A!
Aalto University

The Undeniable Truth:
How Remote Attestation Circumvents Deniability Guarantees in Secure Messaging Protocols

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Two trends

1. Hardware-based trusted execution environments (TEEs) are pervasively deployed

2. Increasing popularity of deniable communication mechanisms in messaging apps

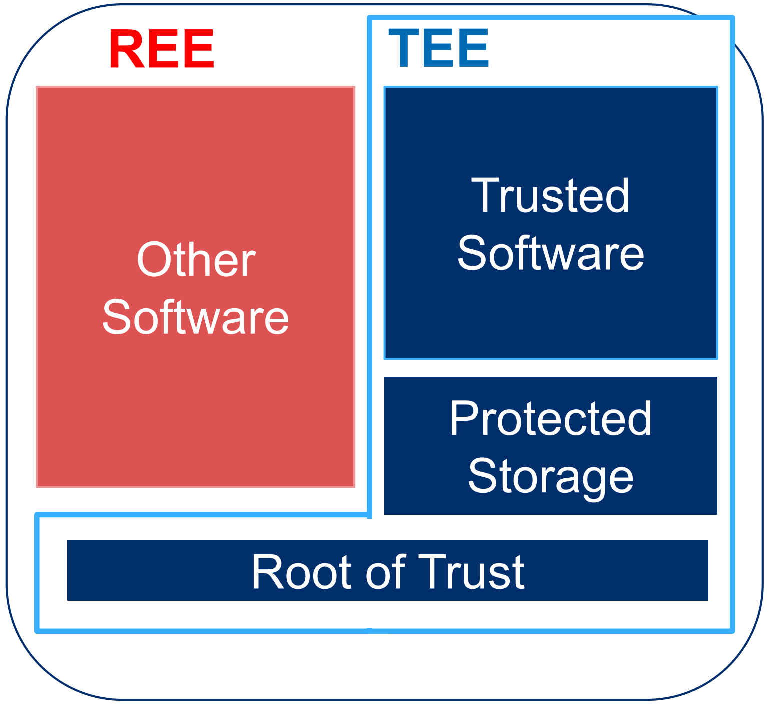
Outline

- What are TEEs and remote attestation?
- What is deniability and why should we care?

- Attack: Breaking deniability of messaging protocols using remote attestation
- Demo video
- Countermeasures

TEEs and Attestation

Hardware-security mechanisms are pervasive



Hardware support for

- **Isolated execution: Isolated Execution Environment**
- **Protected storage: Sealing**
- **Ability to convince remote verifiers: Remote Attestation**

[Trusted Execution Environments (TEEs)]()

Operating in parallel with "rich execution environments" (REEs)

Cryptocards

https://www.ibm.com/security/cryptocards/

Trusted Platform Modules

https://www.infineon.com/tpm

ARM TrustZone

https://www.arm.com/products/security-on-arm/trustzone

Intel Software Guard Extensions

https://software.intel.com/en-us/sgx

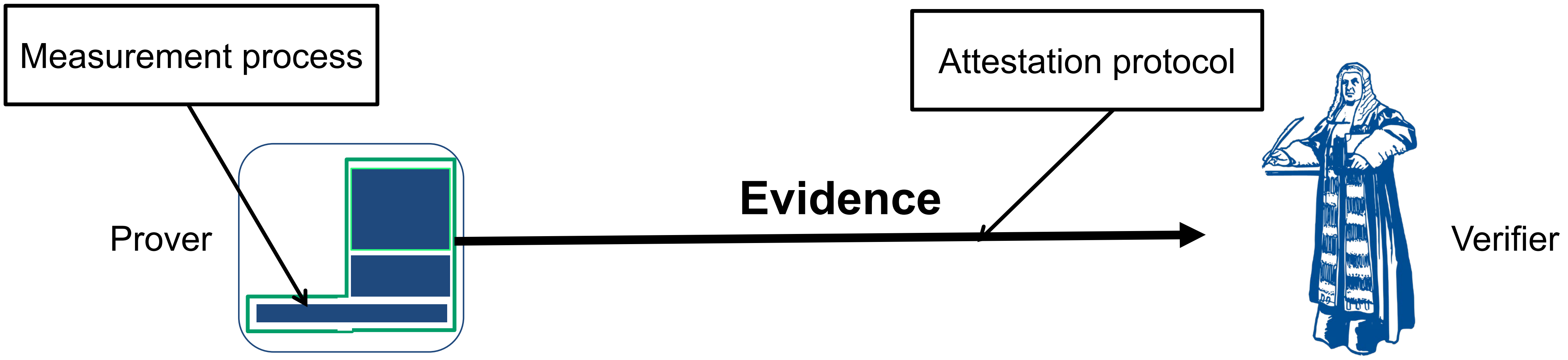
[A+14] "Mobile Trusted Computing", Proceedings of the IEEE, 102(8) (2014)

[EKA14] "Untapped potential of trusted execution environments", IEEE S&P Magazine, 12:04 (2014)

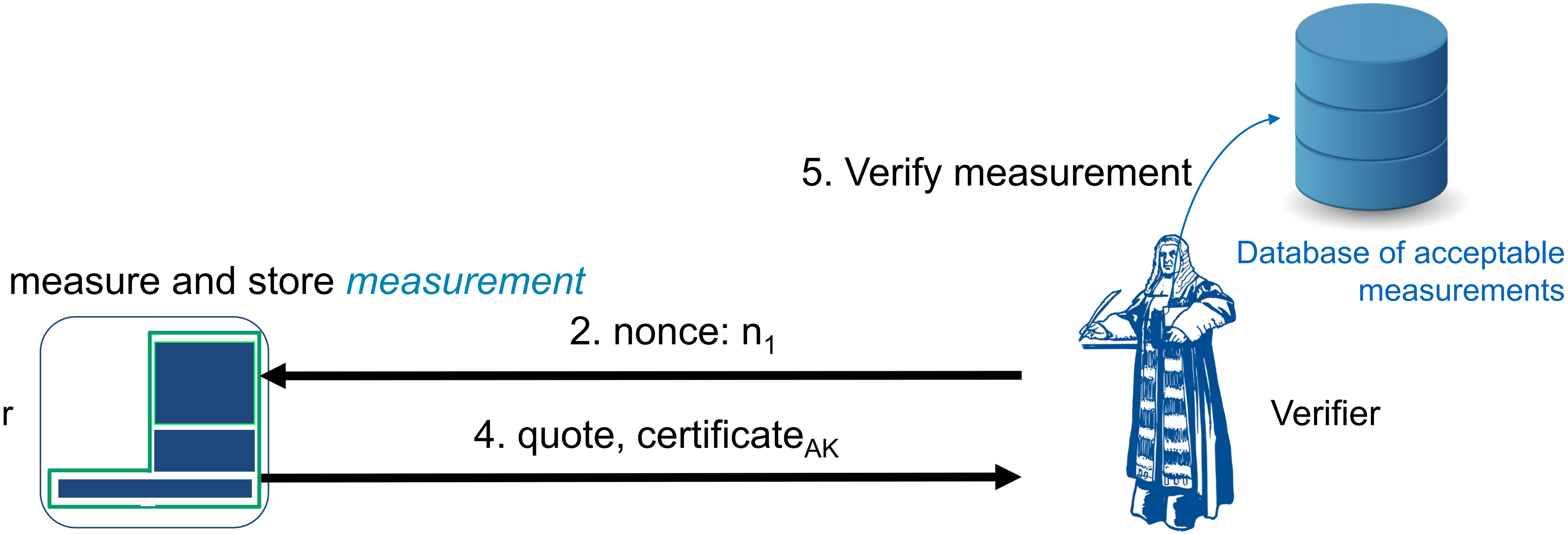
What is remote attestation?

Verifier **ascertains current state and/or behaviour of** ***Prover***

What are the security requirements?



Attestation Protocol



5. Verify measurement

Database of acceptable measurements

1. securely measure and store *measurement*

2. nonce: n_1

Prover

4. quote, certificate_{AK}

Verifier

3. quote = signature_{AK}(*measurement*, n_1 || channel info)

AK: attestation key known only to root-of-trust on device

Certificate_{AK}: certificate for AK issued by a CA trusted by verifier

Attestation in practice

Introduced in late 1990s by Trusted Computing Group for Trusted Platform Modules

Supported in modern TEEs (Intel SGX, certain Trusted OSs for ARM TrustZone)

Measurement: hash of executable (“binary attestation”); can be of arbitrary property

Attestation can be chained

- Binary attestation to verify some application (and its key) and some application-provided data
- Property attestation verified by application and signed by application key

If your TEE can locally verify some property, it can convince a remote verifier of the same

Deniable Messaging

Desiderata for messaging protocols

1. Authenticity. If I send you a message, you can tell whether it is authentic

Deniable protocols have an extra, seemingly conflicting objective:

2. Deniability. You can’t prove to anyone else that a message came from me

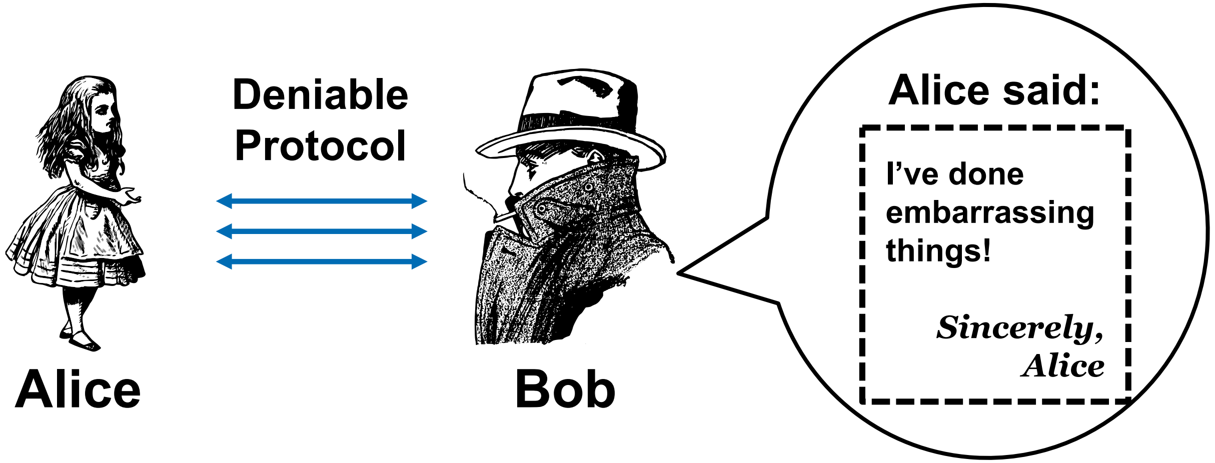
- Recipient can differentiate between real messages and forgeries
- Goal: easy to make forgeries that look realistic to everyone else

Signal, WhatsApp, Pidgin etc. now include protocols for cryptographic deniability

The limits of deniability?

A naïve view:

- Alice: “I can tell Bob things that can damage me, because he can’t convince anyone else without irrefutable evidence.”



Alice said:

I’ve done embarrassing things!

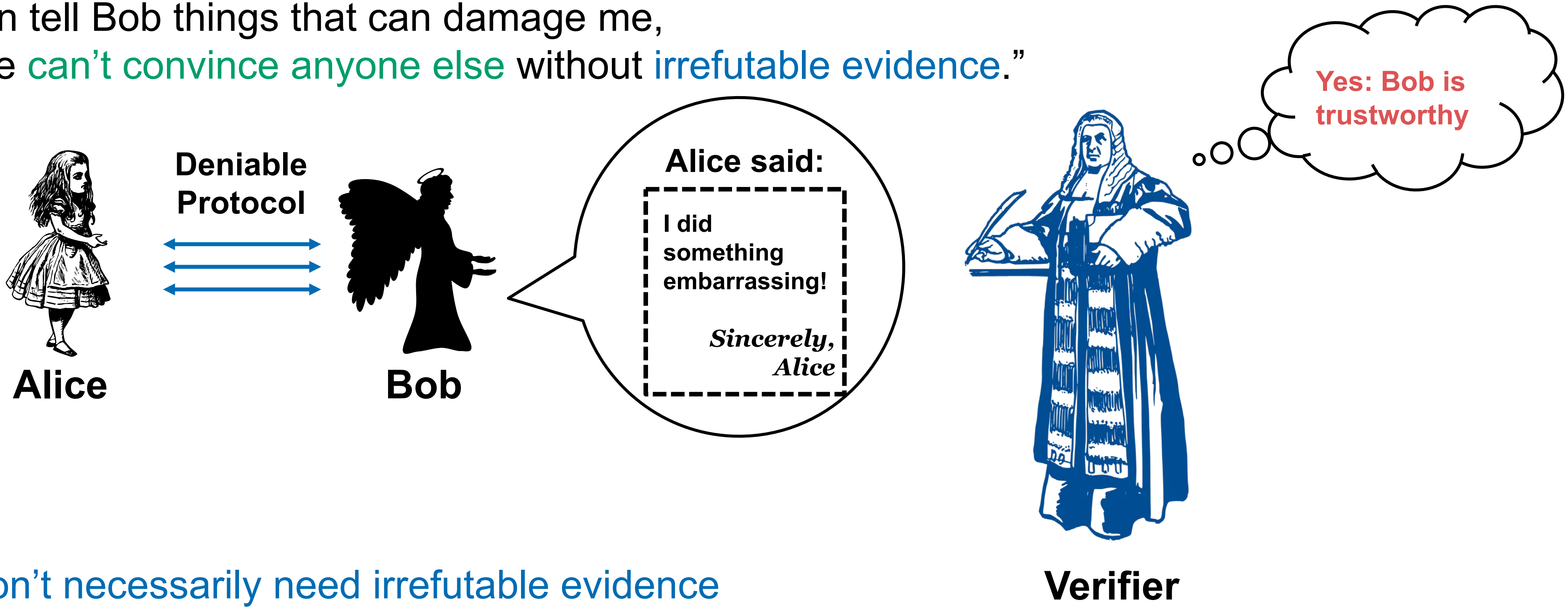
Sincerely,
Alice

Verifier

The limits of deniability?

A naïve view:

- Alice: “I can tell Bob things that can damage me, because he can’t convince anyone else without irrefutable evidence.”



The reality:

- Verifiers don’t necessarily need irrefutable evidence
- Plaintext is enough if conveyed by a trusted informant

When is (cryptographic) deniability useful?

When the informant is untrustworthy

People may trust:

- Witnesses under oath
- Journalists
- …

But may not trust, e.g., APT28, a.k.a.

- Fancy Bear
- Sofacy
- Guccifer 2.0
- GRU Units 26165/74455

A new kind of attack

Data dumps are now common:

- World Anti-Doping Agency (2016)
- US Democratic National Committee (2016)
- En Marche (2017)
- Yousef Al Otaiba (2017)
- International Olympic Committee (2018)

But can include fabricated material

- thus limits attacker credibility

The dangers of undeniable communications

But the material itself may contain proof of origin

After the DNC 2016 email leaks:

- Some claimed emails were doctored

BRAZILE ON SUGGESTIONS SHE LEAKED TOWN HALL QUESTION TO CLINTON
FOX NEWS ALERT
FOX NEWS channel

https://www.foxnews.com/politics/dnc-boss-brazile-claims-wikileaks-emails-doctored-in-contentious-interview

"I have seen so many doctored emails. I have seen things that come from me at two in the morning that I don't even send”

The dangers of undeniable communications

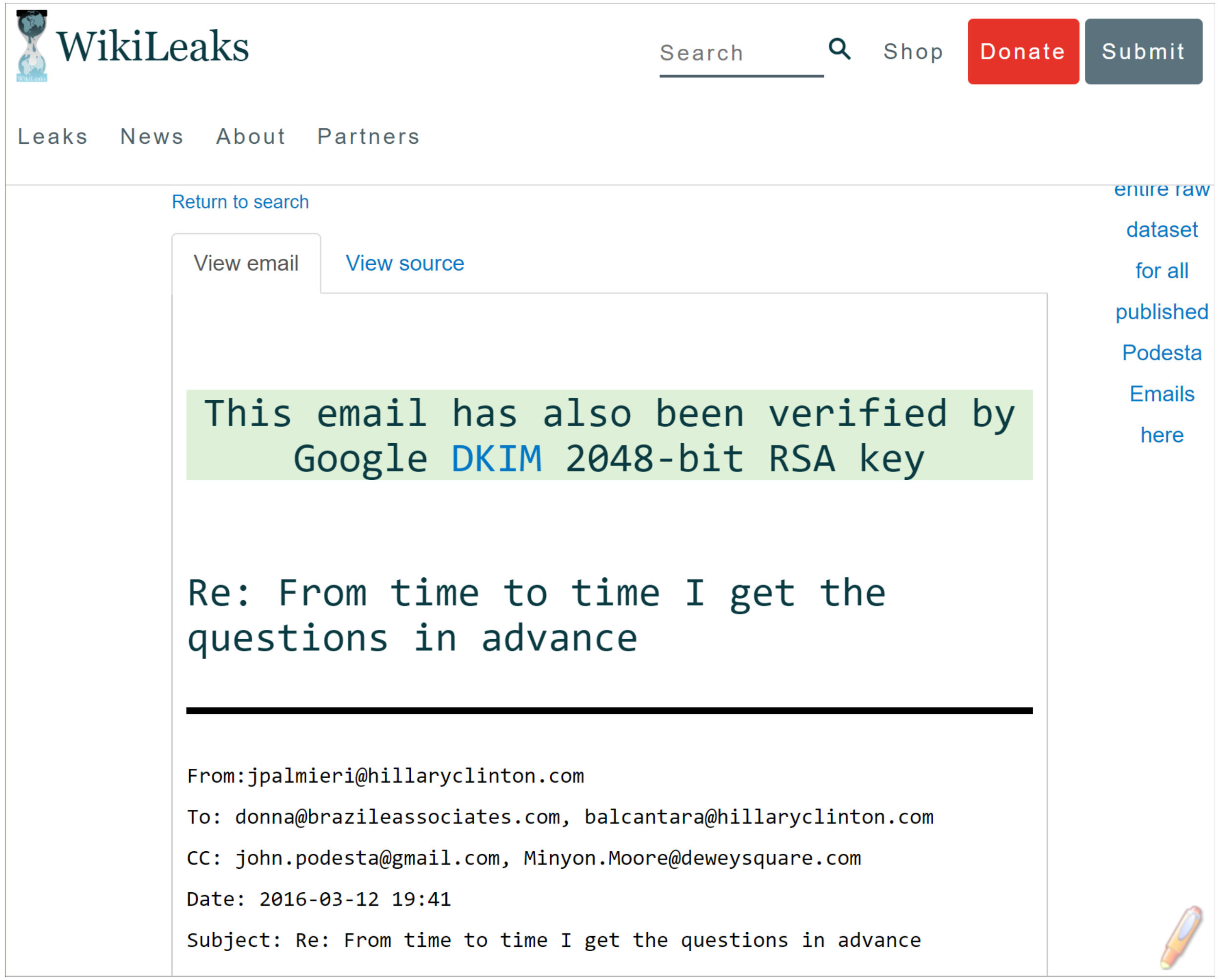
But the material itself may contain proof of origin

After the DNC 2016 email leaks:

- Some claimed emails were doctored

Shortly afterwards, WikiLeaks publish DKIM signatures

If you want deniability, you need to use deniable protocols

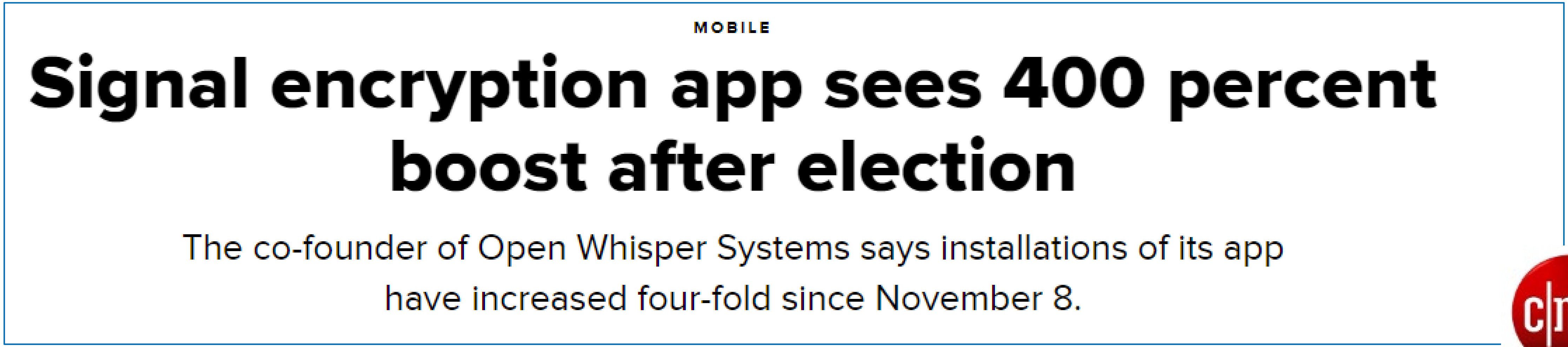


This email has also been verified by Google DKIM 2048-bit RSA key

Re: From time to time I get the questions in advance

```
From:jpalmieri@hillaryclinton.com
To: donna@brazileassociates.com, balcantara@hillaryclinton.com
CC: john.podesta@gmail.com, Minyon.Moore@deweysquare.com
Date: 2016-03-12 19:41
Subject: Re: From time to time I get the questions in advance
```

https://wikileaks.org/podesta-emails/emailid/5205



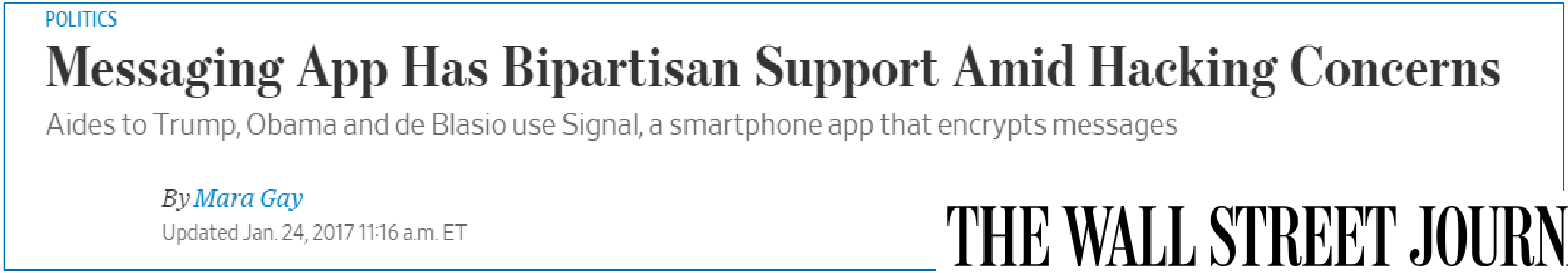
MOBILE

Signal encryption app sees 400 percent boost after election

The co-founder of Open Whisper Systems says installations of its app have increased four-fold since November 8.

c|net

https://www.cnet.com/news/signal-open-whisper-systems-donald-trump/



POLITICS

Messaging App Has Bipartisan Support Amid Hacking Concerns

Aides to Trump, Obama and de Blasio use Signal, a smartphone app that encrypts messages

By Mara Gay

Updated Jan. 24, 2017 11:16 a.m. ET

THE WALL STREET JOURNAL.

https://www.wsj.com/articles/messaging-app-has-bipartisan-support-amid-hacking-concerns-1485215028

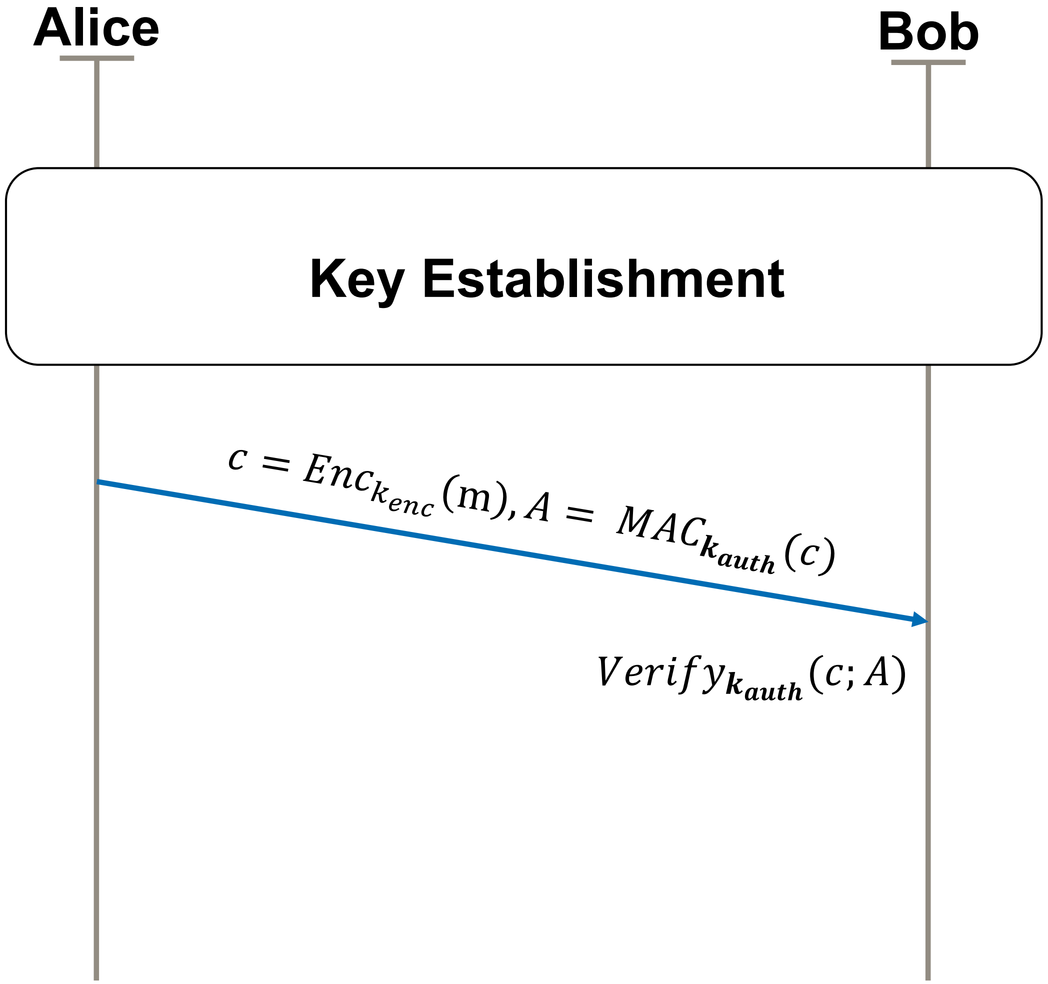
What do deniable protocols look like?

Asymmetric key-exchange protocol

- Result: shared symmetric key

Symmetric session crypto

- Verifying MAC requires the same key
- Able to verify ⇒ Able to forge


Alice
Bob
Key Establishment
$c = Enc_{k_{enc}}(\mathrm{m}), A = MAC_{k_{auth}}(c)$
$Verify_{k_{auth}}(c; A)$

Easy to forge transcripts that look realistic

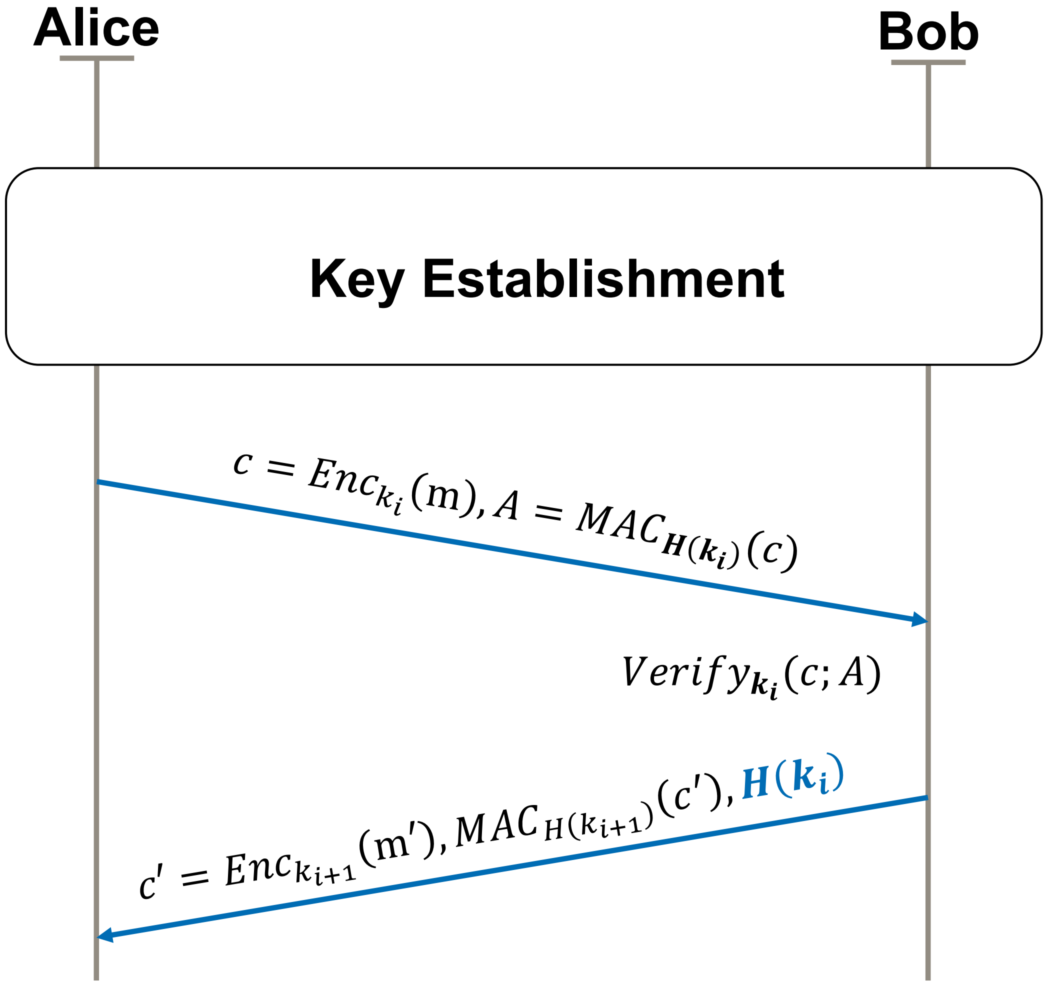
Deniable protocols: Off-the-Record (OTR)

First messaging protocol designed for deniability

Protocol flow:

1. Wait for message
2. Verify MAC on new message
3. Update MAC key; release previous MAC key

Anyone can now make valid authentication tags



Alice
Bob
Key Establishment
$c = Enc_{k_i}(\mathrm{m}), A = MAC_{\boldsymbol{H}(\boldsymbol{k_i})}(c)$
$Verify_{\boldsymbol{k_i}}(c; A)$
$c' = Enc_{k_{i+1}}(\mathrm{m}'), MAC_{H(k_{i+1})}(c'), \boldsymbol{H}(\boldsymbol{k_i})$

Easy to forge transcripts that look realistic

Deniable protocols: Signal Protocol

Notation

x:	Diffie-Hellman private key
g^x:	Diffie-Hellman public key

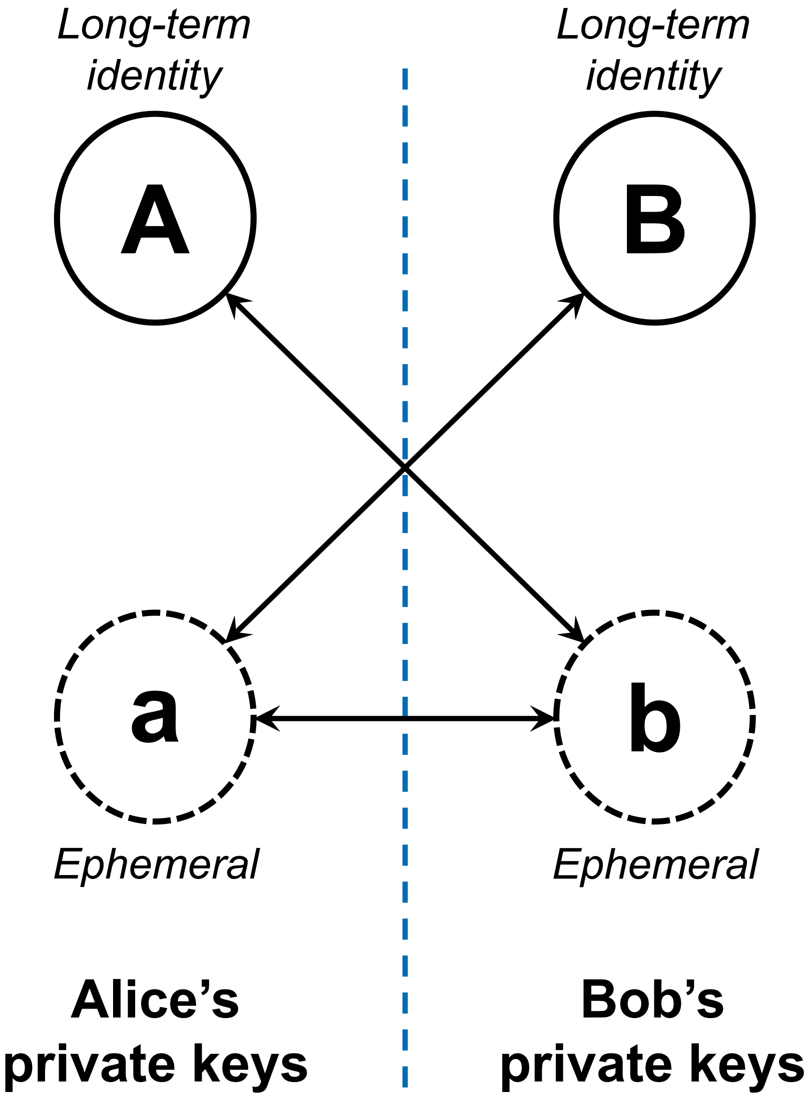
Key exchange: X3DH

$$k = H(\, g^{Ab} \parallel g^{aB} \parallel g^{ab} \,)$$

To get the key, need each Diffie-Hellman pair:

- A or b
- a or B
- a or b

If I know a and keep it secret, then I share the key with someone who knows B.

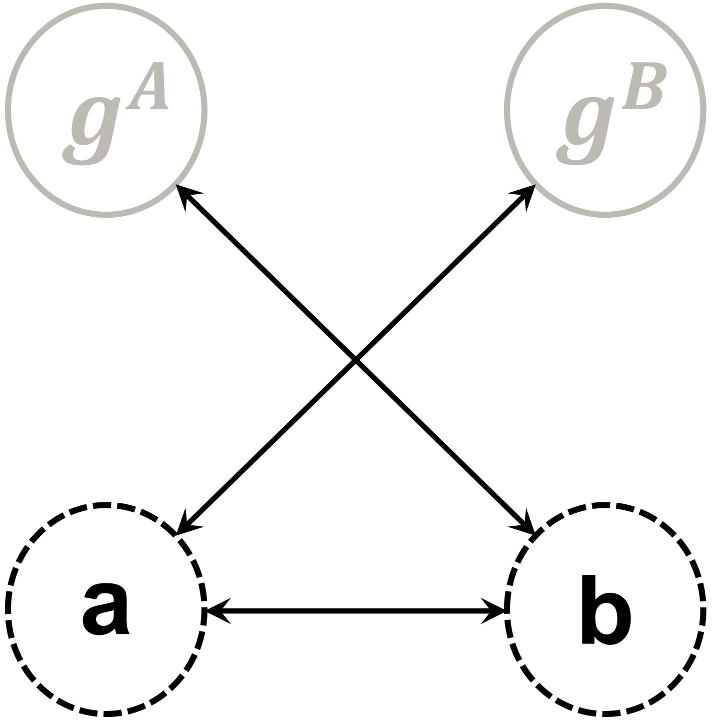


Deniable protocols: Signal Protocol

Anyone can forge the key exchange:

1. Pick random ephemeral private keys $\boldsymbol{a}$, $\boldsymbol{b}$
2. Look up public keys $\boldsymbol{g^A}, \boldsymbol{g^B}$
3. Compute $\boldsymbol{k}$ from *a*, *b*, and the public keys

But Bob can still authenticate Alice



$$\boldsymbol{k = H\left(\, g^{Ab} \parallel g^{aB} \parallel g^{ab} \,\right)}$$

Easy to forge transcripts that look realistic

The Attack

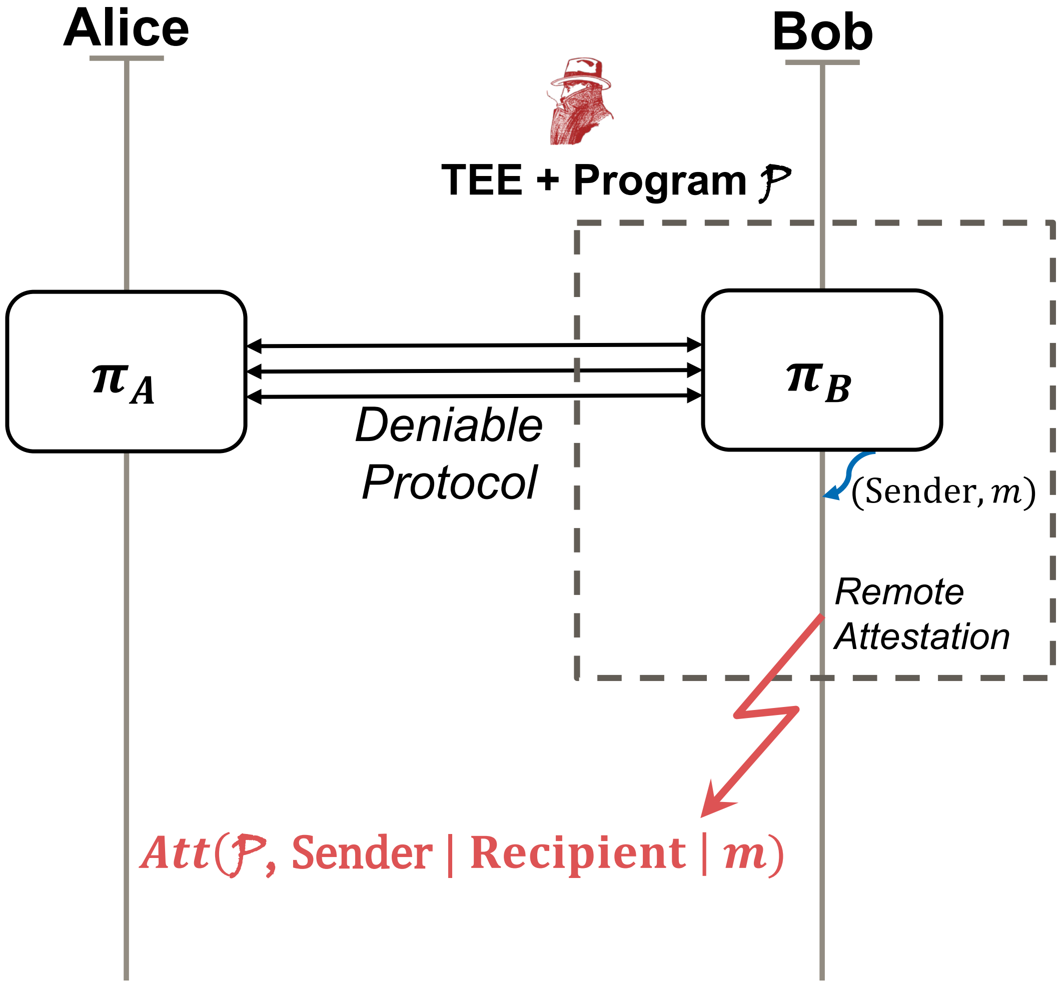
An overview of our attack

1. **Take a normal messaging client**

2. **Modify it to run inside a TEE**

3. **Produce a transcript of each session**

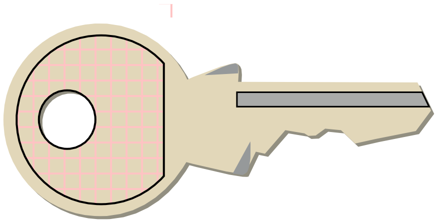
4. **Emit an attestation**
   - Shows that the transcript came from a correct client


Alice
Bob
TEE + Program $\mathcal{P}$
π_A
π_B
Deniable Protocol
(Sender, m)
Remote Attestation
$Att(\mathcal{P}, \text{Sender} \mid \text{Recipient} \mid m)$

Key point: TEEs let us prove that a key was secret

Symmetric authentication:

- Able to verify ⇒ Able to forge



No restrictions on usage.

Key point: TEEs let us prove that a key was secret

Symmetric authentication:

- Able to verify ⇒ Able to forge

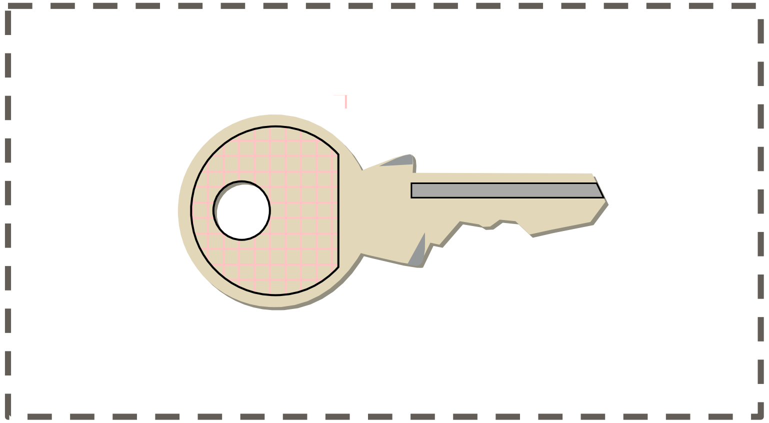
A key in a TEE is protected.

- Only program $\mathcal{P}$ can use it

Remote attestation:

- Assures verifiers that TEE runs program $\mathcal{P}$
- Proof that Alice’s messages in the transcript were not forged!

TEE + Program $\mathcal{P}$

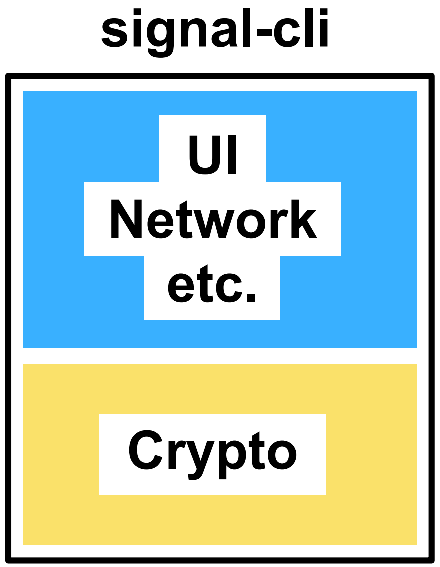


Follows the rules of $\mathcal{P}$

Modifying a Signal client

We use Signal as an example:

- Popular
- Convenient software architecture
- But any protocol would do



Modifying a Signal client

We use Signal as an example:

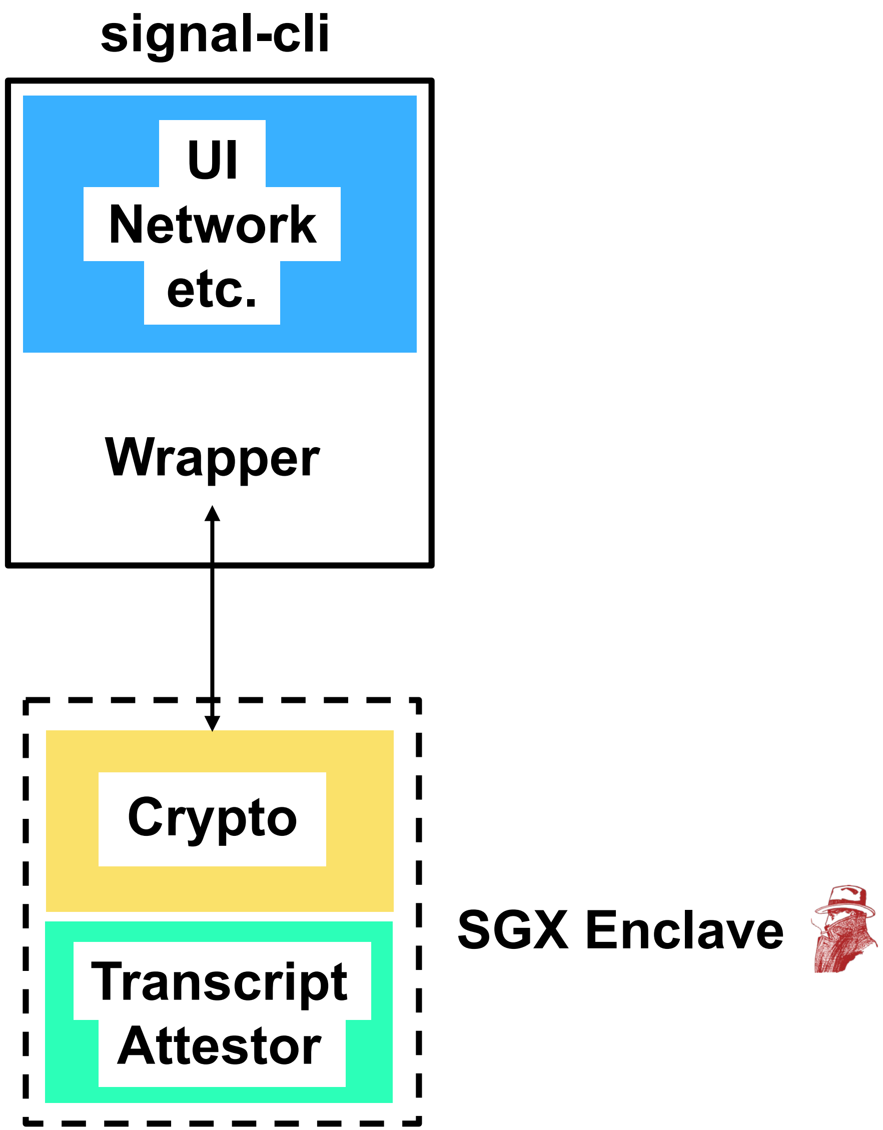
- Popular
- Convenient software architecture
- But any protocol would do

SGX enclave contains:

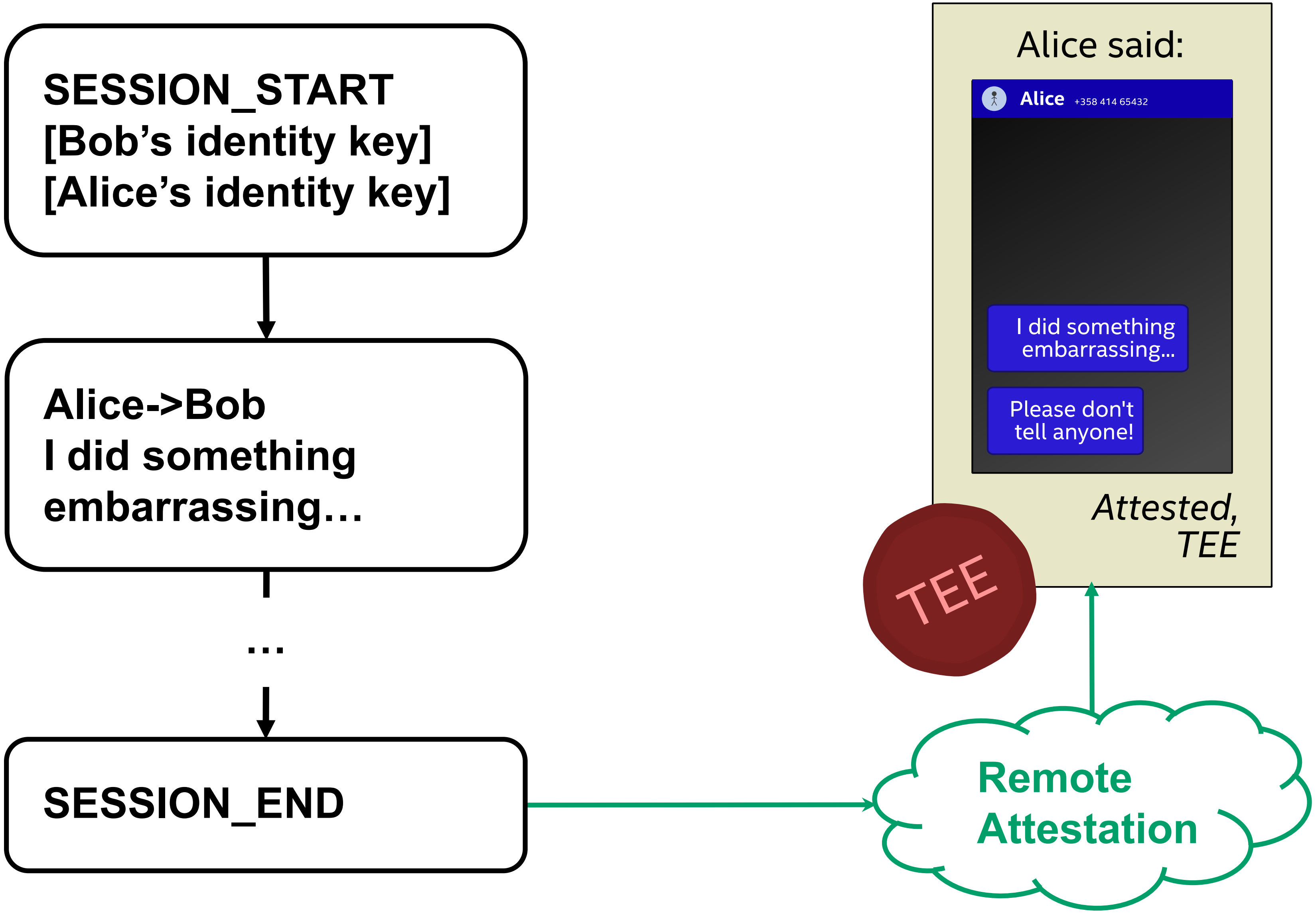
- *libsignal-protocol-c*
- Transcript generation

Modified (unofficial) *signal-cli*:

- Uses enclave for crypto



The result: an attested transcript



SESSION_START
[Bob’s identity key]
[Alice’s identity key]

Alice->Bob
I did something embarrassing…

…

SESSION_END

Alice said:

Alice +358 414 65432

I did something embarrassing...

Please don't tell anyone!

Attested,
TEE

Remote Attestation

Demo

Countermeasures

Countermeasures

Skip to summary

Switch to online-deniable protocols

Defensive remote attestation

Put a human in the loop

Switch to online-deniable protocols

“Classic” deniability fails with an interactive verifier

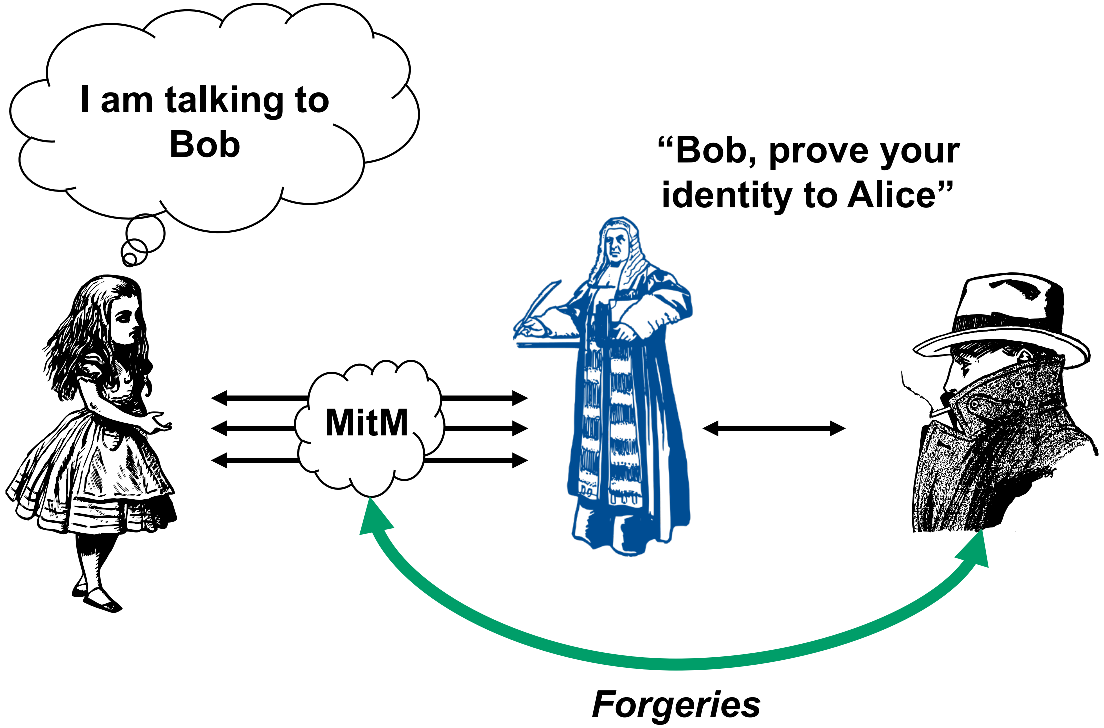
- Verifier becomes the endpoint
- Bob used as identity-key oracle

Solution – Online-deniable protocols:

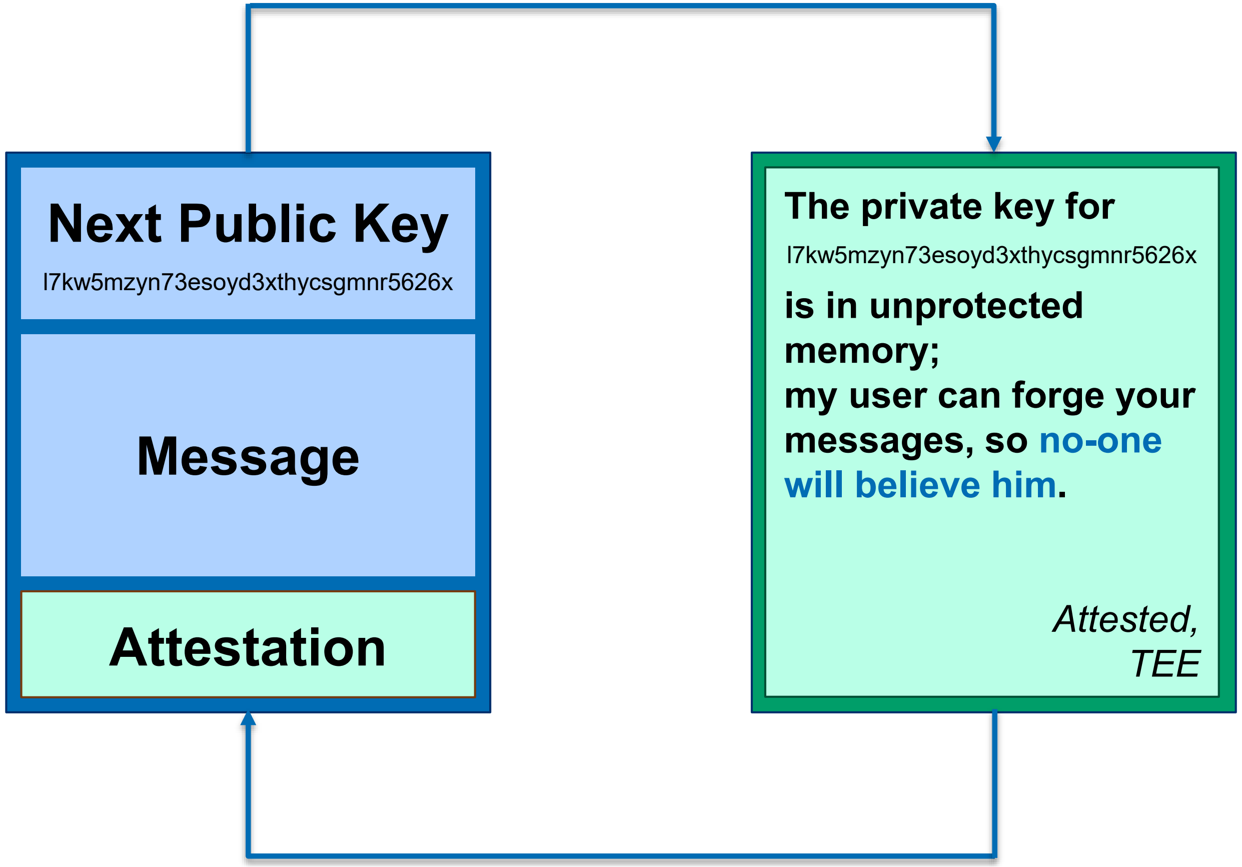
- Let identity-key holder MitM the session
- Verifier needs to trust Bob!

OTRv4 is online-deniable
https://github.com/otrv4/otrv4

Attack still possible if identity-key created within the attack TEE



Defensive remote attestation

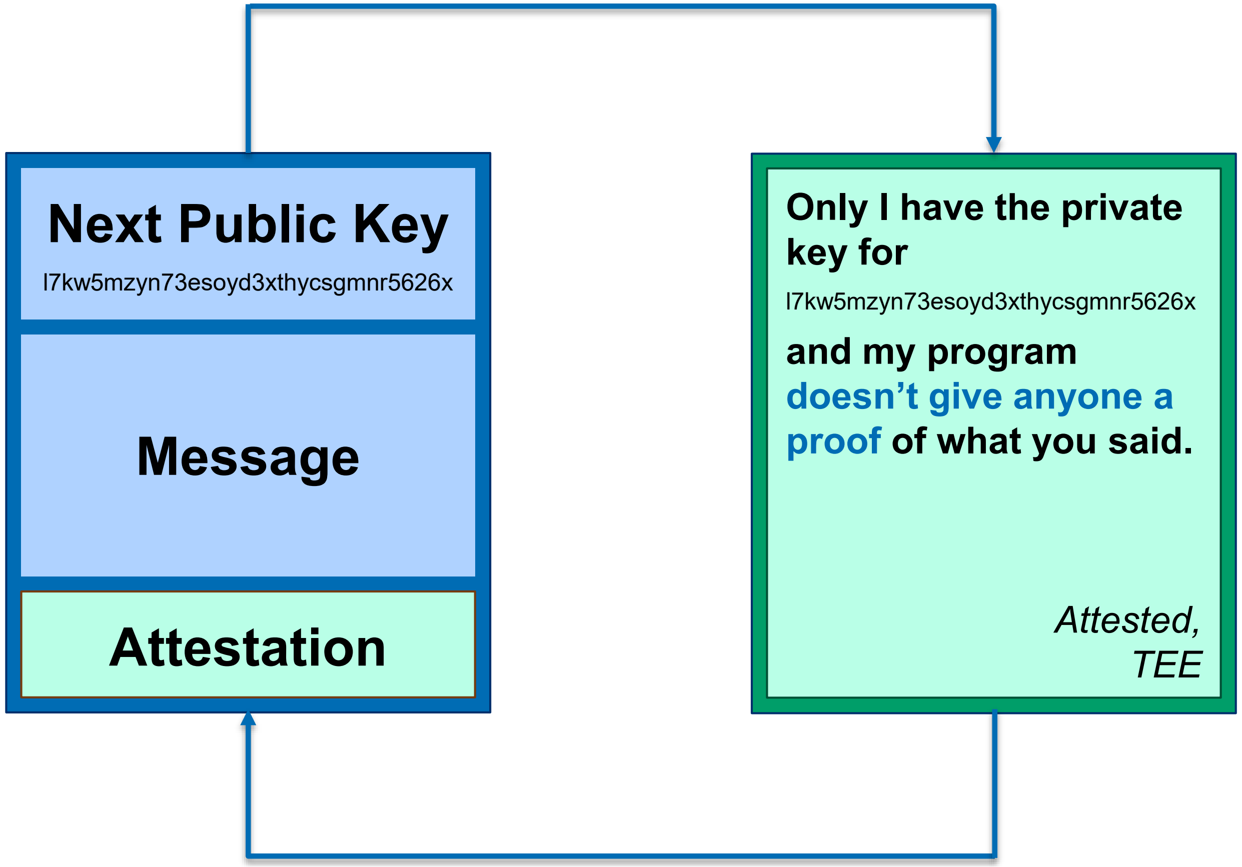


The private key for l7kw5mzyn73esoyd3xthycsgmnr5626x is in unprotected memory;
my user can forge your messages, so no-one will believe him.

Attested,
TEE

Use attestation to assure Alice about the behavior of Bob’s TEE

Defensive remote attestation



Next Public Key

l7kw5mzyn73esoyd3xthycsgmnr5626x

Message

Attestation

Only I have the private key for

l7kw5mzyn73esoyd3xthycsgmnr5626x

and my program doesn't give anyone a proof of what you said.

Attested, TEE

Use attestation to assure Alice about the behavior of Bob's TEE

Put the human in the loop

Hardware can only attest what is verifiable on the machine

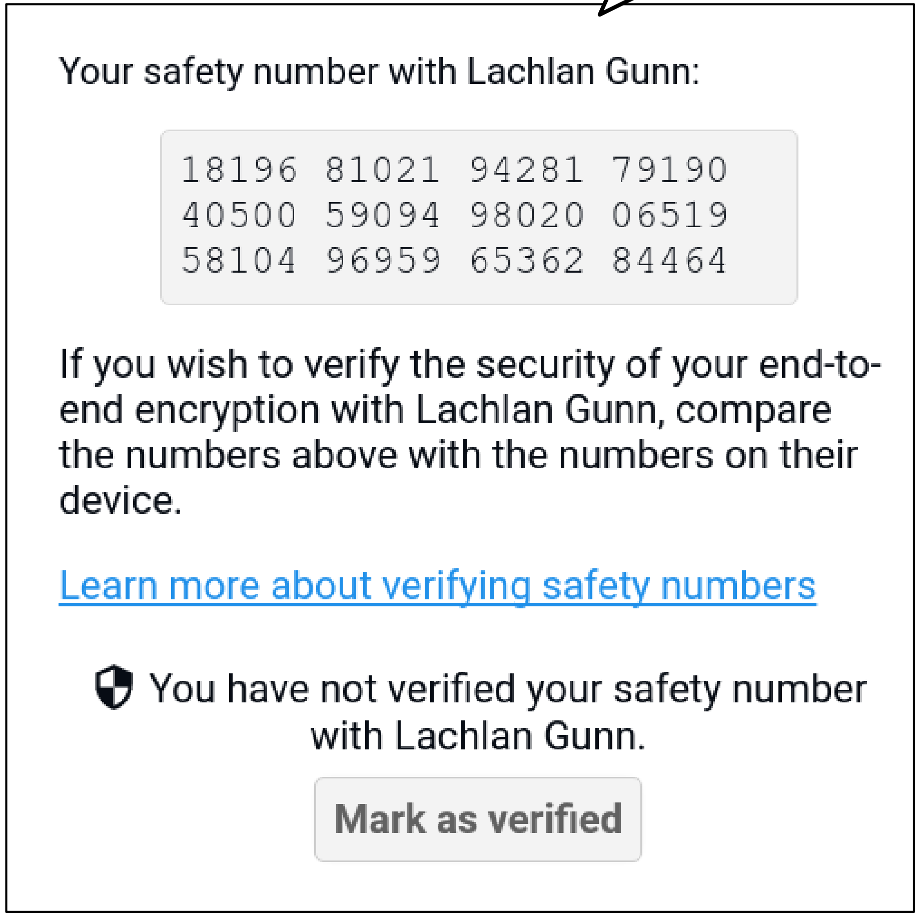
Requiring human input is helpful:

- Use a different identity key for each recipient
- Verify fingerprints manually

Attack attests only a key but not who owns it

Compatible with current UIs

Signal's UI



Your safety number with Lachlan Gunn:

```
18196 81021 94281 79190
40500 59094 98020 06519
58104 96959 65362 84464
```

If you wish to verify the security of your end-to-end encryption with Lachlan Gunn, compare the numbers above with the numbers on their device.

Learn more about verifying safety numbers

You have not verified your safety number with Lachlan Gunn.

Countermeasures

Switch to online-deniable protocols

- *Deployability: high*
- *Effectiveness: medium*

Our recommendation

Defensive remote attestation

- *Deployability: low*
- *Effectiveness: high*

Put a human in the loop

- *Deployability: medium*
- *Effectiveness: medium*

Takeaway messages

- Deniability is important
- Attestation undermines deniability guarantees in messaging protocols
- Online-deniable protocols (e.g. OTRv4) reduce attack window

ia.cr/2018/424 (to appear in PETS 2019)

https://asokan.org/asokan/
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