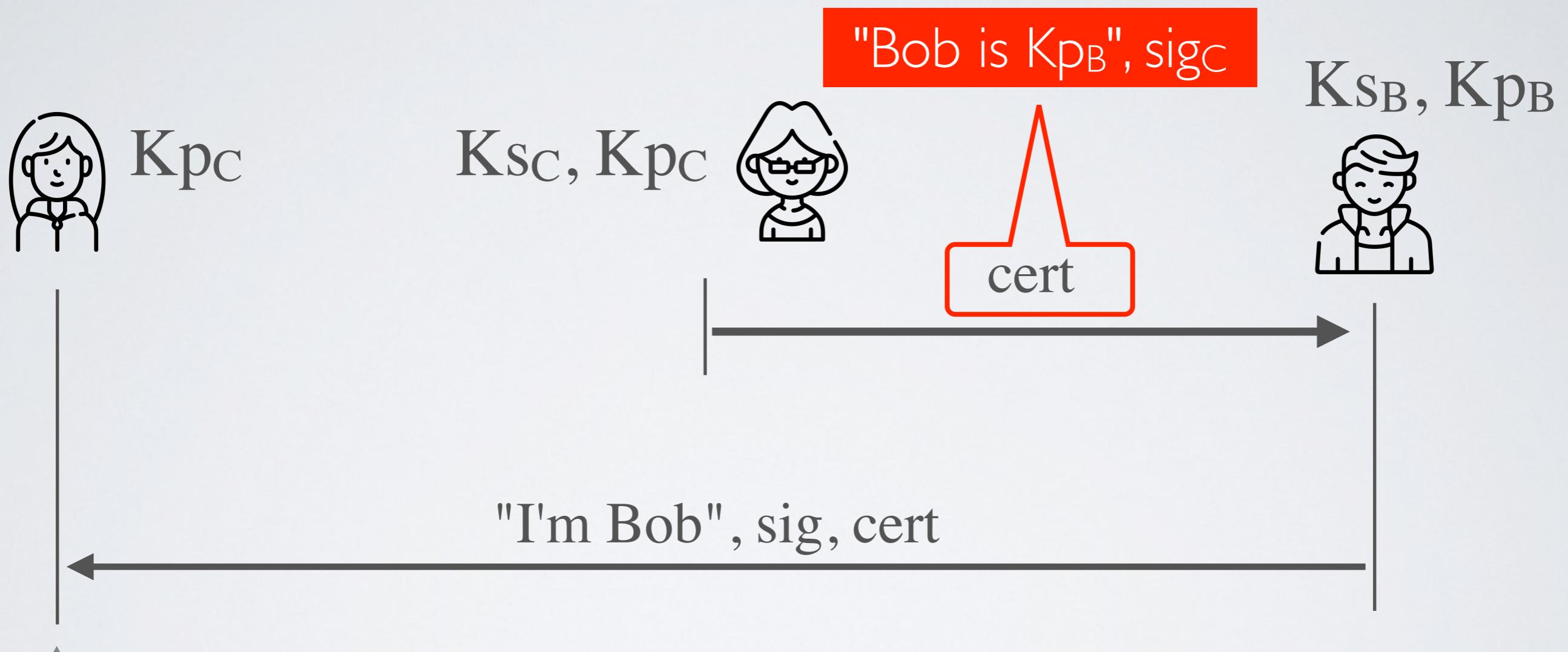
- ✓ Charlie is a Trusted-Third Party for Alice

Solution I: Online Public Key Registry



1. check verify("Bob is K_{PB}", sig_C, K_{PC})
2. check verify("I'm Bob", sig_B, K_{PB})

Solution 2 : Offline Public Key Certification



1. `check verify("Bob is K_{pb} ", sig_C , K_{pc})`
2. `check verify("I'm Bob", sig_B , K_{pb})`

Putting everything together

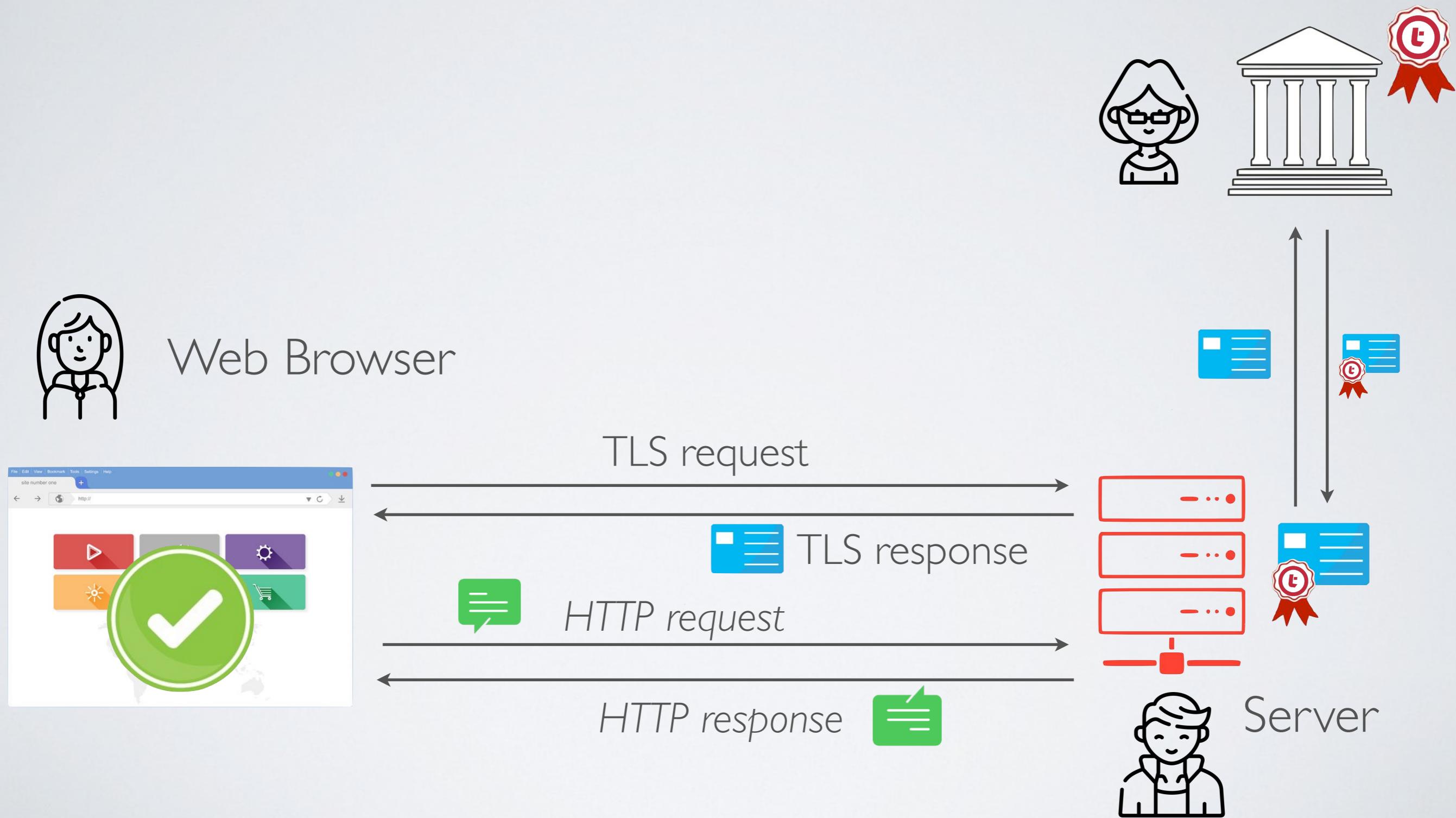
Understanding HTTPS

HTTPS = HTTP + TLS

- Transport Layer Security (formerly SSL) provides
 - **confidentiality:** end-to-end secure channel
 - **integrity:** authentication handshake
- ✓ Prevents all kinds of eavesdropping and tampering protecting many internet protocols

How HTTPS works

Certificate Authority (CA)



Your browser trusts many CAs **by default**

Keychain Access

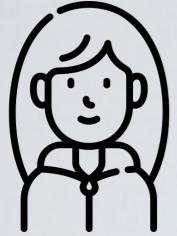
Click to unlock the System Roots keychain.

Keychains	Name	Kind	Expires	Keychain
login	Echoworx Root CA2	certificate	Oct 7, 2030, 1:49:13 PM	System Roots
Microsoft_Intermediate_Certificates	EE Certification Centre Root CA	certificate	Dec 18, 2030, 2:59:59 AM	System Roots
Local Items	Entrust Root Certification Authority	certificate	Nov 27, 2026, 11:53:42 PM	System Roots
System	Entrust Root Certification Authority - EC1	certificate	Dec 18, 2037, 6:55:36 PM	System Roots
System Roots	Entrust Root Certification Authority - G2	certificate	Dec 7, 2030, 8:55:54 PM	System Roots
	Entrust.net Certification Authority (2048)	certificate	Dec 24, 2019, 9:20:51 PM	System Roots
	Entrust.net Certification Authority (2048)	certificate	Jul 24, 2029, 5:15:12 PM	System Roots
	ePKI Root Certification Authority	certificate	Dec 20, 2034, 5:31:27 AM	System Roots
	Federal Common Policy CA	certificate	Dec 1, 2030, 7:45:27 PM	System Roots
Category	GeoTrust Global CA	certificate	May 21, 2022, 7:00:00 AM	System Roots
All Items	GeoTrust Primary Certification Authority	certificate	Jul 17, 2036, 2:59:59 AM	System Roots
Passwords	GeoTrust Primary Certification Authority - G2	certificate	Jan 19, 2038, 2:59:59 AM	System Roots
Secure Notes	GeoTrust Primary Certification Authority - G3	certificate	Dec 2, 2037, 2:59:59 AM	System Roots
My Certificates	Global Chambersign Root	certificate	Sep 30, 2037, 7:14:18 PM	System Roots
Keys	Global Chambersign Root - 2008	certificate	Jul 31, 2038, 3:31:40 PM	System Roots
Certificates	GlobalSign	certificate	Mar 18, 2029, 1:00:00 PM	System Roots
	GlobalSign	certificate	Jan 19, 2038, 6:14:07 AM	System Roots
	GlobalSign	certificate	Jan 19, 2038, 6:14:07 AM	System Roots
	GlobalSign	certificate	Dec 15, 2021, 11:00:00 AM	System Roots
	GlobalSign Root CA	certificate	Jan 28, 2028, 3:00:00 PM	System Roots
	Go Daddy Class 2 Certification Authority	certificate	Jun 29, 2034, 8:06:20 PM	System Roots
	Go Daddy Root Certificate Authority - G2	certificate	Jan 1, 2038, 2:59:59 AM	System Roots
	Government Root Certification Authority	certificate	Dec 31, 2037, 6:59:59 PM	System Roots
	Hellenic Academic and Research Institutions RootCA 2011	certificate	Dec 1, 2031, 4:49:52 PM	System Roots
	Hongkong Post Root CA 1	certificate	May 15, 2023, 7:52:29 AM	System Roots

177 items

Simplified TLS 1.3 (2018)

Key exchange and encryption only



Generate K_{s1}, K_{p1}



K_{p1}

1. Generate K_{s2}, K_{p2}
2. Derive $k = \text{kex}(K_{s2}, K_{p1})$

K_{p2}

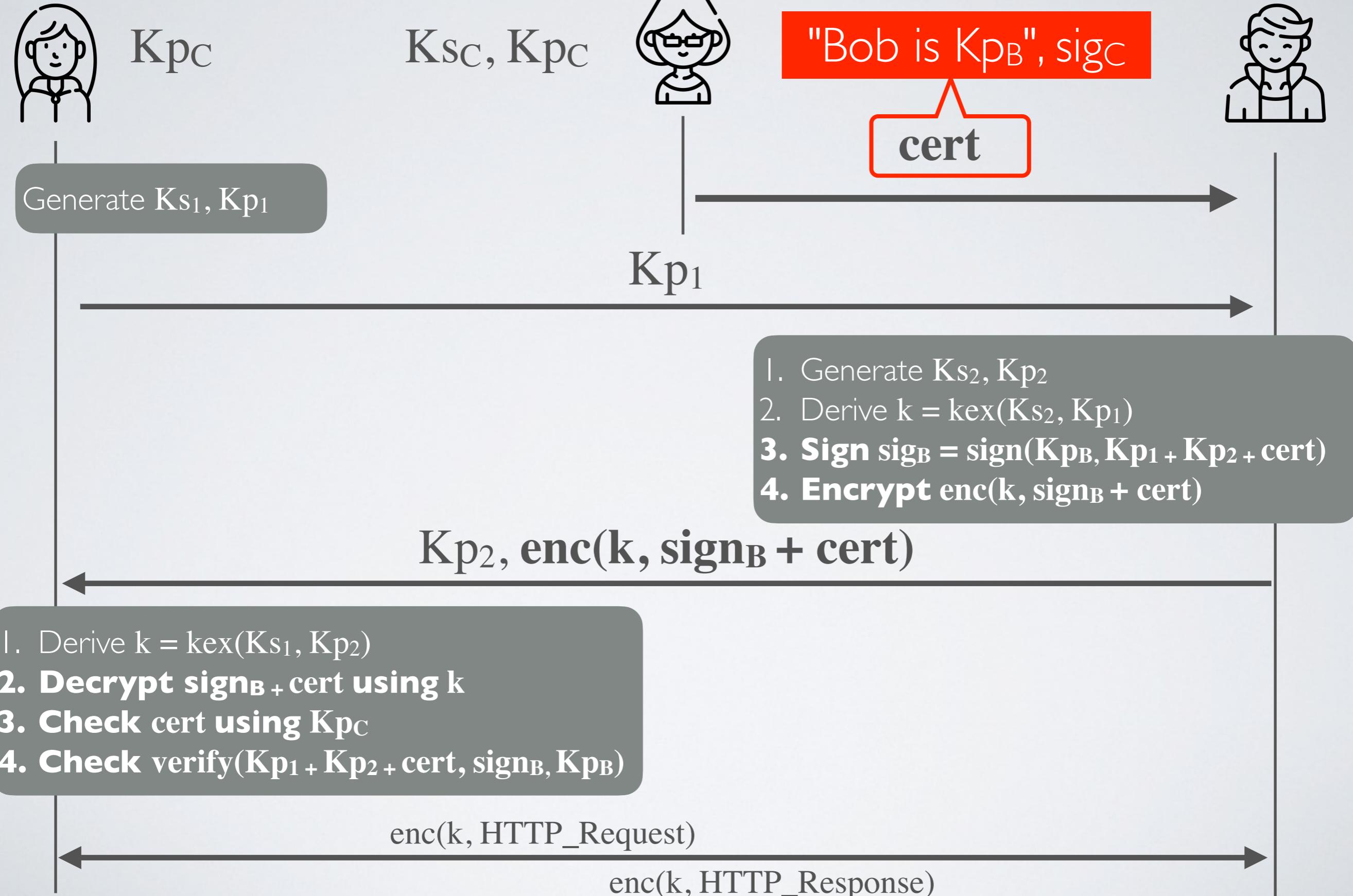
Derive $k = \text{kex}(K_{s1}, K_{p2})$

$\text{enc}(k, \text{HTTP_Request})$

$\text{enc}(k, \text{HTTP_Response})$

Simplified TLS 1.3 (2018)

Adding one-way authentication



This afternoon,
let's implement HTTPS in Python